Temporal variability of Black Carbon in Kigali.

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June 2022

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A dissertation submitted in partial fulfillment of the requirements for the degree of Master of Atmospheric and Climate Science
in the College of Science and Technology.

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DECLARATION

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

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ACKNOWLEDGEMENT

I would like to express my gratitude to my supervisor Dr. Jimmy Gasore for his guidance. His valued advice and bright ideas have been a great help and inspiration for this thesis.

Many thanks to the University of Rwanda lecturers and Prof. Bonfils Safari, Head of Physics Department and Coordinator of MSc in Atmospheric& Climate Science, College of Science and Technology, for the knowledge they gave me and their administrative and supporting roles. I would like also to extend my gratitude to Rwanda Climate Observatory for providing me with the data I used in this Research.

Many thanks to my family, friends, and colleagues from the Master of Science in atmospheric and climate science in the College of Science and Technology; it was a valuable experience to work with enthusiastic and dedicated colleagues, your help and encouragement have been useful throughout my Masters' studies.

ABSTRACT

Kigali, the capital city of Rwanda, is characterized by an increasing population and a rising rate of transport facilities. African countries, including Rwanda, are concerned with the air pollution problem. Different pollutants produced by burning wood for cooking and household chores, cookstoves, generators and engines with substandard fuel use and others, could be detected.

This study provides the daily data of BC at UR-CST, Nyarugenge campus site, during different seasons continuously for the period from September 2019 up to July 2020 and different conditions with a special emphasis on the COVID-19 Lockdown period, using a Magee Scientific 7-wavelength Aethalometer® Model AE33-7. Different trends were done and analyzed.

The seasonal variation of BC showed that the September-October-November (SON) and March-April-May (MAM) seasons had the lowest mean concentration of 4.130410 µg/m^3 and 3.493238 µg/m^3 respectively. This is explained in the first place by the fact that the wet removal is believed to be the primary removal of BC in the atmosphere and secondly by the COVID-19 lockdown period that reduced many activities in Kigali. On the other hand, December-January-February (DJF) season presents higher BC concentration with a mean of 5.665593 µg/m^3 followed by the months of June-July with an average of 5.613771 µg/m^3. The data for August were missing but previous studies indicate that the Long dry season (JJA) presents the highest BC concentration compared to other seasons as it has been proven that there is a positive correlation of BC with temperature, and the JJA season presents the highest average annual temperature. The weekdays, weekends and hours of the day's differences in BC concentrations showed that BC concentrations follow a daytime pattern with peaks in the morning because of traffic density and late afternoon in hours of leaving offices and late in the evening during cooking hours with less pollution found in office hours. The study also found an overall pollution during weekdays and less pollution in weekends which is explained by less activities in weekends that generates BC. The study also shows that nighttime presents higher BC concentrations compared to daytime and that BC pollution can be globally transported.

Key words

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

ACRONYMS AND ABBREVIATIONS

µm: Micrometer

AGL: Above Ground Level

AM: Ante Meridiem

ARL: Air Resources Laboratory

BB: Biomass Burning

BC: Black Carbon

COVID-19: Coronavirus Disease 2019

CST: College of Science and Technology

D.R.C: Democratic Republic of Congo

DJF: December-January-February

FF: Fossil Fuel

GHG: Greenhouse gases

H.R: House of Representatives

HFCs: Hydrofluorocarbons

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory

ICCT: International Council on Clean Transportation

IPCC: Intergovernmental Panel on Climate Change

JJA: June-July-August

LLGHGs: long-lived GHGs

LPM: Liters Per Minute

MAM: March-April-May

nm: Nanometer

NOAA: National Oceanographic and Atmospheric Administration

PM 10: Particulate Matter less than 10 microns

PM 2.5: Particulate Matter less than 2.5 microns

PM: Particulate Matter

PM: Post Meridiem

RH: Relative Humidity

SLCFs: Short-lived Climate Forcers

SON: September-October-November

STD: Standard Deviation

T: Temperature

UR: University of Rwanda

UTC: Universal Time Coordinated

UV: ultraviolet

WHO: World Health Organization

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CHAPTER 1. INTRODUCTION

1.1. Background of the study (of BC)

In the early 1970s, researchers did not put much effort in recognizing soot as a major pollutant and climate forcer. Much emphasis was shifted to photochemical smog that caused severe eye irritation and decreased visibility. Arctic haze was also recognized and in mid 1980s until the late 1990s, sulfates started being recognized as well as aerosols that cools the earth but less attention was on BC as a particulate matter that produces heating effects (Novakov & Rosen, 2013).

Urban pollution was a major problem along the years and blackness was the term used to indicate the pollution caused by BC in the early 1990s. It was since then that scientists started to isolate BC and make studies on it. Later in the year 2000, (Mark Z. Jacobson, 2000) pointed out that BC might presently warm the atmosphere about one third as much as CO_2. With the interaction of BC with sunlight, BC warms the atmosphere by its capacity of absorbing light which contrasts with the cooling effects of other aerosols (Bond et al., 2013).

(Mark Z. Jacobson, 2002) and (Ramanathan & Carmichael, 2008) suggested that Black Carbon is second to CO_2 when it comes to contribution to present global warming. With remarkable effects in polar regions over snow and ice where in addition to heating the atmosphere, it can reduce the surface albedo when deposited in the snow. These effects have a great contribution to the increase in temperature in arctic regions and in the reduction of sea ice over the decades but also the retreating of glaciers in the Himalayas (Hansen & Nazarenko, 2004; Novakov & Rosen, 2013).

In general, human health problems were the first reason to regulate the particulate matter, among those, respiratory and cardiovascular problems (Pope et al., 2009). In urban arears, high pollution in PM is found where there are sources of BC and to intense exposures in indoor air (Grahame & Schlesinger, 2007; Smith et al.,2010; Janssen et al., 2011). With a high level of attention all around the world, countries and organizations started to study on mitigation options for BC both domestically and internationally not only for its health impacts but also for its climate impacts (Novakov & Rosen, 2013).

This research aims at analyzing and comparing the concentrations of BC from September 2019 till July 2020 across all seasons in Kigali/Rwanda. But also with an emphasis on the period including COVID-19 lockdown from March 2020. The Aethalometer® Model AE33-7 is used to measure the BC concentration data to be analyzed.

1.2. Problem statement

As previously reported, Black Carbon is among the major pollutants in Africa from biomass burning, and one in eight (12.5%) of premature deaths is linked to poor air quality particularly in developing countries. BC affects world health, contributes to atmospheric heating and thus to climate change (Langley Dewitt et al., 2019).

In Rwanda, anthropogenic activities like emissions from vehicles and motorcycles, fuel products of poor quality, industries, traffic and others are the main sources of air pollution (Lamek et al., 2016).

Although the level of pollution in Rwanda is not high compared to other countries, Kigali city is polluted compared to other parts of the country mainly because of many human activities in the capital, population exodus, urbanization rate growing, vehicle density with predominance of old ones, and lack of regular control and assessment of pollution (Nahayo et al., 2019).

1.3. Interest of the research

Rwanda like many other countries in the world is faced to a major environmental health problem of indoor and outdoor air pollution associated with the use of fossil fuels. Approximately, air pollution causes 2 million premature deaths and 1.5 million deaths for indoor and outdoor air pollution respectively. Children under the age of 5 are the most vulnerable of indoor air pollution in developing countries because of pneumonia.

Particulate matters are a threat to human health. BC in particular, are more dangerous since, when inhaled, they may reach the peripheral regions of the bronchioles, and interfere with the exchange of gas in the lungs mainly because of their small size. When someone is exposed for a long period of time, it can contribute to cardiovascular and respiratory diseases as well lung cancer (Nduwayezu et al., 2015).

The main interest of this research is to assess the status of BC concentration in Kigali at UR-CST site; and how BC concentration varies with time across seasons, hours of the day, weekdays, weekends, daytime, nighttime and other special periods like the COVID-19 lockdown period.

This will help policymakers for the revision of mitigation measures to reduce BC emissions in Rwanda and in Kigali in particular. Also, this work may serve as a foundation for further researches in Rwanda because the related topics are still low.

1.4. Objectives of the study

1.4.1. Main objective

The main objective of the research is to evaluate the temporal variability of BC in Kigali.

1.4.2. Specific objectives

The objective of this project is to quantify the temporal variability of BC as one of the PM causing air pollution and global warming.

The aim extends to finding:

- To determine the temporal variability of BC concentration over Kigali city during the JJA and DJF (dry seasons), SON and MAM (Rain seasons).
- To assess the variability of BC during different hours of the day.
- To assess the variability of BC over Kigali during weekdays and weekends.
- To assess the relationship between daylight and nighttime concentrations of BC in Kigali.
- To assess the impact of COVID-19 lockdown measures on BC concentration levels

1.5. Organization of the thesis

This thesis is subdivided in five chapters. The first chapter is the introduction, which is composed of the background about black carbon, problem statement, interest of the research, and objectives of the research.

The second chapter is the literature review, which includes an overview of Black carbon, Definition, composition, and sources of BC, BC and Air pollution, BC and climate impacts, BC and health impacts, BC over Kigali city, and control technologies that can reduce BC.

The third chapter is methodology, where there is the description of Site selection, Measurement of BC, and data analysis. The fourth chapter is results and interpretation and the fifth chapter comes as a conclusion and recommendation.

CHAPTER 2. LITERATURE REVIEW

2.1. Overview

This section provides an overview on BC, Definition, Composition, Sources, Black Carbon and air pollution, climate change &global warming and the impacts BC has on human health in Kigali-Rwanda. Finally, an overview of the control technologies that reduce has been discussed in this section.

2.2. Black carbon: Definition, composition, sources

Black Carbon are small, dark particles (diameter < 2.5µm) produced from incomplete combustion of biomass and fossil fuels (Novakov & Rosen, 2013; Stocker et al., 2013).

Soot is combination of microscopic particles namely BC, organic carbon and smaller amounts of Sulphur and other chemicals. Soot from diesel appears black because of high fractions in BC, which absorbs all colors of light. Because of the less efficient combustion, smoke from open biomass burning may appear brown, blue or gray because of high fractions of organic carbon compared to that of BC. Particles of organic carbon scatter light but can also absorb light partially at some wavelengths, thus a brown colour of the smoke (M.Z. Jacobson, 2007; Bachmann, 2009).

Among the major source contributions for BC, there is 40% from coal, industry and mobile sources (transport, road), 18% from heating and cooking in residents (residential: biofuel, residential: coal), and 42% from open biomass burning (agriculture, forests fires…) (Bachmann, 2009).

Carbonaceous fuels, when burnt, results in the emission of particulate air pollutants. One of them is BC, an aerosol species exhibiting very large optical absorption across the visible part of the optical spectrum. BC has no non-combustion source, is inert and can be transported along long distances. BC is associated to adverse health effects and reducing air and black carbon in particular must be addressed at a global scale (Drinovec et al., 2015).

