Seasonal Variability of Ambient Ozone over Nyarugenge District in Kigali City

Jean de Dieu Ndayisenga

College of Science and Technology

School of science

Master of science in atmospheric and climate science

June 2022

Seasonal Variability of Ambient Ozone over Nyarugenge District in Kigali City

By

Jean de Dieu Ndayisenga

Registration number: 2019025173

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

MASTER OF ATMOSPHERIC AND CLIMATE SCIENCE

In the College of Science and Technology

Supervisors:

Dr. Jimmy Gasore

Prof. Bonfils Safari

Declaration

This thesis is submitted to the University of Rwanda in partial fulfillment of the requirements for award of the Master of Science in Atmospheric and Climate Science. This is to certify that the best of my knowledge, the content of this thesis is my own work.

This thesis has not been submitted for any degree. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Jean de Dieu Ndayisenga

June 2022

Acknowledgement

I would like to express my sincere gratitude to my supervisor, Dr. Jimmy GASORE for his continuous and generous scientific, practical and emotional support throughout my candidature. This work would not have been possible without the help and support of my supervisor mainly advice and guidance and also highly appreciate him for his data accessibility.

I would like also to acknowledge gratefully Professor Bonfils SAFARI the coordinator of masters of Science in atmospheric and climate science at University of Rwanda for his greater assistance and advice. In addition, I convey my sincere appreciation to the staff of the Department of Physics. Many thanks to the master's program colleagues for their friendship collaboration from the beginning entering this program up to this work and hope in the future.

Finally, I am thankful to my family, for their inspiration and motivation. I really appreciate their encouragement, support and patience.

Abstract

This research consists of analysis of the ambient ozone over Nyarugenge district in Kigali City, using openair model (R package) which is an open-source tools for analyzing air pollution data. The ambient ozone over Kigali varies seasonally, this research analyzes the near surface ambient ozone within a period of three years starting from 2010 to 2012, and correlated with its corresponding meteorological parameters including air temperature, relative humidity, wind speed and wind direction. The highest ambient ozone concentration along a day was observed between 10am to 3pm, this is because its chemical formation is a photochemical reaction, and during this period of time, the solar radiation intensity is maximum. For wind speed above 2.81m/s ambient ozone increases as solar radiation increase while for wind speed level greater than 2.81m/s the ambient ozone concentration decreases by increasing of atmospheric relative humidity. The average wind speed recorded was at 3.7402 m/s with calm condition of 0% during July to September 2020 and pollution rose of 22.85 from 17th to 23rd September 2020. The dominant wind direction was elaborated together with their frequency. During dry seasons the ambient ozone concentration in Kigali is very high compare to the wet seasons and this affect the nearby rural area (downwind), the major cause of this increase include the biomass burning, higher solar radiation intensity, contribution of transboundary pollutants and lower pollutants removal processes. For mitigating increase of ambient ozone and generally air pollutants there is a need to install lower cost air quality monitoring instruments in different zone across the country for its monitoring, mobilizing smart driving, the use of motorcycle and auto cycle which use electric power instead fuels as trafficking emission is among the main pollutants sources in Kigali, the use of air filter on chimney of the manufacturing industries and other technics for minimizing emission.

Acronyms and Abbreviations

AGAGE:	Advanced Global Atmospheric Gases Experiment
AQI:	Air quality index
CH_4:	Methane
CO:	Carbon Monoxide
CO_2:	Carbon Dioxide
IT:	Interim Target
MINEMA:	Ministry in charge of emergency management
NO:	Nitrogen Monoxide
NO_2:	Nitrogen dioxide
NOx:	Nitrogen Containing Compounds
NST:	National Strategy for Transformation
O_3:	Ozone
RCO:	Rwanda Climate Observatory
REMA:	Rwanda Environment Management Authority
RS:	Royal Society
SO_2:	Sulphur Dioxide
STT:	Stratospheric to Tropospheric Transport
USEPA:	United States Environmental Protection Agency
VOC:	Volatile Organic Compounds
WHO:	World Health Organization

Contents

List of Tables

List of Figures

Chapter 1. INTRODUCTION

1.1 Background

Nowadays, Kigali City as a national capital of Rwanda is among the fastest green growing City in Africa. This is one of the causes of urbanization growth rate in this city (Monks et al., 2015), and this becomes a big matter to the air quality as the air pollutants emission increases in this City. Even though there are few scientific research conducted on Kigali air quality and generally in Africa, the truth as mentioned by WHO is that a big number of premature deaths are associated with poor air quality and this is mostly abundant in the developed countries mainly in their cities (Dewitt et al., 2019). Thus there is a need to improve national air quality monitoring and even at local levels, to link it to health surveillance and diseases related to air pollution exposure for health impact assessment (WHO, 2018). The interaction of regional weather and atmospheric circulation feature including wind (Hastenrath, 2011; Nicholson, 2017), topography, human activities lead to the air (Ebi et al., 2008).

Generally, in Rwanda 12 million people live in an area of 26,338km^2 this shows that 456 inhabitants/Km^2 and this density of population will become more and more in future (MINEMA, 2019). The increase of citizen in Kigali is proportional to the emission from trafficking activities even if there are policies regarding smart transport by using automobiles and motorcycles using electric power and encouraging the public transport (REMA, 2019) and the urban emission will continue to increase as the NST1 goal is to accelerate urbanization from 17.3% by 2014 to 35% by 2024 (MINEMA, 2019), this will increase greenhouse gas emissions leading to global warming effect (REMA, 2016), some study shows that tropospheric O_3 varies, as a result of its chemistry change (i.e. sources, reactions and sinks) and dynamics (Ebojie et al., 2014), and was discovered by C. F. Schonbein in the middle of the nineteenth century (since 1840); he was first to detect ozone in air. Some nations including developing country like India decide to reduce their emission without looking to the other developed country position (Greenstone et al, 2014).

The air pollution problems in Kigali is mainly due to traffic emission, City growth which is the increase in populations living in the City (Ndayisenga, 2020) from the rural area for different reasons including job opportunity, availability of infrastructures and for its cleaning compared to other Cities. Another cause includes also population density increase, economic development and industrialization (increase of energy consumption) and also the rural area the pesticides usage evolve some kinds of pollutants (Dewitt et al., 2019). We do not neglect the main energy sources used by many Kigali households which is charcoals while few households use woods or LPG (Dewitt et al., 2019) and power generation (UNEP, 2018, REMA, 2018). Tropospheric air pollution has several causes and effects such as greenhouse effect, particulate contamination, increased level of ultraviolet radiation, acid rain, increases of ground level ozone concentration and increased level of nitrogen oxides (Monks et al., 2015), especially in developed zone that have high population densities and exposure (Li et al., 2013). The air quality problems are a regional matter that can be managed and overcome under regional policy, but it is more necessary to reduce pollutants emission in order to reduce also its transport due to the wind circulation before its removal (Ndayisenga, 2020). In Rwanda, wind direction changes from northerly during December-January-February (DJF) to southerly during June-July-August (JJA) (Dewitt et al., 2019). The wind speed, direction, continuity and also its availability play a big role in pollutant transport (Safari and Gasore, 2011).

There exist two main classes of pollutant sources which are primary sources and also secondary sources. The primary are emitted directly from the sources like solvent use (WHO, 2008), ash from volcanic eruption, biomass burning, motorcycle exhaust gases including hydrocarbons, CO, CO_2, nitrogen oxide (NO_X) which is poisonous and highly reactive gases (Li et al., 2013 ; RS, 2008) formed under highest pressure and temperature in an engine and sulfur dioxide (SO_2) from manufacturing industries, while the secondary comes from the chemical interaction between primary pollutants, the major example here is ground level ozone production which is the result of nitrogen oxide (NO_X) and volatile organic compound (VOC) including hydrocarbons like CH_4 and CO (WHO, 2003), in the presence of sunlight (Nsengimana et al., 2011) and also there is a clear impact of atmospheric temperature and humidity (WHO, 2003; Abbatt et al., 2019). NO_X increase ozone concentration for short term and many research conducted shows that NO_X regulation reduces long term ozone levels (Li et al., 2013). The ground ozone is a short-lived climate forcer (Dewitt et al., 2019). The ground O_3 level is a major component of smog and some of O_3 health impacts include eyes irritation, lungs damages and aggravate respiratory problems (Nsengimana et al., 2011; Schultz et al., 2017), even O_3 is a trace gas and constitutes $< 0.001\%$ of the air by volume (Heue et al., 2018). There are several study shows that the peak of ozone concentrations is observed during Rwanda's dry seasons (Dewitt et al., 2019) and without new policies developed for emission management, by 2050, air pollution is set to become the world's top environmental cause of premature mortality (Nsengimana et al., 2011). In Rwanda, 2,227 deaths were addressed by poor ambient air exposure since 2012 (REMA, 2019). The concentration of NO_2 in the rural area is law compared to that measured in urban area, the highest monitored concentration was obtained at Nyabugogo even if it was below the Rwanda annual mean ambient standards which is 0.05ppm (96µg/m^3), while the ozone concentration monitored was 58.9 µg/m^3 at Nyabugogo (roadside), 42.4 µg/m^3 at Gitega Meteo (urban background) 33.0 µg/m^3 at Kawangire (rural) (REMA, 2019) this indicate also that the ambient ozone concentration was high in urban area than the rural region.

1.2 Problem Statement

The air pollutants in Nyarugenge/Kigali City increase daily as the City develops (REMA, 2019). The anthropogenic activities which evolve pollutants (including the reactants forming ambient ozone) in atmosphere are increased, including manufacturing industries located in Kigali special economic zone and others districts' industrial zone in Kigali city, and from the surrounding area, where the pollutants arrive in Kigali by wind movements. There is also increase of automobiles and motorcycles in the City, development of aerial transport, increase of landfill area located at Nduba, incineration activities and many others development activities emitting different pollutants. As the pollutants emission increase it becomes a key driving health impacts to the ambient ozone sensitive population living or working in Kigali. Most health effect related to the ambient ozone exposure is respiratory diseases, and as the emission will continue to increase (REMA, 2019), the results also will be not only health effect but also worming effect as the ambient ozone is among the greenhouse gases.

