Diurnal and Seasonal Variability of Particulate Matter Concentrations over Kigali

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Declaration

I, **HABINEZA Theobard (219013866),** declare that this dissertation "**Diurnal and Seasonal Variability of Particulate Matter Concentrations over Kigali",** for the award of Master of Science in Atmospheric and Climate Science is my original work except where specifically acknowledged and has never been presented anywhere else for the same purpose.

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Signature **Date** **/07/2022**

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Abstract

The measurement of atmospheric particulate matter of two distinct size <2.5 µm and <10µm was collected in Kigali since 2018 and as sample from Apr-2019 to March 2020 at air quality and climate change monitoring project located at Meteo Rwanda head quarter was used in this dissertation. This measurement has several purposes but, in this research, data was carried out with a purpose of analyzing the diurnal and seasonal variability in PM mass concentration within different seasons of the collected time and access the potential causes associated with this variation. The Environmental Protection Agence compliant TELEDYNE API, Model T640 Particulate Matter (PM) Mass Monitor was used in this research. Meteorological parameters are from Met-o Rwanda Kigali station where the instrument is installed. Complex factors determining the PM variability, relation between PM and meteorological parameters such as temperature, Relative Humidity, wind direction, wind speed and solar radiation was analyzed using statistical analysis techniques associated with tools available in Openair package of R language. The Atmosphere that is laden with dust due to occurrence of transported haze, the summer heating, traffic emissions in Kigali, PM from fossil fuel burning, forest fire from neighboring countries, other forms of combustion process either local or regional that reach the sampling site and the lack of air pollutants removal process (wet deposition/wash out and rainout) in the dry season (June July August and January February(JJA and JF) are observed to contribute to the higher PM mass concentration level. Two peaks (06:00 to 08:00 am and 6:00to 9:00 pm) of the evident diurnal cycle in all seasons was observed. The elevated temperature, favorable atmospheric diffusion conditions that could dilute the daytime aqueous particulates matter and particulate accumulation at low temperature during the night times phenomena resulted in higher level of PM mass concertation in the night times than the day times in all seasons. Back trajectories and wind rose demonstrated that some PM are from anthropogenic and traffic with a few transported hazes. An adoption of green city, moto vehicle inspection, use of quality fuel (gasoline and diesel) and the use of clean energy associated with more air quality monitoring sites in Kigali and countryside are recommended to keep our air clean.

Acronyms and Abbreviations

AQG:	Aerosol Sample Conditioner
AQI:	Air Quality Index
ASC:	Aerosol Sample Conditioner
BC:	Black Carbon
COMEAP:	Committee on the medical Effects of Air Pollutants
COPD:	Chronic Obstructive Pulmonary Disease
LMICs:	low- and middle-income countries
LPG:	Liquefied Petroleum Gas
MDA:	Mineral Dust Aerosol
MINEDU	Ministry of Education
PBAPs:	Primary Biological Aerosol Particles
PM:	Particulate Mater
REMA:	Rwanda Environment Management Authority.
WHO:	World Health Organization
EPA:	Environmental protection agency
MAM	March April May season
SOND	September October November and December season.

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Chapter I: INTRODUCTION

The air we inhale is becoming dangerously contaminated: 90 percent of people now breathe a polluted air, which kills seven million people each year(WHO 2010). Air pollution has major health consequences; it is responsible for 30% of death from stroke fatalities, as well as lung cancer and heart disease (World Health Organization (WHO) 2018).

In Rwanda, ambient air pollution was responsible for 2,227 deaths in 2012, resulting in a total loss of 108,622 years of life (REMA 2018). lower respiratory disease or stroke were the leading causes of death in Rwanda and are due to poor air quality (C 2018; REMA 2018, 2019; UN Environment 2018). Long-term health conditions caused by polluted air can also cause a burden on health services; in 2012, acute respiratory infections were the major cause of deaths in Rwandan health centers, accounting for 21.7 percent of all patients admitted to health centers and 6.8 percent of patients admitted to hospitals (REMA 2018). In Rwanda, the leading cause of death for kids under the age of five is respiratory infections (Henninger 2009;REMA 2018).

In 2021, Poor air quality was regarded as the world's "largest single environmental health risk"; in 2012, poor ambient air quality was responsible for more than three million premature deaths worldwide (WHO 2018). Around 87 percent of these deaths occurred in low and middle-income countries(Henninger 2009; Dias et al. 2012;UN Environment 2018; World Health Organization (WHO 2018).

Human activities, and natural sources can both be contribute to air pollution. Road congestion, domestic fuel burning, and industry are the main sources of air pollution in Rwanda. According to a review of study data and existing air quality data, the main pollutants of concern in Rwanda are: Nitrogen dioxide(NO_2) and particulate matter (UN Environment 2018).

High PM_{10} and $PM_{2.5}$ concentrations in Rwanda are attributed to: high vehicle emissions (due to the heavy reliance on imported, used vehicles with poor or degraded emissions control technology), use of biomass resources (wood and other solid fuels), emissions from industrial processes, and seasonal burning of vegetation in the tropics (Langley Dewitt et al. 2019).

Rwanda is located in the midst of Sub-Saharan Africa's two major seasonal biomass burning zones. During JF and JJA, large-scale biomass burning occurs in Rwanda's north and south respectively (Langley Dewitt et al. 2019).

Rwanda's climate may experience the impacts of fire haze pollution, as the country has two dry seasons that coincide with these two continental burning seasons, making long-distance transit with low rain out.(Africa 2017; Langley Dewitt et al. 2019) The predominant wind direction in Rwanda goes from northerly (JF) to southerly (JJA) at the same time that the large-scale biofuel burning region shifts from north central Africa to southern Africa(Langley Dewitt et al. 2019)

Rwanda is positioned to experience both large-scale (transported) haze due to fires and human activities and local diffuse emissions. To advance our scientific understanding of variation of the particulates matters (PM2.5 and PM_{10}) in different seasons of Rwanda and their possible sources, ground data (May-2018 to Mach-2021) was collected and combined with meteorological data from Meteo Rwanda to study the diurnal and seasonal variability of PM in all seasons and their main cause over Kigali City.

1.1. Background

Kigali, Rwanda's capital, is in the country's geographic center. In the last decade, Kigali has grown dramatically into a modern city, becoming not only Rwanda's most crucial business center, but also the country's main port of entry (Kigalicity.gov.rw 2021b).Gasabo, Kicukiro, and Nyarugenge are the three districts that comprise Kigali City. On an area of 738 km^2, it currently has 1.2 million people(Kigalicity.gov.rw 2021a). Kigali, with a population density of 1,644 people per square kilometer, is one of Africa's most crowded cities(Ministry of Infrastructure 2014)

Kigali's terrain, which accounts for approximately 83 percent of the city's land area, is made up of natural unplanned areas and rural agrarian land. Residential, commercial, industrial, social and infrastructure facilities occupy only about 17% of the city's total land area (UN Environment 2018). Kigali City's urban area is concentrated around Nyarugenge's Central Business District, with some spread along the east-west highway towards Kigali International Airport in the east.

The city's new growth areas are emerging along major transportation corridors (UN Environment 2018)

Rwanda is located in the midst of Sub-Saharan Africa's two major seasonal biomass burning regions (Langley Dewitt et al. 2019).

Kigali is confronted with a rapid increase in motor vehicle congestion on its roads, particularly during peak hours, resulting in air pollution. This is due to rapid population growth and an exponential rise in personal vehicles. However, improvements in public transportation services have recently occurred, with high-capacity buses and minibuses gradually gaining prominence in addition to motorcycle taxis (taxi-moto).The city's road infrastructure has also improved significantly, with the majority of the city's roads now being paved (Ministry of Infrastructure 2014).

In terms of household cooking energy, biofuel production account for 97 percent of all consumption, with firewood accounting for 86 percent. Charcoal accounting for 11 percent, crop waste accounting for 2 percent, and other fuels accounting for 1percent. Electric stoves and microwave ovens are used to a lesser extent in urban centers. Liquefied Petroleum Gas (LPG) is progressively being used by commercial establishments and affluent households (LPG)(Gashakamba 2018; UN Environment 2018)

While it is expected that the energy balance will shift in the coming years due to increased demand for electricity, biomass will continue to be Rwanda's primary energy source for the time being, primarily used in cooking.(Report 2011) This biomass source of energy will result in remarkable sight of urban background PM10 and PM2.5 concentrations in the cities that will be well above international standards and WHO guidelines as well(Kendel et al. 2008)

In Kigali, the transportation industry continues to be a major source of urban air pollution. According to the United Nations Environment Program, motor vehicles are responsible for up to 80% of urban air pollution in most cities of developing-country including Kigali. NO2 and PM2.5 are the major emissions from motor vehicles in Kigali (REMA 2018). As of 2017 Rwanda had a total of 191,015 registered motor vehicles whose new vehicles account for only 15 per cent whereas imported used vehicles accounting for 85 per cent(Bathmanabhan and Saragur Madanayak 2010).

The building and manufacturing sectors are responsible for the majority of Kigali's industrial air pollution. The main emissions from the construction sector include PM10 and PM2.5 from demolition and earthworks, as well as NO2 and PM10 from energy use. Construction sites and small-scale brick kilns are the major sources of these emissions in Kigali (UN Environment 2018)

It is estimated that 45 percent of the energy used in the manufacturing sub-sector originates from furnaces/heavy oils, with the remaining 3 percent coming from wood, both of which emit substantial amounts of pollution (Onainor 2019). Because Kigali and Rwanda still have a modest manufacturing base, emissions from this sub-sector are limited and concentrated in the Gasabo area Ndera sector (Onainor 2019)

Emissions in Kigali come not only from within the city, but also from transboundary sources such as forest fires in nearby countries such as Uganda and the Democratic Republic of the Congo. Kigali is also vulnerable to both large-scale (transported) haze from fires and human activity, as well as local, diffuse emissions (World Health Organization (WHO) 2018)

1.2. Problem statement

As the world becomes hotter and more crowded, our engines continue to emit dirty emissions, and half of the world lacks access to clean fuels or technologies (e.g., stoves, lamps), the very air we breathe is becoming dangerously polluted: 90 percent of people now breathe polluted air, which kills 7 million people (approximately twice the population of Oklahoma) each year. Air pollution has major health consequences, accounting for one-third of all stroke deaths, as well as lung cancer and heart disease (REMA 2019).

Long-term health conditions associated with poor air quality can also put a strain on health services; in 2012, acute respiratory infections were the leading cause of morbidity in Rwandan health centers, accounting for 21.7 percent of all patients admitted to health centers and 6.8 percent of patients admitted to hospitals (REMA 2018). In Rwanda, respiratory infections are the leading cause of death in children under the age of five (REMA 2018).