2.3. Black carbon vs elemental carbon

Both black carbon and elemental carbon are light absorbing compounds and sometimes in environmental sciences these two terms can be substituted in place of one another, but black carbon comes from incomplete combustion in reduced or anoxic environments and the term ‘elemental carbon’ is used for carbon fractions measured after oxidative combustion in the presence of oxygen above a certain temperature threshold (Shrestha et al., 2010).

2.4. Black carbon: Air pollution

WHO defines air pollution as "substances put into the air by the activity of mankind into concentrations sufficient to cause harmful effects to health, property, crop yield or to interfere with the enjoyment of property” (WHO, 1997).

In local context, the official gazette of the Republic of Rwanda, No 04/2005 of 08/04/2005 defines the atmospheric pollution as “a voluntary or accidental contamination of the atmosphere and the surrounding air, gas, smoke, any particles or substances that may endanger biodiversity, human health and their security or disrupt agricultural activities, disrupt installations or the nature of tourist sites and mountains” (Government of Rwanda, 2005).

BC is a harmful air pollutant that contributes to both air pollution and climate change. It is classified in air pollutants called particulate matter. Particulate matters cover all small particles of soot, wood smoke particles, dust and liquid droplets that have become suspended in the air. They are very small in size and their diameter is less than that of human hair. Some are seen as haze, dust or smog and others can be seen only with microscopes. BC is very small in size and because of that, it can easily reach the lungs. It can also cause eyes, throat and nose irritations. An exposure to BC sources is very risky to people with asthma or other lung disease. Also exercising in places with higher BC concentrations is risky because air is inhaled and goes deeper into the lungs and at a high speed (Sierra Club, 2016; Schneidemesser, 2017).

BC has a shorter lifetime compared to CO_2 and remains in the atmosphere for several days up to four weeks. It has a greater impact on local and regional air quality, but due to its shorter lifetime, efforts to reduce its emissions can have positive effects on air quality and in near-immediate way (Schneidemesser, 2017).

2.5. Black carbon: Climate impacts

BC is estimated to be 2nd or 3rd contributor to global warming after carbon dioxide and possibly methane. According to IPCC, BC has the 3rd largest global warming potential after carbon dioxide and methane. It has a short lifetime but is a potent climate-forcing agent. BC contributes largely to temperature changes and it has been estimated to contribute one-sixth of global warming since 1750 (Carver, 2011; Stocker et al., 2013; Kholod & Evans, 2016).

A remarkable impact of BC as a climate forcer has been pronounced in the arctic and the arctic is more vulnerable to BC emissions globally. By darkening the surface of the snow and reducing the albedo of the snow, black carbon facilitates the absorption of solar radiation, which makes air temperatures increasing and accelerates the melting of ice and snow (Hirdman et al., 2010; U.S. EPA, 2012).

BC has an influence on world climate through different mechanisms. By absorbing sunlight and reducing the albedo when suspended in the atmosphere, BC particles absorb both ongoing and outgoing radiation of all wavelengths thus contributing to the warming of the atmosphere. It has been found that BC may either increase or decrease cloud cover under different conditions. By absorbing solar radiation, this disturbs the structure of the atmosphere, increasing atmosphere's heating rate and altering humidity profiles and consequently altering cloud distribution (Koch & Del Genio, 2010).

There are two ways in which BC warms the climate: The first one is when suspended in air, BC absorbs sunlight and generates heat in the atmosphere. This can affect regional cloud formation and precipitation patterns. The second way is when BC particles are deposited on ice and snow, they make snow and ice darker and absorb sunlight, again this process generates heat and causes warming of the air above and the ice and snow below, thus accelerating melting (Stocker et al., 2013).

In few, BC or soot absorbs heat in the atmosphere (leading to a 0.4 W m^{-2} radiative forcing from anthropogenic fossil and biofuel emissions) and, when deposited on snow, reduces its albedo, or ability to reflect sunlight. Reductions of black carbon emissions can therefore have a cooling effect, but the additional interaction of black carbon with clouds is uncertain and could lead to some counteracting warming (Stocker et al., 2013).

BC has short lifetime, from several days to four weeks and because of that, its climate effects are strongly regional. For comparison, methane emissions remain in the atmosphere for 8 – 12 years and carbon dioxide emissions for centuries. This means that BC mitigation and control can offer possible opportunities compared to the control of CO_2 and methane and can also offer immediate effects for slowing or reversing climate change (Koch & Del Genio, 2010; Carver, 2011).

Reduction of warming of methane and BC can limit warming to 1.5°C above pre-industrial levels. Reductions of several warming SLCFs are constrained by economic and social feasibility (low evidence, high agreement). As they are often co-emitted with CO_2, achieving the energy, land and urban transitions necessary to limit warming to 1.5°C would see emissions of warming SLCFs greatly reduced (Masson-Delmotte et al., 2018).

2.6. Black carbon: Health impacts

In addition to its climate effects, BC has been associated with adverse effects on human health. Some suggested that BC may pose greater health risk as indicated by the higher effect estimates per mass unit for BC particles compared with PM mass as a whole (Janssen et al., 2011).

Studies indicate that fine particles pose a serious public health problem. Due to their small size, fine particles (PM2.5), including black carbon, can penetrate deep into the lungs. Even the largest fine particle is about 30 times smaller than the diameter of the average human hair. Exposures to black carbon can cause premature death and harmful effects on the cardiovascular system (the heart, blood, and blood vessels). Fine particle exposure also is linked to a variety of other public health problems, including respiratory diseases, and when the exposed to higher concentrations those health problems may lead to mortality or morbidity. The people most at risk include people with heart or lung disease (including asthma), older adults, children, and people of lower socioeconomic status (Brown & Epa, 2013; WHO, 2018).

Reducing BC would have considerable co-benefits because despite tackling climate change, this will also have a great impact on improved health because of the decrease in air pollution (Li et al., 2016).

2.7. Black carbon over Kigali

The population of Africa is growing to a very higher rate compared to the rest of the world and is projected to increase by 200% from 2010 to 2050. Taking Rwanda as an example, there is a high increase in population growth and urbanization. This has caused an increase in the generation of air pollutants including BC (Kalisa, 2019).

As reported by (Henninger, 2009), the concentration of air pollutants in Kigali namely PM10 and PM2.5 has reached and surpassed the WHO recommended levels and thus creates a high risk to the population. The higher stability of the urban atmosphere caused by an increasing urban heat island results in a lower transportation and dispersion of pollutants including BC from the points of emission to other places. This results in an accumulation of those pollutants in residential areas and that plays an important role in the contribution to the populations' health risks.

In Kigali, the weekends present low concentrations in PM2.5 compared to weekdays and dry seasons present high concentrations in PM2.5 compared to wet seasons. Local sources also play a big role to the high concentrations of BC in Kigali as they contribute to about two third of the BC in wet seasons and half of the BC in dry seasons. Controlling local sources of air pollution like biomass burning can also have a great impact to Kigali's air quality (Kagabo, 2018; Subramanian et al., 2020).

2.8. Black carbon: Proposed control technologies for reduction

As previously discussed, BC has a lifetime of several days to four weeks. Hence, implementing policies and control technologies for reducing BC emissions can be effective for a near-term response to slow warming.

The proposed technologies to reduce BC pollution include retrofitting diesel vehicles with filters to capture BC or switch from diesel to natural gas, replace cookstoves that generates BC with efficient ones that do not generate BC like solar cookers or cook stoves that burn fuel completely, and putting in place those alternatives would have a great impact in densely populated cities including Kigali and improve the living standard of the population (REMA, 2011).

Reducing BC emissions would have an immediate cooling effect on the Earth's climate, potentially delaying temperature increases in the short run and at the same time helping reduce the risk of irreversible tipping points in the climate system, and it would reduce air pollution, resulting in fewer premature deaths and health problems.

CHAPTER 3: METHODOLOGY

3.1. Site selection

3.1.1. Geographic description of the site and general meteorology

Rwanda is located in Central /East Africa at the coordinates 2°S and 30°E with an area of 26,338 km^2. The country is bordered by Uganda to the north, D.R.C to the west, Burundi to the south and Tanzania to the East.

The City of Kigali is the capital and largest city of Rwanda with an area of 370 Km^2 and a population of around 1.6 million predicted to reach 4 million by 2050 (Sudmant, 2020). The city of Kigali (latitude of 1º 40’-2º 00’South and longitude of 30º 00’-30º 40’ East) typically represents a more than 70 percent urban setting with a tropical climate, having four distinct seasons, i.e. two rainy seasons MAM and SON, and two dry seasons DJF and JJA. The average annual temperature is 20.1 °C with the warmest month being August. The average rainfall is about 1000mm per year. The lowest rainfall is recorded in July (8mm) while in April the rainfall is high (168mm). RH varies from 15 to 100% (Nahayo et al., 2019).

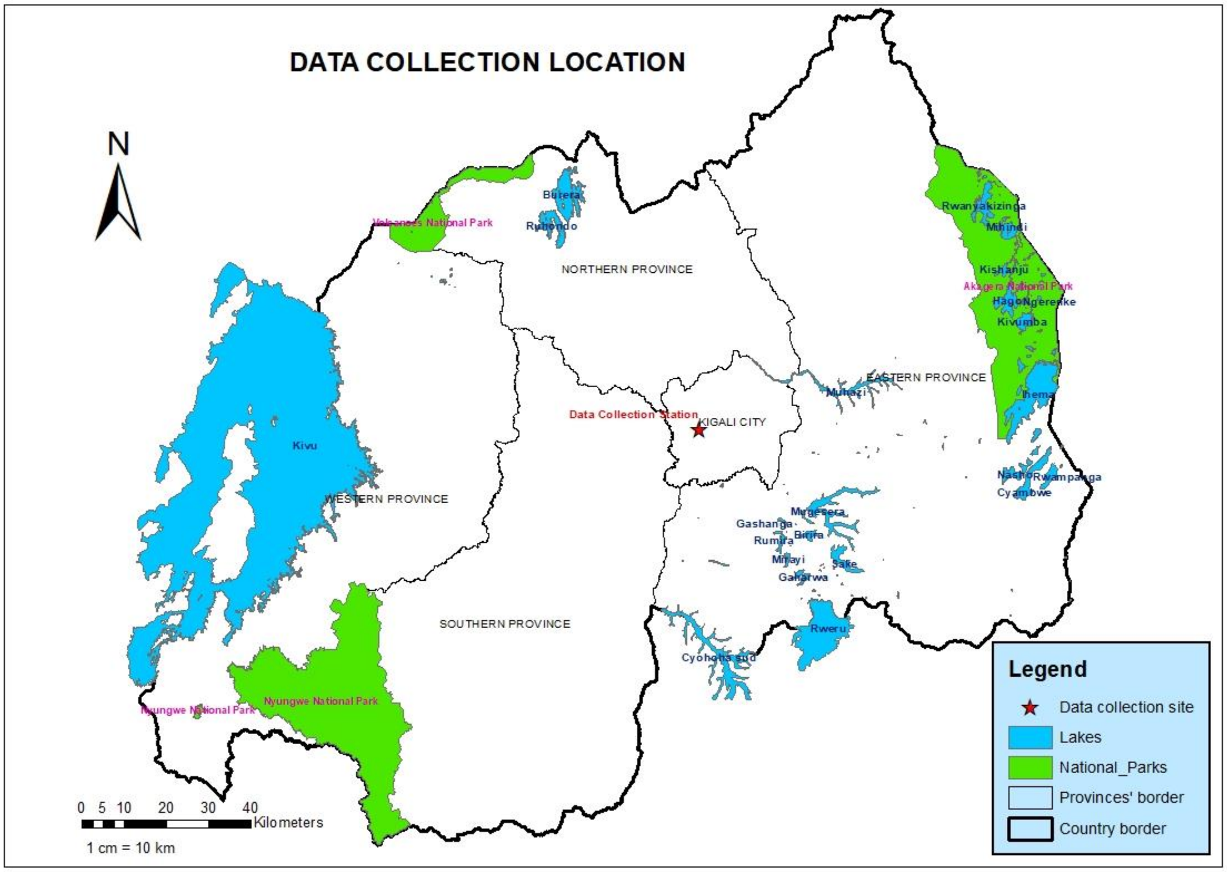

Figure 1: Location of Kigali city and its bordering provinces in Rwanda showing the data collection site.