1.3 Objectives of Thesis

1.3.1 General Objectives

In this thesis it is very necessary to analyze the ambient ozone concentration variability and seasonal variability of ground ozone level in order to relate to the anthropogenic activities in Kigali and the surrounding areas which emit different pollutants forming ambient ozone, including those from open biomass burning known as "complete combustion" and also from chemical reaction of some products of "incomplete combustion". The output of this thesis was more useful by students of atmospheric and climate sciences, researchers and the policy makers to formulate national policy related to the pollution control and regulation. Thus, this thesis was strongly necessary to the Rwandan community.

1.3.2 Specific Objectives

The specific objectives of this thesis include:

- To find out the time variation of ambient ozone concentration level in Nyarugenge /Kigali City (daily, weekly, monthly, general trend and seasonal variation) and to correlate near surface ambient ozone level with meteorological parameters.
- To specify the transboundary pollution trajectory sources using NOAA HYSPLIT Model to the near surface point and to determine regional sources and dispersion of ambient ozone.

1.4. Research Questions

The following are the questions which are the drivers of making this study on surface ambient ozone level in Nyarugenge/Kigali City for coming up with a scientific response at the end of this thesis:

- Is ambient ozone varying in the analysis period interval in Nyarugenge/Kigali City? If yes, why?
- Is surface ambient O_3 seasonally varies in Nyarugenge/Kigali City?
- Is there a correlation of ambient ozone and different meteorological parameters including air temperature, solar radiation, and relative humidity?
- What are the main sources of ambient ozone in Nyarugenge/Kigali City?
- Are there the health effects in case of exposure?
- How far and in what direction the pollution was transferred?

1.5. Hypothesis of the Thesis

The infrastructure in Kigali increases yearly, some of them together with other factors attract the investors this cause the increases of different anthropogenic activities sometimes emitting air pollutants. The traffic emission also evolves more air pollutants, the use of different sources of energies in cooking and even if there is the neighboring region's emission contribution including biomass burning, emission from manufacturing plants and even the transboundary contribution (REMA, 2018). The ambient ozone is diurnal and seasonally changes.

1.6. Scope of the Study

The trend and even the seasonal ambient ozone concentration variability analysis over Nyarugenge/Kigali City was covered in this thesis, by investigating the possible sources and mechanisms of its formation. Kigali as national city was taken to be analyzed in this thesis, as it is the most vulnerable City in Rwanda due to its pollutants emission sources which are higher than the corresponding Cities including emissions from traffic, power generation, industrial and domestic sources (REMA, 2018). It is more necessary to take care on this City, for regulating the local emission pollutants sources, to protect the population living and working in Kigali and generally environment against the health effect caused by ambient ozone exposure.

Chapter 2: LITERATURE REVIEW

2.1 Ambient Ozone

Air pollution is among the major problems in many developing country's cities (Gwilliam et al., 2004; Balajee, 2017), and the clean air is a basic requirement for human health and wellbeing (Markus et al., 2008). Ambient O_3 is a colorless air component for which we breathe (USEPA, 2009; Pollution Prevention and Abatement Handbook, World Bank Group, 1998), it has been linked to early death, plant and crop damage, and is also a global air pollution problem and an important greenhouse gas with a radiative forcing since 1750 third only to carbon dioxide (CO_2) and methane (CH_4) (Markus et al., 2008), and known as pulmonary irritant that affects the respiratory mucous membranes, other lung tissues, and respiratory function (Ebi et al., 2008; Balajee, 2017) for which 10% of ozone is located in troposphere while 90% is known as stratospheric ozone (Dentener et al., 2000), and there is evidence showing that daily O_3 exposure increase both mortality and respiratory morbidity rates (WHO, 2008; Balajee, 2017). The ground ozone is among the main greenhouse gases with effect of surface worming by trapping longwave radiation from the earth' surface (Bell et al., 2007; Kassahun et al., 2020) and referred as a short-lived climate pollutant (Monks et al., 2015), and this pollutant will continue to increase globally up to 2100 (Hayman et al., 2009). The most important photochemical oxidant in troposphere is ground ozone (WHO, 2003). Some natural phenomenon has influence on tropospheric O_3 here an example of El Niño can be taken (Daron, 2014; Ummenhofer, 2018), this phenomenon leads to enhancements of upper tropospheric O_3 and note that this influence does not affect ambient air (Lin et al., 2015). Simply ground ozone has both anthropogenic and natural sources (Hu et al., 2017).

There are two different types of ozone known as good or bad ozone depending where it occurs. Good ozone is located at the lower stratosphere 16Km to 48Km above the surface, and it is good because it absorbs the ultraviolet and visible radiation (Rasseur et al., 2001) from the sun which are dangerous to the human health when reaching the earth's surface as it causes skin cancer while the bad ozone forms near the ground chemically mostly during wormer months (USEPA, 2009), this thesis only consider the bad ozone. O_3 acts as both an important radiative gas and a pollutant (Hess et al., 2007). Ground O_3 is a byproduct of the very oxidation chemistry as mentioned in its formation session below (Monks et al., 2015), and it affect vegetation, materials and human health and is a GHGs in the troposphere (WHO, 2008). WHO air quality guideline for ozone indicate that maximum daily 8-hour average 100 μg/m^3, interim target (IT_{-1}) of maximum daily 8-hour average 160 μg/m^3 and high level of maximum daily 8-hour average 240 μg/m^3 (WHO, 2008).

2.2 Ground Ozone Formation

Ground ozone has two main sources: transport of air containing O_3 (Ridley et al., 2007) from the stratospheric layer and photochemical production in the troposphere (Ebojie et al., 2014), among the two sources ground O_3 is a mainly produced by a secondary pollutant by nitrogen dioxide (NO_2) and VOCs photochemical reaction but we do not neglect the contribution of atmospheric air temperature and humidity (Balajee, 2017; WHO, 2003), as global temperature increase the specific humidity will continue to increase as more water vapor increase in atmosphere (Ogwang et al., 2014), thus the higher temperature increase reaction rate for producing ozone by reducing NO_X concentration available in atmosphere. Emissions of methane also promote O_3 formation and global climate change and simply less ozone in atmosphere will result in less damage to vegetation (WHO, 2008). Trickl (2018) quantify stratosphere-to-troposphere transport (STT) of ozone as long as over more than half a century, and different followed study identify general mechanism even if there is still a considerable uncertainty of the results. The most active regions of STT exchange are in upper troposphere mainly in cyclonic, near jet streams, troughs, and cut-off lows (Ridley et al., 2007).

Starting to the dissociation of nitrogen dioxide (NO_2) by photolysis in order to form nitric oxide (NO) and an oxygen atom O(^{3}P) the ground electronic state of oxygen atom. And this is followed by the O_3 formation from molecular oxygen (O_2) reacting with the photoproduct oxygen atom O(^{3}P). In presence of hydrocarbons, NO is converted to NO_2 thus leaving little NO_2 to react with O_3. This reaction becomes the main atmospheric O_3 sources. As discussed above the sources of both NO_2 and VOCs are anthropogenic activities (Adegoke, 2014).

$$NO_2 + h\upsilon \longrightarrow NO + O\,(^3P) \qquad (J_1) \qquad (1)$$

$$O\,(^3P) + O_2 + M \longrightarrow O_3 + M \qquad (k_2) \qquad (2)$$

The reaction (2) is the production of ozone in the urban area and the interconverted of NO_2 and NO is known as chemical family NO_x Photolysis of NO_2 is fast approximately $J_1 \approx 10^{-2}S^{-1}$

$$HO_2 + NO \longrightarrow NO_2 + OH \quad (3)$$

$$O_3 + NO \longrightarrow NO_2 + O_2 \quad (k_3) \quad (4)$$

By considering the reaction (1), (2) and (4) we can delive the a ratio of $[NO_2]/[NO]$ known as the Leighton ratio (where $[O_3]= J_1[NO_2]/ k_3[NO]$ and this shows how O_3 formation is directly proportional to the solar intensity) and this depend on the local equilibrium concentration of ground ozone. In the urban region in addition of VOCs such as CO, the mechanism of formation of O_3 is writen below where O_3 is the sources of hydroxyl radical (OH) as shown by (6) and (7)

$$CO + OH + (O_2) \longrightarrow CO_2 + HO_2 \quad (5)$$

$$O_3 + h\upsilon \longrightarrow O(^1D) + O_2 \quad (6)$$

$$O(^1D) + H_2O \longrightarrow OH + OH \quad (7)$$

Where excited state $O(^1D)$ comes from photolysis of atomic oxygen at wavelengths < 320 nm. Also O_3 is formed by interaction of VOCs such as methane CH_4, NO_X and generaly from alkanes:

$$C_2H_6 + OH + O_2 \longrightarrow C_2H_5O_2 + H_2O \quad (8)$$

$$C_2H_5O_2 + NO \longrightarrow C_2H_5O + NO_2 \quad (9)$$

Here $C_2H_5O_2$ represents organic peroxy radicals represented also as RO_2 where R is used to represent alkyl, ally, or aryl groups, all of which possess the ability NO_X chemical family (Monks et al., 2015; Huang et al., 2015). The O_3 formation rate is controlled by reaction (3) and (9) and there is an increases with VOC increase and ozone decreases with increasing NO_X (Carletti et al., 2017; Ying et al., 2013)

Tropospheric ozone formation rate increases with increasing NO_X. By the increase of NO_X allows a greater number of free-radical propagated ozone forming cycles to occur prior to termination. In contrast, the ozone formation rate is insensitive to the changes in CH_4 or CO and to inputs of other VOC concentration. This is because OH reacts with the organics exclusively as part of the free-radical propagated ozone forming cycles, with no competing radical termination reaction being available under the prevailing conditions (Ebojie et al., 2014).

An other well known tropospheric O_3 formation is "photochemical smog mechanism." This mechanism involves the photo-oxidation of VOC and CO in the presence of NO_X as mention from reaction (10) up to reaction (16) (Ridley et al., 2007).

$$RH + OH \longrightarrow R + H_2O \quad (10)$$

$$R + O_2 + M \longrightarrow RO_2 + M \quad (11)$$

$$RO_2 + NO \longrightarrow RO + NO_2 \quad (12)$$

$$RO + O_2 \longrightarrow HO_2 + R'CHO \quad (13)$$

$$HO_2 + NO \longrightarrow OH + NO_2 \quad (14)$$

$$NO_2 + h\upsilon \longrightarrow NO + O \quad (15)$$

$$O + O_2 + M \longrightarrow O_3 + M \quad (16)$$

Net: $RH + 3O2 + 2\,h\upsilon \longrightarrow R'CHO + H_2O + 2O_3$ (17)

Where R′CHO is an aldehyde or a ketone, additional ozone molecules can then be produced from the degradation of R'CHO. And even in addition to the oxidation of hydrocarbons, ozone can be produced from CO oxidation as shown by reaction (5), (14), (15), and (16).

