A Study on Spatial and Temporal Variability of Black Carbon in Urban and Rural Background in Rwanda

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A Study on Spatial and Temporal Variability of Black Carbon in Urban and Rural Background in Rwanda

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Declaration

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

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Signed……..

Date……..

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ABSTRACTS

Air pollution is an environmental problem because of its effects on the health and quality of life. Rwanda is currently facing severe air quality problems that is due to a rapid urbanization process, land use changes, socio-economic transformation and a high population growth. This study focused on the spatial and temporal variability of Black Carbon mass concentration in two different backgrounds. BC data was measured continuously for the period from 7th July to March 31st at CST, an urban background by using a BC 1054 Multi-spectrum BC Monitor and another at MUGOGO station a rural using Magee Scientific 7-wavelength Aethalometer. Diurnal, monthly, seasonal and day of the week trends and correlation with meteorological parameters (T, RH) were analyzed. From the analysis, the concentration of BC were significantly low in the rainy compared to the dry season. The maximum hourly mean in Kigali was 15.007±2.216 µg/m^{3}compared to 10.252±1.649 µg/m^3 at Mugogo. A weekend effect was observed in Kigali with a decrease of BC concentrations during the weekend likely resulting from the reduction of emission activities but at Mugogo, there is no effect as the activities responsible for the emission of BC are present throughout the week. A positive correlation was found between Black Carbon and CO (R=0.70) at Kigali. A weak negative (R=-0.2180) and positive(R=0.249) correlation were observed between BC and T, RH in Kigali respectively and no correlation was found between them in Mugogo

Monthly variation was observed by having the maximum monthly concentrations in July of 6.40 µg/m^3 and 3.99 µg/m^3 and the lowest in October (3.12 µg/m$^{3)}$ and November (0.47 µg/m$^{3)}$ for Kigali and Mugogo respectively and higher values were reported at Kigali.

As biomass is the dominant cooking fuel used in Rwanda and is likely to lead to the local pollution and adverse health impacts. Other alternative cooking fuels which are pollution free should be used and the use of renewable energy should be prioritized.

As the present study only focused on 2 background areas, it is recommended that future work should be conducted in the remaining areas to get a better overall view on BC trends in Rwanda.

KEY WORDS

Black Carbon (BC), Air pollution, Particulate Matter, Air quality, Mugogo, Kigali

LIST OF SYMBOLS AND ACRONYMS

µg: Microgram

BC: Black Carbon

CMU: Carnegie Mellon University

CO: Carbon Monoxide

CST: College of Science and Technology

EPA: Environmental Protection Agency

IAQ: Indoor Air Quality

PM: particulate Matter

PM10: Particles that are 10 micrometers in diameter or less

PM2.5: Particles that are 2.5 micrometers in diameter or less

ppb: part per billion

ppm: part per millions

REMA: Rwanda Environment Management Authority

RH: Relative Humidity

T: Temperature

WAM: West African Monsoon

WHO: World Health Organization

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CHAPTER 1. INTRODUCTION

1.1 Background of the study

Pollution is the unwanted change in natural characteristics of air, land and water which may be dangerous to the human life, living conditions and cultural resources or that may waste or deteriorate raw natural resources [1]. Air pollution is recognized as one of the serious environmental problem because of the several negative impacts caused by many air pollutants on the health and the quality of life [2].

According to reports of WHO, at a global level one in eight premature deaths can be associated presently to poor air quality, and these deaths are more intense in developing countries [3].

Black carbon is known as the primary elements of atmospheric aerosols emitted from incomplete combustion of fossil fuels and biomass burning [4]. Because of the capacity of Black Carbon to absorb light and its known agent as a driver of global warming, the way that it is distributed spatially and its change of time cause Black Carbon to have an atmospheric significances [5]. Black carbon is a global environmental problem that has negative effects for both human health and our climate. Nowadays, researchers are interested in studies on atmospheric aerosols like Black Carbon because of their negative implications like influence on climate, changes in precipitation patterns, negative influence on the visibility and causing harmful effects on human health [6].

Studies done on short-term health effects have revealed that those associated with Black Carbon are more strong than those with PM2.5, PM10, signifying that Black Carbon ban be the best indicator of dangerous particulate matter emitted from combustion sources rather than Particulate Matter mass [7, 8].

The unceasing use of expensive fossil fuel have many negative side effects on human health damage, degradation of the environment, lowering the productivity of human effort, causing a low economic development in a country which has a high number of population and landlocked like Rwanda [9].

The primary source of energy in Rwanda continues to be biomass principally used in cooking and represent 85% of the energy balance in Rwanda. The most forms of biomass used in Rwanda are firewood which accounts for 57%, charcoal with (23%) and crop waste with other fuel which account (6%) [10].

The relative importance of local and regional emission sources of Black Carbon has not been well quantified yet in many areas of Rwanda, which does not facilitate in the preparation of the design mitigation. Therefore, it is important to do an improved scientific understanding of the variation of Black Carbon pollution in urban and rural areas in Rwanda which will help policy makers and other environmental authorities in designing effective mitigation options.

The main objective of this study therefore was to assess the spatial and temporal variation of Black Carbon mass concentration in Rwanda in urban and rural background.

1.2 Problem statement

Air Pollution is currently known today as the largest environmental cause of diseases and premature deaths in the world [11].

Air pollution is an international problem with many negative effects on health and the environment. Because of the the high level of population growth in Rwanda and an increase in number of vehicles and urbanization, air quality is being worsened which affects the day to day life of the entire Rwandan population and its environment [12].

The air pollution is mainly caused by the general use of fossil fuels in transport, power generation, domestic and industry sectors. Other contributors to pollution are the use of firewood, agricultural and animal waste as cooking fuels [13].

Air quality problems are being presently threatening our country Rwanda because mainly of the rapid urbanization processes in the country, land use changes, socioeconomic transformation and high population growth. A large fraction of Rwandan fleet is made by older vehicles and they are responsible for emitting more pollutants [14]. In Rwanda, in 2012, 2,227 deaths were attributed to ambient air pollution and resulted in a total of 108,622 years of life lost. The main cause of death and years of life lost from poor air quality in Rwanda was acute lower respiratory disease or stroke. Long term health conditions associated with poor air quality can also put a strain on health services; in 2012 the top cause of morbidity in health

centers in Rwanda was acute respiratory infections, accounting for 21.7% of all patients admitted to health centers and 6.8% of patients admitted to hospitals. Respiratory infections are the largest cause of deaths in children under the age of five in Rwanda [15].

The relative importance of local and regional emission sources of Black Carbon has not been well quantified yet in many areas of Rwanda, which does not facilitate in the preparation of the design mitigation. Therefore, it is important to do an improved scientific understanding of the variation of Black Carbon pollution in urban and rural areas in Rwanda which will help policy makers and other environmental authorities in designing effective mitigation options.

1.2 Objectives of the Study

The main objective of the study is to assess the spatial and temporal variation of BC in two different background (rural and urban) in Rwanda.

In this project we will be achieved through exploring the following specific objectives:

- ✓ To assess the variability of BC over urban and rural areas during the week days and weekends
- ✓ Assess the correlation between meteorological parameters (T and RH) with BC concentration
- ✓ Evaluate the diurnal and seasonal fluctuations of Black Carbon concentrations,
- ✓ To assess the monthly variation of Black Carbon concentration
- ✓ To evaluate the contribution of BC in PM2.5 in Kigali

1.3 Hypothesis of the Study

Based on the population growth, the rapid urbanization, the increase of vehicles and use of biomass fuel as the main fuel for cooking in Rwanda, The concentration of BC in urban and rural areas in Rwanda is expected to be high. There is a diurnal and seasonal fluctuation of BC, weekdays are more polluted than weekend days.

CHAPTER II. LITERATURE REVIEW

2.1 Basics of black carbon

Black carbon are small, dark particles (with a diameter less than 2.5micrometer) produced from incomplete combustion of biomass and fossil fuels [16].

Along with soot, other particles such as sulfur dioxide, nitrogen oxides and organic compounds are also emitted from the combustion. Elemental carbon (EC) is a subset of BC that includes only carbon not bound to other elements, but possibly present in one or more of multiple allotropic forms [4].

Black carbon (BC) in the atmosphere impacts the Earth's energy balance through the absorption of solar radiation (direct aerosol effect) and the altering of clouds (indirect and semi-direct aerosol effects), but with large uncertainties associated with its individual and total climate effects [17].

The life time of BC is of the order of days to several weeks, depending on the location. Thus the BC concentration and its global heating will decrease almost immediately after reduction of its emission.

BC has many harmful effects on climate, ecosystems and human health. BC has a global warming effect on climate, as indicated by its radiative forcing values. BC influences climate through multiple mechanisms, it has a direct effect of directly absorbing sunlight and reducing the planetary albedo when suspended in the atmosphere., BC particles also absorbs both incoming and outgoing radiation of all wavelengths, which contributes to warming of the atmosphere and dimming at the surface. The Semi-direct effect of is that it can absorb incoming solar radiation, disturbing the structure of the temperature of the atmosphere and influence cloud cover by which BC increases the atmospheric heating rate and alters humidity profiles and consequently altering cloud distribution. BC may either increase or decrease cloud cover under different conditions [18].

BC particle also has a Snow/ice albedo effect: when deposited on snow and ice, they darkens the surface and decreases reflectivity, therefore lead to increasing of absorption and accelerating melting, black carbon particles reduce the total surface albedo available to reflect solar energy back into space [19].

Black Carbon has many other effects like indirectly cause changes in the absorption or reflection of solar radiation through changes in the properties and behavior of clouds. BC has also effects on altering the properties of clouds, BC disturb the reflectivity, lifetime, stability and precipitation. Research showed that black carbon plays a role second only to carbon dioxide in climate change [20]. Effects of Black Carbon are complex, resulting from a variety of factors, but due to the short life of black carbon in the atmosphere, about a week as compared to carbon dioxide which last centuries, control of black carbon offers possible opportunities for slowing, or even reversing, climate change [21, 22].

2.2 Sources of Black Carbon

BC is produced in a variety of combustion sources either natural or anthropogenic. At a global scale, major sources are diesel-powered off and on road vehicles, open burning of forest and savannas and solid fuels used for cooking and house heating [23]. Approximately 20% of black carbon is emitted from burning biofuels, 40% from fossil fuels, and 40% from open biomass burning [24].