The data of BC used in this research were recorded at the University of Rwanda /College of Science and Technology (UR-CST) Nyarugenge campus, from September 2019 to July 2020. CST is located in the Capital city of Rwanda, Kigali; in Nyarugenge district. The geographical coordinates of the site are 1.961667° S ,30.06472° E.

The Aethalometer used to collect the data is located at UR-CST and is installed on top of the building known as KIST 4. In general, the city of Kigali is associated with anthropogenic activities throughout the year and is characterized by many small and medium-scale industries. Such anthropogenic activities inject significant amounts of pollutants, especially BC into the city's environment.

The prevalence of many anthropogenic activities, business activities, restaurants, high traffic, many residents in the area that generates pollution, and the fact that the area is open to the air coming from different places in Kigali, is the reason behind the choice of that area as the sampling site.

3.2. Measurement of BC

3.2.1. Introduction on Aethalometer® model AE33-7

The Aethalometer is an instrument that helps to provide a real-time readout of the concentration of BC aerosol particles in the air stream. The Aethalometer comprises of a cyclone impactor on the inlet that enables PM2.5 to pass. Data is recorded every minute at a flow rate of 5LPM and particles are captured on a quartz fiber filter tape. The main problem with the instrument is that the air that enters is not dried, which means that the RH is not controlled and may lead to increased uncertainties when RH is high (Sharma et al., 2014).

The collected particles pass through a filter material and creates a deposit of increasing density.

A light beam that passes through the deposit is attenuated by those particles which are absorbing (black).

The instrument measures the transmitted light intensities through the filter tape on which the aerosol spot is being collected, and a reference portion of the filter as a check on the stability of the optical source. It deduces the optical properties and the instantaneous concentration from the rate of change of the attenuation of light in the particle-laden filter, and the results are available immediately without having further analysis of the sample to the laboratory. It is an automatic instrument and it only need periodic check of the air flowmeter response as calibration (Sedlacek, 2016).

BC 1666 ng/m³
UVPM 2900 ng/m³
REPORTED FLOW (AMCA) 5.0 LPM
TIMEBASE 60 s
TAPE ADV. LEFT 105
STATUS ● 0
02 Dec 2020 11:22:28

Figure 2: The Aethalometer® Model AE33-7

3.2.2. Measurement principle

The optical absorption is measured at 7 wavelengths simultaneously; 370, 470, 520, 590, 660, 880, and 950 nm. The measurement obtained at 880nm (channel 6) is the defining standard used for reporting BC concentration:

BC concentration: BC = BC6.

Attenuation of light through filter paper at 880 nm (channel 6) is the one that is considered for calculating BC concentration as there is no other major aerosol species that exhibits absorption at this wavelength. Data from the other channels are used for source apportionment like BB (%) that represents the percentage of BC created by biomass burning, determined by the Sandradewi model (Wang et al., 2010).

3.3. Data analysis

The following software were used in presenting data:

R: The R package has helped in the generation and visualization of plots for a better presentation of the data.

HYSYPLIT Modelling: The HYSPLIT model developed by the ARL in NOAA (Stein et al., 2015) was used to model and determine the sources air pollution incidences across all seasons at the monitoring site. In 2019, (Langley Dewitt et al., 2019) used HYSPLIT to determine the sources of BC in their study. In our study, the model was run at 10 m,20m and 30m AGL to determine the possible location of biomass burning sources that caused high concentration of BC as measured at UR/CST.

3.3.1. Statistical analysis

Statistical analysis has helped in analysis interpretations or explanation and presentation of data. It helped in calculating the daily, hourly and monthly mean BC concentrations, and other statistics in order to get a meaningful idea about the data.

The mean value is a measure of the center value of the data. It is defined to be the sum of the measurements or data values divided by the number of observations or the number of measurements (Ott & Longnecker, 2010).

In our study, the calculation of the mean was used to calculate the daily, hourly, monthly and seasonal mean concentrations.

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} Xi \qquad (1)$$

Where $\bar{X}$ is the mean value,

n is the number of BC data values considered,

and Xi is any starting value of BC.

The formula enabled me to calculate the seasonal mean values of BC concentration.

CHAPTER 4: RESULTS AND INTERPRETATION

4.1. Annual and seasonal mean

The results of the seasonal average BC concentrations expressed in µg/m^3 are summarized in table 1. The SON season in 2019 has an average BC concentration of 4.130410 µg/m^3, DJF season has 5.665593µg/m^3, MAM season of 2020 (the months where COVID-19 lockdown was introduced) has an average BC concentration of 3.493238µg/m^3 and finally the JJ months of 2020 after lockdown presented an average BC concentration of 5.613771µg/m^3. Note that the data for the month of August were missing.

4.2. Interpretation of results

R package helped in data visualization and data are presented in terms of timeseries plots for a better understanding of the variability of BC across seasons. Bar plots and boxplots were also used for a better comparison of BC concentrations across all seasons.

Black carbon data from the monitoring site are used to see the hours of the day, weekdays, weekends, daytime, nighttime, and seasonal variation for September 2019 to July 2020 and with a special emphasis on the lockdown period that started in March 2020 to analyze the trends for that special period. The BC concentrations varies across the rainy seasons (MAM and SON) and dry seasons (DJF and JJA).

4.2.1. Temporal variations in black carbon concentrations

Figure 3 shows the variation in temporal variability of BC in Kigali from September 2019 to July 2020. It comprises of 4 seasons that we have in Rwanda, 2 dry seasons (DJF and JJA) and 2 wet seasons (MAM and SON) but the data taken does not comprise the month of August 2020. It is a crucial month that was supposed to have high amounts of BC as it is a dry month and has a high average temperature. The temporal variations also highlight the seasonal, weekday/weekend and hours of the day, nighttime and daytime differences in BC concentrations, illustrating also the COVID-19 lockdown trends without forgetting the HYSPLIT trajectories to assess the possibility of transport of BC from other places to the monitoring site.

4.2.1.1. Seasonal variations in BC concentrations in Kigali

BC concentrations were high in Kigali at the monitoring site and were influenced by local traffic and residential activities like cooking. Missing periods in the times-series like a large part of data in January 2020 and data of August 2020 are due to periods where monitoring was not undertaken mainly due to maintenance of equipment as it can be seen on figure 11 that shows the BC summary plot over Kigali.

As presented in Figure 7, as expected, the seasonally averaged BC mass loading revealed high BC concentrations during the dry seasons namely DJF season and June-July months of 2020 (5.665593 µg m^{-3} and 5.613771 µg m^{-3} respectively), and lower during the wet seasons namely SON and MAM seasons (4.130410 µg m^{-3} and 3.493238 µg m^{-3} respectively).

The long and short dry seasons, presented high mean concentration and that can be associated to meteorological factors, local traffic, household emissions, like domestic heating and note that the surrounding areas of the city often usually burn biomass (e.g., straw and/or wood) for domestic heating, forest fires, bush burning during the dry seasons. Burning these fuels results in the emission of large BC particles and The figure 4 highlights the BC that can be attributed to biomass burning. The changes in meteorological conditions over the seasons have also been recognized as a key driver in BC dynamics across Kigali (Kagabo, 2018).

The wet seasons (MAM and SON) presented lower BC concentration compared to the dry seasons as presented in figure 7. As stated above the average concentration for the short and long wet seasons were 4.130410 µg m^{-3} and 3.493238 µg m^{-3} respectively.

During the two seasons, there is much rainfall mainly during MAM season. Washout process is the most effective means of removing BC from the atmosphere, resulting in the lowest values of BC occurring in MAM and SON season. There will be also wet removal of BC from the atmosphere and hence lower BC concentrations.

During the wet seasons, the neighborhood of Kigali city does not burn biomass and the local influence on BC concentration will not be high like in the dry seasons.

The other notable reason for the reduction in BC concentration during the MAM season of 2020 is the COVID-19 lockdown measures that were introduced starting from 21st March 2020 as explained in 4.2.1.5

4.2.1.2. Weekday/weekend and hours of the day differences in BC concentrations

Black carbon concentrations were found to follow a daytime pattern with peaks in the morning around 7 AM associated with traffic density (‘rush hour’) and late afternoon from 5 PM corresponding to hours of leaving offices, more traffic, and cooking activities around 8-9 PM. There is less pollution from 10 AM to around 3 PM corresponding to office hours. These emission patterns of BC in Kigali are shown in figure 9.

Weekends in Kigali are characterized by a reduction in anthropogenic activities and other activities that generate BC during weekends and also car-free days and Umuganda programs that are planned during weekends. Note also that Mondays presents not much BC concentrations. All those factors have great influence in reducing emission levels of air pollutants in the atmosphere compared to the weekdays. Variations in BC levels based on weekday/weekend patterns were found to be low during weekends and high during weekday with a peak found on Wednesday as shown by Figures 8 and 10.

4.2.1.3. Nighttime and daytime trends across the seasons

As shown by Figure 12, the nighttime presents high average BC concentrations compared to daylight across all seasons with the highest nighttime concentrations observed during the June-July months.

The reason for this is that most of the cooking activities in the area are conducted during the night time around 8-09 PM as also seen in figure 9.

The area of data collection is surrounded with restaurants and dense households that burns wood and charcoal when cooking.

The other probable reason for this may be the buildup of particles under inversion conditions and/or atmospheric stability that can lead to high concentrations of pollutants in the affected area. (Bathmanabhan & Saragur Madanayak, 2010) also reported the same in his study where he was doing the analysis and interpretation of PM emissions near an urban roadway.

MAM season presented low concentrations during daytime and nighttime because of the washout processes all along the season and the unstable atmosphere because of the rain.

4.2.1.4. COVID-19 lockdown trends

As shown by Figures 3, 7 and 13, the BC data that starts from 21 March 2020 and ends in May 2020 corresponding to the period of the COVID-19 lockdown, presents a low average concentration of 3.1 µg/m^3, with a maximum concentration of 14.8 µg/m^3. In general, this period presents lower BC concentration and this is explained by The COVID-19 lockdown measures implemented in Rwanda from 21 March 2020 that led to a downturn in several economic, traffic sectors, and other sectors with an impact on air quality and BC concentration levels.