There exist also different natural sources of ambient ozone including natural emissions from vegetation, soil, and lightning, and are strongly influenced by several environmental factors, including temperature, light, humidity, meteorology, vegetation cover, leaf size or plant age (Markus et al., 2008).

2.3 The Lifetime and Atmospheric Budget of Tropospheric Ozone

The lifetime of ambient O_3 is determined by removal processes (known also as sinks) which lead to loss of O_3 from the atmosphere. The average lifetime of O_3 in the troposphere has been estimated at 22 days (Stevenson et al., 2006; Ebojie et al., 2014); however, it can change between 1 to 2 days based on altitude for instance on the boundary layer here at this position dry deposition is the major O_3 sink, to several weeks in the upper troposphere (Markus et al., 2008). This, in combination with the potential for O_3 to be produced from precursors long after they have been emitted, makes O_3 a global pollutant. The atmospheric O_3 or O_3 budget, is determined by the rates of O_3 production and its destruction (Markus et al., 2008).

2.4 Ambient Ozone Removal

Tropospheric ambient ozone can be a trans-boundary pollutant (main that located in upper troposphere) based on its lifetime, and it is more concentrated during dry season mainly in afternoon (seasonal and diurnal patterns) (WHO, 2003). The increase of water vapor in atmosphere cause decomposition of ozone, therefore water vapor and temperature have opposite effect on ozone concentration in the atmosphere (WHO, 2008). Ambient O_3 has short lifetime of hours in low troposphere but in urban regions (polluted) where its concentrations are maximum, its lifetime is of several weeks (WHO, 2003), but before its removal ambient ozone contributes to the tropospheric removal of other pollutants (Ebojie et al., 2014), Simply, removal of tropospheric ozone is done in different processes which are the transport to, removal at the surface (earth), and in situ chemical destruction (Ridley et al., 2007).

The rate of ambient ozone removal is influenced by vegetation and the human population exposure. There is a vertical transport of ambient ozone to the surface layers occurred during the day and maintain mixing ratios within 10 % of the boundary layer mean values, except in urban areas or near major roads, where local nitric oxide sources remove ozone by titration (Monks et al., 2015).

2.4.1 Dry and Wet Deposition

Dry deposition is among the dominant O_3 removal processes and is affected by different meteorological parameters including temperature and soil moisture conditions. The natural emission of some precursors including CH_4, other VOCs such as isoprene, and NO_X from lightning and soil are affected by climatology (Markus et al., 2008).

This is a result of reactions with the external surfaces of vegetation and soil and uptake by plant stomata located under leaves of plants as detailed by Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland (2018), ozone is chemically reactive and sinked by wide variety of processes take place on the surfaces, as its solubility is low this cause its direct washout process to be small but the major removal is dry deposition, the global deposition range is 710 to 1470 Tgy^{-1} , the above different deposition ways differs by location, season, and even year by year (Young et al., 2018). Based on RS EAS 751 2010 Air quality specification, the ambient O_3 air quality standards are 200 µg/m^3 for industrial area and 0.12 ppm for residential, rural & other (where time weighted average is 1hour) while for time weighted average of 8hour, the standard for industrial area is 120 µg/m3 and 1.25 ppm for residential, rural & other (REMA, 2018).

2.5 Ambient Ozone Exposure Health Impact

Climate change may lead to increased ozone concentrations (WHO, 2008). Several peoples are sensitive to the ground ozone level at the outdoor as its concentration increases in outdoors where the main sources are located and by breath the ozone concentration increases in the body due to the long term exposure. The sensitive groups include the people having lung diseases, children, active peoples working outdoor and even older adults (Bell et al., 2007; USEPA, 2009) and other people having respiratory illnesses (WHO, 2008; Tammy, 2019; Balajee, 2017). Some research shows that ground ozone cause cardiovascular and respiratory disease (WHO, 2003; Tammy, 2019; Balajee, 2017; Pollution Prevention and Abatement Handbook, World Bank Group, 1998). The long term exposure may cause many different health effects like to irritate your respiratory system by coughing, feel irritation or soreness in your throat or experience chest tightness or pain when taking a deep breath, the second effect is to reduce lung function by becoming difficult to breathe when exercising, the third effect is to inflame and damage cells that line your lungs, the fourth is to make lungs more susceptible to infection, the fifth effect is to aggravate asthma (chronic lung diseases) including emphysema, chronic bronchitis etc., and the last health effect is to cause permanent lung damage (Balajee, 2017; Li et al., 2020;Tsai et al., 2008; USEPA, 2009; Pollution Prevention and Abatement Handbook, World Bank Group, 1998), and also lung cancer (WHO, 2003).

Ozone can cause direct oxidative damage to cells or secondary damage by diverting energy away from primary cell functions to the production of defense mechanisms such as antioxidants (Markus et al., 2008). reacts with antioxidants, like ascorbate within the lung lining fluid (LLF), which protect the lungs from oxidative damage. In those instances, when O_3 reacts with protein or lipid or other substrates in the LLF, the secondary oxidation products arise which lead to a number of cellular responses within the lung including an influx of inflammatory cells (Markus et al., 2008). As a consequence, the delicate blood/air barrier is damaged and lung does not function as efficiently as it should. These is not similar to all individual but react differently to ozone exposure and many factors affecting the amount of ozone taken up by an individual organism, mainly the dose. Thus this makes the determination of a dose response relationship for the assessment of human health impacts extremely complex. The mechanisms that control the balance between beneficial and detrimental interactions in the LLF compartment are not well established but these may contribute, in part, to an individual's varying sensitivity to ozone (Markus et al., 2008).

Mathematically, the health outcomes associated with pollutants exposure using a health impact function was estimated. The health impact used during this analysis has four major components which are air quality changes, the affected peoples, the baseline situation incidence rate, and lastly the estimated effect drawn from the epidemiological studies. Fann (2011) mention a typical function of log-linear health impact as follows:

$$\Delta y = y_0(e^{\beta\Delta x} - 1)Pop \qquad (18)$$

Where y_o represent the baseline incidence rate for the health endpoint assessed; Pop is the population affected by the change in air quality; x is the change in air quality; and β represent the effect coefficient drawn from the epidemiological study.

Fann (2011) shows the way of calculating the life years lost using the following formula:

$$\text{Total Life Years} = \sum_{i=1}^{n} LE_i \times M_i \qquad (19)$$

Where LE_i is the remaining life expectancy for age interval i, M_i is the change in number of deaths in age interval i, and n is the number of age intervals.

2.6 Ambient Ozone Effects on Vegetation

The most important and well-documented environmental effects of ozone, are those on terrestrial vegetation. O_3 also cause the reductions in crop production (Jillian, 2003); Bell et al., 2007; Pollution Prevention and Abatement Handbook, World Bank Group, 1998), tree growth and carbon sequestration, and to modify species composition (Markus et al., 2008; Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, 2008). In terrestrial ecosystems, the most direct effects of O_3 are those on leaf physiology and plant growth; many other indirect effects on ecosystems flow from these primary direct effects (Markus et al., 2008, Gwilliam et al., 2004). The flux into the leaf of ozone from the boundary layer above the plant canopy is regulated by the atmospheric and leaf surface resistances including the stomata. Even if all these resistances vary with meteorological conditions, this flux is not constant, but varies greatly through time and space even with a constant ozone concentration above the plant canopy. Impacts of ozone within the leaf also depend on the capacity for detoxification of the incoming ozone flux, which itself may be partly under environmental control (Markus et al., 2008). In simple terms, there are two possible modes of action of ozone within the leaf. At high exposures, ozone flux may overwhelm the detoxification capacity and cause a range of direct effects. Ambient ozone has several impacts on crop yield and quality, impacts on tree growth and carbon uptake, ecological impacts (Markus et al., 2008; Gwilliam et al., 2004).

2.7 Technique to Avoid Health Effect of Ground Level Ozone Exposure

Based on the AQI, the ground ozone level is good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy when AQI belong between 0-50, 51-100, 101-150, 151-200, 201-300 respectively (USEPA, 2009). In case ground O_3 ranging to unhealthy levels, there is a higher probability of being affected as you are exposed. Thus when the level of O_3 are unhealthy, there is a need to avoid its exposure to your health by reducing as short as possible the time of exposure, scheduling the activity to the time of lower ozone level such as the morning or evening time.

2.8 Drivers of Ground Level Ozone Change

The main important drivers of ground O_3 level are the emissions of gases including NO_X, non-methane VOC, CH_4, CO followed by several climatic factors which regulate the rates of many of the processes in O_3 production and destruction (Markus et al., 2008; Balajee, 2017) and topography. During this century, economic growth and global population growth and others anthropogenic activities drive the processes that lead to emissions of O_3 precursors (Markus et al., 2008; Huang et al., 2017). Changes in climate and land use influence also the production of emissions from natural sources. Increased demand for energy (Huang et al., 2017), transport, food and non-food crops and other resources influence emissions arising from anthropogenic activity, and changes in patterns of consumption and production affect the distribution of O_3 (Huang et al., 2017).

Globally, the O_3 level in the northern hemisphere is in the range of 35–40 ppb (Markus et al., 2008). High O_3 concentrations occur episodically throughout the year depending on the region's weather condition. In such period, its concentrations become higher (about 200 ppb) as happened in France since 2003 heat wave (Fiala et al., 2003). Even the great values, of up to 400 ppb, were also observed during the smog episodes in Southern California in the 1960. In some cities in the USA and Latin America (WHO 2006) and in metropolitan areas in Asia (Emberson et al., 2003) episodes of this magnitude is a common feature (Markus et al., 2008).

The long-range transport and precursors of O_3 has an important impact on its concentrations at regional and local scales. Markus et al. (2008) demonstrate an example, where O_3 concentration from Asia and Europe contributes to O_3 concentrations in North America. Similarly, concentrations entering Europe from the West are substantial and range from 20 to 40 ppb through the year due to emissions of O_3 precursors elsewhere in the Northern Hemisphere, notably North America and Asia. Thus depend on air pollutant type and its lifetime, air pollutants becomes transboundary issues. Ozone is also an important pollutant at the urban scale (WHO 2006, Markus et al., 2008). In and around urban areas large gradients of O_3 can be observed; concentrations are generally larger in sub-urban and rural areas than in busy urban centers because of rapid chemical interactions between O_3 and other pollutants especially nitric oxide (NO).