Black carbon is mainly emitted from different sources, like residential combustion, off and on road vehicles, industries and forest fires. Black Carbon is removed in the atmosphere via two mechanisms, which are Dry and wet deposition [25].

The main sources of black carbon emissions are diesel-driven combustion engines (in road vehicles, non-road mobile machinery and ships), residential burning of wood and coal, power stations using heavy oil or coal, field burning of agricultural wastes, as well as forest and vegetation fires.

2.3 Black carbon variation in Africa

Many studies have been done to see the variation in BC concentration in Africa. Many sampling methods have been used and the most used are aethalometers, Black smoke reflectometer and Particle Soot Absorption Photometer.

An investigation on large-scale variability between aerosol and precipitation and other meteorological variables in the West African Monsoon (WAM) region were done and found that in cold seasons high African aerosols are significantly associated with reductions in cloud amount, cloud top height and surface precipitation and that the radiative effect of BC is the main cause of the reduction in observed precipitation [26].

A study in Uganda has been done by using laboratory and field measurements on BC on Kerosene-fueled wick lamps and showed that 7-9% of kerosene is converted into carbonaceous particulate matter, and found the majority of emitted PM mass was BC, with measured BC/TC ratios ranging from 0.88–1.00 and an EF_{BC} of 76 ± 15 g/kg kerosene [27].

A study on spatial, temporal and source contribution assessments of black carbon over the northern interior of South Africa, showed that in many backgrounds, household combustion contributed to the highest concentrations in cold winter months(June-August) and that in the dry season(May to mid-October) savannah and grassland fires where the main contributor of the highest concentration in these months. They reported that the BC concentration peaked in the early morning 5 AM to 9 AM and in the early to late evening with the highest hourly value of 3.4 $\mu g/m^3$ [28]

Also in Kenya, studies have been done on BC mass concentration variation and found that BC concentration was 1.4 ±0.1 $\mu g/m^3$ and 0.72±0.06$\mu g/m^3$ in Meru and Nanyuki respectively [29].and high concentrations were found at the three major roads of 50 $\mu g/m^3$, 14.0 $\mu g/m^3$ and 14.44 $\mu g/m^3$ at Ladris road, Nakumatt junction site and Pangani roundabout site respectively [30].

2.4 Air pollution

Also air pollution can be defined as a complex mixture of a variety of substances produced by incomplete combustion reactions mainly resulting from anthropogenic activities but also through natural phenomena [31].

Air pollutants may be classified as anthropogenic and natural. Natural sources of pollution include soil erosion (the wind carries airborne particulate matter produced through erosion), evaporation of sea water (which carries with it various materials), volcanic eruptions and forest fires (which send toxic substances directly into the atmosphere) [32]. Anthropogenic activities that lead to air pollution are fuel combustion from motor vehicles, industries, waste incinerators, municipal and agricultural waste sites, heat and power generation and mainly from residential cooking, heating and lighting by using fuel that release pollutants.

Air pollution both indoor and outdoor have adverse impacts on human health. At a global level, 6.5 million deaths were attributable to the combined effects of household and ambient air pollution in 2012. The Western Pacific and South East Asian regions bear most of the burden with 2.4 and 2.2 million deaths, respectively. About 700 000 deaths occur in Africa, almost 400 000 in the Eastern Mediterranean region, 268 000 in Europe and 150 000 in the Americas. The remaining deaths occur in high-income countries of Europe (311 000), Americas (45 000), Western Pacific (44 000), and Eastern Mediterranean (10 000) [33].

Ambient air pollution accounts for an estimated 4.2 million deaths per year due to stroke, heart disease, lung cancer and chronic respiratory diseases. Around 91% of the world's population lives in places where air quality levels exceed WHO limits [2]. Pollutants which are known to have a great impacts on human health include particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2).

In Rwanda, air pollution is caused mainly by the use of biomass which accounts for 85% as a cooking fuel and from fuel combustion as the country is being urbanized, the number of industries and the number of vehicles are increasing. Natural sources of air pollution are

volcanic eruption, forest fires, evaporation of Volatile Organic Compounds (VOCs) and wind erosion of soil [34].

Anthropogenic air pollution are from industry, domestic fuel burning and road traffic. The key pollutants of concern are: Nitrogen oxides (including oxides of nitrogen (NOx) and nitrogen dioxide (NO2)), Sulphur dioxide (SO2), Particulate matter (including particulate matter with an aerodynamic diameter of less than 10 microns (PM10) and 2.5 microns (PM2.5)), Ozone (O3) and Carbon monoxide (CO) [15].

A recent study conducted on PM2.5 and PM10 levels during public holidays and Kigali car-free days showed that the levels of concentrations are lower compared to normal working days and they found that the levels exceeded WHO guidelines in Rwanda, observed concentrations of PM2.5 and PM10 were 133 and 156 microgram/m3 respectively [35].

Another study conducted on O3, NO2, SO2, CO in Kigali and Nyamagabe in 2012-2013 showed that their concentration were varying NO2 (0.119-0.050 ppm);, SO2 (0.014-0.000ppm); O3 (0.033 – 0.009 ppm); and CO (3.148 – 0.000ppm)and they concluded that large amounts of air pollutants are released into the atmosphere of Kigali City by both petrol and diesel vehicles [36].

Another study in 2009 on PM10 have found that the level were higher (a concentration of 650μg/m3) than the limit sets by the WHO and they concluded that the origins of the different airborne particles were from the combustion of biomass and from traffic [37].

CHAPTER 3. METHODOLOGY

3.1 Area of study

Rwanda is known as a second country which is most densely populated in Africa, next to Mauritius and is located in East-central Africa, it has a population of approximately 11.6 million people and has an area 26,338 square kilometers. Many people in Rwanda are involved in subsistence agriculture. The climate in Rwanda as an equatorial country is temperate tropical characterized by two distinct dry and wet seasons. The dry long dry season take place between the months of June and September, and the short one between December and February. The first short wet season is observed during the months of March to May, then the second long rainy between September and December.

In our study we will take two stations, one in urban and another in a rural background. Kigali, the capital of Rwanda, is located between $29^{o}43^{o}$ E and 29 .44 ^{o} E of longitude and, 2.35 ^{o} S and 2. 37 ^{o} S of longitude. The city have a big number of population (1.2 Millions) and is built on many hills and have many wetlands in between. Kigali city is composed mainly with a commercial center, a special economic zone and an administrative center. The choice of the sampling sites was motivated by the main activities operating in these areas, so to allow us sampling the background concentrations of measured air pollutants in 2 different sites in addition to local emission concentrations. The Mugogo site is located in the Northern province outside Byangabo center on the summit of Mt. Mugogo (1.586^{o}S, 29.566^{o} E, at 2590 m above ground level. Mt Mugogo is at about 70km to the north-west part from Kigali.

3.2 Sample size and instrumentation

An intensive field data collection was carried out from during July 2017 and March 2018. A BC 1054 Multi Spectrum installed at College of Science and Technology Campus by the

Carnegie Mellon University (CMU) and a Magee Scientific Aethalometer in an urban background and at The Rwanda Climate Observatory in a rural area outside of Byangabo on the summit of Mt. Mugogo and had been used to collect the required data.

The meteorological parameters (relative humidity, air temperature) were recorded at the same stations provided by CMU for the Kigali site but other parameters like rainfall intensity was collected at Meteo Rwanda Gitega station. At Mugogo site Temperature and Relative Humidity were collected at the site using a WXT520, Vaisala, Finland an automatic weather station which is attached to a fixed, hinged arm 35 m above ground level and connected to the communications tower with 2m clearance from the tower. The flow rate for both aethalometers was set to be 5 L min−1. The equivalent BC measurements at the 880 nm wavelength, which is considered as the standard channel to determine equivalent BC mass concentration was used, The BC concentration measured at 880 nm was used as the actual BC concentration in the atmosphere, as the absorption of other species of aerosols is greatly reduced in this wavelength of 880 nm [38, 39, 40].

3.3 BC measurements

3.3.1 Black Carbon Monitor BC 1054

Black Carbon Monitor known as BC 1054 Multi Spectrum is an instrument which measures the transmission of light at ten separate wavelengths through a filter media onto which particulate matter “PM” containing black carbon “BC” is accumulating in real time and calculates concentrations at 370, 430, 470, 525, 565, 590, 660, 700, 880, and 950 nm with a standard time resolution of 1 minute.

The Met One Instruments, Inc. model BC 1054 Multi Spectrum Carbon Monitor is a ten-wavelength black carbon monitor, which automatically measures and records optical transmission across filter media onto which particulate matter has been deposited at ten wavelengths ranging from 370 nm to 950 nm. From this information the concentration of black carbon “BC” and particulate matter absorbing in the near-ultraviolet regions may be determined.

The BC 1054 was operating with an in-line PM2.5 fractionator through a flexible tubing which is connected to the back of the instrument.

The sampled air is subsequently drawn through special glass fiber filter tape thereby trapping ambient particulate matter. Optical transmission at each of the wavelengths is measured through the filter tape thereby allowing BC mass concentrations to be calculated at each wavelength.

BC concentration in the BC 1054 is determined by measuring the change in optical transmission as BC-containing particulate matter accumulates onto a filter and then converting this transmission data into BC concentration.