These measures include the unnecessary movements, visits and travel outside the home and between districts and cities that were prohibited. This means that the public and private transport including buses, taxi, motos were not permitted. These measures were the reason for the decrease in BC concentration levels in Kigali.

4.2.1.5. The hysplit trajectory

The Hysplit trajectory model accessed from the NOAA website, by using the backward trajectories ending at 03h00 UTC 15 December 2019 over Kigali at 10m, 20m and 30m AGL shows that at all the three levels, the trajectories that arrive at the source come from the neighboring country Tanzania near the border with Rwanda as it can be seen on figure 14. The rural areas often burn biomass during the dry seasons.

As shown in Figure 15, the backward trajectories ending at 06h00 UTC 16 February 2020 come from the neighboring country Tanzania and this area corresponds to Burigi Forest Reserve. The contributions may be due to forest fires in the area.

The backward trajectories ending at 01h00 UTC 15 November 2019 over Kigali – UR/CST site at 10m, 20m and 30m AGL, shows that the trajectories that arrive at the monitoring site comes from the neighbouring country of Rwanda, Tanzania, all along lake Victoria as it can be seen on figure 16.

As it can be seen on figure 17, the Hysplit Backward trajectories at UR-CST on 29 March 2020, 01h00 and from 10 m,20m and 30m AGL, generated from NOAA website shows that the trajectories that arrive at the monitoring site comes from the border between Uganda and Tanzania. For the figure 18, the trajectories that arrive at the site come from the northern part of the neighbouring country Burundi in Gisuru area.

The model was run across all seasons basing on the days that presented very high concentrations in BC to see the contribution of neighboring provinces to Kigali or even neighboring countries. The contributions may come from burning of fossil fuels, forest fires, agricultural activities and others.

All the figures indicate a global transportation of pollution mainly because of wind.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In the present study, the diurnal, weekly, and seasonal trends of BC concentrations emitted from Kigali city at the CST site were investigated. The analysis done between September 2019 and July 2020 showed the following trends:

1. Across the seasons, the dry seasons namely DJF and JJA seasons presented higher BC concentration trends compared to wet seasons (SON and MAM). The rainfall in wet seasons helps in the reduction of BC concentrations due to washout. MAM season presented lower BC concentration also because of the COVID-19 lockdown period implemented in Rwanda starting from 21, March 2020 which helped in the reduction of many activities in the whole country.

2. In the diurnal cycle, two peaks were observed corresponding to morning and evening rush hour traffic and cooking activities.

3. High-level BC concentrations were observed during the weekdays compared to the weekends because the weekday traffic movement at the study site was significantly higher compared to weekends (Saturday and Sunday) traffic. Car-free days and Umuganda implemented on weekends are also a factor to take into consideration.

4. Across the season, there were a high overall BC concentration during nighttime compared to daytime. This is due to complex meteorological factors, daytime high wind speeds, the built up of particles under inversion conditions and/or atmospheric stability as also reported by (Kagabo, 2018).

5. Pollution can be transported. Neighboring locations can influence the local BC concentrations.

5.2. Recommendations

As a recommendation, there is still a need for more studies about BC, at longer time scales and correlation with many weather parameters like Temperature, rainfall, Relative humidity, wind speed, and others.

There is also 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.

The city of Kigali should put more effort into increasing the number of car-free days to incite people to use other means of transport that do not generate pollution. Also, sensitizing the population on the importance of using public transport rather than their cars because as the number of private cars continues to increase, the pollution and BC generation will also follow the same trend. This goes with building knowledge of the population about air quality, using efficient cookstoves, and many other technologies.

The use of e-moto and Air pollution law would also help in tackling BC generation and pollution in general as suggested by (Sudmant, 2020).

APPENDICES

LIST OF TABLES

Table 1: Seasonal mean values of BC concentration from September 2019 to July 2020

Month	**Season**	**Seasonal average BC in μg/m^3**
September 2019	S-O-N	4.130410
October 2019		
November 2019		
December 2019	D-J-F	5.665593
January 2020		
February 2020		
March 2020	M-A-M (COVID-19 Lockdown Period)	3.493238
April 2020		
May 2020		
June 2020	J-J (After Lockdown)	5.613771
July 2020		

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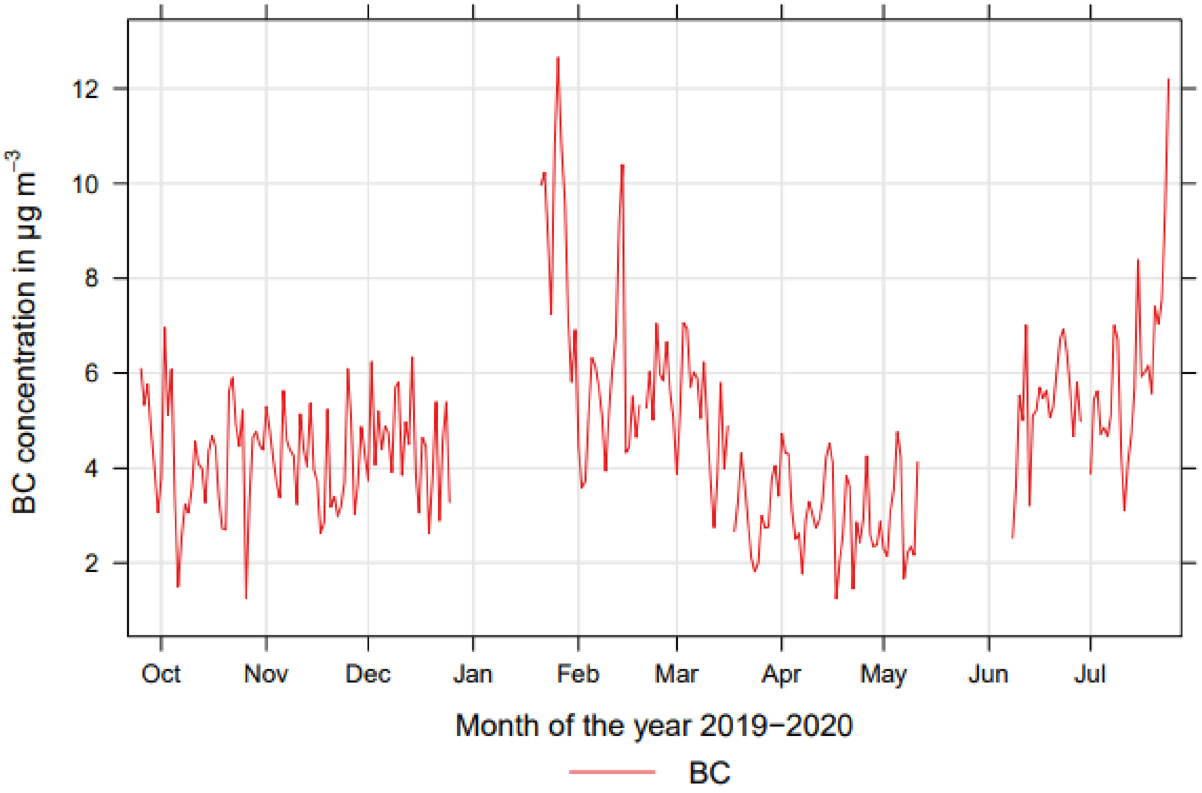


Figure 3: Variation plot of BC concentration across 2019-2020 in Kigali.

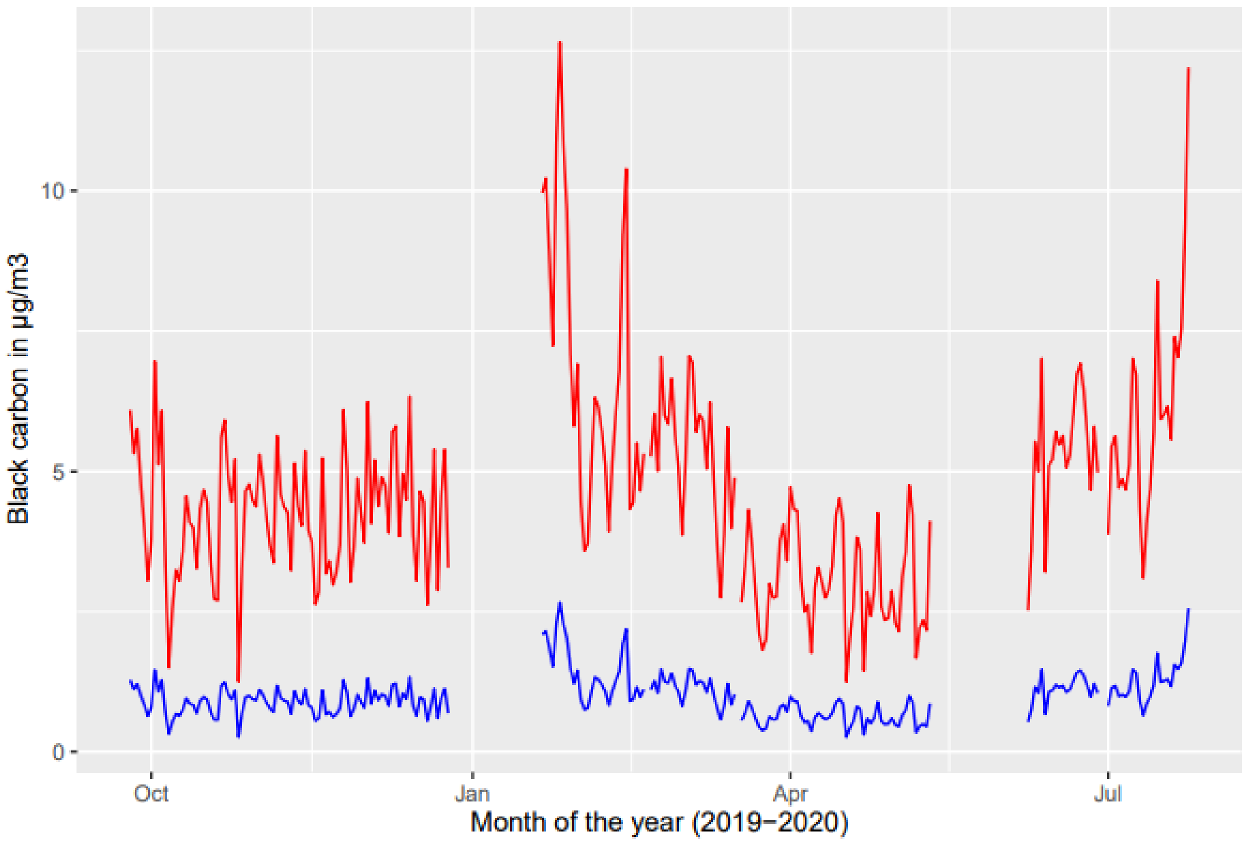


Figure 4: BC concentration trends in Kigali from Sept 2019 to July 2020. Blue line represents BC from biomass burning and red line represents total BC (soot).