Impacts of O_3 on the human and environment are well established in this thesis. Major human health impacts are related to the respiratory system and include reduced lung function, lung irritation and in extreme cases, mortality. The studies show that about 21,400 premature deaths in Europe are derived by O_3 (Huang et al., 2017; EEA, 2007; Bell et al., 2007). Impacts on vegetation generally occur above 40 ppb, although this is species dependent and varies according to environmental conditions. Ozone has been shown to damage sensitive plant species, to reduce tree growth and carbon sequestration and to affect the composition of natural plant communities. Ozone also reduces the yield of staple crops (Li et al., 2020). This has clear implications for future food security, as increasing O_3 concentrations may place further pressure on agricultural systems already under stress from climate change, pests and diseases, and land degradation (Markus et al., 2008; Sharon, 2018).

2.9 Effects of Weather and Topography on Ambient Ozone Level

The processes through which the climate system affects tropospheric O_3 levels are complex, and involve many interactions between the atmosphere, the land surface and ecosystems. Ozone production varies diurnally and seasonally (Markus et al., 2008).

As the chemistry of O_3 formation requires photolysis, and this implies that the rate of some of the reactions increase with temperature, O_3 production is generally at its maximum during warmer sunny weather. In hot, sunny conditions, production of O_3 approaches a maximum and if soils are dry, the soil water deficit leads to closure of plant stomata leading to larger surface O_3 concentrations. The very strong effect of weather on O_3 production and loss creates much of the observed variability in concentrations with time. Over longer time scales, changes in climate due to GHGs emissions are likely to influence the production and loss processes for O_3. The concentrations of O_3 at any specific location depend on topography and meteorology as well as background and regional sources of O_3. In general, rural areas, hill tops and coastal areas experience larger exposure to O_3 because at these locations the supply of O_3 from higher levels in the boundary layer exceeds the rate of depletion by dry deposition. By contrast in sheltered valleys the loss by dry deposition, especially at night, often leads to a sharp decline in O_3 concentrations, in this case dry deposition is depleting O_3 faster than transport from above. It is the balance between vertical transport and surface deposition that causes the diurnal cycle of O_3 in rural areas, with small concentrations at night and large values in the daytime. The lower O_3 concentrations in urban areas are mainly due to reaction with NO, all processes operate simultaneously and dry deposition contributes to the decline in urban O_3 concentrations at night (Markus et al., 2008).

Wind direction is very important in determining the concentrations of O_3 precursors within a region. Easterly winds bring continental air with O_3 precursors, generally at lower wind speeds and often in sunny weather which is associated with the anticyclone conditions. Thus the peak O_3 values generally occur in sunny, anticyclone weather.

Chapter 3. METHODOLOGY

The Openair Model (R package) was used for high frequency data analysis (five minutes' frequency data) in this thesis for achieving the objectives mentioned above. The R programing language is used for different analysis including time variation plot for summarizing the diurnal cycle, weekly cycle, monthly cycle, seasonal variation and to correlate ambient ozone with some meteorological parameters, Box plot for monthly mean data information in a full year and even in determination of some statistics.

3.1 Data Collection Site

Rwanda is landlocked country of 26 338 km^2 known as "a country of thousand hills" this simply describe how Rwanda is a mountainous topography. In Rwanda there is a limited number of on-ground data collection sites on air quality and climate change. The most known air quality data collection sites are under air quality and climate change monitoring project also known as Rwanda Climate Observatory (RCO) which is a part of the Advanced Global Atmospheric Gases Experiment (AGAGE) network, and a first global network of high-frequency trace greenhouse gas measurements in Africa (Dewitt et al., 2019) established by government of Rwanda and Massachusetts Institute of Technology (MIT) with the objectives of measuring long-lived GHGs and short-lived climate forcers in East Africa. The pollutants measured by RCO includes methane (CH_4), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Black Carbon (BC), Nitrous Oxide (N_2O) and Ozone (O_3). RCO has several station including one located at mount Mugogo near Byangabo in Northern Province of Rwanda and another located at Meteo Rwanda headquarter in Kigali city which is a reference station, and data used in this thesis (July to September 2020) are the high frequency data collected at air quality reference station of REMA and MINEDUC through air quality and climate monitoring project located at Gitega meteo station (Longitude:30.06, latitude:-1.96,elevation: 1474m), in Gitega Sector, Nyarugenge district as shown on figure1, at the same time meteorological data was also measured at this station (meteo headquarter). This station is located in a residencial area where most household use charcoal in cooking and the few households use Liquefied Petroleum Gas (LPG) and other sources of energy and there is a main paved road used by many Automobiles and a small sloped unpaved road, this caused the dust during dry season and even the car moving on this sloped road evolve high pollutants. There is also a hospital incinerator near this station.

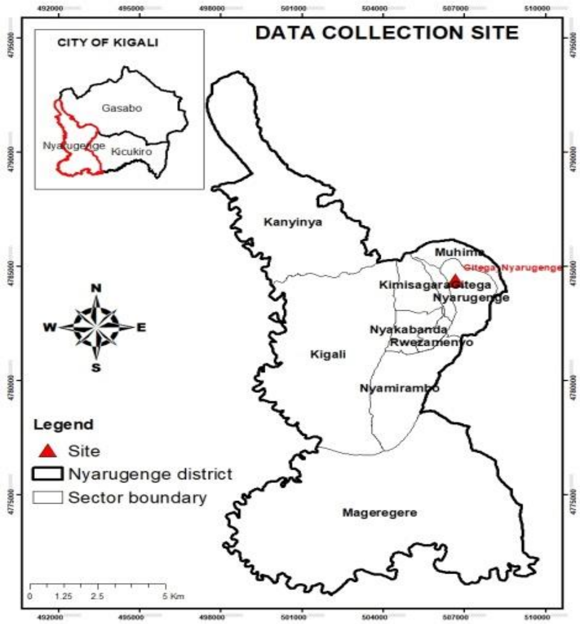

Figure 1. Data collection Site

3.2 Instrument Description and Calibration

The instrument used for sampling the ground ozone level by RCO is Teledyne T400 (ozone analyzer) which is best in high frequency data collection, the data used was taken each five minutes. The data used during 2010-2012 period analysis was from horriba instruments installed in CST chemistry laboratory. The instruments are not currently in operation due to the lack of spare parts.

This instrument (T400, Teledyne Advanced Pollution Instrument, USA) was used to measure ambient ozone and the regular checks were performed using internal span and zero O_3 calibrations using installed zero air generator and calibrator model T400 with associated connected to three different tanks with a well-known gas concentration, where the outlier data were removed and its flow was calibrated periodically two to three times per year. Teledyne API, (2018) detail the various methods for calibrating a Model T400 O_3 analyzer as contained in its section 9 including: Basic manual calibration checks and calibration of the analyzer, manual calibration checks and calibration with valve options, automatic zero/span cal/check (autocal), O_3 photometer electronic calibration, calibrating the IZS option O_3 generator.

For meteorological data, the station's technicians check for each working day if the instrument are working (visual checks). In case of any mal-working instrument, the technician informs chief scientist of the station to fix it.

Chapter 4. RESULTS AND DISCUSSIONS

4.1. The Variation of Ambient Ozone in Kigali

In Rwanda the indoor air pollution is the most intense than the outdoor air pollution (Nsengimana et al., 2011), in this thesis only ambient ozone as outdoor pollutant was considered. By analyzing the observed data, in this thesis the summarized basic statistics was mentioned in appendix 1, table 1.

This table shows the mean (average) of the used data, the median (P_{50}) of the data set or second quartile a point that splits the data base in half while 25^{th} percentile is called the first (lower or P_{25}) quartile, and the 75^{th} percentile is called the third quartile (P_{75}) (Ndayisenga, 2020). The minimum and maximum values indicate the range of our data (the figures 5 and 6 shows these statistics for diurnal, weekly and yearly variability). As discussed above, the main sources of ambient ozone are the chemical formation from other air pollutants. In Nyarugenge/Kigali and even the surrounding, there are several emission sources including the exhaustive from automobile (and other incomplete combustion sources), industrial emission and other different anthropogenic pollutants producer. Some pollutants interacting in chemical processes of ambient ozone formation comes from the manufacturing factory. By analyzing the air quality based only on ambient ozone over Kigali, the study analyze the recent (2010-2012) and current ambient ozone monitored (July to September 2020) as the period expecting the highest ambient ozone concentration within a year separately.

4.2 The Recent Variability of Ambient Ozone over Kigali

4.2.1 The Variability Trends

During this section the data for three years (2010 – 2012) was analyzed. The daily mean was used to plot the trend (see figure 2, appendix 2), this figure shows the time series linear trends of ambient ozone during that period interval. The figure 3 (appendix 2) shows the daily mean data density. In particular ways, the data density used are mostly intense in the range of 5 to 50μgm^{-3} (for ambient ozone) and around zero for rainfall data. The analysis of the seasonality variability was conducted.

4.2.2 The Seasonal Variation of Ambient Ozone in Kigali City

The ambient ozone concentration in Nyarugenge /Kigali varies seasonally (figure 5 and 6), as known Rwanda has four seasons like other equatorial countries. Simply, the most ambient ozone exposure health effect in Nyarugenge over Kigali was in dry seasons. More generally during wet seasons there was no dramatic health effect related to ambient ozone exposure in Nyarugenge over Kigali City due to the removal processes present in these seasons, water contained in atmosphere which decompose ambient ozone and even some pollutants sources reduced including biomass burning etc. The seasonal increase of ambient ozone is contributed by biomass burning and even the rising of solar radiation intensity and temperature, O_3 concentration in Nyarugenge over Kigali is formed by VOCs and NO_X emitted directly in Kigali City or from others parts of Rwanda or elsewhere across the earth anthropogenic activities through trans-boundary air movement (figure 11) under favorable meteorological condition including solar radiation etc. as equation 1,6,15 and 17 shows and the required radicals existence (equation 1 to 17).