Because there is no exact definition of soot, also to quantify it cannot be made exactly. The BC-1054 does report the BC concentrations by using a presumed relationship between the optical attenuation measured through the filter tape as BC accumulates on it and the ambient BC levels based on historical measurement data collected by thermo-optical methods. The mass attenuation cross section "MACS" and its wavelength dependence are derived from the empirical relationship based on absorption onto quartz filter media and thermo-optical measurements shown in Equation 1.

$$\sigma(m^2 g^{-1}) = \frac{14{,}625}{\lambda(nm)}$$ *Equation 1: MACS Relationship*

BC is calculated by measuring the changes in transmission of light through the portion of the filter accumulating particulate matter relative to the transmission of light through a portion of the filter not accumulating particulate matter. The relative measured intensity, It is defined as the measured signal at time t through the filter accumulating the PM divided by the measured signal at time t of light through the reference as shown in Equation 2.

$$I_t = \frac{SB(t) - SZ(t)}{RB(t) - RZ(t)}$$ *Equation 2: Measured Relative Intensity*

(t) is the measured signal at time "t" with the illumination source on through the sampled filter spot. (t) is the measured signal at time "t" with the illumination source off through the sampled filter spot. (t) is the measured signal at time "t" with the illumination source on

through reference portion of the filter and (t) is the measured signal at time "t" with the illumination source off through the reference portion of the filter.

$$(t)=-ln\ [\frac{I_t}{I_o}]$$ *Equation 3: Attenuation*

(t) as defined in Equation 3 is calculated from the change in measured optical transmission through the filter that occurs over the time period Δt as PM accumulates. The filter-based aerosol absorption coefficient of the collected particulate matter is defined in Equation 4. A is the cross sectional area of the filter spot, Q is the volumetric flow rate, and $\Delta ATN\Delta t$ is the measured change in attenuation during time Δt.

$$b_{ATN} = \frac{A}{Q}\frac{\Delta ATN}{\Delta t}$$ *Equation 4:Aerosol Absorption Coefficient*

The filter-based aerosol absorption coefficient of the collected particulate matter is known to differ significantly from the true aerosol absorption coefficient of black carbon..

$$b_{abs} = b_{ATN}\frac{1}{C.R(ATN)}$$ *Equation 5:True Aerosol Absorption Coefficient*

C is the part of the difference between the true aerosol absorption coefficient and the filter-based aerosol absorption that is constant and depends only on the filter medium. (ATN) is the part of the difference between the true aerosol absorption coefficient and the filter-based absorption coefficient that is not constant, but instead is attenuation-dependent. BC concentration is determined by dividing true aerosol absorption coefficient by the mass attenuation cross section as is shown in Equation 6.

$$M_{bc}=\frac{b_{abs}}{\sigma_{abs}}=\frac{b_{ATN}}{\sigma_{abs}.C.R(ATN)}=\frac{A}{Q.\sigma_{abs}.C.R(ATN)}\frac{\Delta ATN}{\Delta t}$$ *Equation 6: Mass Calculation*

In the BC 1054, the spot size A, the flow rate Q, the mass absorption coefficient σabs, and the filter tape constant C, are constants. Therefore the BC concentration MBC is calculated by

multiplying the change in attenuation over time $\frac{\Delta ATN}{\Delta t}$ as is measured by the BC 1054 by the inverse of (ATN) and a proportionality constant $\frac{A}{Q.\sigma_{abs}.C}$

3.3.1.1 Instrument Calibration

The Met One Instruments BC 1054 has as its default calibration values the historically used mass absorption cross sections "MACS" shown in Equation 1 but adjusted for the change in filter media. This is shown in Equation 7 and Equation 8. Note that $Cquartz$ =2.14.

$$(m^2 g^{-1}) = \cdot \sigma abs \cdot Cquartz = \frac{14{,}625}{\lambda(nm)}$$ *Equation 7: Filter Media Influence on MACS*

$$\sigma abs\ (m^2 g^{-1}) = \frac{6{,}834}{\lambda(nm)}$$ *Equation 8: True Aerosol MACS used in BC 1054*

σabs is set to 7.770 m2/g for 880 nm illumination. In order to calculate the true aerosol absorption coefficients for other illumination wavelengths a 1/ʎ wavelength dependence is presumed.

The raw BC 1054 data may be processed into filter loading compensated data and MBC by determining (ATN) as shown in Equation 6. This is done with the BC LoadComp software retrospectively. For data in which the measured attenuation is very close to 0 or when highly time resolved data is unnecessary (ATN)≈ 1 and post processing of the data is unnecessary [41].

3.3.1.2 BC load Comp software

BC Load Comp is a software package used to post-process the raw data obtained from a Met One Black Carbon (BC) units. This software uses the bin method to minimize the effect of spot loading effects inherent to filter-based optical black carbon measurements

To calculate their corrected concentrations raw data were loaded into the program to be post processed .The software package uses some algorithms and calculations discussed below:

1. **Correcting Concentration and K-Factors**

For the correction of the concentration, a k-factor was calculated and applied to the un-corrected concentration. The k-factor is determined the following equation:

$$k = \frac{slope}{\text{intercept}}$$

Using the spots algorithm, we find the slope and the intercept of these concentration averages over our bins. The following equations are to determine the slope (b) and intercept (a).

$$b = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\Sigma(x-\bar{x})^2}$$

$$a = \bar{y} - b\bar{x}$$

Once we have a k-factor, we can use the following equation to correct our concentrations. Where BCc is the corrected concentration, $BC0$ is the concentration from the BC instrument, k is our k-factor, and ATN is our attenuation.

$$BC_c = BC_0 \times \frac{1}{(1-k \times ATN)}$$

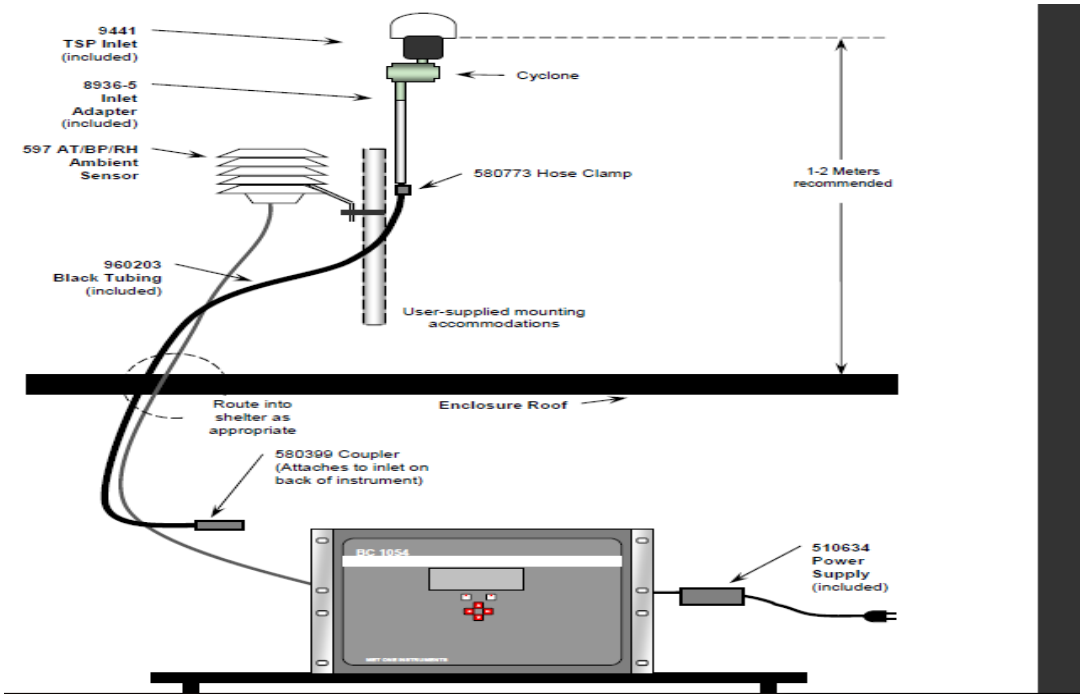

Figure3. 1 Black Carbon Monitor

3.3.2 Magee Scientific Aethalometer

Magee Scientific 7 wavelength Aethalometer with dual-spot technology that is able to correct for filter artifacts [39]. The Aethalometer is an instrument that provides a real time read out of the concentration of black carbon aerosol particles in the air stream [42]. On the inlet of the aethalometer a PM2.5 cyclone impactor is installed to enable only Particulate matter less than 2.5 microns (PM2.5) to pass. Data is recorded every minute at a flow rate of 5LPM and particles are captured on a quartz fiber filter tape. The air stream is not dried and the relative humidity (RH) is not controlled, and may lead to increased uncertainty when the relative humidity is high. This instrument comprises of seven channels from 370nm, 470nm, 520nm, 590nm, 660nm, 880nm and 950nm respectively.

Attenuation of light through filter paper at 880 nm channel is considered standard for calculating BC concentration as there is no other major aerosol species which exhibits absorption at this wavelength [23].

The attenuation of light is converted to the recorded BC mass concentration using wavelength dependent calibration factors as recommended by the manufacturer (Aethalometer Manual, Magee Scientific).

3.4 Methods

Descriptive Statistics was used in with the presentation of data, in either tables or graphs form, and with the methodology of analyzing the data. Statistical analysis are done to see the relationship between variables.

3.4.1 Standard deviation

The standard deviation is the common measure of the spread of the data, it provides a summary of the differences of each observation from the mean value. And is calculated by first working out the squared deviation of each observation from the sample mean and it is

calculated as:

$$SD=\sqrt{\frac{\sum_{t=1}^{n}(x_1-X)}{n-1}}$$

Where X is the sample mean, x_1 is the i^{th} observation, n is the sample size and the notation $\sum_{t=1}^{n}$ represents the addition or summing up of all the squared deviations from the sample mean from the first(t=1) to the last (n^{th}) observation.

3.4.2 Correlation coefficient

To assess the association between two variables, a statistical method called correlation coefficient or Pearson R correlation is used and calculated by:

$R=\frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2\Sigma(y-\bar{y})^2}}$ where X and Y are the observations and $\bar{x}$, $\bar{y}$ the mean of observations

3.4.3 T-test

The T-test is used to evaluate if the mean of different groups are significantly. The "T" statistic which is the difference between the sample means (in either direction) divided by the (estimated) standard error

The standard error of the difference between two sample means is the standard deviation of the sampling distribution of the difference between the sample means. Statistical theory shows that under the assumptions of the t-test, the standard error of the difference is

$$SE\ (diff)=\sqrt{\frac{SD1\hat{}2}{n1}+\frac{SD2\hat{}2}{n2}}$$

Where n1 and n2 are the group sample sizes and SD1 and SD2 the standards deviation of group 1 and 2 respectively

And the T-test is computed as:

$$T=\frac{\mu1-\mu2}{\sqrt{\frac{SD1\hat{}2}{n1}+\frac{SD2\hat{}2}{n2}}}$$

In conducting the T test, we have to pose the hypothesis. A null hypothesis is made assuming that the mean of the 2 population are equal (H_o: $\mu_1 = \mu_2$) where the symbol H_o indicates the null hypothesis and μ_1, μ_2 the mean of population 1,2 respectively

Another alternative hypothesis is taken assuming that the two population means are unequal, and is written as $H_1 = \mu_1 \neq \mu_2$ where the symbol H_1 indicates the alternative hypothesis and μ_1, μ_2 means of group1 and group 2 respectively.