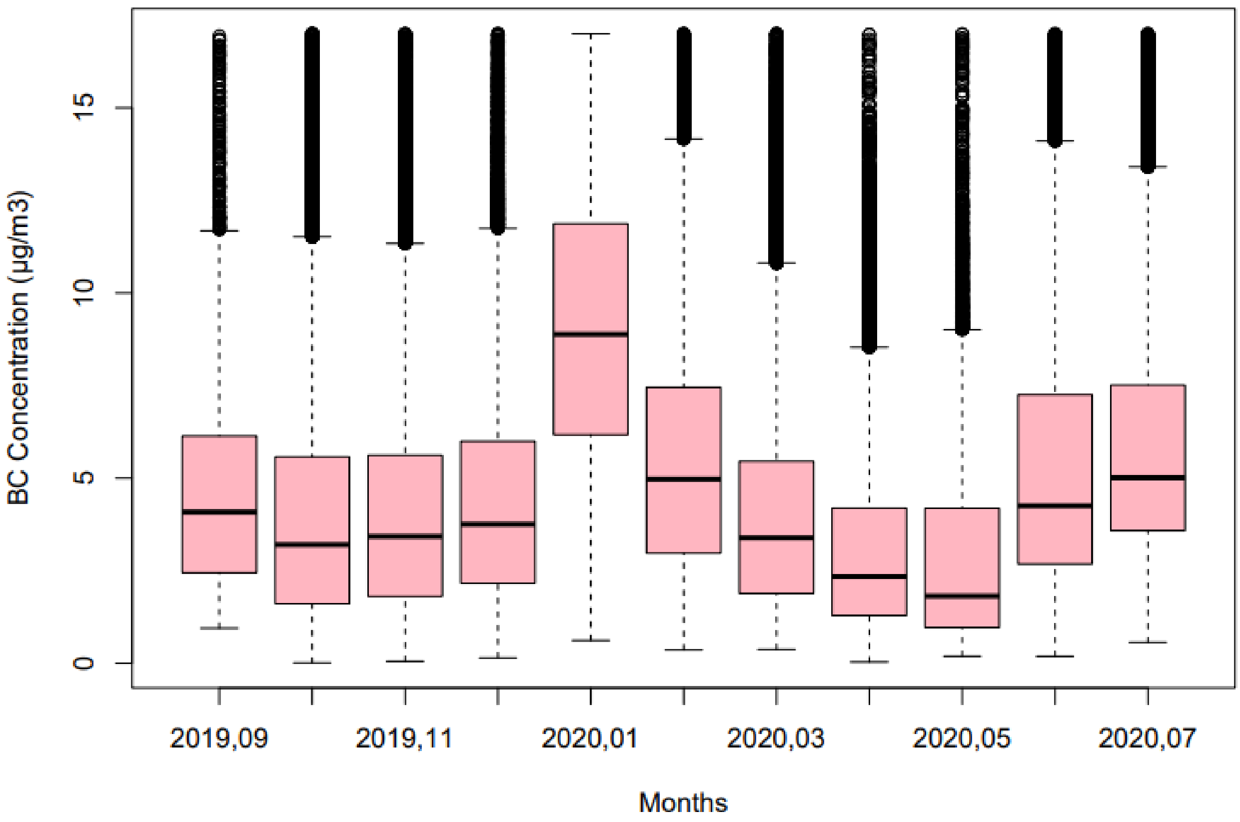


Figure 5: Boxplot of BC concentration in Kigali.

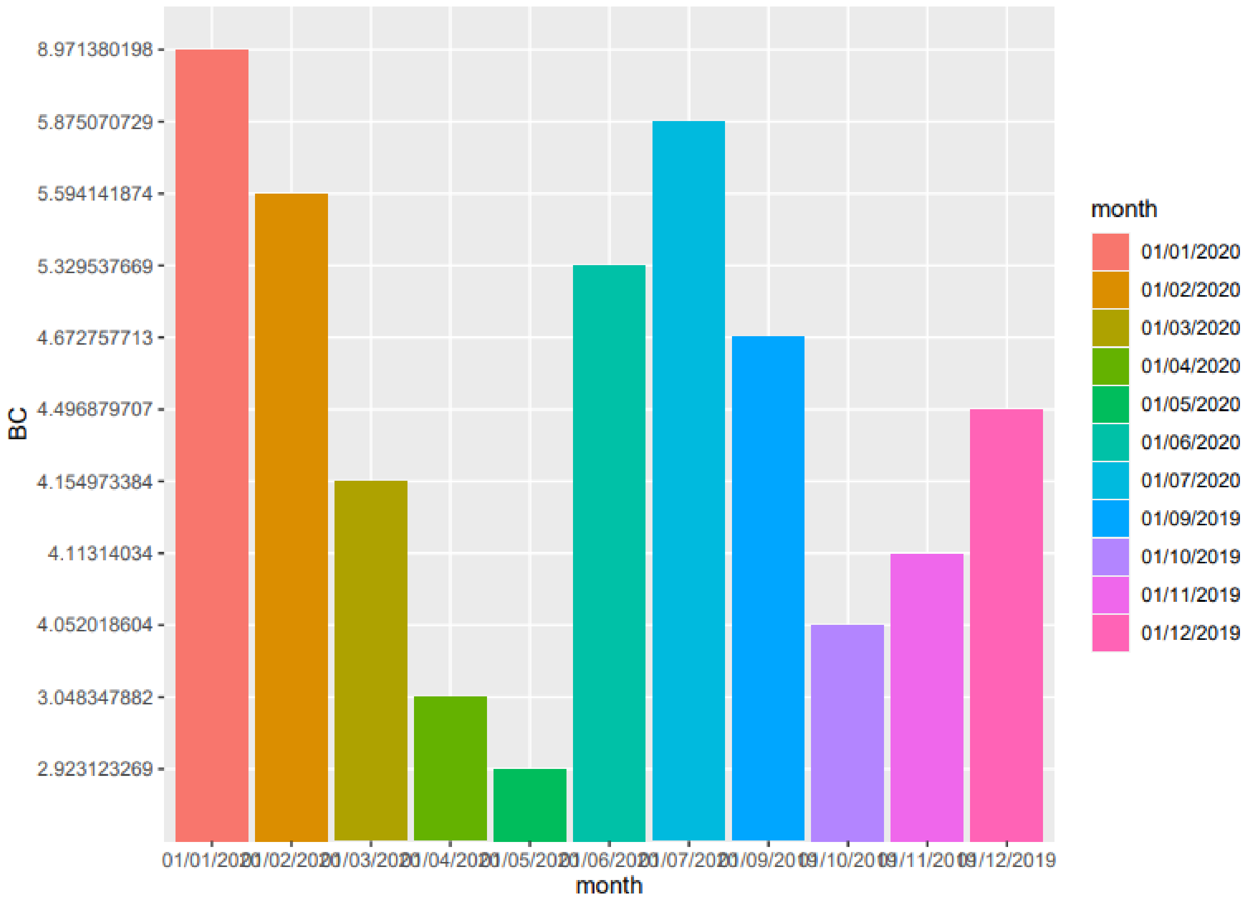


Figure 6: Monthly comparison of BC concentrations over Kigali for the year 2019-2020.

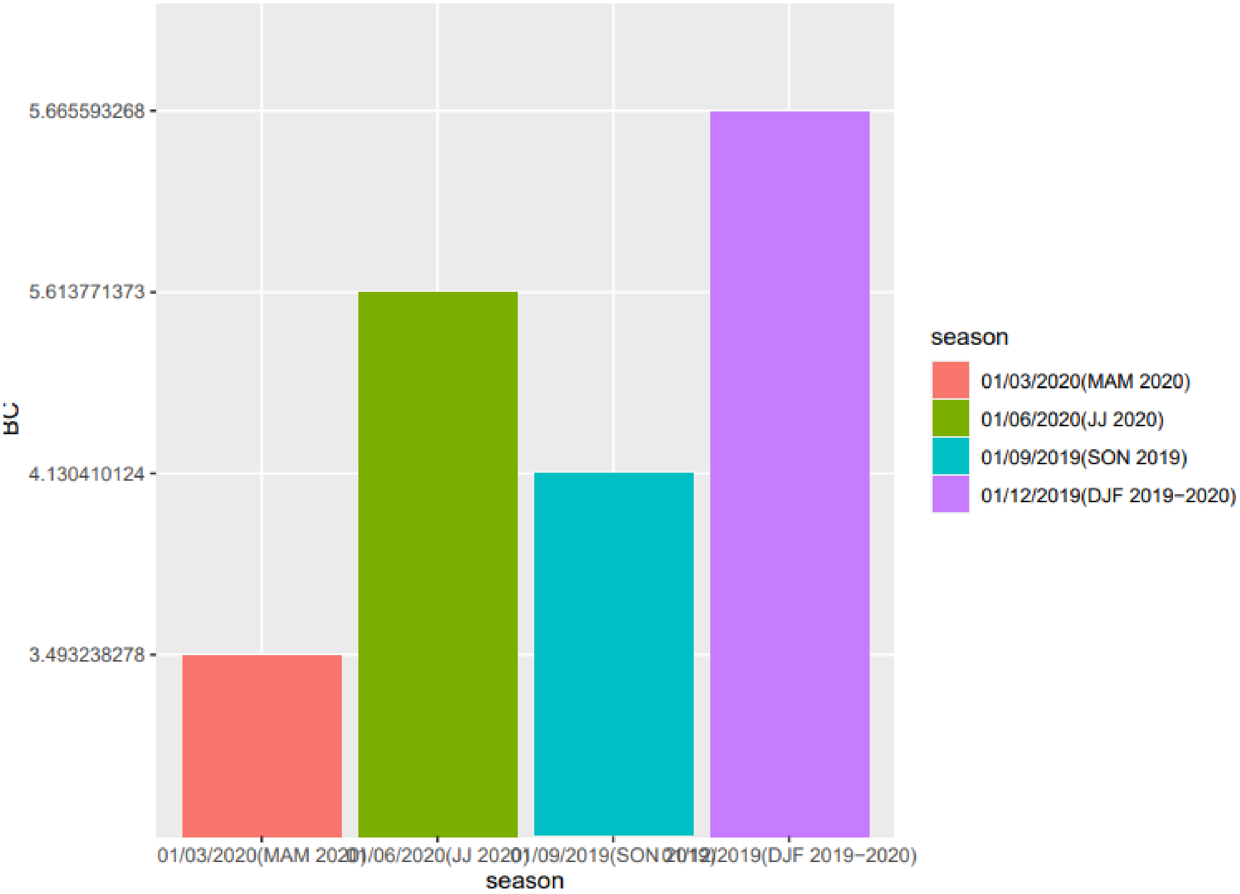


Figure 7: Seasonal comparison of BC concentration over Kigali for the year 2019-2020.