High PM10 and PM2.5 concentrations in Rwanda are attributed to the following factors: high vehicle emissions (due to a heavy reliance on imported, used vehicles with poor or degraded emissions control technology), use of biomass fuels (wood and other solid fuels), emissions from industrial processes, and seasonal burning of vegetation in the tropics (REMA 2018; UN Environment 2018)

Particulate matter, a mixture of solid and liquid particles emitted primarily by fuel combustion and vehicle traffic, is the most serious air pollutant. Nitrogen dioxide from traffic or indoor gas stoves; Sulfur dioxide from the combustion of fossil fuels; and ozone at ground level, created by the reaction of sunlight with contaminants from vehicle emissions have a great contribution to the air quality degradation in developing cities

The pollutant that has the greatest impact on people in low- and middle-income countries (LMICs) (African, South-East Asia, the Eastern Mediterranean, and the Western Pacific regions) is particulate matter, which contributes to respiratory tract infections, which resulted in 543 000 deaths in children under the age of five in 2016 (UN Environment 2018)

Kigali's population increased to roughly 1,320,000, with a population density of 1780 people/km2 in 2020 and expected to be 5750 people/km2 in 2040, resulting in a sustained decline of urban air quality (REMA 2018). Old, poorly maintained mopeds, motorbikes, and cars increase the quantity of various air contaminants. Aside from transportation emissions, another type of air pollution common in underdeveloped countries is the use of basic stoves and open fires. Burning wood for domestic energy, cooking, and household tasks generates a significant amount of emissions, both indoors and outside (Edwards et al. 2014; Deutsche Umwelthilfe 2016).

Rwanda's economy has rapidly industrialized because of a successful government policy.

Since the early 2000s, Rwanda has experienced an economic boom that has improved the living conditions of many Rwandans, with the government's progressive aspirations serving as a catalyst for the rapidly developing knowledge-based economy (UNDAP 2011).

This rapid industrialization has resulted in a proven increase in the industry sector, traffic (with more motorbikes, tracks, and private automobiles), and business operations, as well as greater in and out movement of people who work but do not live in Kigali. This contributes to a variety of emissions, which may have an impact on Kigali's air quality. Particulate matter (PM 2.5 & PM 10) and black carbon are the primary pollutants.

There have only been a few studies that have monitored air quality in Rwanda. The majority of these research have been conducted in Kigali, with short sample periods and low-cost low-quality air quality equipment (Kalisa 2019). These studies do not provide comprehensive information on the variability of particulate matter mass concentration over Kigali during the day and night, nor seasonal variations.

This study will provide scientific meaning and data to provide a sound scientific basis for the establishment of cost-effective control strategies and measures to reduce air pollution in Rwanda, particularly in Kigali.

1.3. Objectives of the thesis

1.3.1. General objectives

The air pollutant within the Cities is high comparing to that in the surrounding rural and remote areas, during this dissertation, the main objective is to determine the diurnal and seasonal variability of particulate matter (PM2.5& PM10) mass concentrations in Kigali with a developed and interpreted scientific cause of this variation.

1.3.2. Specific Objectives

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

- To access the seasonal variation of the PM over Kigali City.
- To access the day and night differences of particulate matter ($PM_{2.5}$ and PM_{10}) mass concentration over city of Kigali.
- To assess the diurnal and weekdays PM mass variation in city of Kigali during all different seasons
- Make a Comparative assessment of PM concentrations with different air quality standard.

- To use different models and techniques to access the PM source apportionment

1.4. Hypothesis of the Study

Based on the increased number and status of vehicles in Kigali, anthropogenic activities in Kigali especially construction activities, meteorological conditions, wind pattern over Kigali, use of biomass fuel as the main fuel for cooking in Rwanda, the concentration of particulate matter in Kigali is expected to be high. The day times fluctuations of PM during wet seasons are expected to be lower than the night fluctuations of the dry seasonal. The diurnal, Weekly and seasonal fluctuation of both PM 2.5 and PM 10, normal days are more polluted than lock down period.

1.5. Scope of the study

This study concerns with the diurnal and seasonal variability of PM mass concetration with their potential causes over Kigali city. The main data were collected from air quality and climate change monitoring project from May 2018 to December 2020. The site used is located at the reference station based at Meteo Rwanda headquarter.

Chapter II: LITERATURE REVIEW

2.1. Review on air pollution

2.1.1. Definition

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. Household combustion devices, motor vehicles, industrial facilities and forest fires are common sources of air pollution. Pollutants of major public health concern include particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide (UN Environment 2018). Outdoor and indoor air pollution cause respiratory and other diseases, which can be fatal (WHO 2010)

The air pollution was a global matter due to its impact on human health and environmental quality (Fuzzi et al. 2015). To assess air pollution, we must insist on the chemical composition of ambient aerosols and the determination of pollution sources. Atmospheric aerosols influence many atmospheric processes and have adverse human health effects, affecting both the respiratory and cardiovascular systems. The urban air pollution can be coarse or fine particles (Kalisa 2019). Briefly Coarse particles are those PM with a diameter ranging from 2.5 to 10 μm and are mostly composed by materials from the earth's crust and dust from vehicles and industrial plants while fine particles have less than 2.5 μm ($PM_{2.5}$) it is made by secondary aerosols, combustion particles and re -condensed organic and metallic vapors. The composition of PM varies depending on emissions, weather conditions, local and regional contributions, and temporal variations and change over time as further mitigation measures are introduced and as modern technologies emerge. Currently there is a need of an improved understanding of the behavior and composition of PM which help to improve the understanding of its impacts on health (Kalisa 2019)

Particulate matter (PM) is the term used to describe condensed phase (solid or liquid) particles suspended in the atmosphere (Sokhi et al. 2021). The particulate matter variability show higher concentrations during the summer as compared to other seasons (Bathmanabhan and Saragur Madanayak 2010; Author 2012; REMA 2018). The requirement to control atmospheric concentrations of particulate matter derives from its well-recognized and quantified effects upon human health, including premature mortality, hospital admissions, allergic reactions, lung dysfunction and cardiovascular disease (Fuzzi et al. 2015).

2.2. Effect of air pollution

Air pollution is intimately connected to the spread of deadly illnesses. Air pollution was connected to one out of every eight fatalities worldwide in 2012, or around 7 million people Around 600,000 of those were children under the age of five (WHO 2010). Each year, one million children worldwide die from pneumonia, with more than half of those deaths directly attributable to air pollution. Children's health might suffer as a result of air pollution(Bartington and Avis 2020).

Today, air pollution presents the greatest environmental health risk globally with many parts of the world recording dangerously elevated levels of air pollution. Updated WHO estimations show that 90 per cent of people worldwide breathe air containing elevated levels of pollutants. Air pollution causes 1 in every 9 deaths globally (WHO 2010).

According to WHO estimates, 7 million people die each year as a result of exposure to fine particles in polluted air that penetrate deep into the lungs and cardiovascular system, causing diseases such as stroke, heart disease, lung cancer, chronic obstructive pulmonary diseases, and respiratory infections, including pneumonia of the total annual air pollution-related deaths, 4.2 million are the result of exposure to ambient (outdoor) air pollution and 3.8 million are the result of indoor air pollution (WHO 2018). Indoor air pollution from solid fuel consumption and urban outdoor air pollution are estimated to be responsible for 3.1 million premature deaths responsible for 3.1 million premature deaths worldwide every year and 3.2% of the global burden of disease More than half of the global burden of disease from air pollution is borne by people in developing countries (WHO 2010). Air pollutants have been linked to a range of adverse health effects, including respiratory infections, heart disease and lung cancer (World Health Organization (WHO 2018)

In addition to the various health consequences, most air pollutants have serious immediate and long-term environmental consequences. Air pollution has a negative impact on plant biodiversity and the ecosystem services that they provide, as well as destroying cultural heritage and contributing to global warming (Kendel et al., 2008; WHO 2010; WHO, 2018).

Over 4 million people die prematurely from illness attributable to the household air pollution from cooking with solid fuels (Vinet and Zhedanov 2011).

- More than 50% of premature deaths due to pneumonia among children under 5 are caused by the particulate matter (soot) inhaled from household air pollution.

- 3.8 million premature deaths annually from noncommunicable diseases including stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer are attributed to exposure to household air pollution (Vinet and Zhedanov 2011).

2.3. Particulate matter

2.3.1. Definition, principal sources, and composition.

Particulate matter (PM) is a mixture of solid particles and liquid droplets that are produced by a variety of sources such as coal, oil, and wood combustion, steel furnaces, boilers, smelters, dust, waste incineration, and brake wear (Pandis 2006), Depending on their sources, these elements can be found in either the fine or the coarse mode (REMA 2019).

PM10 refers to particles with aerodynamic diameter less than 10µm and cannot be inhaled PM2.5 refers to fine inhalable particles with aerodynamic diameter less than 2.5µm.

Sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water are the most common constituents of PM.

Particles with a diameter of 10 microns or less (PM10) are the most dangerous to one's health because they can penetrate and lodge deep within the lungs.

Chronic particle exposure increases the risk of developing cardiovascular, respiratory, and lung diseases, as well as lung cancer. Routine air quality measurements typically describe such PM concentrations in terms of micrograms per cubic meter (µg/m3). When sufficiently sensitive measurement tools are available, concentrations of fine particles (PM2.5or smaller), are also reported (Pandis 2006; Fuzzi et al. 2015).

Primary particulate emissions from industries, transportation, power generation, and natural sources are mixed with secondary material formed by gas-to-particle conversion mechanisms to form urban aerosols. Particles smaller than 0.1 m dominate the number distribution, while the majority of the surface area is in the 0.1-0.5 m size range. The aerosol size distribution is found near sources, but its concentration decreases rapidly as one moves away from the source. Aerosols in rural areas are primarily of natural origin, with a minor contribution from anthropogenic sources (Pandis 2006).

Atmospheric aerosol particles can be emitted as primary particles or formed by secondary processes and can come from either natural or anthropogenic sources (Pandis 2006). Marine aerosols, which are emitted from the marine environment, are one of the largest components of primary natural aerosols (such as mineral dust, biological aerosols, and volcanic ash) in the Earth's atmosphere (Pandis 2006).

They can scatter light and act as cloud condensation and ice nuclei (IN), potentially influencing the radiation budget in the atmosphere as well as cloud physics (Pandis 2006). Mineral dust aerosol (MDA) is another natural source which is often a dominant component of atmospheric aerosol in large regions of the planet (Pandis 2006; Fuzzi et al. 2015).