CHAPTER 4. RESULTS AND DISCUSSION

In Rwanda, the main sources of anthropogenic air pollution are use of biomass , firewood, crop residues , road traffic, domestic fuel burning and industry, Agricultural burning, cooking fires, charcoal making, kerosene lightning, brick kilns, and older diesel generators/vehicles . Rwanda experiences two rainy seasons roughly occurring in March-April-May (MAM) and September-October-November (SON), and two dry seasons during December- January-February (DJF) and June-July-August (JJA). Black Carbon data from two sites CST and Mugogo are used to see the diurnal, weekly, monthly and seasonal variation for the month of July to December(J,A,S,O,N)

4.1 Spatial variation of BC concentration at CST and MUGOGO

To see the spatial variability of BC mass concentration at both sites, the data analyzed are of the months from July to December. Diurnal variation was investigated by calculating hourly mean. Statistical analysis was done to calculate minimum, maximum and standard deviation of BC concentrations from the daily data for each month. Hourly mean have been performed to see at which hour we have the highest concentration and to see the reasons attributed to it.

4.1.1 Hourly concentration variations of BC

From figure 4.1 representing the one-hour average time series of BC concentration for both stations (Mugogo and CST) from July 2017 to December 2017 we see that from July to end August the concentration of BC were very higher than the mean but from September to end November the concentration were fluctuating around the mean for the Kigali station. It was not the case for the Mugogo station as in July-August the value of the concentration was higher than the mean and in September-December the concentration of BC were lower than the mean and can be attributed to the wash-out of the pollutants as it was in the rainy season.

From Statistical analysis (Table4.1) the hourly mean BC concentration the maximum value at CST was 15.007±2.216 μg/m^{3}compared to 10.252±1.649 μg/m^3 at Mugogo. The minimum values were 0.144±2.216 μg/m^{3}and 0.013±1.649. μg/m^3 the concentration at CST were higher than that of Mugogo as the emission sources are higher at Kigali than in Mugogo.

4.1.2 Diurnal variation of BC mass concentration

The figure 4.2 represents the diurnal variation of BC mass concentration at both sites for the data from July to December. Diurnal fluctuation of BC were marked with 2 distinct peaks, the first peak occurred at 7:00 am with a concentration of 6.649 μg/m^3 and another peak at 09:00 pm with 4.829 μg/m^3, afternoon hours showed low values with a value of 2.118 μg/m^3, These two distinct peaks occurred due to gradual increase in the anthropogenic activities and rush hour traffic at CST. For Mugogo, two peaks are observed, one during 10:00-12:00 am with a value of 2.004 μg/m^3 and the lowest value was found at 23:00 pm with a concentration of 1.511 μg/m^3.

4.1.3 Seasonal variation of BC mass concentration

Rwanda has two rainy seasons roughly occurring in March-April-May (MAM) and September-October-November (SON), and two dry seasons during December- January-February (DJF) and June-July-August (JJA).To see the seasonality in variation of BC mass concentration for the two sites JJA and SON have been used.

4.1.3.1 Black Carbon mass concentration variation in JJA

For the JA season, The concentration of BC in July was higher than that of August, but the shapes of the diurnal patterns show similarities by having a morning rush-hour peak at 7:00 am and a strong decrease in concentrations between 9:00am-16:00 pm. Low value of BC concentration during afternoon hours can be attributed to the dispersion of aerosols and to the low traffic density. During morning hours, there is an increase of BC concentration due the results from anthropogenic sources and effect after the local sunrise of the boundary layer.

By looking at the diurnal variations on figure 4.3, in the JA season the first peak in concentration variation can be attributed in terms of increased emissions (traffic and cooking activity) at around 7:00 AM. BC levels decrease sharply during the central hours of the day, and may be attributed to the increase in wind speed and the change in wind direction during the day and the decrease of the traffic flow.

The levels of BC concentration start to increase again showing a second maximum at around 20:00 PM and also start to decrease during the night time owing to the reduction of vehicle emissions and other anthropogenic activities.

From Table 4.2, showing the statistics of mean hourly average data for CST and Mugogo in JA season, The lowest concentration and the highest concentration in the JA season was observed to be 3.131±0.613 µg/m3 and 5.548±0.613 µg/ m3 while was noted to be 2.924±0.334 µg/m3 and 2.924±0.334 µg/m3 µg/m3 for Kigali and Mugogo sites respectively. The concentration of BC at Kigali was about 23% higher than that of Mugogo.

4.1.3.1 Black Carbon mass concentration variation in SON

From figure 4.4 representing the variation of BC mass concentration in SON (September, October, November) season it can be seen that during the SON season, the BC concentration attained two significant peaks at 7:00 AM and 20:00 PM at the CST site and at 6:00 AM and 19:00 PM at Mugogo site. In the month of September concentrations were high compared to other two months at both sites. At CST BC concentrations in October and November were fairly the same but November has a high evening peak compared to that of October. At Mugogo station there is a remarkable difference between the 3 months, BC concentrations are higher in September, averaging 4.343±0.732 µg/m^3 but lower in Oct/Nov, averaging 0.369±0.732 µg/m^3.

From Table 4.3, showing the statistics of mean hourly average data for CST and Mugogo in SON season, the lowest concentration in the SON season at CST was1.534 ±0.938 µg/m3 while the highest concentration was 4.944 ±0.938 µg/ m3. At Mugogo, the lowest concentration was 0.789±0.155 µg/m3 and highest BC was 1.280±0.155 µg/m3. The average concentration of BC at Kigali was about 38% higher than that of Mugogo.

Comparison between JA and SON

Monitoring was undertaken during the wet and dry seasons at the urban and rural sites in Kigali and Mugogo. Mean 24-hour BC concentrations were lower at both sites in the wet season compared to the dry season. A reduction of approximately 50% was measured.
From figure 4.5 Seasonal variation of BC concentrations was also observed, with maximum concentrations in dry season and minimum concentrations in rainy season. This was attributed to changes in the air mass origin from dry to rainy season and on the fact that the primary removal of BC in the atmosphere is believed to be the wet removal.

The rainfall intensity for the months of September, October and November were as follows: 27, 61 and 93 mm respectively for the CST site. At Mugogo site, which is located in the Northern part of the country the difference in the BC concentration in dry(JA) and wet(SON) season may be due to the differences in biomass burning proximity (far in JJA, closer in DJF) and primary wind direction (southerly versus northerly).
BC concentration variation has two peaks, a sharp mid-morning and early evening peaks that coincided with both cooking times and kerosene/generator use times. The evening peak likely due to more use of generator and kerosene lanterns for lighting in the evening (dark at 6 pm) as people around that site do not have access to electricity and the peaks persisted throughout the rainy and dry seasons for the Mugogo station.

4.1.4 Day of the week patterns of BC

The weekend effect is characterized by the reduction in the level of primary pollutants due to the decrease in emissions in anthropogenic activities in the weekend.

The weekly cycle of BC concentrations at CST and Mugogo sites from figure 4.6 did not show a weekend effect for all the sites. At CST the change or reduction observed in BC concentrations levels during weekend (Saturday and Sunday) were consistent with the reduction in human activity and traffic volume at the weekend which results to a decrease in pollutants emission. A high weekend effect was observed on Sunday in Kigali because of

some reasons like the reduction of traffic on Sunday because of car free day organized for every first Sunday of the month, and a small reduction on Saturday may be due to the reduction of traffic on special days like Umuganda day which is planned every last Saturday of the month. The situation changes for Mugogo site, as the emissions are from small-scale agricultural burning, charcoal making, cooking fires, brick production as those actions are being done in the valley which is located below the station and are being done in different places around the site also vehicles, diesel and heavy fuel-oil power plants, and diesel generators are being the source of emission. A weekend effect was not observed at that site because all the activities responsible of emitting the Black Carbon are present throughout the whole week.

4.1.5 Monthly variation of BC

To see the monthly variation of Black Carbon concentration, monthly mean have been calculated for the 2 sites from July to December.

Among all the 6 months of sampling period, the highest monthly average were observed during July while lowest during October and moderate in November with 6.40 $\mu g/m^3$, 3.12 $\mu g/m^3$ and 3.98 $\mu g/m^3$ respectively for the CST site. For the MUGOGO site the situation was not fairly the same as the highest monthly averages were observed during July while lowest during November and moderate in September with 3.99 $\mu g/m^3$, 0.47 $\mu g/m^3$ and 1.80 $\mu g/m^3$ respectively from figure 4.7.

4.1.5 Correlations between BC and Meteorological Variables

The correlation between BC concentration and meteorological parameters is investigated to know their influence on BC as the prevailing meteorology plays an important role in surface movement and vertical dispersion of pollutants. Local meteorological parameters such air temperature and relative humidity are used. To find the correlation statistical analysis of data have been performed and R Pearson correlation coefficient was calculated. The BC data and

meteorological data (T and RH) collected for the Dry and Wet season are used to evaluate the association between them and the Pearson were used.

From the correlation analysis figures 4.8, 4.9, 4.10, 4, 11, Pearson correlation coefficient have been produced by using the python language for all the 2 seasons. Data used were from July to November. A weak negative correlation was observed between BC concentration and Temperature(R= - 0.218) and a weak positive correlation with Relative humidity (R= 0.249) during both dry and wet season in Kigali while at Mugogo station low values of correlation were observed indicating that there is no correlation between the variable with R= 0.0328 and R= -0.0547 for Black Carbon -Temperature and BC-Relative Humidity respectively.

4.2 Temporal variation of Black Carbon over Kigali

To see the temporal variation, data used were from July to March. The main reason was to assess the behavior in the variation of BC in the period of the 2 dry seasons (JJA and DJF) and compare it with one in the rainy season (SON).

4.2.1 Contribution of Black Carbon and PM2.5

Black carbon is the sooty black material emitted from gas and diesel engines, coal fired power plants, and other sources that burn fossil fuel. It comprises a significant portion of particulate matter or PM, which is an air pollutant so BC is an important component of atmospheric particulate matter [43].