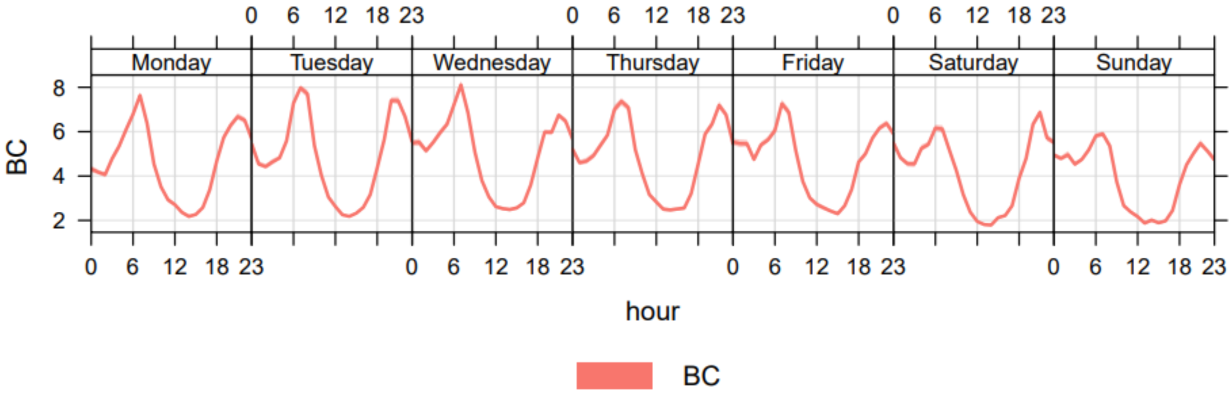


Figure 8: Days of the week's hourly variations in BC concentration in Kigali.

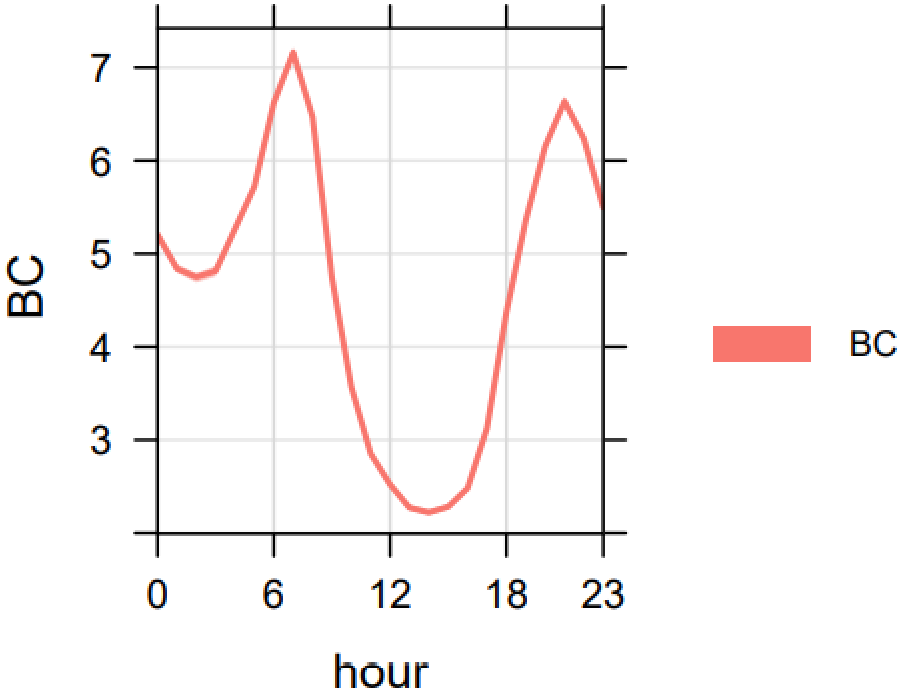


Figure 9: Hours of the day variations in BC concentrations in Kigali.

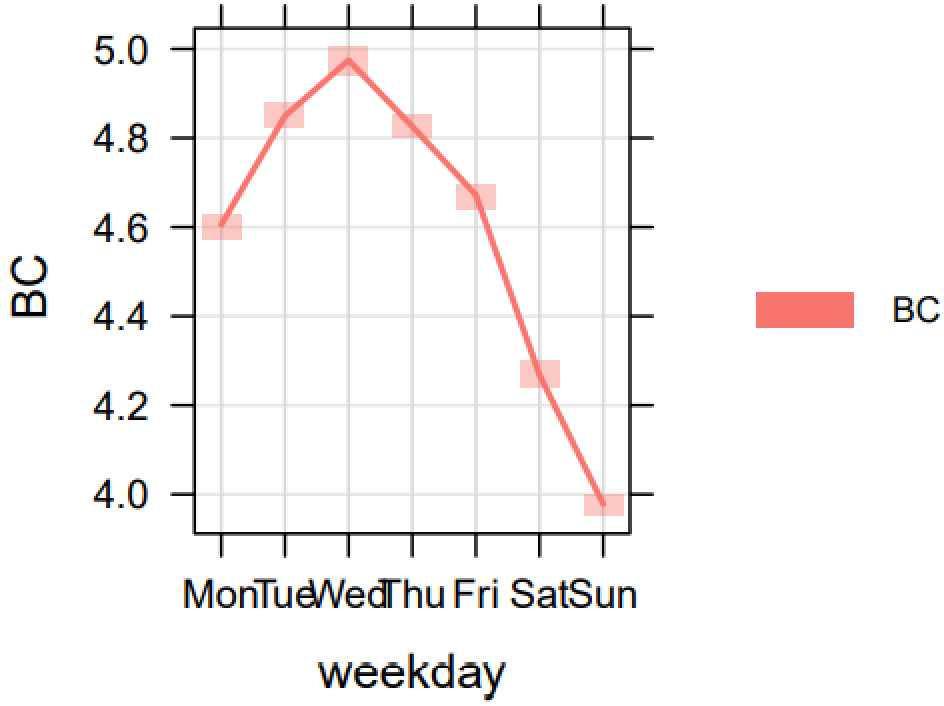


Figure 10: Weekday/weekend variation of mean BC concentration in Kigali.

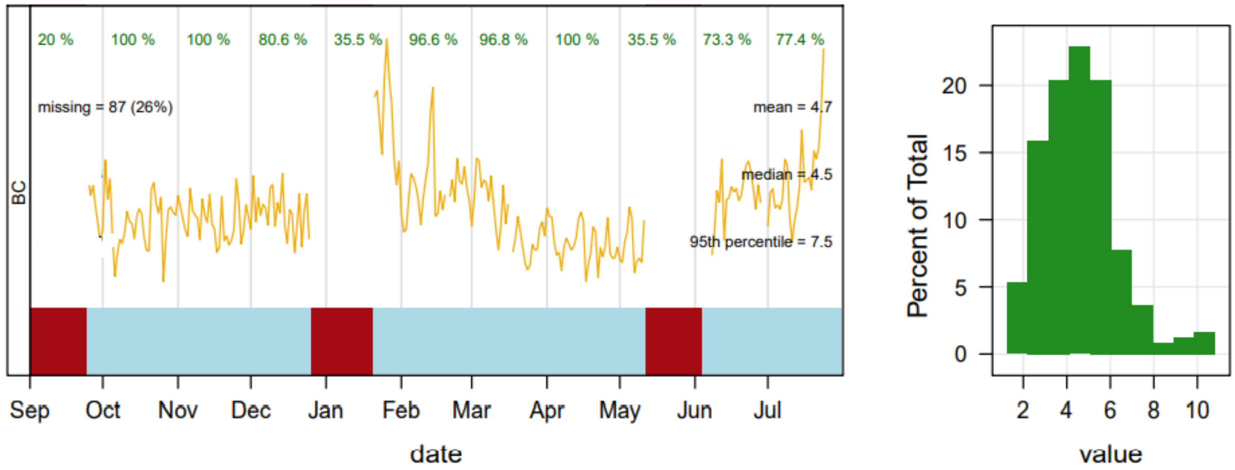


Figure 11: BC Summary plot over KIGALI and BC density distribution over Kigali.

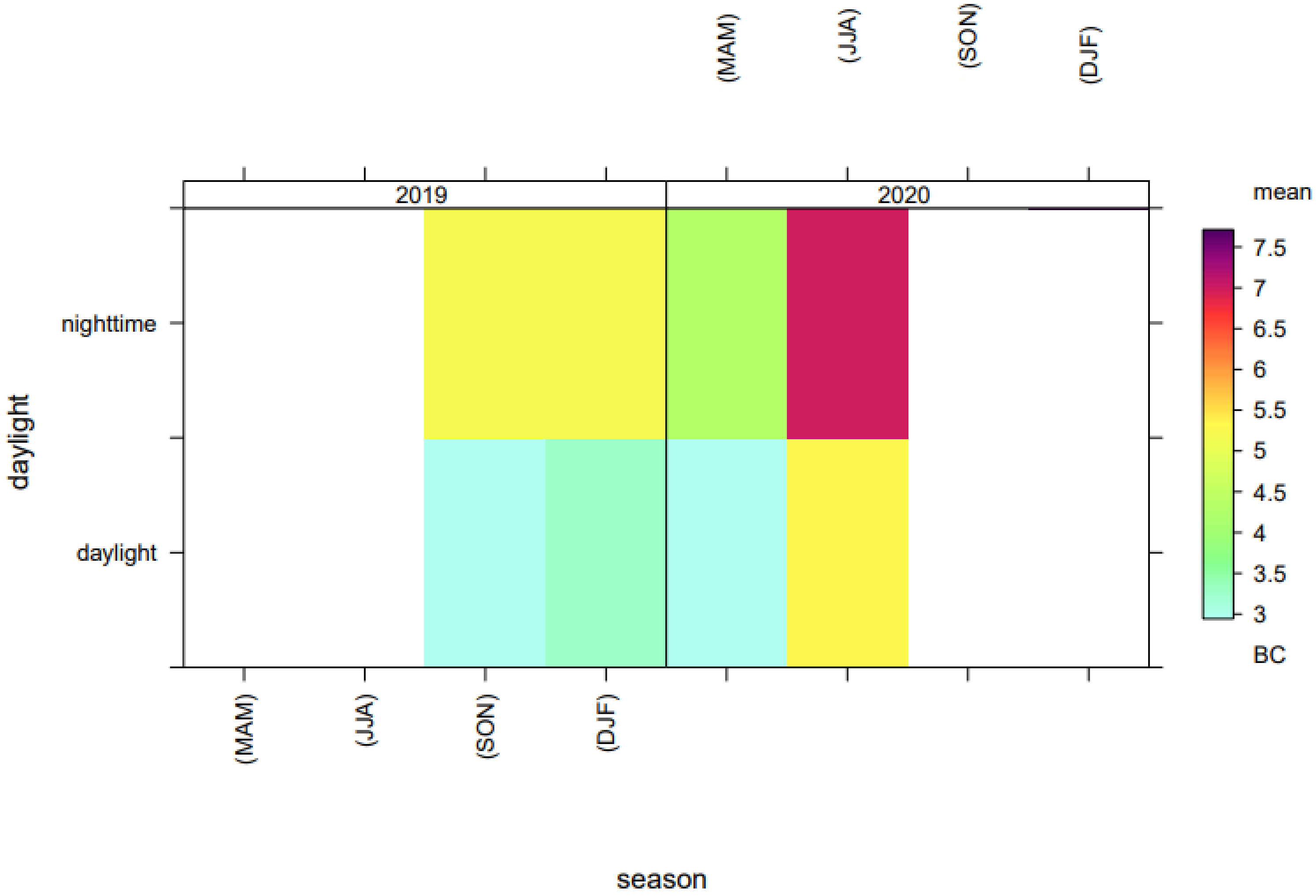
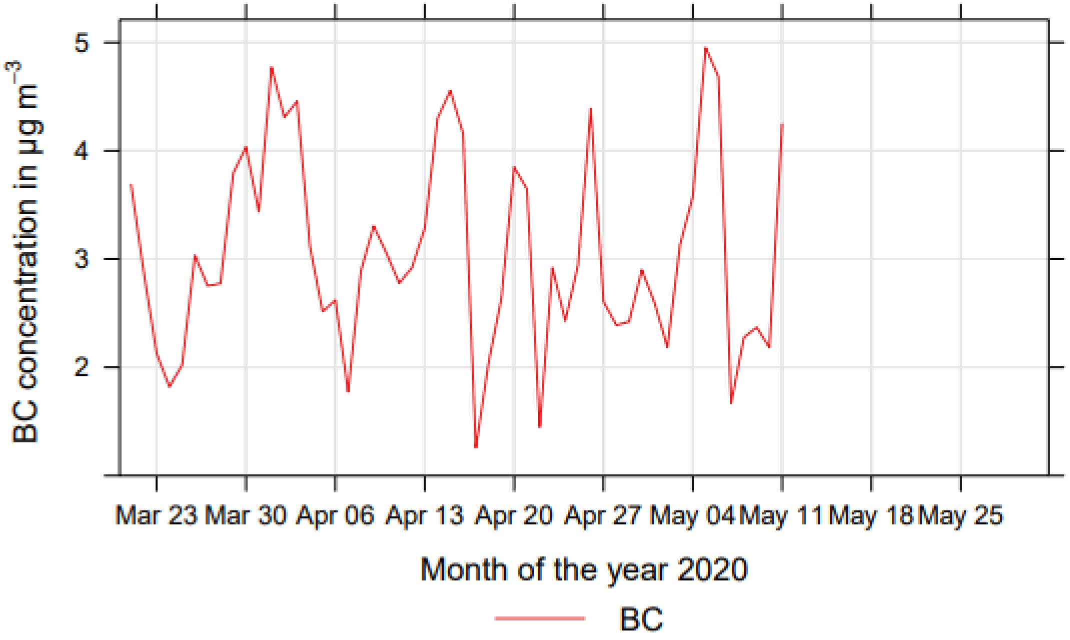