To quantify the direct ambient O_3 concentration emitted from Kigali itself is difficult as it may be formed by VOCs and NO_X emitted from other part of Rwanda or elsewhere. The region's emissions contributing to the ambient O_3 formation include: agricultural burning, charcoal making, cooking fires, brick production, vehicles, diesel and heavy fuel oil power plants, and diesel generators. These mentioned emission sources exist in all the seasons (Dewitt et al., 2019). And the only main causes of differences in ambient O_3 concentration along the seasons is caused by the difference in rate of pollutants removal processes (including VOCs, NO_X and even existing O_3) for each season, solar radiation intensity and biomass burning (figure 5 and 6).

The weekly and diurnal variability of ambient ozone concentration is shown on figure 4, the ambient ozone concentration reach its maximum between 11am to 4pm for all the week's days (at noon) at this time the solar intensity and even air temperature are high, and O_3 concentration becomes minimun between 6am to 7am where the temperature are low and relative humidity are high, this is almost similar (slightly changing) for all the days (see figure 4), the only difference is the level of concentration which is unique for each day. During the morning the most household are preparing the breakfast and even dinner preparation, this increase the level of ambient ozone concentration in air as the most household use charcoal, LPG etc and also it is the time of high trafficking movement where most worker start their job, and the key reason of highest peak of ambient ozone concentration around the noon is the existance of solar radiation, from that time its concentration start to reduce due to the air dilution and re-increase again to reach another peak during the mid night due to the similar process as that of the morning which are super preparation and traffic emission where the workers return to their homes. The mid night ambient ozone concentration over kigali is very low compared to the noon observed concentration, the main cause of highest peak at noon is the presence of higher solar radiation intensity and air movement alowing to transport the regional and transboundary pollutants in order to contribute to the air pollutant over Kigali while during the night the atmospheric condition are nearly calm and no solar radiation and even air temperature are low.

By yearly consideration, by looking on monthly mean the highest ambient ozone concentration was observed in July in JJA dry season (figure 5) as the existing emission was increased due to the biomas burning done by Rwandan farmers and even the regional and during this season the wet deposition took place was minimum and increase of solar radiation intensity while the minimum concentration was observed in May in MAM wet season, here the biomas burning level was very low, solar radiation intensity also was low and removal processes was intense (rainout and washout processes together with ozone decomposition with water molecules).

For weekly mean the study realise that during weekend the ambient ozone concentration is low compared to the remaining day (figure 4), and generally the minimum concentartion was observed on sunday, this is due to the trafficking movement which was low and even car free day which block the vehicles to use some roads and reduces its emission where many people are conducting sport.

In Rwanda during JJA most farmer burn their farm, bushes for fast grass growth to be consumed by their caws (even this activities decrease as years come but in some nearby counties steal exist and may contribute to the air quality in Kigali by wind movement) and even in land preparation for the proceeding agriculture season the farmer burns grasses, this emit amount of air pollutants in atmosphere and ground ozone formation increase (figure 4 and 5), many aerosols concentration also increases including dust, soot etc. not only from Rwanda but also from the surrounding countries, and even the far countries and thus the rainout processes was minimum which is one ways of pollutants removal, this is common in Sub-Sahara African countries and through trans-boundary air movement the pollution moves at large scale (depending on its life time) as there is some study shows that the trans-boundary pollution may affect air pollution in

Kigali. Contrary during MAM and generally in wet seasons there is a decrease of ambient ozone concentration, this is due to the rainout process took place which was maximum and which reduce the air pollutants (ozone formation reactant) in atmosphere, and also during this season the higher level of water vapor content in the atmosphere cause decomposition of the contained ambient ozone. The above seasonality variability of ambient ozone in Kigali City was also founded by other researchers (Dewitt et al., 2019).

Generally, in Nyarugenge/Kigali the higher concentration of ambient ozone was observed during the daylight compared to the night condition (see figure 7) and becomes more during the dry seasons (see figures 5,6,7 and figure 8), these increases of ambient ozone concentration during the day was mainly due to the solar radiation intensity, high air temperature as the study corrolate ambient ozone with different meteorological parameters in the following section and even we do not neglect the contribution of transboundary ambient ozone sources due to the air movement. During the night the atmosphere was nearly in calm condition.

4.3 The Variability of Ambient Ozone over Kigali (July to September 2020)

As the variability of ambient ozone (2010-2012) and seasonal ozone variability is analyzed in the previous section, it is more necessary to take care on the dry period analysis and the correlation with meteorological parameters as the period of highest ambient ozone concentration existence.

4.3.1 The Variability of Ambient Ozone over Kigali and its Correlation to Meteorological Parameters

The three months period data interval are used in this part, from July to September 2020 and the correlation with meteorological variables was elaborated. At this time, the study only consider different parameters including air temperature, relative humidity, rainfall, solar radiation, wind speed and wind direction. The study clearly analyse the influence of meteorological variables mentioned above to the ambient O_3 present in Kigali during dry period mentioned above.

The daily mean data analysis shows that the air temperature over Nyarugenge/Kigali does not change dramatically, the solar radiation intensity was high as it is in dry season and change dramatically. Some statistics based on data collected for the ambient O_3 together with the meteorological variables within this three months are summarized in table 1 (appendix 1).

The figure 9 shows some information on daily mean, monthly mean and seasonal mean data variability. The ambient ozone data density is almost between 20µgm^{-3} to 30µgm^{-3} and that of air temperature, relative humidity, solar radiation, wind direction and wind speed are around 19^{o}C, 52, 210w/m^{2}, 230 and 3m/s respectively during July to september 2020.

There is a clear relation between O_3 with the analysed meteorological variables (table 2). The ground O_3 variability over kigali is directly proportional to the ambient air temperature and even solar intensity (see figure 4 and 6) and this is contrary to the relative humity which is inversly proporitional to the ambient O_3 concentration this implies that the higher atmospheric humity cause the ambient ozone to be decomposed by the atmospheric water content (table 2).

In most cases it is necessary and more useful to visualise data in a special familiar way. The coefficient of determination (R) shown in table 2 for relating ambient ozone with rainfall, relative humidity, maximum temperature, minimum temperature and mean temperature are -0.791943259209992, -0.861873857688754, 0.34362590453831, -0.501968722966917 and 0.289409890647354 respectively (during 2010-2012) while during July to September 2020 the correlation coefficient between ambient ozone with air temperature, solar radiation, relative humidity are 0.485986446, 0.372497113 and -0.385744685 respectively and this represent the information in the Y variable that can be given by the linear regression model. Generally, the R value ranges from -1 to 1. If the value of R is multiplied by 100%, then this indicates the percentage of diversity (information) within Y (dependent variable) that is influenced by X (independent variable). The greater the value of R, the better the regression model obtained. Therefore, the ambient O_3 concentration in Nyarugenge/Kigali during July to September 2020 increases by the increases of solar radiation intensity. This is why the higher ambient O_3 concentration was observed during the dry seasons.

As discussed above the real correlation between ambient O_3 concentration with the atmospheric relative humidity is that as the atmospheric relative humidity increase , the ambient O_3 concentration decrease as discussed in section 4.2.2. Thus the more water vapor content in atmosphere the more O_3 decomposed (see equation 7).

4.3.2 Ambient Ozone Transport over Kigali

Ambient O_3 can be emitted, formed and transported from a region to another, this transport process is supported by its lifetime of about 22days (high level troposphere) and about 1 to 2days (planetary tropospheric boundary layer). At a favorable meteorological condition the ambient O_3 can cross long distance it self, or its forming reactant orginate far away and form ambient O_3 any time at a necessary formation condition. The main contributor of ambient ozone transport include air movement (wind speed and wind direction is necessary during this analysis). The different techniques for ploting was used in this analysis including wind rose, and even NOAA HYSPLIT Model.

4.3.2.1 Local Sources and Dispersion of Ambient Ozone over Kigali

WindRose show how pollutant's concentration, wind speed and direction vary along the seasons. In this analysis the study only infacise on ambient ozone local sources direction, and even the local or international dispersion direction. This plot shows the dominant wind direction and the largest wind speed over a period of time under consideration, and this indicate how far and where the pollutant is potentially dispersed from the source to any specific receptor generally human and environment. Therefore, the pollutants sources can be identified by knowing the wind distribution direction. The scale of windrose can be divided into several wind directions at a given angle, the wind is named based on its dispersion direction (see figure 10).

The windrose is mainly summarizing the meteorological data including Ws and Wd and transport. This is done in different technical ways.

The Ws are represented by different width where the plots show the proportion (by percentage) of time that the wind is coming to a certain angle and Ws range. The windRose function also calculates the percentage of calms condition (when the wind speed is zero) and also this function correct for bias when wind directions are rounded to the nearest 10 degrees but are displayed at angles that 10 degrees is not exactly divisible into (like 22.5 degrees).

The figure 10 shows the dispersion of ambient ozone by concentration levels in Kigali during September 2020. The ambient ozone concentrations suspended in Nyarugenge lower troposphere was transported within wind direction and speed as shown on figure 10. The only difference was on the frequencies. The average ozone measured during september 2020 and mean wind speed recorded at lower level was $18.51\mu gm^{-3}$ and $5.255ms^{-1}$, the highest level was $25\mu gm^{-3}$ to $35\mu gm^{-3}$ and the transport $21.25251\mu gm^{-2}s^{-1}$ with calm condition of 0% where the calm condition means that wind speed is recorded at 0 meter per second, thus no calm atmospheric condition realised during this period under study. Pollution rose of $22.85\mu gm^{-2}s^{-1}$ was observed (from 17th to 23rd

september 2020) see figure 10. Pollution comes from south-easterly 50% of the time at the station (17% of total time 15-20µgm^{-2}s pollution comes from south-easterly, about 16% of total time 20-25µgm^{-2}s pollution comes from south-easterly and 17% of total time 25-30µgm^{-2}s pollution comes from south-easterly), 17% of total time 20-25µgm^{-2}s pollution comes from southerly.

4.3.2.2 Transboundary Ambient Ozone Concentration Sources

Like other air pollutants some ambient ozone concentration measured in Kigali has transboundary sources as figure 11 shows, the study consider one-week back trajectory (168hours back) and realize that there were several trans-boundary sources of air pollutants including ambient ozone and even their formation reactants in Kigali and the sources differ due to the windward direction.