On average, BC containing particles comprise around 10% of PM2.5 mass in ambient air [44] [45].but it can reach up to 30% depending on the location and dominant sources(like residential heating, cooking with solid biomass fuels [46].

Table 4.3. Showing the contribution of the BC in PM2.5 mass ratios at the CST site during the sampling period. From the table, the highest ratio was found in November, a ratio of 21.148 % where the lowest ratio was found in February compared to other months. The ratio varied between 10.230-21.148 %. It is seen that transportation related emissions, pollutants from fossil fuel related sources and biomass burning are major sources of BC in Kigali air.

4.2.2 Correlation of BC with CO

Black Carbon and Carbon Monoxide are products of incomplete combustion of carbon-based fuels [47]. Because BC and CO are emitted from many similar sources, will cause also to their emission ratios to vary significantly for different sources and from those facts also the concentration of BC and CO are expected to be correlated.

From figure 4.12 showing the correlation between BC and CO concentrations, a high positive correlation (R=+0.70) was found in dry season (July and August) and in wet season i.e. September, October and November). The positive correlation found between two species confirm that both are produced from the same source in the combustion of fossil fuels and biomass burning and that their sources are located in the same region.

4.2.3 Variation of BC in JJA, SON and DJF seasons

From the Figure 4.13 showing the variation of Black Carbon mass concentration in 3 different seasons, Black Carbon aerosol concentrations in dry season (JJA) were significantly higher than that in SON and DJF. During all the seasons, the diurnal patterns has the same shape, having the first sharp peak at 7:00 am and another at 20:00 pm. After 7:00 am as there is increase of solar radiation causes a gradual decrease in BC concentration thus reaching the lowest level between 11:00 am and 15:00 pm .The minimum value of black carbon concentration in the afternoon hours may be related to two factors, first there is a strongest solar radiation and second there is the most intense atmospheric convection that causes the BC particles to do not easily concentrate. At around 16:00 pm as the solar radiation decreases gradually, BC particles concentration start to increase (because there is no intense atmospheric convection and the particle are able to concentrate), together with the increase in the emission from anthropogenic activities because it at from that hours where many people are moving from work and many activities also at home are being done reaching a second peak at 20:00 pm.

From table 4.5 the concentration of Black Carbon was higher in the Dry season (JA) with a value of 5.548±0.614 μg/m^3 and the minimum value was observed in SON with a value of 1.534±0.938 μg/m^3. The lowest value observed in SON can be attributed to the effect of the rain as SON is known as the rainy season.

4.2.4 Monthly variation of BC at Kigali

To see the monthly variation of Black Carbon concentration, monthly mean have been calculated for the whole period from July to March.

Among all the 9 months of sampling period, the highest monthly average were observed during July while lowest during October and moderate in February with 6.6 μg/m^3, 3.6 μg/m^3 and 3.1μg/m^3 respectively on figure 4.14 .

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Measurement of BC concentrations over the period of 9 months from 7th July to 31st March have been made by using the Black carbon Monitor 1054 and Magee Scientific in Kigali and Mugogo background areas. Diurnal, weekly, monthly and seasonal variation of BC concentration have been made.

The maximum mass concentration of BC were significantly low in the rainy season compared to the dry season. The decrease of mass concentration of BC in the rainy season were attributed to the precipitation that remove particles by inertial scavenging.

A weekend effect was observed in Kigali with a decrease of BC concentrations during the weekend resulted from the reduction of emission activities but at Mugogo, there is no effect as the activities responsible for the emission of BC are present throughout the week.

A positive correlation was found between Black Carbon and CO (R=0.70) confirming that both are produced from the same source in the combustion of fossil fuels and biomass burning and that their sources are located in the same region.

A relative contribution was observed between BC and PM2.5.a highest ratio of 21.148% was found in November.

A weak negative(R=-0.2180) and positive(R=0.249) were observed between BC and T, RH in Kigali respectively and no correlation was found between them in Mugogo

Monthly variation was observed by having the maximum concentrations in July for both stations and the lowest in October and November for Kigali and Mugogo respectively.

5.2 Recommendations

As over as 2 million households in Rwanda rely on wood as a cooking fuel the local pollution is increased and is likely to lead to adverse health impacts. Other alternative cooking fuels which are pollution free should be used. The Government should continue to increase the energy capacity by prioritizing the use of renewable energy.

This study focused on 2 background areas, future work should be conducted in the remaining areas to get a better overall view on BC trends in Rwanda.