The Sahara Desert is the primary source of natural MDA. Primary biological aerosol particles (PBAPs) are another source because they contain a wide variety of biological components, including microorganisms (bacteria, archaea, algae, and fungi) and dispersal material such as fungal spores, pollen, viruses, and biological fragments that are directly emitted to the atmosphere from their sources (Pandis 2006). Anthropogenic activities, such as transportation-related aerosol and wood combustion for residential heating, are also sources of pollution (Pandis 2006)

Table 1: Source of aerosols and their types

Emission sources	**Marker elements**
Soil	Al, Si, Sc, Ti, Fe, Sm, Ca
Road dust	Ca, Al, Sc, Si, Ti, Fe, Sm
Sea salt	Na, Cl, Na^+,Cl^-, Br, I, Mg, Mg^{2+}
Oil burning	V, Ni, Mn, Fe, Cr, As, S, SO_4^{2-}
Coal burning	Al, Sc, Se, Co, As, Ti, Th, S
Iron and steel industries	Mn, Cr, Fe, Zn, W, Rb
Non-ferrous metal industries	Zn, Cu, As, Sb, Pb, Al
Glass industry	Sb, As, Pb
Cement industry	Ca
Refuse incineration	K, Zn, Pb, Sb
Biomas burning	K, C_{ele}, C_{Org}, Br, Zn
Automobile gasoline	C_{ele}, Br, Ce, La, Pt, SO_4^{2-}, NO_3^-
Automobile diesel	C_{ele}, C_{Org}, S, SO_4^{2-}, NO_3^-

Secondary aerosols	SO_4^{2-}, NO_3^-, NH_4^+

Source:(Fuzzi et al. 2015)

2.3.2. Particulate matter chemical composition

Aerosol particles in the atmosphere contain sulfates, nitrates, ammonium, organic material, crustal species, sea salt, metal oxides, hydrogen ions, and water (Fuzzi et al. 2015). Sulfate, ammonium, organic and elemental carbon, and certain transition metals are found in abundance in the fine particles of these species (Fuzzi et al. 2015). The coarse aerosol fraction typically contains crystalline materials such as silicon, calcium, magnesium, aluminum, and iron, as well as biogenic organic particles (pollen, spores, plant fragments) (WHO 2018).

Nitrate can be found in both fine and coarse modes. Fine nitrate is typically the product of the nitric acid/ammonia reaction for the formation of ammonium nitrate, whereas coarse nitrate is the product of coarse pm(Pandis 2006; Fuzzi et al. 2015; Myong 2016).

2.3.3. The removal processes of particulate matter

Particulate matter removal from the atmosphere is done by the mechanism of wet or dry deposition where it is removed by precipitation (Fuzzi et al. 2015). The growth of cloud droplets leads to the formation of raindrops, which will deposit particulate matter contained in solution to the earth's surface. Due to the solubility of gases like SO_2, HNO_3, NH_3, etc. in rainwater, it is not possible to distinguish the relative contributions of gases and particulates by measurement of concentrations in precipitation (Fuzzi et al. 2015; Myong 2016). The indirect effects of PM on ecosystems through wet and dry deposition can be assessed by the impact of total deposition on soil processes, and therefore on ecosystems, expressed as a "critical load" (Fuzzi et al. 2015; Myong 2016). A critical load is defined as "A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" ((Quality and Group 2012; Myong 2016)).

2.3.4. Particulate matter over Kigali

Kigali's baseline air quality data published in January 2018 indicates significantly elevated urban background concentrations of PM10 and PM2.5 in the city that is well above international standards (REMA 2018; UN Environment 2018; Kalisa 2019; Langley Dewitt et al. 2019). During public holidays and Kigali car-free days, air pollution reduced compared to normal working days as there are fewer traffic on the road. The studies point to emissions from domestic stoves (wood fuel) as the main influencers of background PM concentrations. In addition, the studies point to significantly high PM10 and PM2.5 concentrations near busy roads in Kigali city, an indication that road traffic is the most significant contributor to high PM concentrations near busy roads (Myong 2016; UN Environment 2018)

The elevated background concentrations of PM10 and PM2.5 in Kigali City are mainly attributed to domestic stoves (Myong 2016; UN Environment 2018). On the other hand, high PM, and NO_X levels close to busy roads in the city point to motor vehicles as the main source (Myong 2016).

Kigali's PM10 levels are increasing in areas with high rates of traffic due to the exhaust of the vehicles and the stirring up of dust from the ground and burning wood for cooking (Report 2011). Higher increase was observed in the evening hours. A study results suggest that the atmospheric concentration of PM in Rwanda could be strongly affected by biomass combustion particulates transported from Eastern and South Africa during the dry season (Report 2011). During the dry season, savannah fires and other combustion sources are high contributors of PM. Back trajectory analysis indicates increased local PM corresponds to activities in neighboring countries (Report 2011).

Elevated levels of PM are associated with the highest moving air masses (about 3500 meter altitude) that originated from neighboring countries such Uganda, Tanzania, and Kenya, as well as South Africa (south-westerly in JJA and northwesterly in JF). These East African countries likely have high concentration of PM from biomass burning. Low levels of PM are associated with slow moving local air masses traveling at lower altitude (500 meter) within Rwanda (Kalisa 2019; Langley Dewitt et al. 2019)

2.3.5. Effects of $PM_{2.5}$ and links to climate change

Different research showed the consequences of airborne PM on the human health, the environment and climate change. There is unmistakable evidence based on the conducted research showing that particulate matter has a significant contributory role in human all-cause mortality and in cardiopulmonary mortality (Use and Solid 2010). $PM_{2.5}$ penetrates deeply into the human respiratory system. The acute effects of particle exposure include increases in hospital admissions and premature death of the old and sick due to diseases of the respiratory and cardiovascular systems (Dias et al. 2012; Quality and Group 2012). Less severe effects of short-term particle exposure also occur during pollution episodes, including worsening of asthma symptoms and even a general feeling of being unwell leading to a lower level of activity and productivity. Long-term exposure to particles is associated with increased levels of fatal cardiovascular and respiratory diseases, including lung cancer, which reveal themselves as increased rates of death in cities with higher concentrations of airborne particles. The best estimate of the chronic health impacts of particulate matter exposure was a 6% increase in death rates per 10 µg m^{-3} in $PM_{2.5}$ concentration (Use and Solid 2010). As with the acute effects of particle exposure no wholly safe level has been identified(Dias et al. 2012; Quality and Group 2012).

Ammonia, SO_2, NOx and VOCs are secondary aerosols. And they have capacity to scatter solar radiation back to space and exert a negative (cooling) radioactive forcing effect on climate and they influence the radiative properties of clouds (Henninger 2009). Therefore, cooling effects of different aerosol may have partly masked the warming effects of greenhouse gases. Black carbon absorbs solar radiation and black carbon aerosols, or mixtures of aerosols containing a large fraction of black carbon, exert a positive (warming) radiative forcing effect on climate (Henninger 2009).

Aerosols, in general, influence indirectly by affecting the radiative properties of clouds by acting as cloud condensation nuclei, increasing droplet number concentrations, and decreasing average droplet size in clouds, all of which affect the clouds' ability to scatter atmospheric radiation. The effectiveness of cloud precipitation is likewise lowered, resulting in a longer lifetime. Overall, the indirect effect of aerosols is cooling; however, the extent of this effect is unknown (Henninger 2009).

Chapter III METHODOLOGY

3.1. Sampling location description

The air quality sampling site used in this research, is in urban area of Kigali city surrounded by dense residence (Gitega) near a heavy traffic road to Nyamirambo. The data are collected using a high frequency Teledyne API's model T640 instrument installed at Meteo Rwanda head office located at -1.9562386, latitude and 30.0573057 longitude. Data are collected from May 2019 to December 2020. This site is selected by Air quality and climate change Monitoring project owned by REMA and MINEDUC based on the geographical location that fully fit the requirements to represent urban residential air pollution monitoring station. The station is located ~100 meter away from busy road, with an inlet installed on the top of the building with open airflow, built in one of the city's urban (Gitega) area of a moderated population density. Elevation of 1520m a.s.l.

3.2 Experimental methods.

Real time high frequency (5 minutes sampling interval) particulate matter ($PM_{2.5}$ and PM_{10}) were collected from high precision Teledyne API's Model T640 PM mass monitor at air quality reference station for the air quality and climate change monitoring project owned by REMA and MINEDUC located at Rwanda meteorology agency HQ.

T640 instrument is installed near a Meteorological station to gain the meteorological parameter to be used in this research. The instrument inlet is installed on the top of small housing open to the air circulation. Rainfall, Solar radiation, Wind Speed (Ws), Wind Direction (Wd), Average Temperature (AT), and Relative Humidity (RH) data were collected from Rwanda meteorology agency (Meteo Rwanda) Kigali stations.

The T640 instrument as all reference station's instruments has an automatic calibration using connected calibration cylinder with known concentration at higher precision form NOAA. A six month manual calibration is performed and the data quality control is performed and reported to the project's chief scientist

3.3. Instrumentation

3.3.1. Teledyne API's Model T640 PM Mass Monitor

According to Lorenz-Mie theory, the Model T640 PM mass monitor is an optical aerosol spectrometer that translates optical data to mass measurements with high precision by measuring sampled particle size via scattered light at the single particle level. In brief, the sampling head sucks in ambient air with various particle sizes, which are then dried using the Aerosol Sample Conditioner (ASC) and transported into the optical particle sensor, where scattered light intensity is recorded to determine particle size diameter.

The particles enter the T-aperture independently via an optically separated measurement chamber that is homogeneously lit with polychromatic light. A polychromatic light source, an LED, paired with a 90° scattered light detector, results in an accurate and clear calibration curve in the Mie range, resulting in a high size resolution.

Each particle produces a scattered light impulse, which is detected at an angle of 85° to 95° and measured for amplitude and signal length; the amplitude (height) of the scattered light impulse is proportional to the particle size diameter. Border zone error is eliminated by using T-aperture and simultaneous signal length measurements (Teledyne API 2021).

3.4. Data analysis methods

The main data analysis methods adopted in this research include multivariable statistical analysis and visualization technologies. The statistical analysis technique principally focused on the descriptive analysis of the PM on the sampling location. Multivariate analysis was used to involves correlation analysis of the different parameters collected on the sampling site and to study the complicated relationship between PM concentrations, meteorological factors, and surrounding factors.

The data visualization methods used in this research is mainly from R libraries and packages where the package of interest was open air that helps to benefit from summary plots, scatter plot, wind rose, time variation plots and trend level plots to intuitively illustrate the atmospheric phenomena varying with time and help to find out the potential development pattern.

The back trajectory (Hysplit dispersion Model) analysis and wind rose was used to track the source of the studied pollutant over Kigali city and its relations with the wind parameters.

To demonstrate the strength of the relationship between the variables, the Pearson's coefficient, commonly known as the Pearson Product Moment Correlation 'r^2,' was calculated.

Chapter IV: RESULTS AND DISCUSSIONS

4.1 Temporal Variability of particulate matter concentration over Kigali City

Temporal variability of PM during this period was analyzed using time series plot (Figure 1) and smooth trend plots (**Error! Reference source not found.**). The time series pattern analysis showed no significant trend in data during the research time. The collected data has an observed seasonal pattern with high concentration in JJA and JF period, this increase can be associated to lack of the remove process of the PM in the atmosphere, meteorological parameters, the occurrence of the transported haze are the result of the dust accumulated in the atmosphere (Giri, Krishna Murthy, and Adhikary 2008; Author 2012; Langley Dewitt et al. 2019), anthropogenic activities and effect of the unpaved road (unpaved road and busy paved road towards Nyamirambo) near the sampling station. The removal of the particulate matter from the atmosphere through the precipitation scavenging process, may be associated to the low observed concentration of PM in MAN and SOND seasons.