For a week ended on 23th September 2020 using GDAS meteorological data, even the pollution toward the source originate from Indian Ocean (between 1500km to 6000km away from the source), Kenya (Nakuru, Meru, Nairobi), Mara, Balingo, and in the western province of Rwanda exactly from Rutsiro near Lake Kivu.

Chapter 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In Kigali and generally in Rwanda there exist two rainy seasons MAM and SON and two dry seasons during DJF and JJA. During this work three years' data range (2010-2012) was considered and that of July to August 2020 to analyze the period of highest expected concentration. This thesis shows that there is diurnal and seasonal variability of ambient ozone (see figure 5,6,7 and 8), during dry seasons the ambient ozone concentration is very high compare to the wet seasons. The higher concentration of ambient ozone also affects the surrounding downwind rural area (figure 10). The increase of ozone concentration during dry seasons is due to the biomass burning which produce VOC and NOx involve in the chemical reaction for ambient O_3 formation, solar radiation intensity and pollutants removal processes which is low. The population density in Kigali also increases household emission and accelerate transport sector (the transport emission increases) and also industrial activities was developing (industrial emission also increase). Thus the population density is proportional to the local emission. There is also a contribution of the transboundary pollutants sources and even the nearby regions' emission contributing to the ambient ozone monitored in Nyarugenge/ Kigali City, based on the information shown on hysplit (see figures 11), and that showing the regional sources and its dispersion (see figure 10). The ambient ozone correlation with meteorological parameters including air temperature, relative humidity, rainfall, solar radiation, wind speed and wind direction are shown in this research and main information shown is that ambient ozone directly proportional to the air temperature, directly proportional to the solar intensity (see figure 4 and figure 5) and inversely proportional to the relative humidity and rainfall.

5.1 Recommendation

As recommendation, to decrease the air pollution in Kigali can be achieved when managed mainly at national level as the air quality is a regional matter, by continuing to develop Rwanda pollution control policy but also global policies must also be considered in order to reduce each country's emission because the trans-boundary pollution also contributes to the local pollution (see figure 11). As ambient ozone is formed from other pollutants mostly VOCs, NOx there is a need of continue in advance different pollution control including smart driving, the use of motorcycle which use electric power instead fuels up to the automobile as this study and even others including (Dewitt et al., 2019) shows that the most local emission comes from trafficking, to reduce the vehicles maintenance and inspection period, adopting low sulphur fuels based on the standards (RS EAS 751 2010 – Air quality specification, Rwanda Standard – Automotive Gasoline (Premium Motor Spirit) Specification, Rwanda Standard – Automotive Gas Oil (Automotive Diesel) Specification etc.) (UNEP, 2018), the use of air filter on chimney of the manufacturing industries is also essential for their pollution control. Regarding biomass burning from small scale agriculture, the Rwanda Agriculture Board should train the farmers how to transform those grasses, and other residuals into fertilizer or even other stakeholders to take it as raw materials to transform into others product like charcoals etc. as pollution minimization techniques. To reduce the emission from charcoals making and even household there is a need to continue to mobilize and invest in smart cooking (using LPG, biogas, etc.). There is also a need to install in all part of the country at least the low cost air monitor instruments for data availability and accurate analysis of country pollution in order to be useful for researcher, academics and policy makers in developing proper air quality policies based on the observed collected data. Therefore, there is a need of many instruments with both high spatial and temporal resolution to be placed at various locations (such as in industrial zones, in locations where there are a lot of transportation, in agricultural zones, etc.) in Kigali and across the country to improve the findings. The instruments measuring vertical profile meteorological parameters and pollutants could improve the researches in the area of meteorology and air quality.

References

A. Markus, A.F. Ross, A. Mike, P. Cox, D. Michael, D.O. Dick, G. Peringe, H. Nick, H. Oystein, J. Mike, F. Kelly, P. Liss, M. Pilling, J. Pyle, J. Slingo, "Ground-level ozone in the 21st century: future trends, impacts and policy implications Science", *The Royal Society*, London, 2008.

B. Safari, & J. Gasore, "Monthly Wind Characteristics and Wind Energy in Rwanda", *Rwanda journal,* Series c, Vol. 20, pp. 6–22, 2011.

B.A. Ogwang, H. Chen, X. Li, & C. Gao, "The Influence of Topography on East African October to December Climate: Sensitivity Experiments with RegCM4", *Hindawi Publishing Corporation, Advanced in Meteorology,* 2014.

B.A. Ridley, M.O. Andreae, W.L. Chameides, R.G. Derwent, I.E. Galbally, J. Lelieveld, A.M. Thompson, "CHAPTE RS Tropospheric Ozone", 2007.

B.M. Greenstone, & R. Hanna, "Environmental Regulations, Air and Water Pollution, and Infant Mortality in India", *American Economic Review,* Vol.104, Issue. 10, pp. 3038–3072, 2014.

B.Y. Kassahun, and C.H. Hamer, "Effects of Climate Variability in South Ari Woreda, South Omo Zone, Ethiopia," *International Journal of Scientific Research in Multidisciplinary Studies*, Vol.6, Issue.12, pp. 42-52, 2020.

C.C. Ummenhofer, M. Kulüke, and J.E. Tierney, "Extremes in East African hydroclimate and links to Indo - Pacific variability on interannual to decadal timescales," pp. 2971-2991, 2018.

D. Huang, Q. Li, X. Wang, G. Li, L. Sun, & B. He, "Characteristics and Trends of Ambient Ozone and Nitrogen Oxides at Urban, Suburban, and Rural Sites from 2011 to 2017 in Shenzhen, China.", *MDPI/Sustainability,* 2017. https://doi.org/10.3390/su10124530

D. Tsai, J. Wang, C. Wang, & C. Chan, "A study of ground-level ozone pollution, ozone precursors and subtropical meteorological conditions in central Taiwan", *Journal of Environmental Monitoring,* pp. 109–118, 2008. https://doi.org/10.1039/b714479b

D.S. Stevenson, "Multimodel ensemble simulations of present-day and near-future tropospheric ozone", *Journal of Geophysical Research*, Vol. 111, 2006. D08301. doi:10.1029/2005JD006338

Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland," Impacts of Vegetation on Urban Air Pollution", 2018.

E. N. Sharon, "The ITCZ and the seasonal cycle", (February), pp. 337–348, 2018. https://doi.org/10.1175/BAMS-D-16-0287.1

EEA "Air Pollution in Europe 1990–2004", *EEA Report No2/2007*. European Environment Agency: Copenhagen, 2007.

F. Ebojie, C.V. Savigny, A. Rozanov, M. Weber, K. Eichmann, and S. Bötel, "Tropospheric column amount of ozone retrieved from SCIAMACHY limb – nadir-matching observations," *Atmospheric Measurement Techniques*, Vol. 7, pp. 2073-2096, 2014. doi:10.5194/amt-7-2073-2014.

G.D. Hayman, M.E. Jenkin, M.J. Pilling, and R.J. Derwent, "Modelling of Tropospheric Ozone Formation. A Final Project Report produced for the Department for Environment, Food and Rural Affairs on Contract Modelling of Tropospheric Ozone Formation," *AEA Technology National Environmental Technology Centre,* Issue. 2, pp. 1-161, 2009.

G.P. Brasseur, J.F. MÜller, X.X. Tie, & L. Horowitz, "Tropospheric Ozone and Climate: Past, Present and Future", *Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling,* pp. 63–75, 2001.

H. Nsengimana, J.P. Bizimana, Y. Sezirahiga, "A study on air pollution in Rwanda with reference to Kigali city and vehicular emissions" (May), pp. 1–129, 2011.

H.L. Dewitt, J. Gasore, M. Rupakheti, K.E. Potter, and R.G. Prinn, "Seasonal and diurnal variability in O3, black carbon, and CO measured at the Rwanda Climate Observatory," *Atmospheric Chemistry and Physics*, Vol.19, pp. 2063-2078, 2019.

J. Fiala, L. Cernikovsky, F. de Leeuw, & P. Kurfuerst, "Air pollution by O3 in Europe in Summer 2003. Overview of exceedances of EC O3threshold values during the summer season April–August 2003 and comparisons with previous years", *Report to the European Commission by the European Environment Agency,* Report 3/2003, 2003.

J. Huang, J.C.H. Fung, & A.K.H. Lau, "Numerical simulation and process analysis of typhoon-related ozone episodes in Hong Kong", *Journal of geophysical research*, Vol. 110, pp. 1–17, 2015. https://doi.org/10.1029/2004JD004914.

J.D Daron, "Regional Climate Messages: East Africa,". Scientific report from the CARIAA Adaptation at Scale in Semi-Arid Regions (ASSAR) Project, pp. 1-29, 2014.

J.D. Ndayisenga, "Climate Risk Assessment and Management in Rwanda," *East African Journal of Science and Technology*, Vol.10 Issue 1, pp. 76-87, 2020.

J.F. Dentener, and J. Lelieveld, "What controls tropospheric ozone," *Journal of Geophysical research*, doi:10.1029/1999JD901011, Vol. 105, pp. 3531- 3551, (February), 2000.

J.P.D. Abbatt, W.R. Leaitch, A.A. Aliabadi, A.K. Bertram, J. Blanchet, A. Boivin-rioux, W. Gong, "Overview paper: New insights into aerosol and climate in the Arctic", pp. 2527–2560, 2019.

J.Q. Adegoke, "The Kansas City, Missouri, Ground-Level Ozone (GLO) Project: A Community-Based Air Pollution Field Experiment", (June), 2014.

K. Ebi, and G. Mcgregor, "Climate Change, Tropospheric Ozone and Particulate Matter, and Health Impacts," *Environmental Health Perspectives*, vol. 116, Number. 11, pp. 1449-1455, 2008.

K. Gwilliam, J. Todd, and M. Kojima, "Reducing Air Pollution from Urban Transport," *The International Bank for Reconstruction and Development/THE WORLD BANK*, Washington, 2004.

K. Heue, K.U. Eichmann, & P. Valks, "TROPOMI/S5P ATBD of tropospheric ozone data products", *Deutsches Zentrum für Luft-und Raumfahrt e.V.*, (November), 2018.

L. Hu, D.J. Jacob, X. Liu, Y. Zhang, L. Zhang, P.S. Kim, and R.M. Yantosca, "Global budget of tropospheric ozone: Evaluating recent model advances with satellite (OMI), aircraft (IAGOS), and ozonesonde observations," *Atmospheric Environment*, Vol.167, pp. 323-334, 2017.