Addendum 1 : Figures

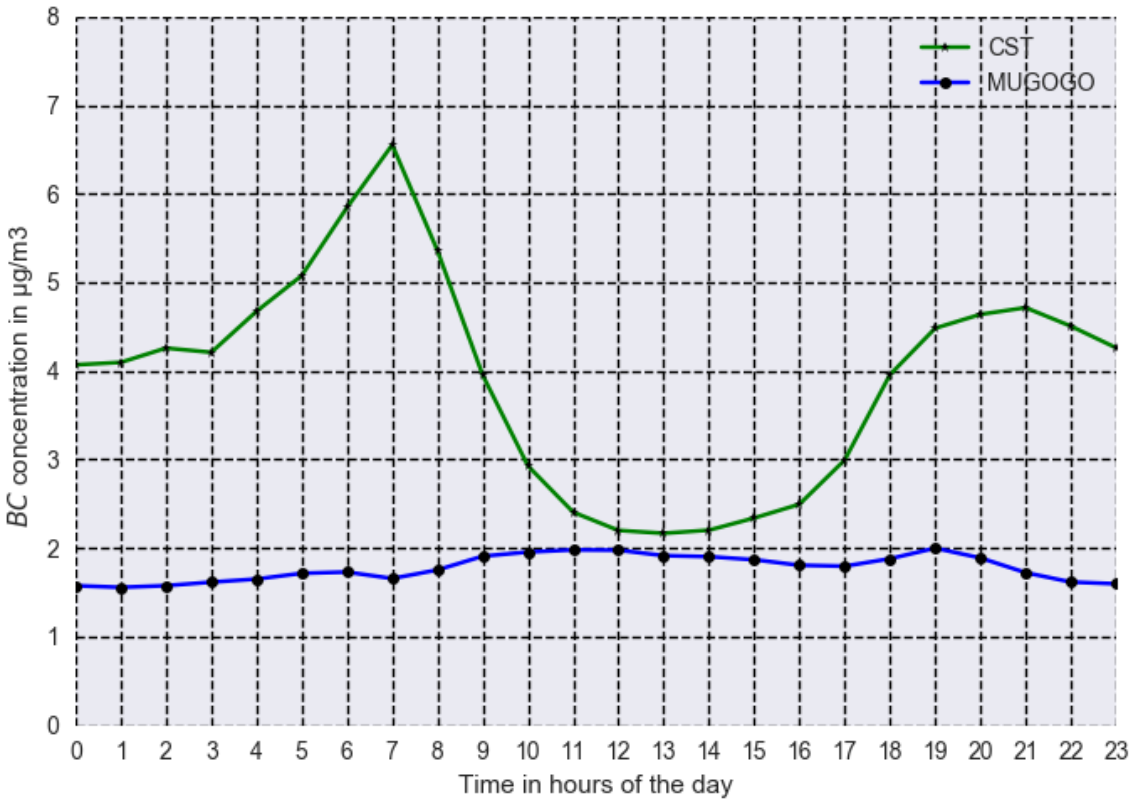

Figure 4. 1Diurnal variation of BC mass concentration at both sites

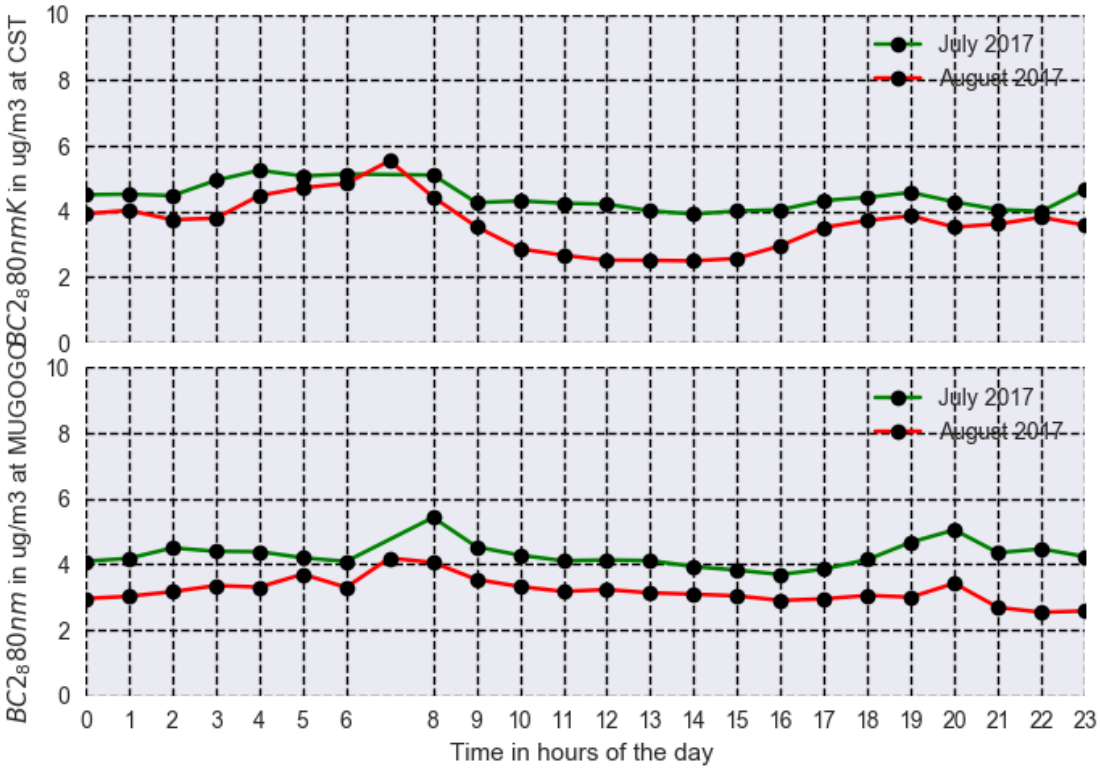

Figure 4. 2 Hourly variation of BC in JA season

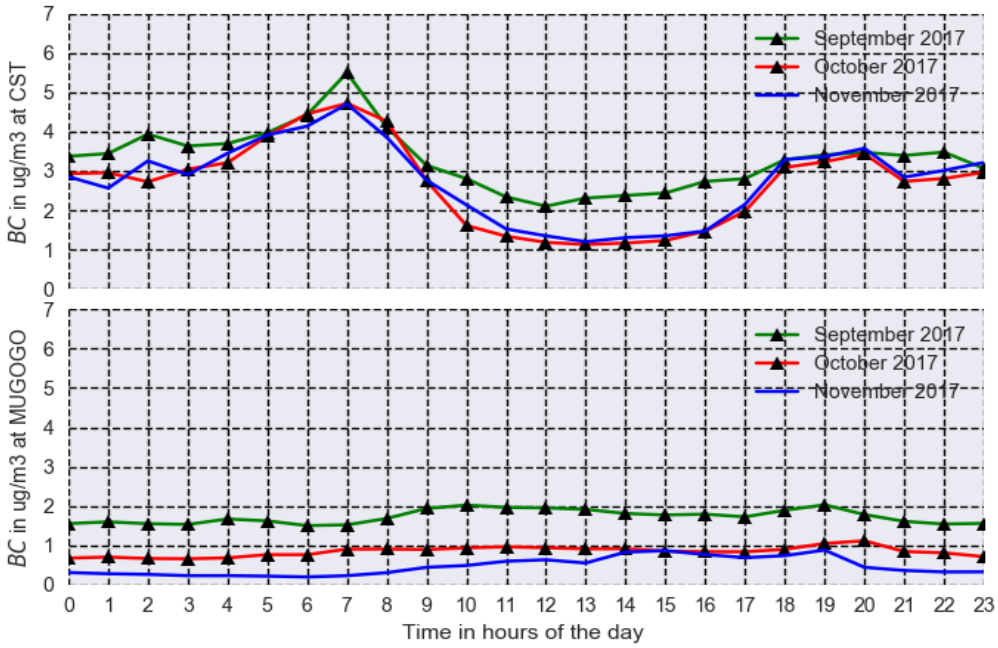

Figure 4. 3 Variation of BC mass concentration in SON season

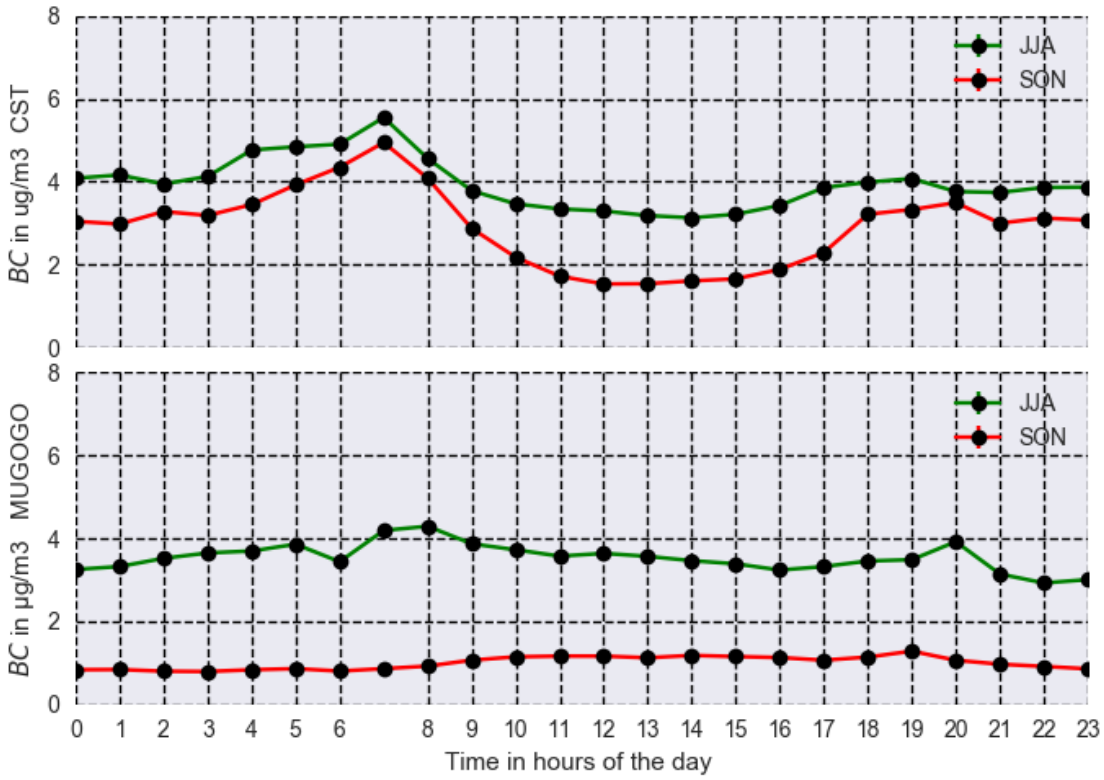

Figure 4. 4 Diurnal cycles of BC mass concentrations during the 2 seasons

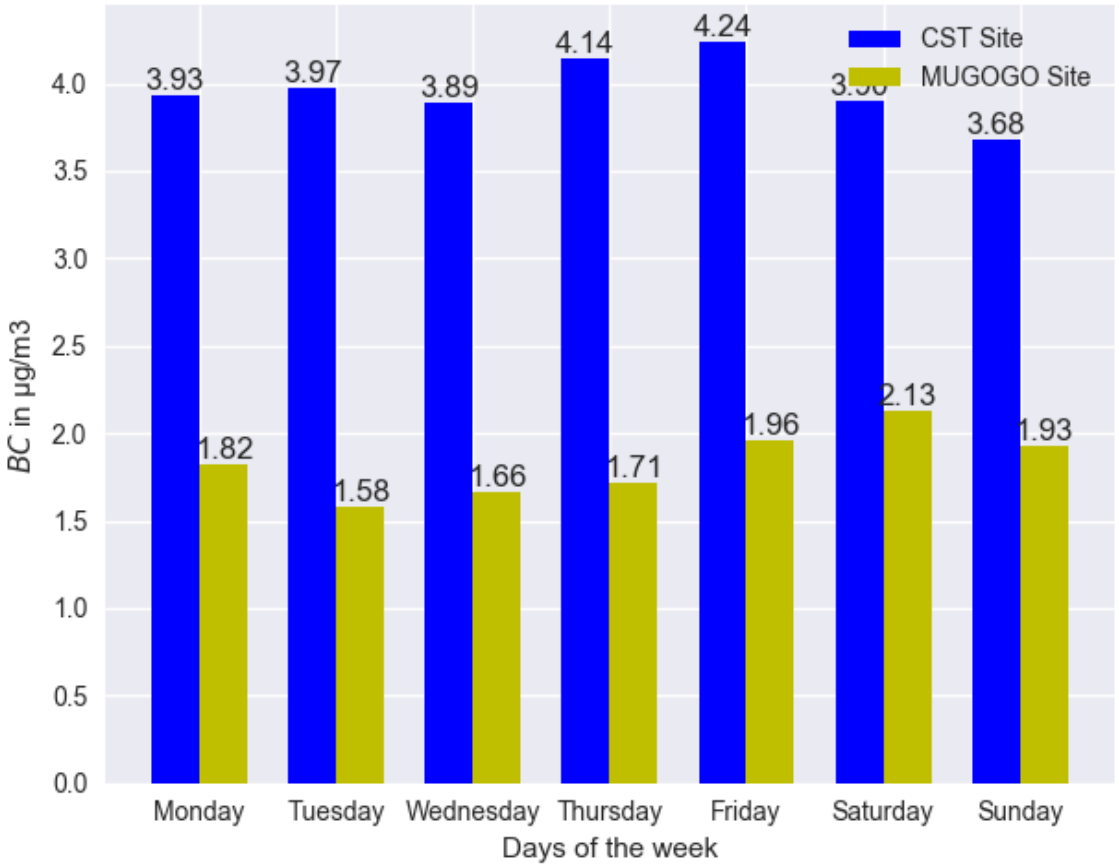

Figure 4. 5 Day of the week trend in BC concentration at the 2 sites for the sampling period. (July to December)