The concentration level analyzed with smooth plot illustrated in **Error! Reference source not found.**. This analysis uses generalized Additive Modeling using the mgcv package with 95 % confidence intervals of the fit. The results showed a proportional increase in concertation in different seasons with a pick in dry seasons of the sampled period. A peak for both $PM_{2.5}$ and PM_{10} was observed in dry seasons (JJA and JF) up to a level of 180 $\mu g/m^3$ in July 2020. A low peak in concentration was observed during wet season and the lowest concentration was observed in April 2020 for $PM_{2.5}$ with 18.3$\mu g/m^3$ and 28 $\mu g/m^3$ of PM_{10} in April 2019. The increased in concentration maybe associated with different factors where we can mention heat wave, primary and secondary sources of PM in Kigali and particulates residence time.

4.1.1. Multivariable Statistical analysis

The daily average Statistical analysis of the collected particulate matter (May 2019 to March 2021) is summarized in the Table 2. Those statistics include mean, which is the average of the data values, the median which is the 50^{th} percentile (P_{50}) of the data set or second quartile. first (lower or P_{25}) quartile, and the 75^{th} percentile or third (upper or P_{75}) quartile, The minimum and maximum values.

As per previous research, PM_{10} concentration over Kigali was high compared to that of PM2.5 concentrations in both mean and quartiles. PM_{10} data densities analyses showed two picks in density with different percentages 40 μgm^{-3} to 60 μgm^{-3} occurred at 15.5% whereas 150 μgm^{-3} to 160 μgm^{-3} occurred at 15%. $PM_{2.5}$ have one pick in density which is 35 to 60 that occupied 14% in total.

The statistical analysis shows moderate high value of PM over KIGALI and its daily change in concentration was analyzed. This analysis ride to a quantitative analysis of the daily average with the WHO guidelines and recommended ambient air quality standards for Rwanda.

4.2 Seasonal variability of PM10 and PM2.5 over KIGALI city

Rwanda experiences four different climatic seasons known as short rain SOND and long rain season MAM that alternate with two dry seasons known as short dry season JF and long dry season JJA. Due to different meteorological variables, anthropogenic activities, PM remove mechanisms and due to possible primary and secondary sources of PM, the level of PM can vary season to season in Kigali. This section discusses the seasonal variability of PM in the four different seasons as discussed below.

4.2.1 Dry season PM mass concentration variability of KIGALI

Kigali as whole Rwanda has one short dry season JF and one long dry season JJA. The short dry season starts in January and end in February the long dry season starts in June and ends in August. This research focused on four dry seasons from 2019 to 2020. As expected, the dry seasons, short and long, have high mean concentration that is associate with several meteorological factors, regional emissions, and anthropogenic activities in this season.

The long-range transport of dust from the east of the country (Figure 11 and Figure 10)that experiences a wildfire in JF resulted in the increase of the $PM_{2.5}$ due to its long lifetime (some days) (Langley Dewitt et al. 2019)

The residents of Gitega (the area near the reference station) uses the wood, charcoal, and petrol as source of energy in their daily cooking activity on this influenced the elevated level of PM observed in this dry season. The effect of the dust forms the unpaved road near the station contributed to the increase PM concentration on this site.

4.2.2 Wet season PM mass concentration variability of KIGALI

As whole Rwanda, we have one short wet season SOND and one long wet season MAM. In this research five wet seasons from 2019 to 2020 was analyzed.

A comparatively low concentration, compare to the dry season, during the rainy season (MAM and SOND) was observed with average mass concentration of 84.3 μgm^{-3} and 35.37 μgm^{-3} for PM_{10} and $PM_{2.5,}$ respectively. PM_{10} mass concentration ranges from 00 μgm^{-3} to 405.94 μgm^{-3} with the median and standard deviation of 79.92 μgm^{-3} and 34.16 μgm^{-3} respectively in MAM_2020. Mass concentration of $PM_{2.5}$ is in the range of 00 μgm^{-3} and 241.11 μgm^{-3} with the median and standard deviation of 30.69 µgm-3 and 19.71 respectively in MAM_2020.

The statistical analysis in this season yielded that the average mass concentration of SOND for the whole period of analysis was 49.54 μgm^{-3} and 105.6 μgm^{-3} for $PM_{2.5}$ and PM_{10}, respectively. $PM_{2.5}$ mass concentration ranges from 00 μgm^{-3} to 150.76 μgm^{-3} with the median and standard deviation of 49.54 μgm^{-3} and 22.10 μgm^{-3} respectively.

Mass concentration of PM_{10} is in the range of 00 μgm^{-3} and 450.9 μgm^{-3} with the median and standard deviation of 125.7 μgm^{-3} and 57.12 respectively in SOND.

A relatively law PM mass concertation was observed during the long-wet season as shown on the seasonal variation plot of the **Error! Reference source not found.**. The level of PM during April and May showed a relatively slight variation that clusters around the lowest value. Uniform pattern in both wet seasons was observed during the sampling period. The above low concentration during this wet season may be associated with the effect of precipitation scavenging process which is a removal mechanism of the particulate accumulated in the atmosphere (Author 2012), Atmospheric circulation and dust storms transported from neighboring countries by easterly wind, gave a significant contribution to PM mass concentration.

In this study area, the author realized that the seasonal, meteorological and weather conditions have a significant effect on the particulate matter mass concentrations (Fuzzi et al. 2015; Zhao et al. 2019).

4.3 Day/Night and seasonal pattern of PM (2.5&10) over Kigali city.

In all the seasons of the research period (MAM, JJA, SOND and JF) particulate matter (PM10&PM2.5) average mass concentration has more concentration during the night condition rather than in day time conditions. Higher concentration were observed in the dry seasons(JJA), (see Figure 4 and), for both $PM_{2.5}$ and PM_{10} as shown in *Table 3*.

In addition to the distinct differentiation of meteorological condition between the day time and the nighttime that can explain the gradient of daytime and night time particulate matter mass concentration, the neighborhood of the sampling site in a dense urban residential area where most of the cooking activity for the family are conducted during night time and their use unclean source of energy especially coal and wood as the main source of cooking energy. This may result in an increased biomass burning which is a kind of PM we measured at the site. Other possible sources that can contributes to this increase of the PM during the night time is the incinerator of CHUK hospital that runs in the night time which is located around 500 meter from the data collection site. The relatively low concentration of $PM_{2.5}$ and PM_{10} during the long rain season is related to the increase of the strong convective air mass, precipitation, and large boundary layer is high in this season. The higher increase in the particulates mater in the summer can be attributed to the summer heating and traffic emissions in Kigali. in addition to this, the elevated temperature and favorable atmospheric diffusion conditions could dilute the daytime aqueous particulates matter mass level compares to the particulate accumulation at low temperature during the night times(Giri 2008)

4 4. Day of the week and seasonal pattern of PM($_{2.5\&10}$) over Kigali city

During this research, The seasonal weekly pattern showed an elevated mass concentration during JJA and except JJA whose highest concentration was observed on Wednesday for both PM_{10} and $PM_{2.5}$, the higher mass concentration was observed on Tuesday. The minimum $PM_{2.5}$ and PM_{10} seasonal concentration was observed during MAM season and except MAM season whose lowest concentration is observed on Friday, all other seasons showed a lowest concentration during weekend (Saturday and Sunday) for both $PM_{2.5}$ and PM_{10} (**Error! Reference source not found.**and **Error! Reference source not found.**). More studies are required to investigate the cause of this increased mass concentration on the site.

4. 6. Diurnal and seasonal patterns of PM (2.5&10) over KIGALI city

$PM_{2.5}$ diurnal and seasonal pattern during all seasons show a two peak at considerably higher level that occur during rush hours (06:00 to 09:00 am and 06:00 to 10:00 PM) with different in magnitude during different seasons. A significant decrease occurs from 11:00 am to 5:00 pm in all seasons. A minimum in peak is observed during long rain season (MAM) and higher mean concentration level in diurnal peaks was observed during the long dry season (JJA). The peak values decrease form JF, SOND, and MAM, respectively **Error! Reference source not found.** and Figure 8. High hourly averaged PM mass concentrations (>60 $\mu g/m^3$ for $PM_{2.5}$ and 115 $\mu g/m^3$ for PM_{10}) level can be associated with automobile source and anthropogenic activities that causes the direct emissions and summer heating. These anthropogenic activities may result from the cooking activities from the household near the station while preparing their breakfast in the morning and the preparation of super during the night times using low quality source of energy that we can mention charcoal, petrol and wood and the higher vehicles toward and back to from their working places.

4.7 Kigali city's PM concentrations vs WHO guidelines and recommended Rwandan ambient air quality standard

Air quality status through April 2019 to March 2021 in this study site was assessed by comparing observed yearly average PM_{10} and $PM_{2.5}$ concentrations with recommended Rwandan ambient air quality standards (REMA 2018) and WHO guideline(WHO 2015) . According to WHO guidelines and recommended ambient air quality standards for Rwanda, the yearly average values should not exceed 10 $\mu g/m^3$ and 25 $\mu g/m^3$ for $PM_{2.5}$, 20 $\mu g/m^3$ and 50 $\mu g/m^3$ for PM_{10} respectively.

The 2019 and 2020-year average of both $PM_{2.5}$ and PM_{10} over Kigali was higher that both recommended Rwandan ambient air quality standards and with WHO guidelines (AQG) as well.

In 2019, $PM_{2.5}$ was 2.7 times higher the WHO limits and 1.15 times higher than the Rwandan recommended limits. PM_{10} was 2.2 times higher WHO AQG and 1.33 higher the Rwandan recommended limits.

In 2020 $PM_{2.5}$ was 3.6 time higher the WHO AQG and 1.5 times higher the Rwandan recommended limits. PM_{10} was 4.3 times higher compares to WHO AQG and 2.57 times higher Rwandan recommended limits. The results indicated that air quality at the station violets the Rwandan recommended ambient air quality standard and WHO standards as well *Figure 9*

4.8. Observed correlations of PM with meteorological variables

In fact, there is a clear linkage of particulate matter ($PM_{2.5}$ and PM_{10}) concentrations in Kigali with the meteorological parameters; this linkage varies seasonally as the meteorological parameters vary by seasons and it not only in Kigali but also across the equatorial zone. Table 4 summarizes the basic correlation of the recorded PM and meteorological.

In all seasons, a weak positive correlation between ambient temperature and PM is observed with a slightly strong (0.36 for $PM_{2.5}$ and 0.44 for PM_{10}) correlation in SOND season indicating that most of the PM collected at the site are generated locally as primary and secondary sources. This modulates correlation of the temperature and PM_{10} indicates the contribution of the unpaved road near station.

This contribution is emphasized by the strong negative correlation of the $PM_{2.5}$ AND PM_{10} and the RH that can justify the wet deposition (washout and rainout) process in this season and can also reflect the importance of dust as one of the Particulate matters source in Kigali.