L.D. Emberson, M.R. Ashmore, & F. Murray, "Air Pollution Impacts on Crops and Forests – A Global Assessment", *Imperial College Press*: London, 2003.

L.K. Balajee, S. Babu, R.A. Suliankatchi, and S. Meena, "Characteristics of the Ozone pollution and its Health Effects in India," *International Journal of Medicine and Public Health*, Vol.7, Issue. 1, pp.56-60, 2017

M. Lin, A.M. Fiore, L.W. Horowitz, A.O. Langford, S.J. Oltmans, D. Tarasick, and H.E. Rieder, "Quality in spring via deep stratospheric intrusions,". (May), pp. 1–11, 2015. https://doi.org/10.1038/ncomms8105.

M.G. Schultz, S. Schröder, O. Lyapina, O.R. Cooper, I. Galbally, I. Petropavlovskikh, V. Sinha, "Tropospheric Ozone Assessment Report: Database and metrics data of global surface ozone observations", *Elementa Science of the Anthropocene*, 2017.

M.L. Bell, R. Goldberg, C. Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J.A. Patz, "Climate change, ambient ozone, and health in 50 US cities", *Climatic Change,* pp. 61–76, 2007. https://doi.org/10.1007/s10584-006-9166-7

M.T. Tammy, "Background Ozone: Challenges in Science and Policy", *Congretional research service*, 2019. https://crsreports.congress.gov Tropospheric Ozone and Climate: Past, Present and Future

MINEMA, "National Environment and Climate Change Policy", (June), pp. 1–59, 2019.

N. Fann, A.D. Lamson, S.C. Anenberg, K. Wesson, D. Risley, & B.J. Hubbell, "Estimating the National Public Health Burden Associated with Exposure to Ambient PM 2.5 and Ozone", *Society for Risk Analysis,* https://doi.org/10.1111/j.1539-6924.2011.01630.x, pp.1-15 , 2011.

P. S. Monks, A. T. Archibald, A. Colette, O. Cooper, M. Coyle, R. Derwent, D. Fowler, C. Grainer, K. S. Law, G. E. Mills, D. S. Stevenson, O. Tarasova, V. Thouret, E. von Schneidemesser, R. Sommariva, O. Wild, and M. L. Williams, "Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer," *Atmospheric Chemistry and Physics,* Vol. 15, pp. 8889-8973, 2015.

P.G. Hess, and J.F. Lamarque, "Ozone source attribution and its modulation by the Arctic oscillation during the spring months," *Journal of Geophysical Research*, doi:10.1029/2006JD007557, Vol. 112, D11303, pp. 1-17, 2007.

P.J. Young, V. Naik, A.M. Fiore, A. Gaudel, J. Guo, M.Y. Lin, & J.L. Neu, "Tropospheric Ozone Assessment Report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends", *Elementa science of the enthropocene,* DOI: https://doi.org/10.1525/elementa.265, pp. 1-49, 2018.

Q. Ying, Y. Chen, J. Hu, H. Zhang, & P. Wang, "Attribution of Tropospheric Ozone to NO x and VOC Emissions: Considering Ozone Formation in the Transition Regime", pp. 1–24, 2013.

REMA, "Rwanda Compendium of Environment, Rwanda Environment Statistics Compendium", Rwanda, (February), 2019.

REMA, “Inventory of Sources of Air Pollution in Rwanda Determination of Future Trends and Development of a National Air Quality Control Strategy”, (January), 2018.

REMA, “Rwanda Environmental Research Strategy”, (July), 2016.

S. Carletti, & G. Passerini, “Tropospheric ozone behaviour as a function of precursor emissions”, (February), *WIT Transactions on Ecology and The Environment*, Vol 181, pp.2–14, 2017. https://doi.org/10.2495/EID140011

S. Hastenrath, “Variations of east african climate during the past two centuries”, pp.209–217, 2011.

S.E. Nicholson, “Climate and climatic variability of rainfall over eastern Africa”, *Reviews of Geophysics*, pp. 590–635, 2017. https://doi.org/10.1002/2016RG000544

T. Trickl, H. Vogelmann, L. Ries, H. Scheel, & M. Sprenger, “The underestimated role of stratosphere-to-troposphere transport on tropospheric ozone”, *Atmospheric chemistry and physics,* (January), pp. 1–37, 2018.

Teledyne API “Operation Manual Model T400 Photometric Photometric Ozone Analyzer”, T*eledyne Api (TAPI),* (October), 2018.

United States Environmental Protection Agency, “Ozone and Your Health,” (February), 2009.

W. H. O. “Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide,” Copenhagen, January, pp.1-98, 2003.

W. H. O. “Health risks of ozone from long-range transboundary air pollution,” *WHO Regional Office for Europe*, Copenhagen, 2008.

W.G. Jillian, G.J. Clive, & E.D. Todd, “Urban ozone depletion Why a tree grows better in New York City Pluto’s atmosphere”. (July), 2003. https://doi.org/10.1038/nature01776.1.

W.H.O. “Air quality guidelines: global update 2005, particulate matter, ozone, nitrogen dioxide and Sulphur dioxide”, WHO Regional Office for Europe: Copenhagen, 2006.

Y. Li, A.K.H. Lau, J.C.H. Fung, J. Zheng, & S. Liu, “Importance of NOx control for peak ozone reduction in the Pearl River Delta region”, *Journal of geophysical research: atmospheres,* https://doi.org/10.1002/jgrd.50659, 2013.

Z. Li, K. Ho, S. Hung, & L. Yim, “Development and intercity transferability of land-use regression models for predicting ambient PM 10, PM 2.5, NO 2 and O 3 concentrations in northern Taiwan”, *Atmospheric Chemistry and Physics*, Vol. 2, 2020.

APPENDIX

Appendix 1: Tables

Table 1. Some Basic Statistics

July to September 2020						
Stat. / parameters	Ground O3 (μgm^{-3})	Temp. (^oC)	RH	SR (Wm^{-2})	Wd	Ws (ms^{-1})
Minimum	10.25	14.16	43.29	32.96	103.4	2
1st Quartile	20.24	17.77	51.09	176.32	159.5	2.81
Median	24.7	19.23	54.31	203.01	214.3	3.43
Mean	23.9	18.83	56.38	187.29	201.6	3.74
3rd Quartile	27.58	20.09	60.41	215.56	237.8	4.24
Maximum	35.61	20.92	86.38	287.6	270.3	7.62

Table 2. Seasonal correlation between ambient ozone with meteorological parameters

Parameters	**Correlation coefficient (R)**
Ambient ozone versus rainfall	-0.791943259209992
Ambient ozone versus relative humidity	-0.861873857688754
Ambient ozone versus maximum temperature	0.34362590453831
Ambient ozone versus minimum temperature	-0.501968722966917
Ambient ozone versus mean temperature	0.289409890647354

Table 3. The seasonal ambient ozone concentration variability

Seasons	**2010**	**2011**	**2012**	**Seasonal mean of [O3]** (μgm^{-3})
DJF	36.381455	35.48213	39.17737667	37.01365389
MAM	22.5224833	26.0254733	22.62857333	23.72551
JJA	49.0846967	52.15248	51.02656	50.75457889
SON	39.2635	34.66449	33.64058333	35.85619111

Appendix 2: Figures

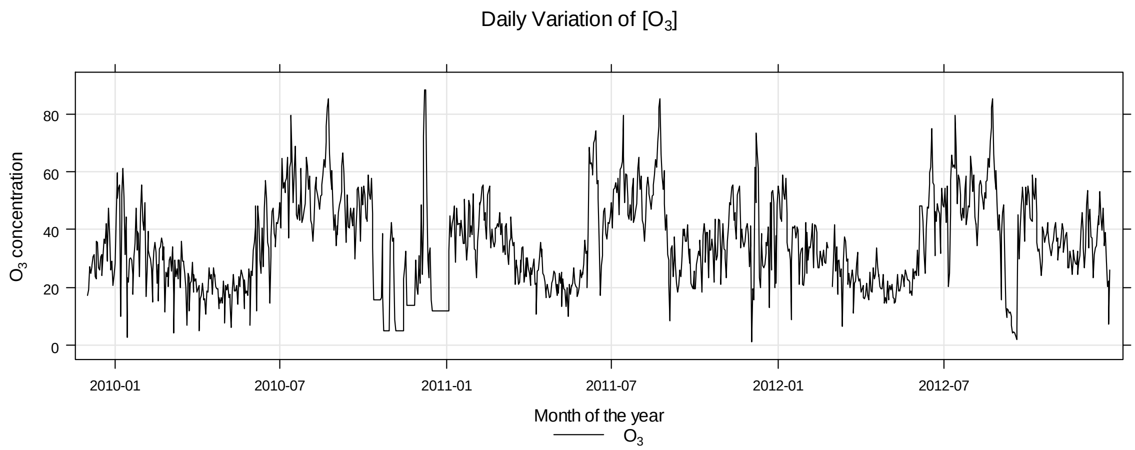

Figure 2. Ambient Ozone Variability over Nyarugenge District in Kigali City (2010-2012)

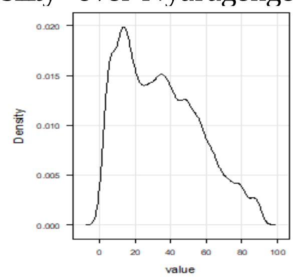

Figure 3. Variability of [O_3] daily data density

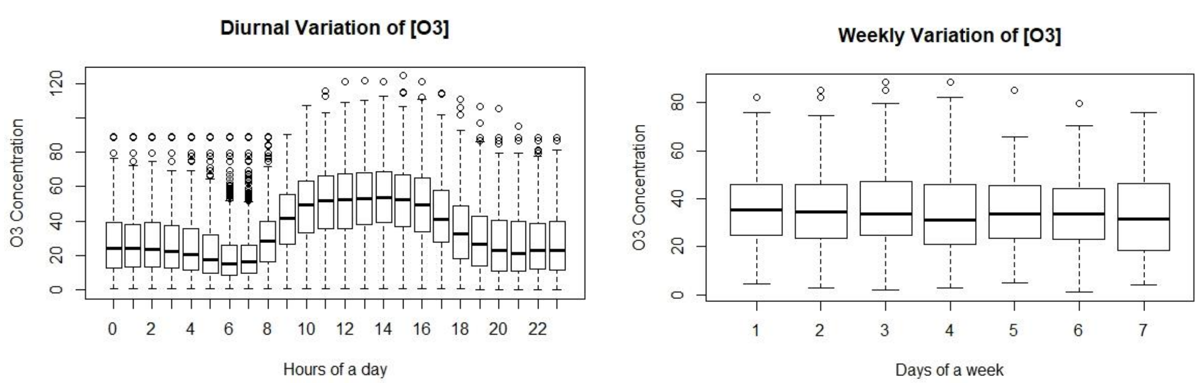

Figure 4. Diurnal and weekly variation plot of ambient Ozone over Nyarugenge District in Kigali City