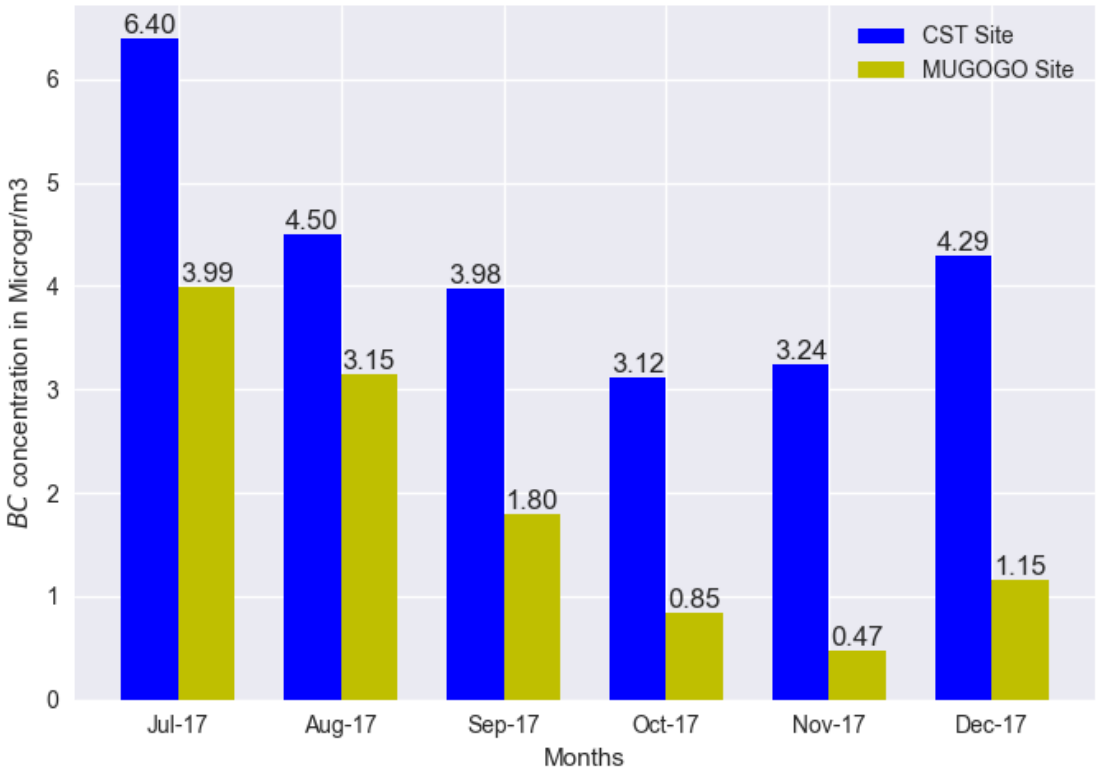

Figure 4. 6 Monthly variation of BC mass concentration in July-December

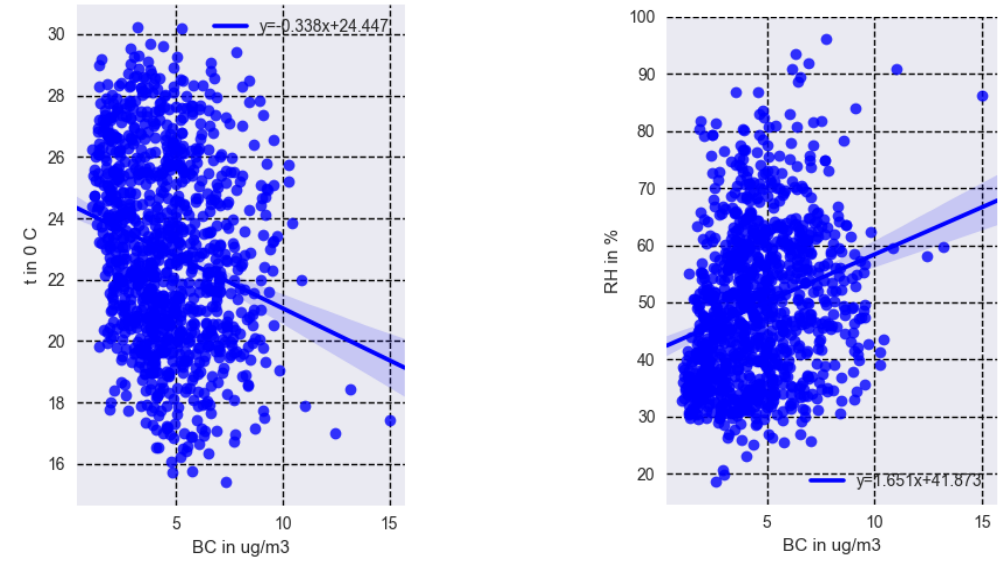

Figure 4. 7 The relationship between BC and temperature, Relative humidity in dry season in Kigali

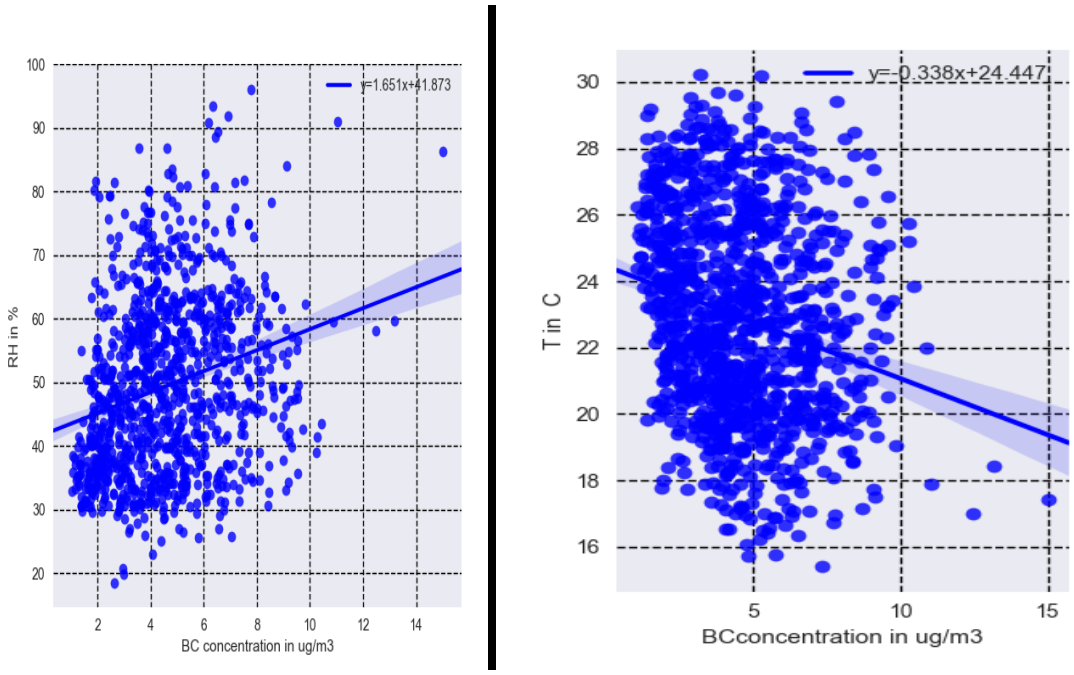

Figure 4. 8 The correlation between BC concentrations with Relative humidity, Temperature at CST station.

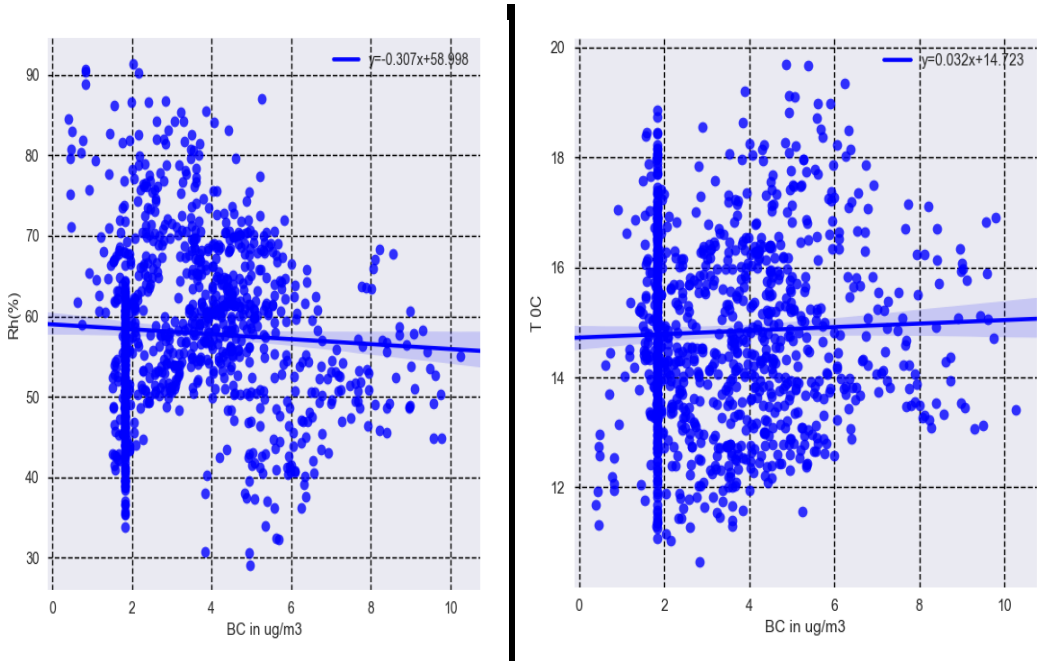

Figure 4. 9 Correlation between BC at Mugogo with Relative humidity and Temperature in Dry season

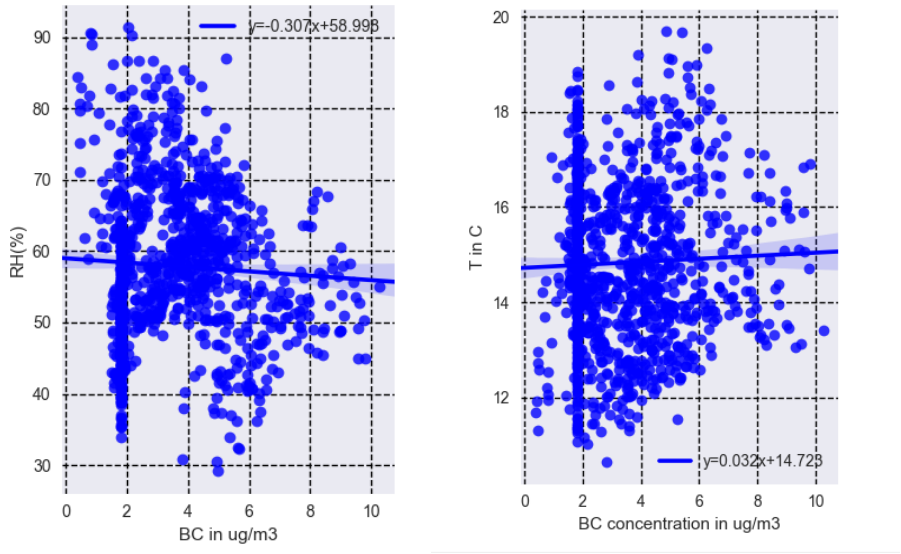

Figure 4. 10 Correlation between BC at Mugogo with Relative humidity and Temperature in Wet season