The weak correlation between temperature and PM during & the dry season JJA (0.12 for $PM_{2.5}$ and 0.11 PM_{10}) indicate that most of the pollution in this season is transported and not local pollution. This is testified by both winds rose and hysplit model indicating that in JJA the station receives the wind of up to 3000 meter passing though DRC, BURUNDI, and TANZANIA. Table 4.

$PM_{2.5}$ and PM_{10} yielded a weakly positively correlation with global radiation in all seasons. This may be attributed to the fact that

Photo chemical reactions in the atmosphere driven by global radiation in atmosphere that leads the formation of secondary particulate matter, may be attributed to the positive correlation of both $PM_{2.5}$ and PM_{10} in all seasons of the study (Author 2012; Zhao et al. 2019).

The negative correlation of the PM and the wind speed in MAM, JJA and in JF indicates a PM dispersion, dilution, and transport of the PM over the site. The positive correlation of PM and wind speed in SOND combine effects of PM loadings and water vapor in this season.

4.9 Kigali Particulate matter mass distribution

Beside the primary and secondary sources of particulates matter in Kigali, the wind plays a major role in the increase of the PM mass concentration as it acts as the driver of the air pollutants either locally or trans boundary. In Kigali, there was no calm condition to take place (zero wind speed), the wind speed and the wind direction show a major information on the sources and even how far the particulate matter may come from, Figure 10 shows how the local wind parameters (wind speed and wind direction) varies in Kigali, with a proportion (here represented as a percentage) of time that the wind is from a certain angle (22.5 degree) and wind speed range. The wind direction and the wind speed is not enough to specify the pollutants sources, there is a need to interlink the Wind speed, wind direction and back trajectories with the PM air pollutants concentration present at different break point concentrations. In general, the pollutionRose indicates that the highest Particulate matter concentrations was associated with the south west(dominant in JJA and MAM) and south east during JF and SOND. Higher concetration was recorded in the dry season.

For the levels of $PM_{2.5}$ concentration ranging from 40-80 ppb and 57.6-103ppb was associated with all direction except the north west Figure 11 , from 31.8-42.6 ppb, 42.6-57.6 ppb of PM2.5 it was from south west and even south east. For PM_{10} ranging in the levels of concentration between 18.8-79ppb and 129-208ppb it was associated with Wd from all direction except that comes from north west and the level of associated concentration differ depend on the direction, between 79-129 ppb PM^{10} associated with the Wd was from All direction except north east (see Figure 10 and Figure 11).

4.10. Back trajectory

During the period of investigation, NOAA HYSPLIT model, which is a complete system for computing simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations, was primarily used specifically its a back trajectory analysis component that determined the origin of air masses and established source-receptor relationships.

A clearly recognized and localized seasonal trans boundary air pollutants that reaches the data collecting station, implying that the observed concentrations of PMs at this station include the trans boundary PMs sources, as indicated by the figure's 24 hour running HYSPLIT model result.

For a week ending on 29 April 2020, wet season where we experience southerlies air masses, the 24 hours running cycle demonstrated that most of the air parcels travel 400km to reach the station and originated in different cities of TANZANIA(ARUSHA , SHINYANGA,COMA,…), BURUNDI (Gakuzo and Bugabira and kirundo) and the other air parcel are from the local area of RWANDA including MUHANGA district) this air parcel passes different polluted area including Nyabugogo tax park hence transport PM toward the station and hence an increase in PM mass concentration. In this season most of the pollution is local and reduced due to wet depositions and no pm dispersion. For a week ending on 29 July 2020,wet season where we experience Northerlies, air masses, the 24 hours running cycle demonstrated that most of the air parcels can travel 700km to reach the station and originated in different cities of DRC (Sud KIVU,), TANZANIA (Manyoni, Katavi forest…), AND BURUNDI (RUYIGI AND MWAKIRO). There is no local generated air parcel in this period. The Tanzanian area are forest and characterized by wield fire during this dry season and can be associate with laden atmosphere to contribute to the elevate PM mass concentration in this season.

For a week ending on 25 January 2020, the model demonstrated that the 24-hour running air parcel can travel 5000 km from north of Rwanda towards the station. Most of the air mass is from UGANDA (Kibaale,kwenjonjo, lake albert, bukoba and KAGERA forest) AND DRC (mongbwalu, djugu and Bunia, this is a forest covers) , Burundi (Muyinga, and Rwanda (Huye, and Muhanga). In this region especially Democratique Republic of Congo(DRC) and Uganda, it is made of forest and lakes, the air passes through several cities with different anthropogenic and natural source of PM that are transported to the station itself. The forest fires in this region also contribute to the increased concentration we measured at this station.

The HYSPLIT model indicated that the 24 running air parcel that reaches the station can travel ~8000km to reach the station , but at low altitude(<1500 m.s.l)Figure 11 this implies that through walker circulation and international air transport, air pollutants chemicals may come far from neighboring countries (depend also on its life time and removal processes) and measured in Kigali hence the transported PM are of significant impact on the increase in mass concentration of PM in Kigali and in RWANDA as well.

Chap VI. Conclusion and Recommendation

VI 1: Conclusion

Diurnal and Seasonal Variations of Particulate Matter Concentrations in Kigali from May 2019 to December 2020 was analyzed using 5 minutes data collected from a reference station located at Rwanda Meteo HQ. From this research the following observation was mode:

During the two dry seasons (JJA and JF) Particulate matter mass concentration was considerably high and reached and 134.38 μgm^{-3} and 57.78 μgm^{-3} PM_{10} and $PM_{2.5}$ respectively during JJA seasons of the study (April 2019-DEcember 2020) and 94.46 μgm^{-3} and 53.72 μgm^{-3} PM_{10} and $PM_{2.5}$ respectively for all JF seasons of the study (April 2019-DEcember 2020). We find that this increase is associated with no removal process (wet deposition, rain out and wash out), the atmosphere that laden with dust due to occurrence of transported haze, summer heating and traffic emissions in Kigali, Primary and secondary source of emissions from fossil fuel burning, vehicular emission, forest fire and other forms of combustion process and natural sources that are locally or regionally used that could reach the sampling site.

The running average demonstrated that during the dry seasons especially in the month of January and July, the running average demonstrated that people in the research area are exposed to an unhealthy level of PM 2.5 (>100 ugm-3) that could be linked to an increase in deadly cardiovascular and respiratory diseases, including exacerbation of asthma symptoms, and simply a general sense of being uncomfortable, leading to a decrease in productivity. (WHO 2010; Gloria et al., 2019; Kalisa, 2019)

Particulate matter (PM10 and PM2.5) mass concentration are high during the night times compares to the day times. This gradient of daytime and night is associate to the distinct differentiation of meteorological condition between the day time and the nighttime, dilution of the aqueous particulates matter during the daytime and the accumulation of particulate matter at low temperature during the night times.

In Kigali, Particulate matter (PM2.5&PM10) exhibited a diurnal cycle with two peaks in concentration the morning times (6:00 to 9:00 am) and evening times (06:00 pm to 9:00 pm), this pattern persists in all seasons (**Error! Reference source not found.** and Figure 8) and occurred on daily timescales with a stead high level in the evenings (after ~22:00) and low level during the midday(11:00am to 5:00 pm).The variation in concentration of both PM10 and PM2.5 are influenced by anthropogenic sources, mobile emissions and complex meteorological factors such as primary wind direction and wind speed, solar intensity (Author 2012, Bathmanabhan and Saragur Madanayak 2010;), nighttime subsidence and boundary layer behavior in the day and nighttime.

The comparative assessment demonstrate that the annual average PM 10 concentration is 3.32 and 1.33 times higher the WHO AQG and recommended Rwanda ambient air quality standards in 2019 respectively and *6.*44 and 2.57 times higher in 2020, respectively. PM 2.5 concentration is 4 and 1.15 times higher the WHO AQG and recommended Rwanda ambient air quality standards in 2019 respectively and *5.39* and 1.5 times higher in 2020 (Figure 9).

VI.2 Recommendations

In many developing nations, including Rwanda, vehicle emissions have been identified as a major source of air pollution, in particular diesel cars that are classified as primary source of particulate matter though tire particles, exhaust emissions etc. Due to the number of old imported cars and motorcycles from Europe and Canada a strict regular vehicle inspection, increasing the number of car free zones, promoting cyclists and public transport and ban of used imported cars is advice in Rwanda and in developing countries.

Even new cars emit different air pollutant through combustion and compression, in a way to promote the air quality in KIGALI and in countrywide, a promoting e-mobility police and strategy that aims to facilitation e-mobility is required as it is proven as sustainable solution to this challenging issue on air quality.

However, the measures in place, only the reduction of the air pollution will occur, but zero air pollution is practically impossible. With this a strong sink and removal processes are required. One of the important sink strategies is greening KIGALI. A strong corroboration between Rwanda housing authority, REMA, RAB and district is required to follow up on successively land used and forest cover. A follow up on the implementation of the building permit in the urban areas is required to make sure the green zone is in place and if possible, encourage the top roof greening on the tall buildings.

Population in Kigali city has increased approximately to 1,320,000 with a population density of 1780 people /km^2 and a projection of 5750 people /km^2 in 2040(Kigalicity.gov.rw 2021). use simple stoves, burning wood and charcoals for domestic energy and this household chores produce a lot of emission, indoor and outdoor (Akbar et al. 2011; The World Bank 2017), we would recommend the use of clean energy like LPG, electricity and if not possible apply the cana rumwe stoves to reduce the emission of air pollutants.

An increase in spatial resolution and coverage in Rwanda is required with as many as possible low cost and high grade instrument with a focus on sensitive areas such as industrial zones, near roads, urban areas and remote areas to improve the analysis and assessment of the air pollutant source and trend.