Figure 12: Nighttime and daylight trend level across all seasons in Kigali.



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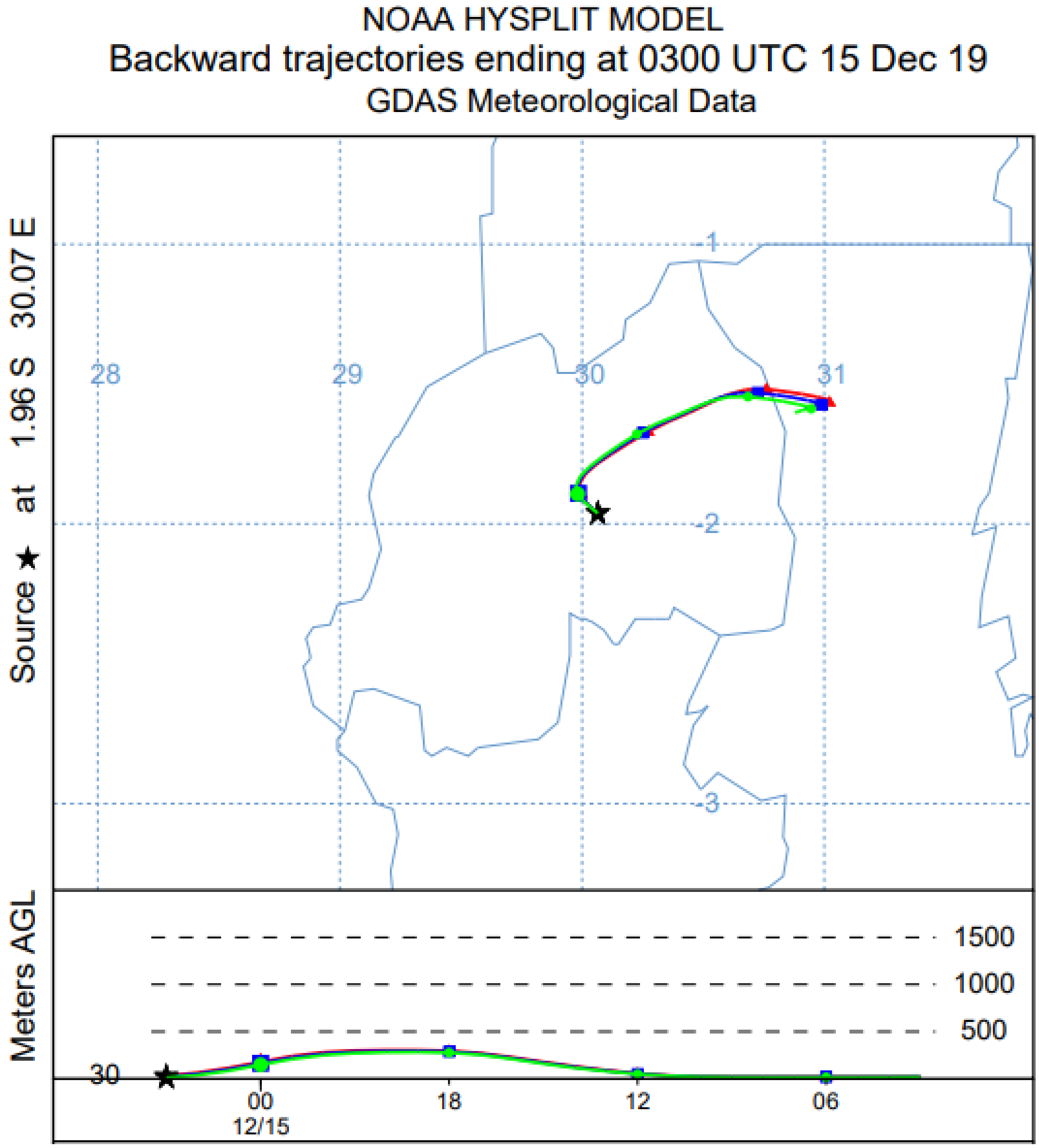

Figure 14: Hysplit Backward trajectories ending at 03h00 at UR-CST on 15 Dec 2019 and from 10 m,20m and 30m AGL, generated from NOAA website.

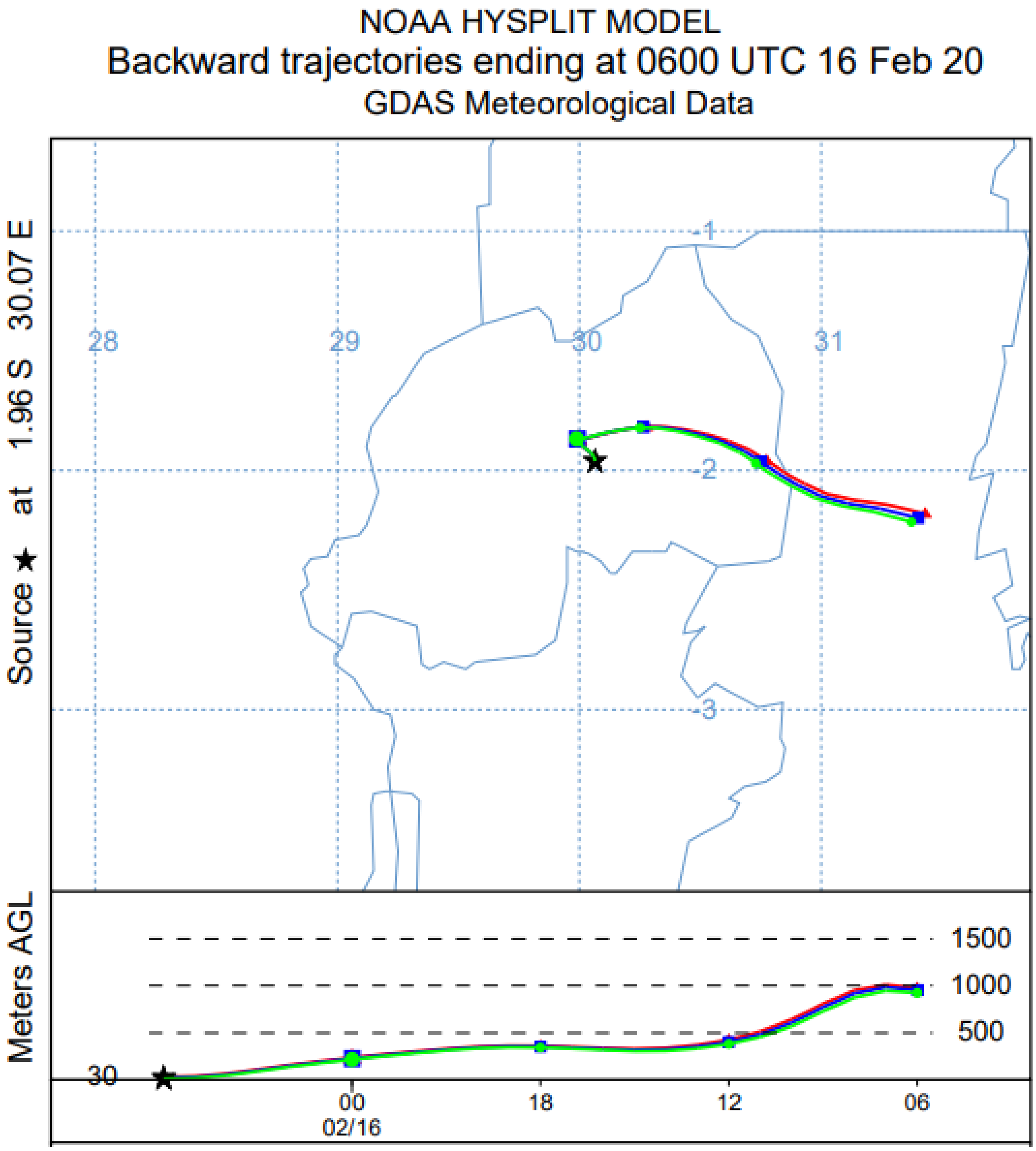

Figure 15: Hysplit Backward trajectories ending at 06h00 at UR-CST on 16 Feb 2020 and from 10 m,20m and 30m AGL, generated from NOAA website.