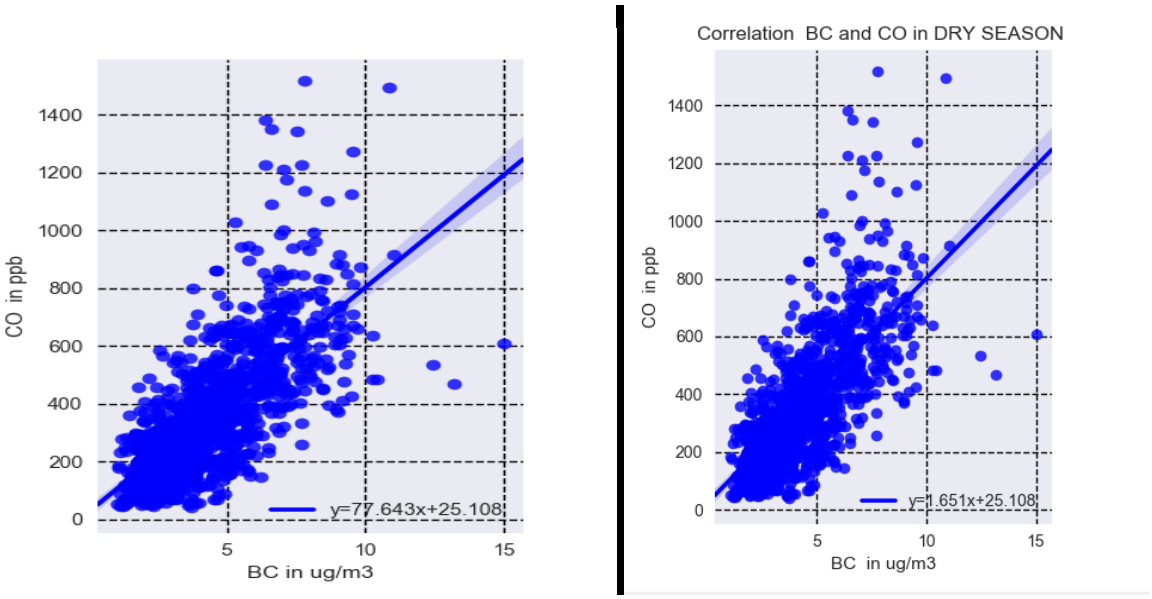

Figure 4. 11 Correlation between BC and CO in Dry and Wet season at CST

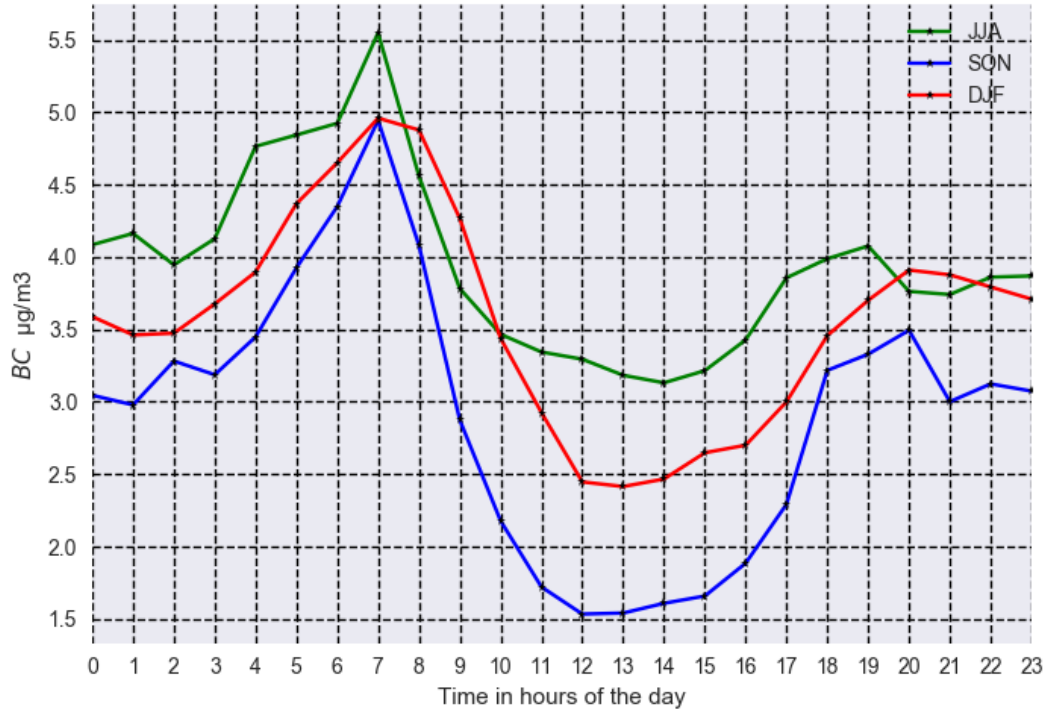

Figure 4. 12 Diurnal Variation of seasonal average BC concentrations

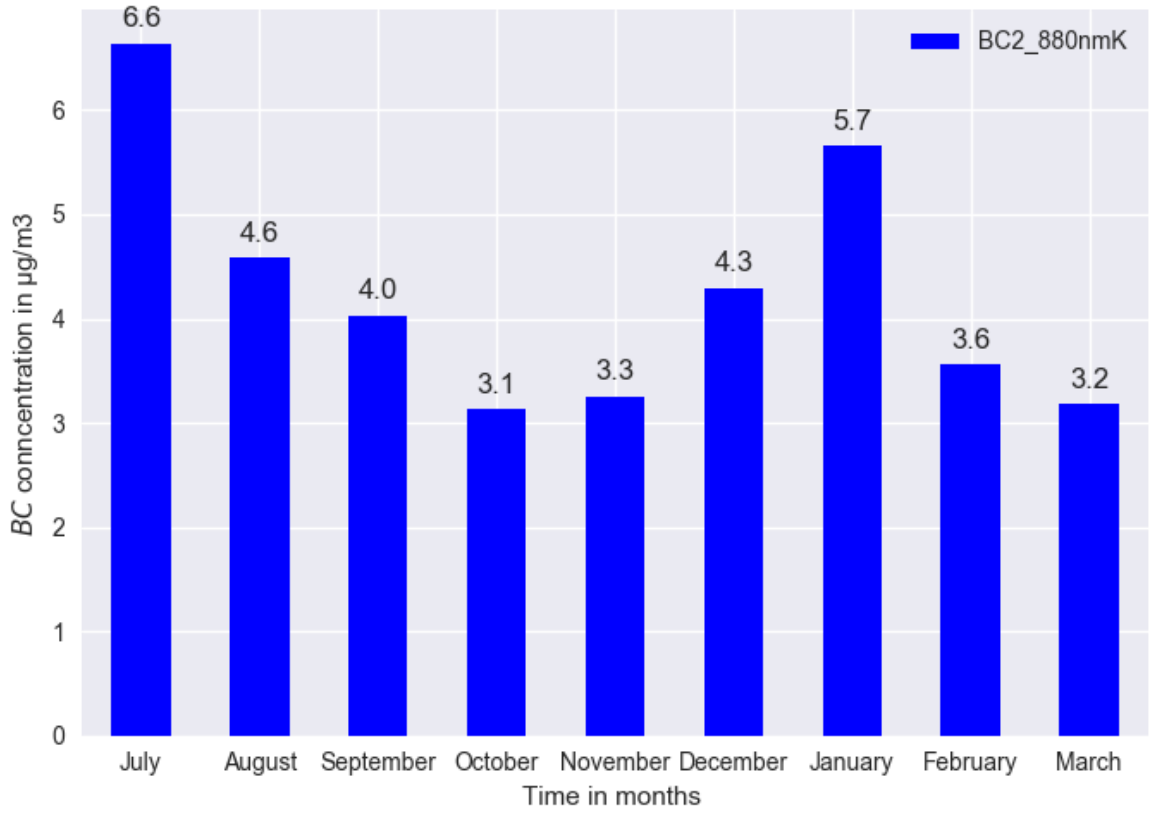

Figure 4. 13 Monthly variation of BC mass concentration for the whole observation at Kigali

Addendum 2 : Tables

	AT(C)	RH (%)	ta	rh	PM 2.5	CO	BC K	BC M
mean	21.995	60.098	14.772	62.762	22.592	418.447	3.885	1.782
std	3.456	18.331	1.626	11.910	10.644	265.800	2.216	1.649
min	14.658	18.548	9.462	29.136	4.177	40.006	0.144	0.013
25%	19.200	44.920	13.527	51.849	14.925	228.272	2.105	0.560
50%	21.467	59.832	14.817	62.265	20.477	372.517	3.522	1.286
75%	24.872	74.944	16.160	70.058	28.007	553.880	5.273	2.402
max	30.809	98.588	19.710	92.833	81.013	2182.907	15.007	10.252

Table 4. 1 Statistical hourly average

JA Statistic						
	T K(^{o}C)	RH K (%)	T M (^{o}C)	RH M (%)	BC K(µg/m^{3})	BC M(µg/m^{3})
mean	22.980	48.315	14.803	58.087	3.955	3.538
Std	2.641	9.337	1.263	4.128	0.613	0.334
min	19.142	36.258	13.103	51.155	3.131	2.924
25%	20.744	38.514	13.660	55.363	3.456	3.320
50%	22.802	48.421	14.845	58.484	3.865	3.501
75%	25.684	56.522	15.728	61.709	4.135	3.702
max	26.595	62.774	16.851	63.781	5.548	4.292

Table4. 2 Statistical data for JA season

Table4. 1 Hourly statistics during SON season

SON Statistic						
	AT K (^oC)	RH K (%)	T M (^oC)	RH M (%)	BC K($\mu g/m^3$)	BCM($\mu g/m^3$)
mean	21.856	62.053	14.761	65.480	2.907	0.995
Std	2.011	7.839	0.274	1.324	0.938	0.155
min	18.876	50.929	14.327	63.052	1.534	0.789
25%	20.108	54.387	14.566	64.557	2.104	0.850
50%	21.695	61.951	14.662	65.401	3.059	1.013
75%	23.775	68.969	15.051	65.916	3.358	1.138
max	24.585	74.032	15.242	68.528	4.944	1.280

K and M stand for Kigali and Mugogo

Table4. 2 Ratio of BC/PM2.5 during July 2017 to March 2018

Months	PM2.5($\mu g/m^3$)	CO (ppb)	BC ($\mu g/m^3$)	BC/PM2.5 (%)
July	36.378	503.783	6.637	18.244
August	27.840	397.8575	4.579	16.448
September	25.375	408.6194	4.031	15.885
October	17.6605	408.7606	3.135	17.752
November	15.384	469.1417	3.253	21.148
December	23.950	503.9416	4.294	17.928
January	42.454	562.4112	5.659	13.332
February	34.790	443.5525	3.559	10.230
March	22.621	498.5369	3.179	14.056

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