Addendum1: Figures

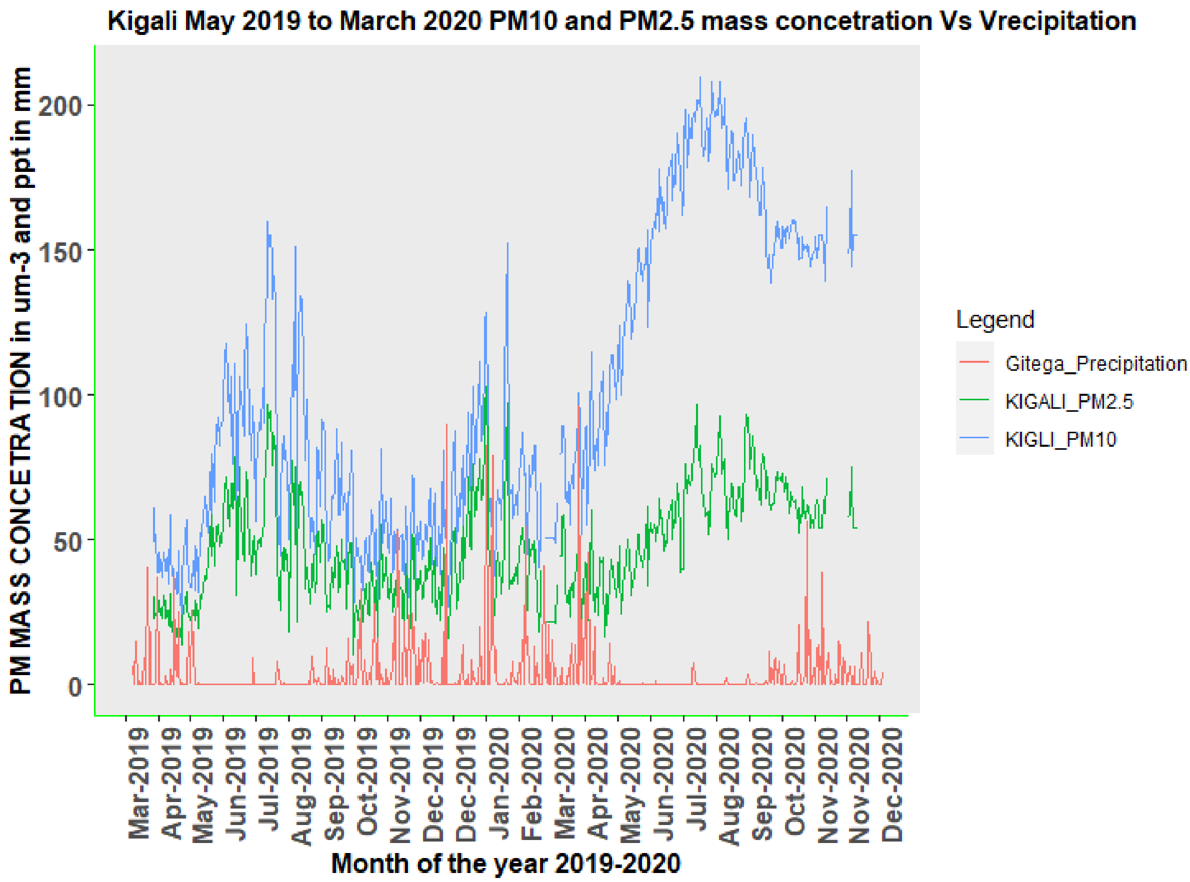

Figure 1: 2019 TO 2020 PM CONCENTRATION Vs PRECIPITATION OVER KIGALI

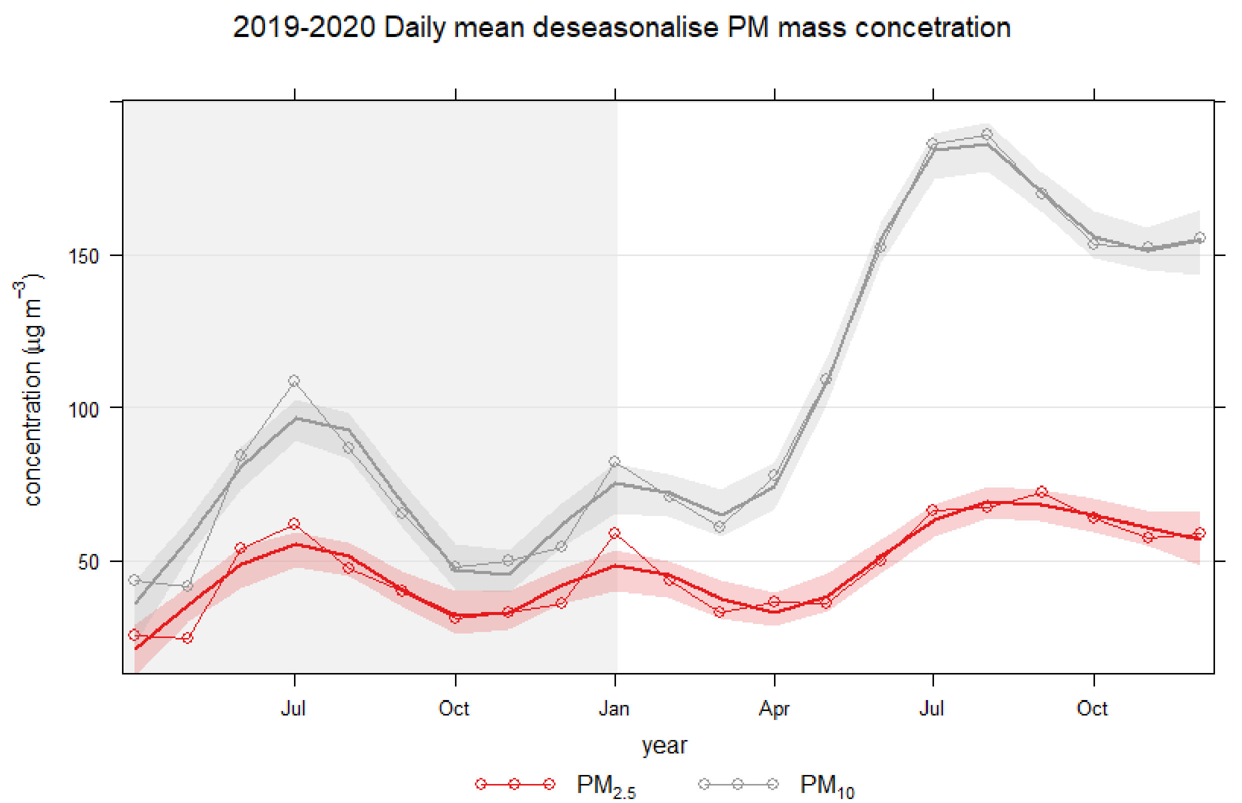

Figure 2: Kigali monthly mean PM 10&$PM_{2.5}$ concentration

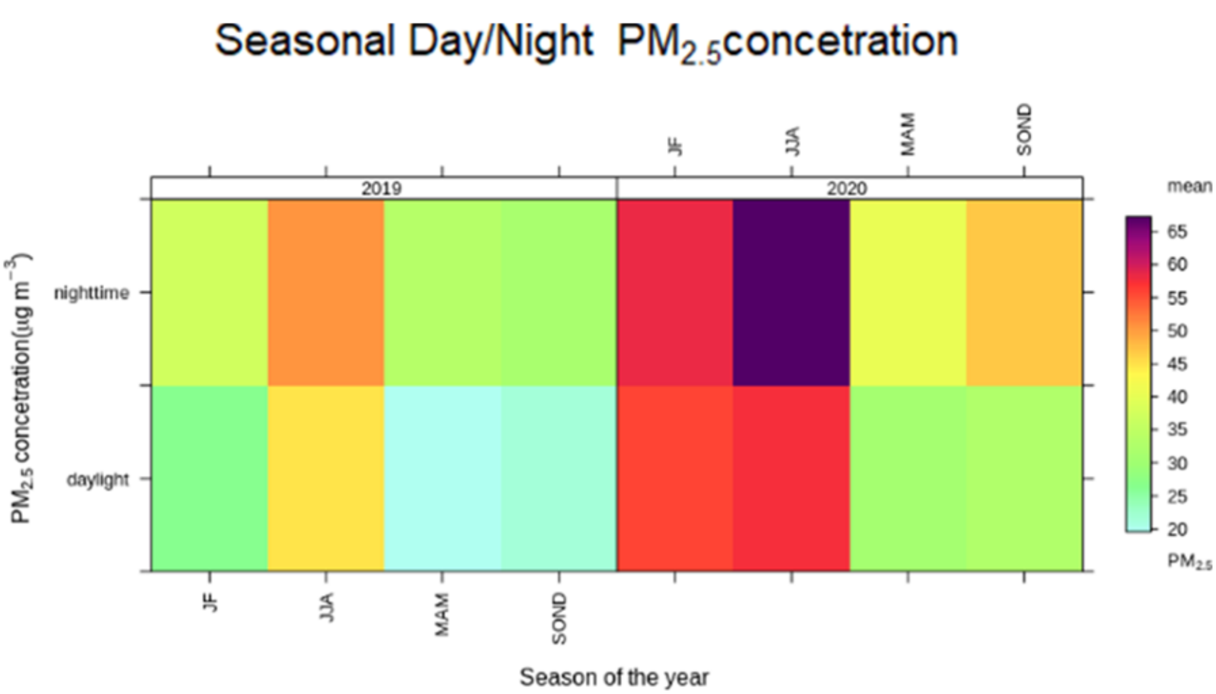

Figure 3: Seasonal Day/Night $PM_{2.5}$ concentration

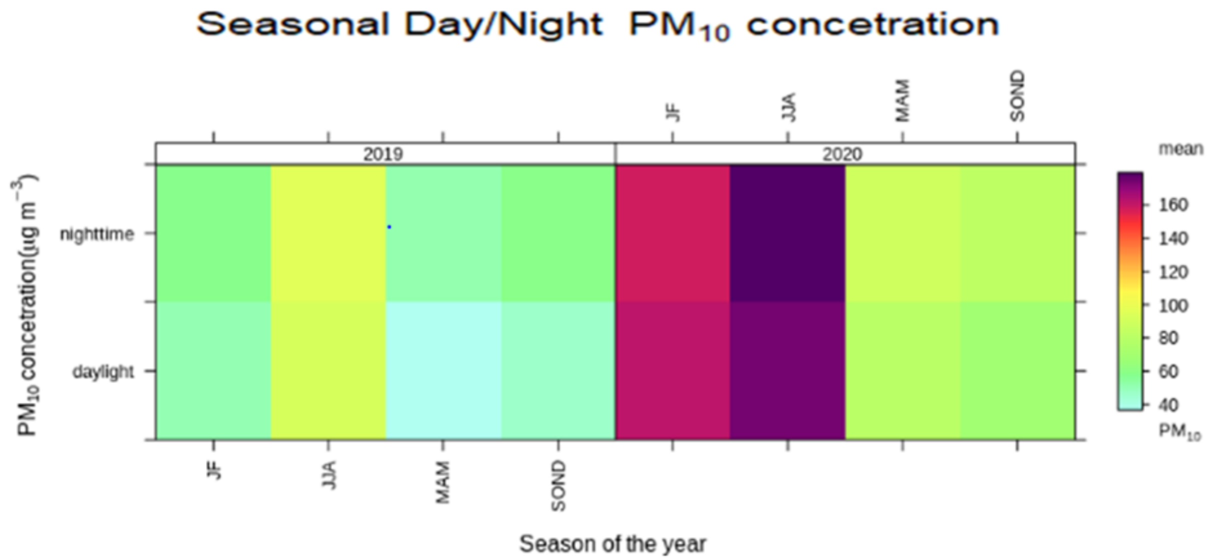

Figure 4: seasonal day/night PM10 variation over Kigali

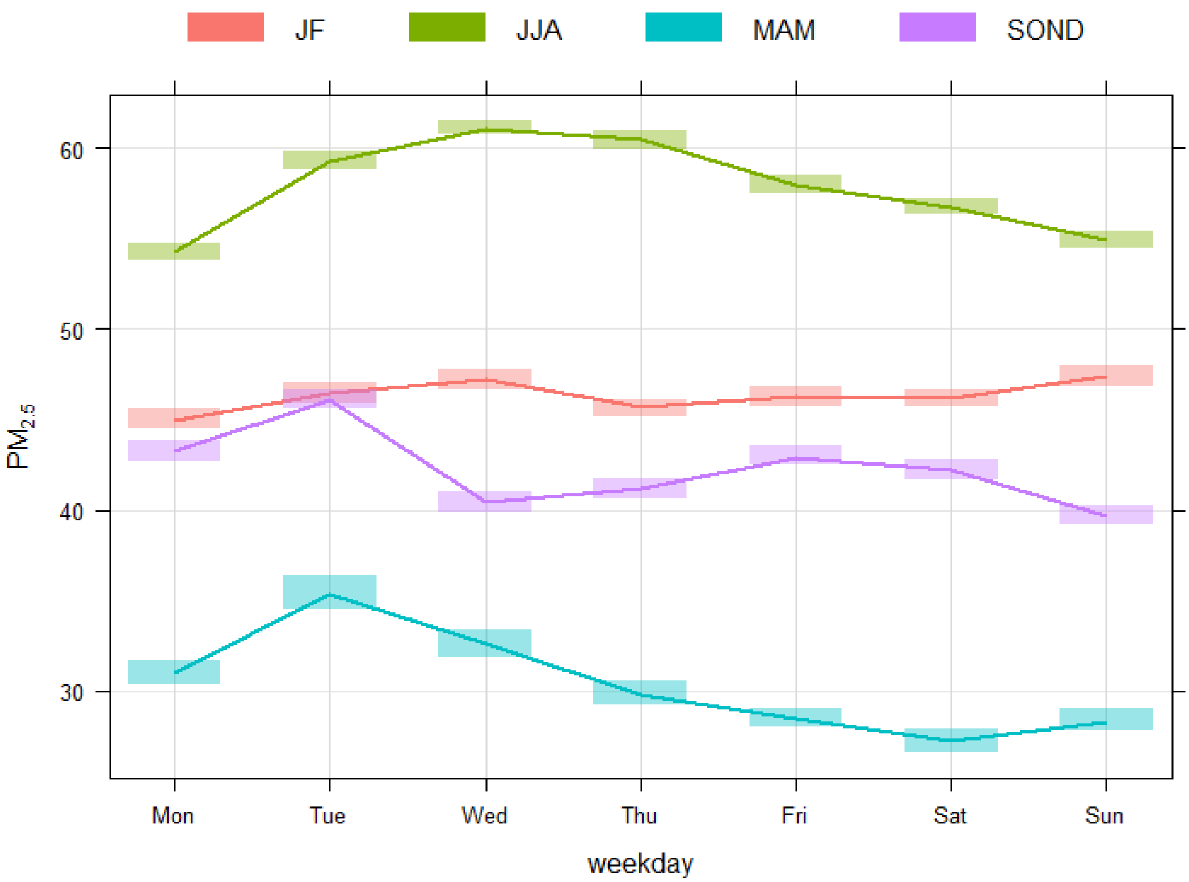