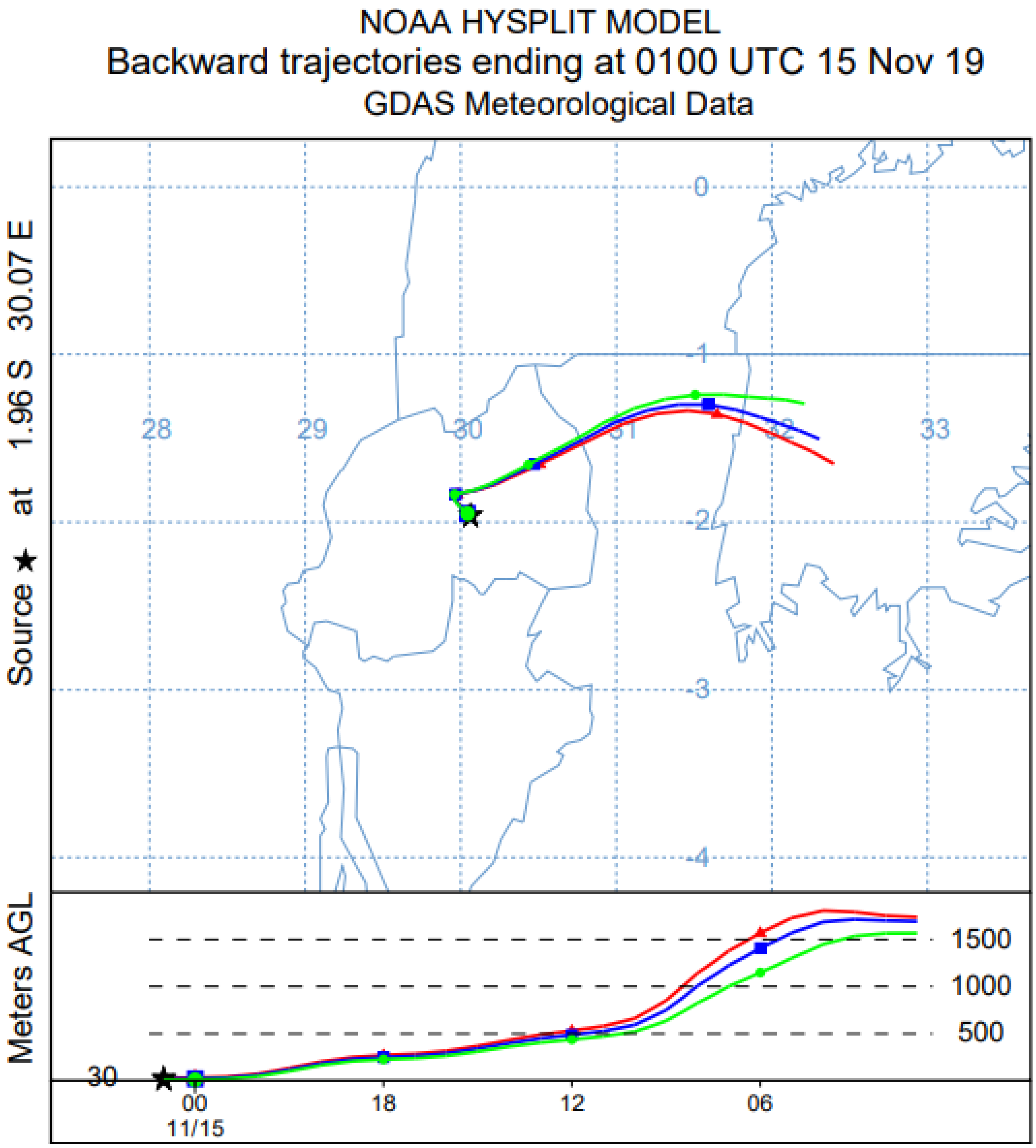

Figure 16: Hysplit Backward trajectories ending at 01h00 at UR-CST on 15 Nov 2019 and from 10 m,20m and 30m AGL, generated from NOAA website.

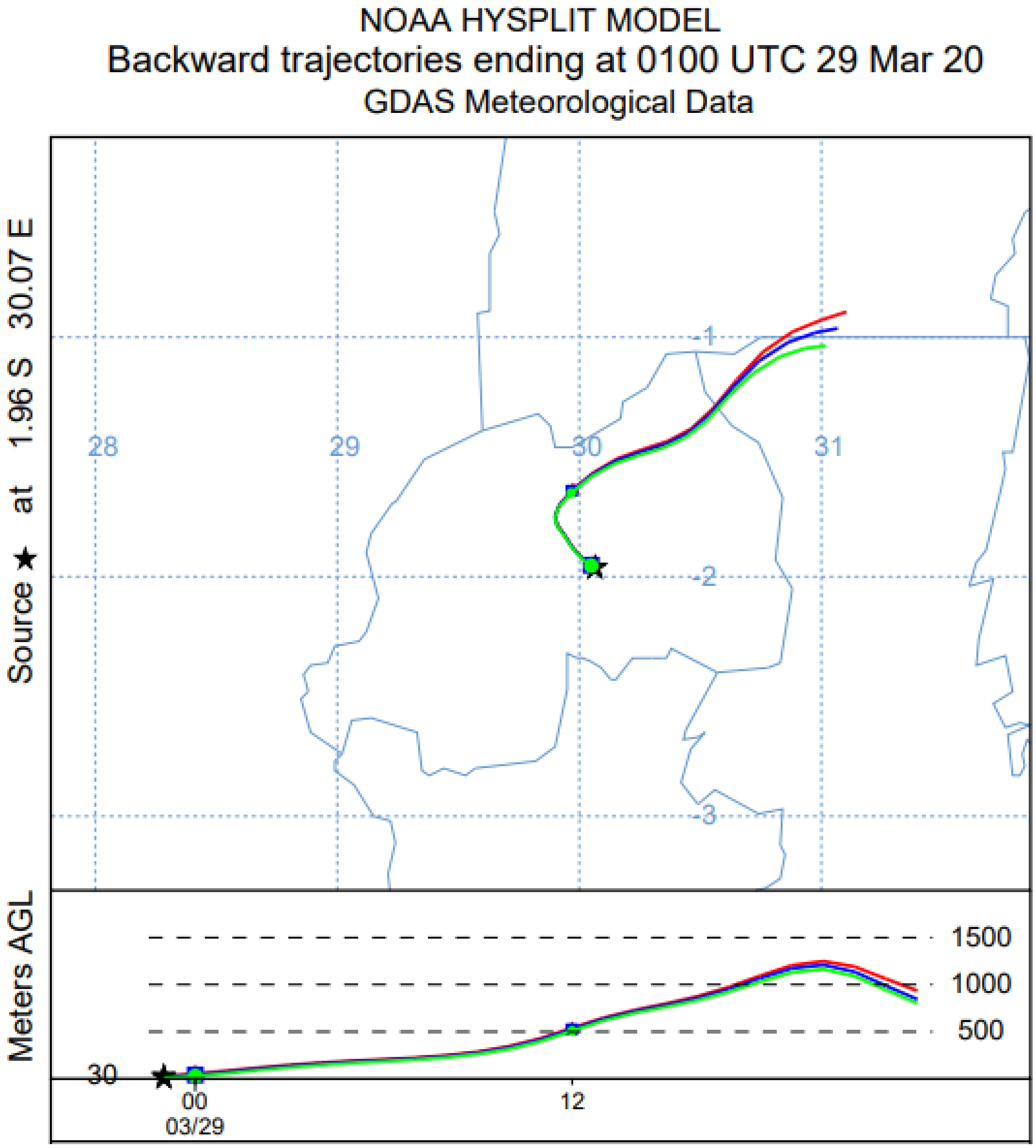

Figure 17: Hysplit Backward trajectories ending at 01h00 at UR-CST on 29 March 2020 and from 10 m,20m and 30m AGL, generated from NOAA website.

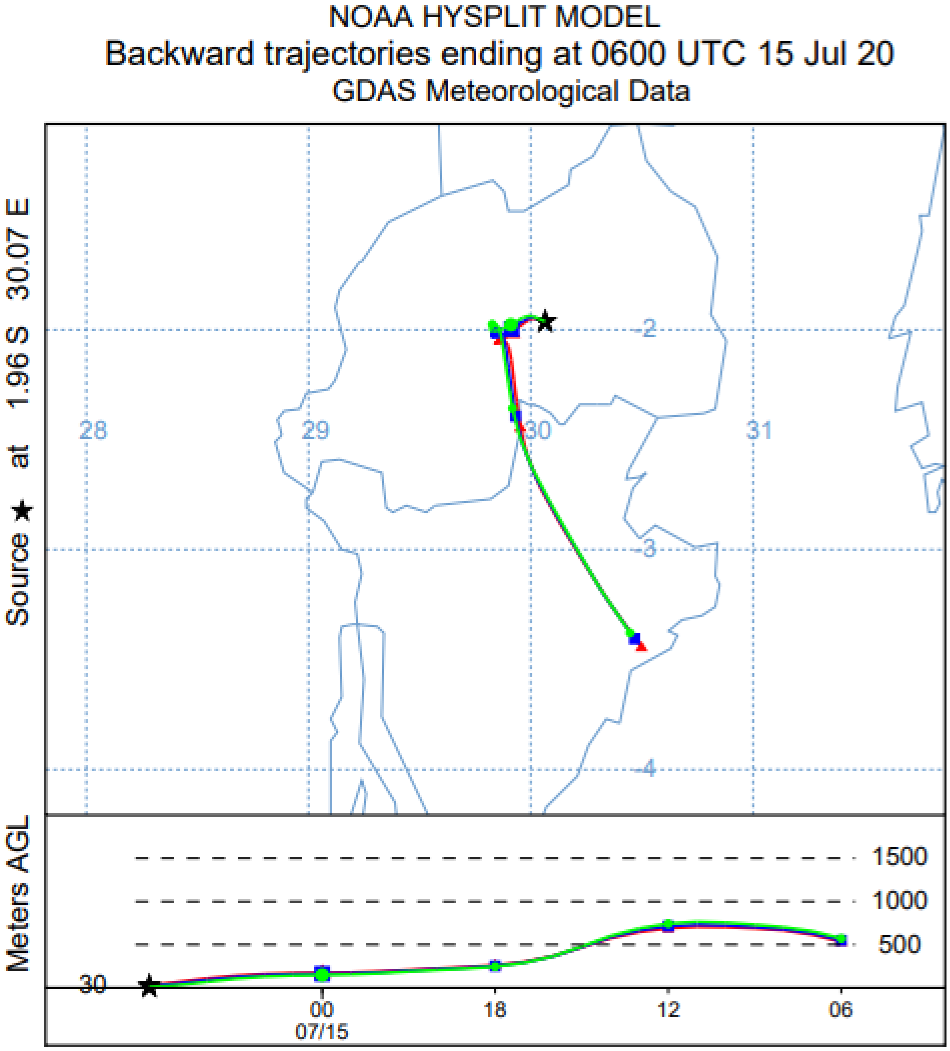

Figure 18: Hysplit Backward trajectories ending at 06h00 at UR-CST on 15 July 2020 and from 10 m,20m and 30m AGL, generated from NOAA website.

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