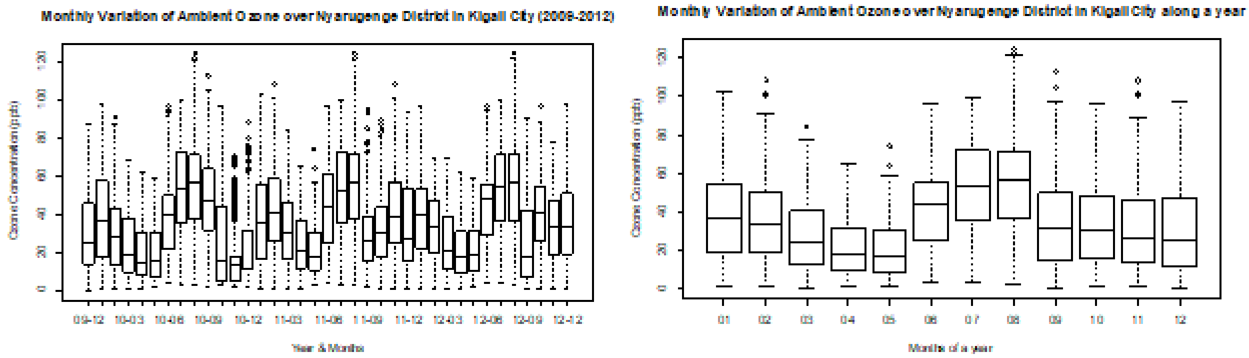

Figure 5. Boxplot of ambient Ozone over Nyarugenge District in Kigali City

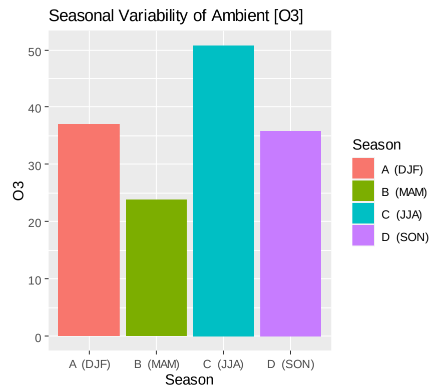

Figure 6. Change of seasonal ambient ozone concentration over 3 years

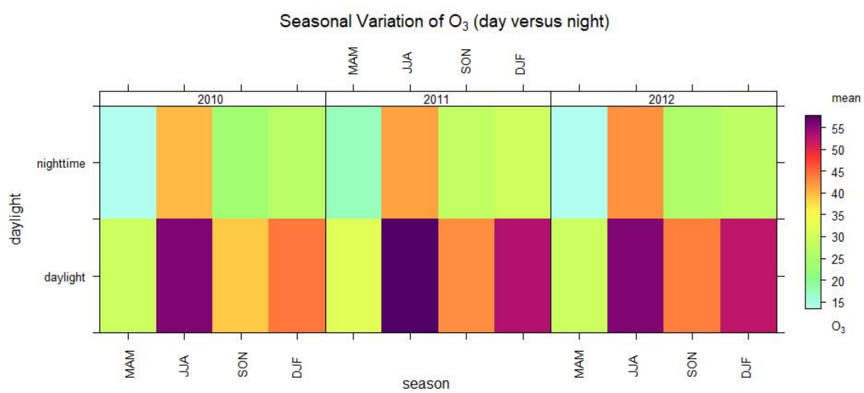

Figure 7. Day and Night Ambient Ozone comparison within the seasons

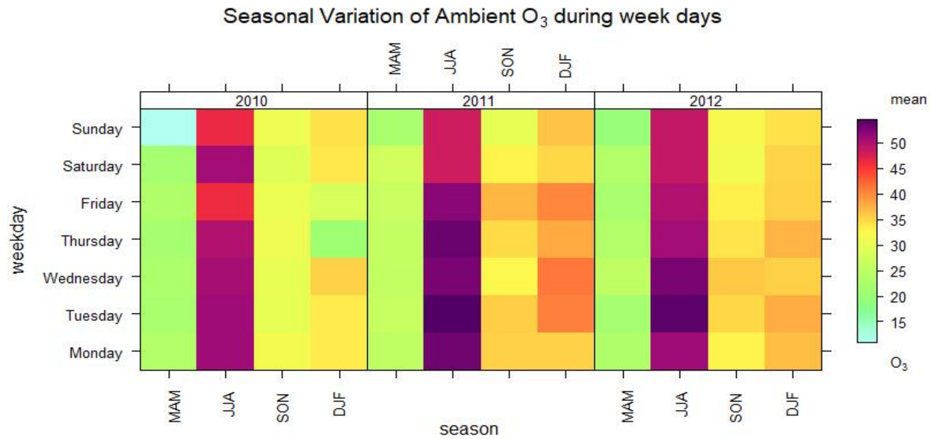

Figure 8. Weekly ambient Ozone within the seasons

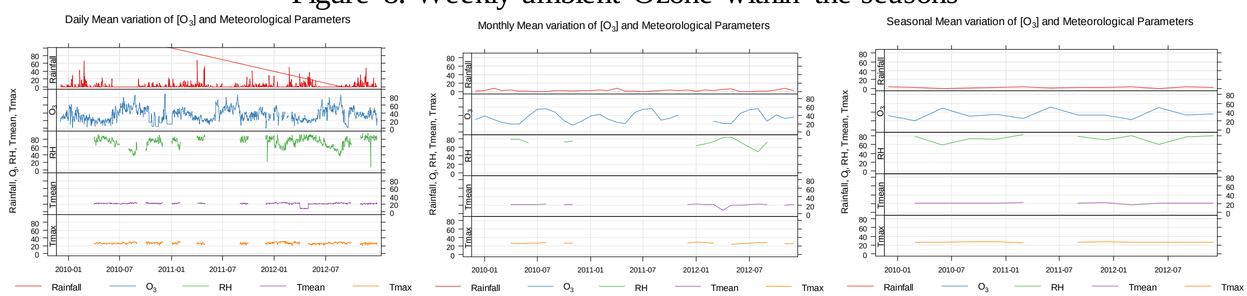

Figure 9. Daily mean, monthly mean and seasonal mean ambient ozone and meteorological parameters variability

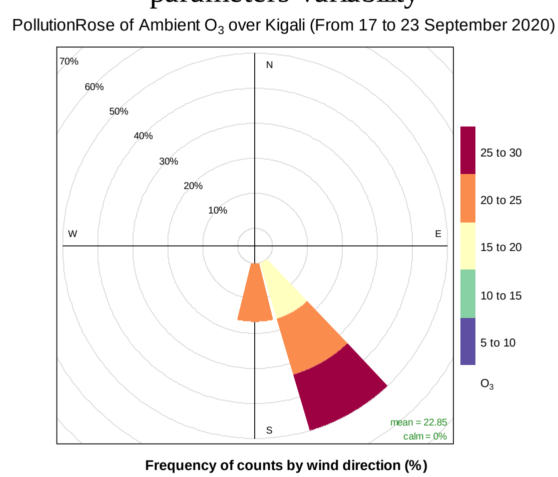

Figure 10. Pollution rose showing which wind directions contribute most to overall mean concentrations

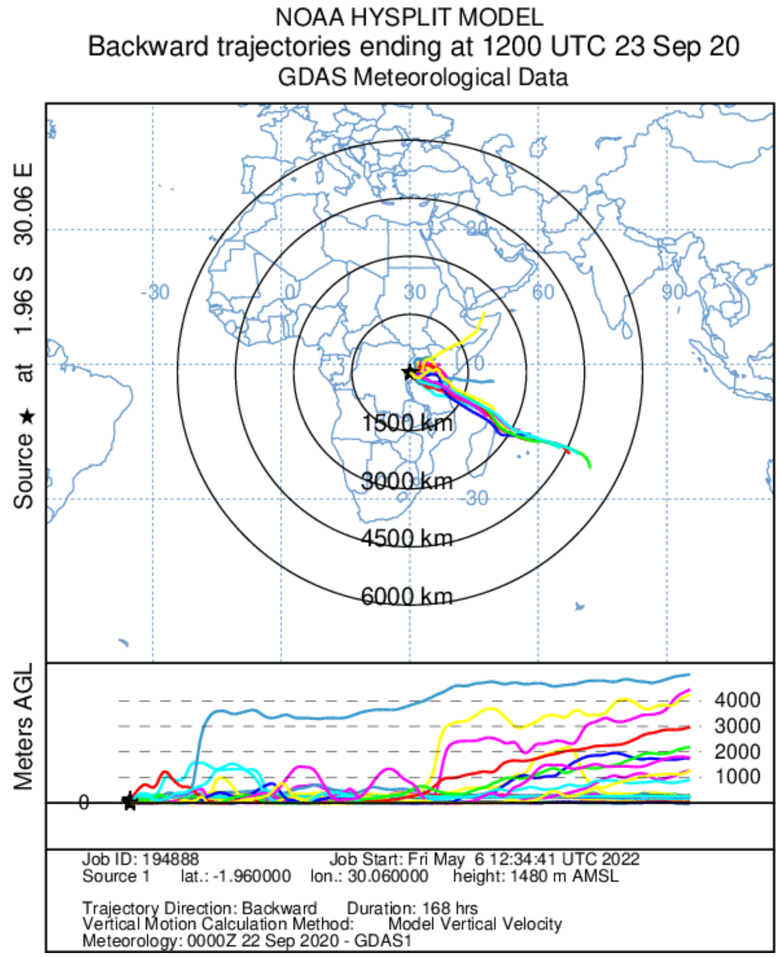

Figure 11. Transboundary sources of air pollutants over Nyarugenge District in Kigali City