Figure 5: Week days and seasonal variability of $PM_{2.5}$ (in ugm^{-3}) over Kigali from 2019 to 2020

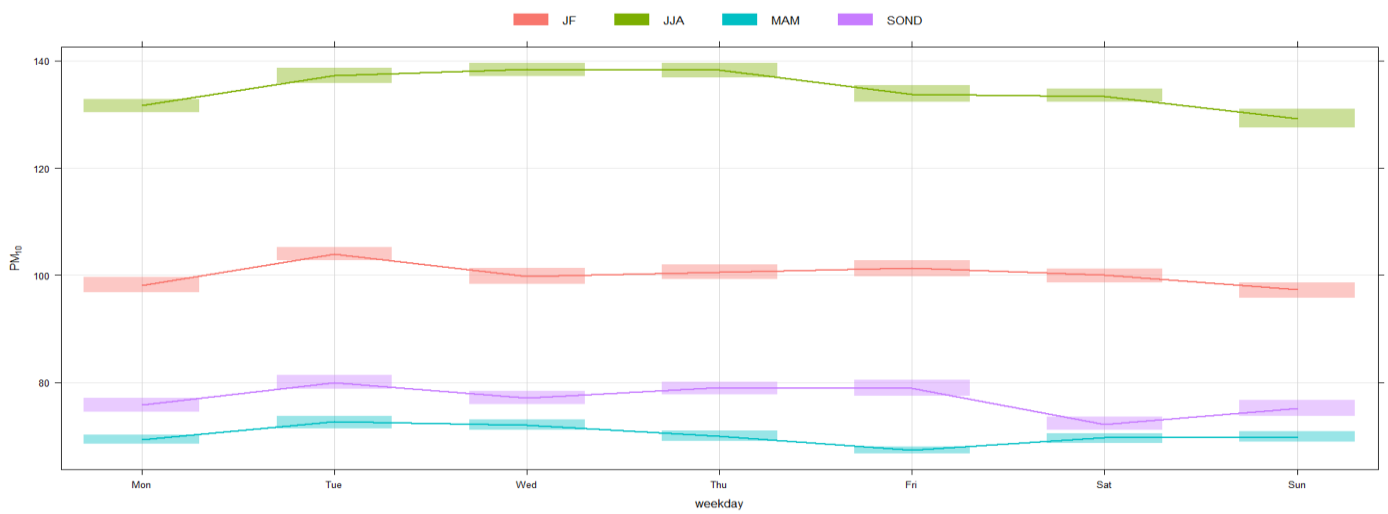

Figure 6: Weekdays and seasonal variability of PM_{10} (in ugm^{-3}) over Kigali from 2019 to 2020

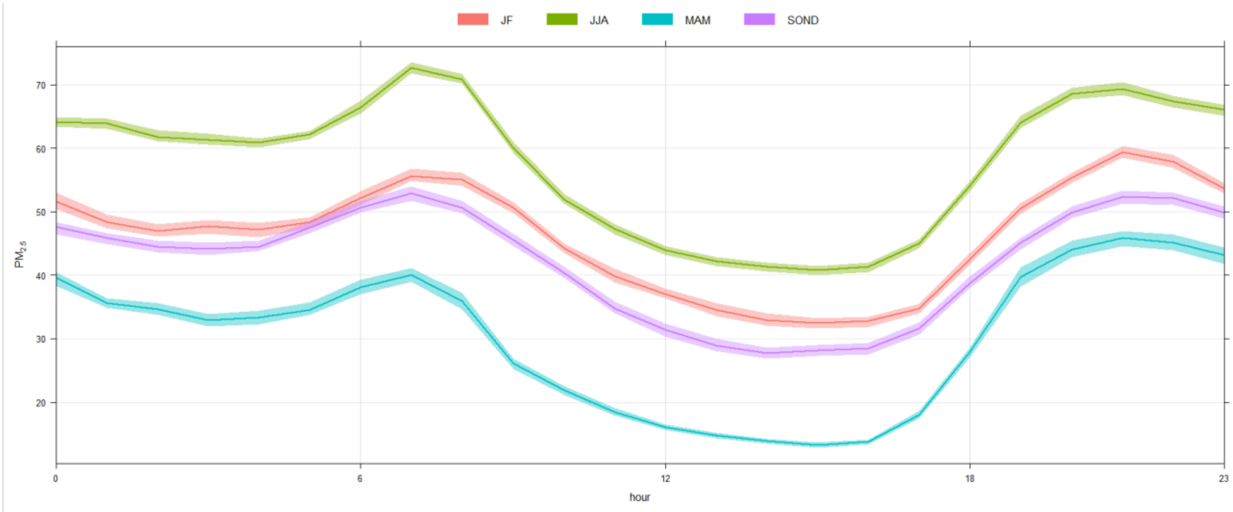

Figure 7: Diurnal and seasonal patterns of PM2.5 (in ugm^{-3}) over KIGALI city from 2019 to 2020

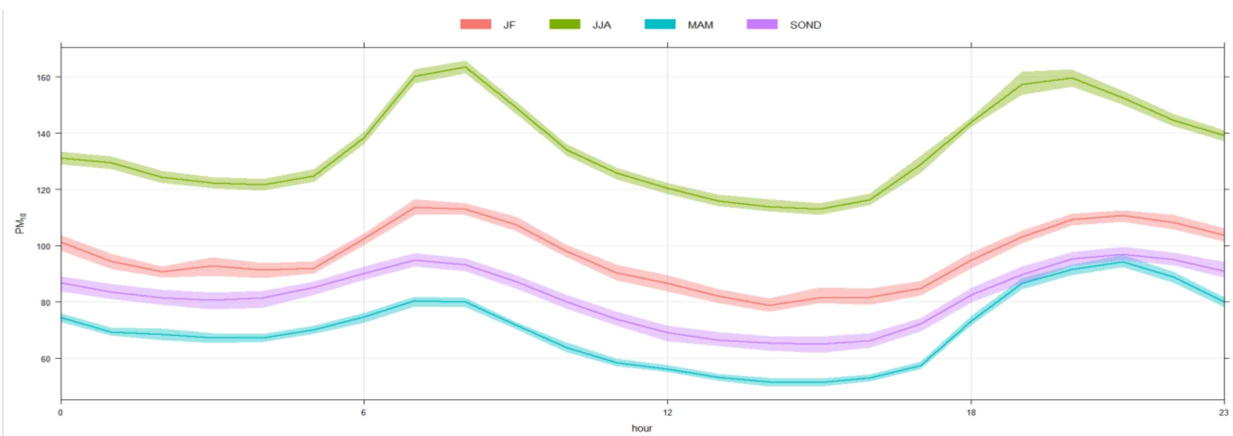

Figure 8: Diurnal and seasonal patterns of PM10 (in ugm^{-3}) over KIGALI city from 2019 to 2020

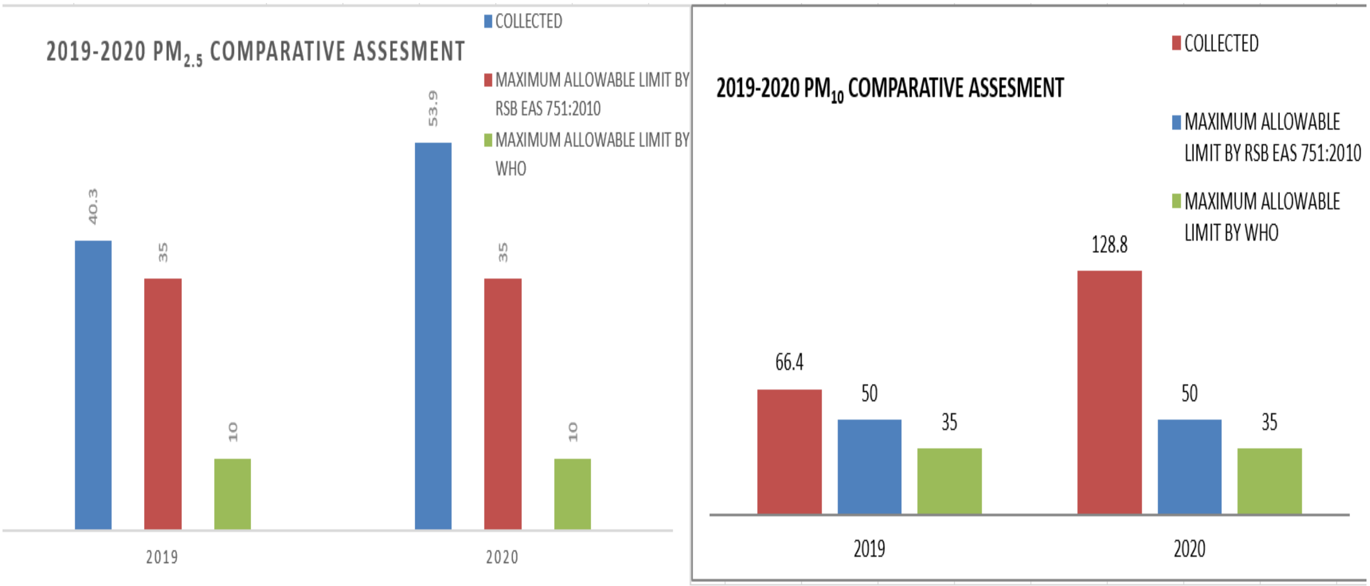

Figure 9: Yearly comparative assessment of PM over Kigali

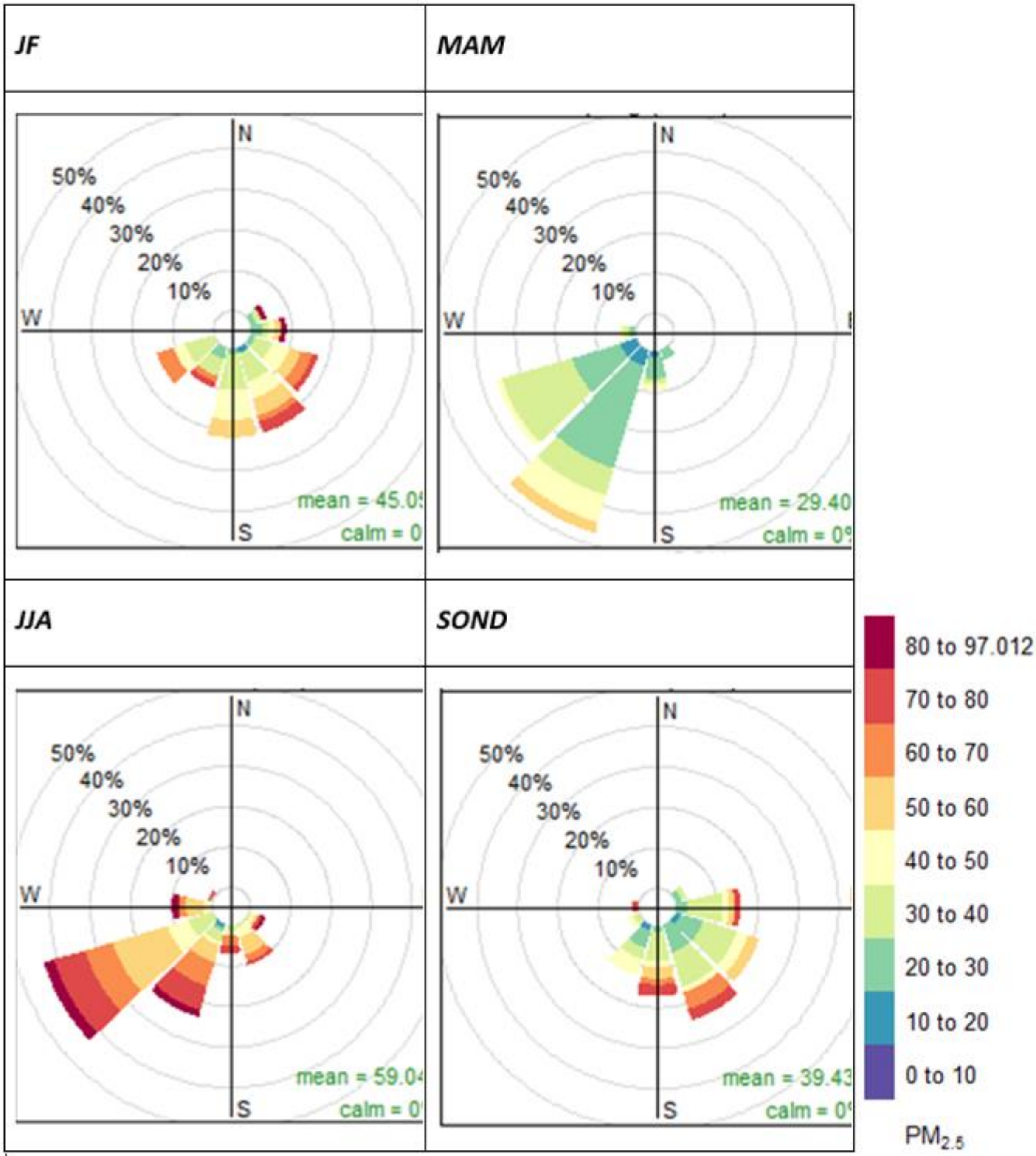

Figure 10: seasonal $PM_{2.5}$ transport in Kigali .

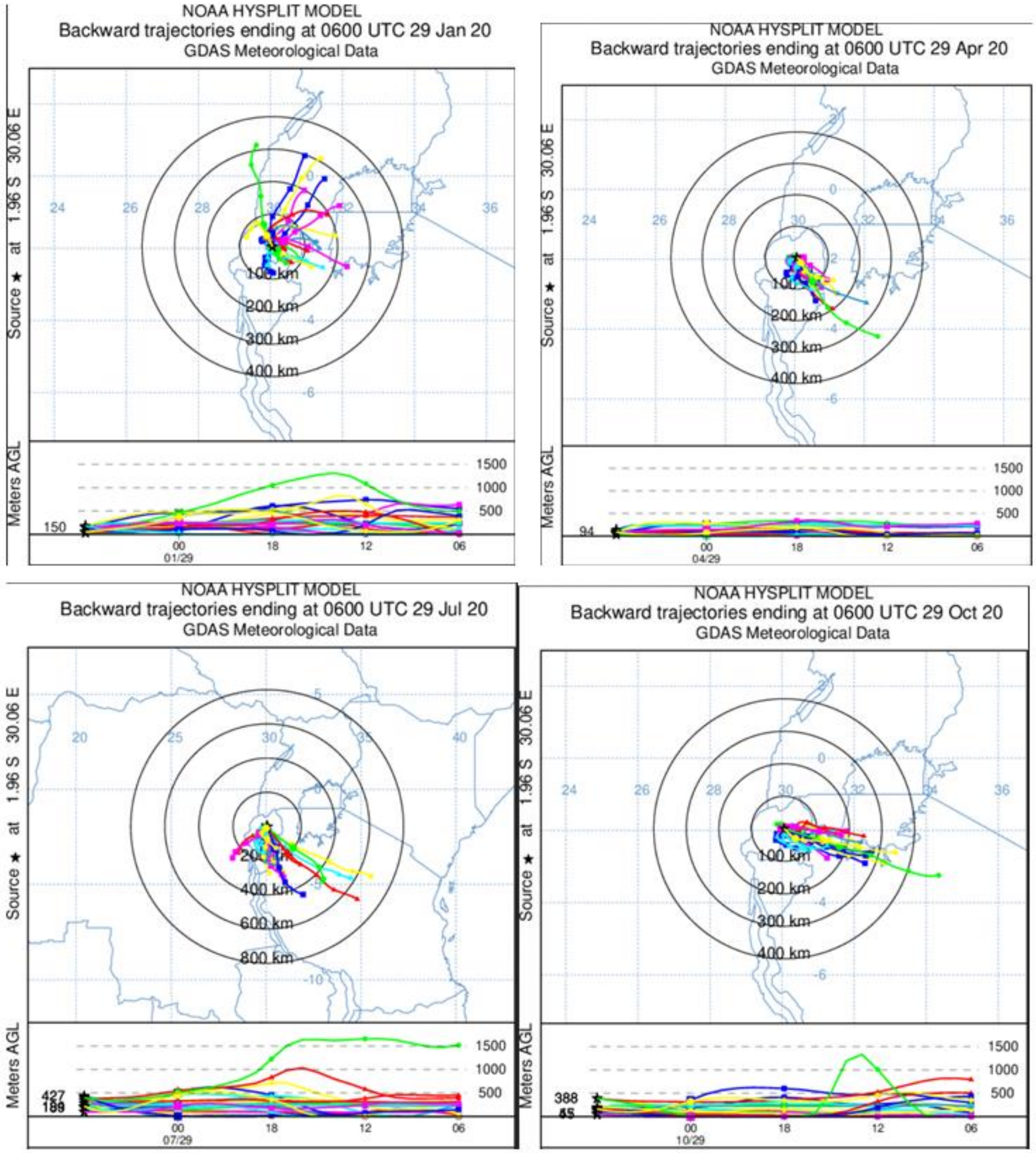

Figure 11: Transboundary sources of PMs within the seasons

Addemndum2: TABLES

Table 2: Basic daily data statistical analysis

Statistics	***$PM_{2.5}$***	***PM_{10}***
Minimum	*0.00*	*0.00*
1^{st} quartile	*34.42*	*59.40*
Median	*49.37*	*92.18*
Mean	*49.41*	*103.42*
3^{rd} quartile	*63.59*	*148.09*
Maximum	*102.90*	*208.13*

Table 3: Seasonal day and night PM trend

Season		**$PM_{2.5}$**				**PM_{10}**			
		MAM	JJA	SOND	JF	MAM	JJA	SOND	JF
Concentration (μg/m³)	**Day time**	25-35	48-60	20-38	45-50	80-110	140-160	60-80	120-150
	Night time	40-45	>60	40-50	55-60	80-110	>160	100-110	100-120

Table 4: Seasonal observed Meteorological parameters correlation POLLUTANTS		**$PM_{2.5}$**				**PM_{10}**			
Season		MAM	JJA	SOND	JF	MAM	JJA	SON	DJF
METEO PARAMETERS	**TEMPERATURE**	0.24	0.12	0.36	0.29	0.21	0.11	0.44	0.44
	RH	-0.36	-0.30	-0.45	-0.26	-0.37	-0.27	-0.53	-0.44
	WS	-0.16	-0.4	0.56	-0.7	-0.12	-0.28	0.57	0
	WD	0.12	0.6	0.16	-0.2	0.27	-0.5	0.14	-0.13
	SR	0.18	0.9	0.11	0	0.28	0.13	0.15	0.9
	PM10	0.71	0.63	0.95	0.96				

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