UNIVERSITY OF NAIROBI

IMPACTS OF AIR POLLUTION ON PEDIATRIC RESPIRATORY INFECTIONS UNDER A CHANGING CLIMATE IN MOMBASA, NAIROBI AND NAKURU CITIES

BY

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I54/31747/2019

A Dissertation Submitted in Partial Fulfillment of the Requirements for Award of The Degree of Master of Science in Climate Change of the University of Nairobi

April, 2022

DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination. Where other people's work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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ABSTRACT

As climate keeps on changing mainly due to anthropogenic causes, almost all sectors are likely to face impacts in one way or another. The health sector is more sensitive to the changing climate, which will affect those most vulnerable, more so children, especially in developing countries. Acute respiratory infections affect children partly due to their small nature and still undeveloped respiratory systems, making climate change a serious threat to their lives. Atmospheric pollutants appear to contribute much in respiratory infections, where they have an effect on spreading viruses and bacteria. This study aimed to assess the impacts of air pollution on pediatric respiratory infections under a changing climate in Mombasa, Nakuru, and Nairobi cities. The data used in this study was open-source: Air pollutants, comprising of particulate matter, sulphur dioxide, carbon monoxide and ozone; and climate data, comprising of minimum temperature and rainfall, were obtained from satellite, through the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) from 1990 to 2020. Minimum temperature was used in this study as a climate change indicator. Pediatric lower respiratory data was obtained from the Institute of Health Metrics and Evaluation (IHME) from the University of Washington, ranging from below 1 to 14 years for periods of 1990 to 2019, constituting of the number of morbidities and mortality cases for the three towns under study. The methods used in order to obtain results were: Mann-Kendall test, to check for trends in atmospheric pollutants and climate parameters, multicollinearity to test for correlation of air pollutants and climate parameters, and a multiple regression analysis to find out the relationship between pollutants and morbidities and mortalities. Results from the study pointed out that air pollutants: $PM_{2.5,}$ carbon monoxide, sulfur dioxide and tropospheric ozone were all increasing over the study period in all three cities. Minimum temperature was also found to be increasing, while precipitation increased in all cities except Mombasa where it shown a steady decline over the 30-year period. Morbidity and mortality cases showed a decrease from 2010

onwards for children below 4 years, while the numbers increased for children above 5 years. $PM_{2.5,}$ carbon monoxide, sulfur dioxide had a direct impact on morbidities and mortalities of lower pediatric respiratory infections in all towns. The rising minimum temperatures observed in Mombasa, coupled by reduced precipitation enhanced the spread of air pollutants, more so particulate matter increasing morbidity cases in the city. Nakuru was observed to have the highest precipitation rates in all three cities, which created a ‘washing effect’ for most pollutants in the air while at the same time having a ‘blanket’ effect on carbon monoxide hence higher values. Nairobi also had high levels of carbon monoxide, sulfur dioxide and black carbon for $PM_{2.5}$, which mostly came from the high number of motor vehicles. Lower pediatric respiratory infections are then expected to increase mainly due to the presence of rising particulate matter (2.5) values in the atmosphere, under which the influence of climate change will enhance its spread and dispersion in various areas, posing huge threats on the current and next generation of children. Seasonal variation of climate variables will also have an impact on lower pediatric respiratory infections, increasing and decreasing their cases annually. The study recommends the use of this information for strengthening policy making in health, transport and industrial sectors, which will enable the reduction of pollution effects on children who are the most vulnerable in the population.

DEDICATION

I would like to dedicate this work to my dad (Yusuf), my mum (Martha), my brother (Musa), my sister (Sheila) and my friends (Pascalia and Victoria).

ACKNOWLEDGEMENTS

First of all I would like to thank God for giving me the resilience to complete this dissertation in good time.

Secondly, I am very grateful for Gandhi Smarak Nidhi Fund for offering me a partial scholarship through the University of Nairobi graduate school, which assisted me in my studies this far.

My deepest gratitude to my supervisors, Prof. Nzioka J. Muthama, Dr. Bethwel Mutai and Dr. Diana Marangu, for their valuable support, suggestions and input in this study. Your input has been very helpful and I greatly acknowledge you.

Many thanks to also my classmates and colleagues from the University of Nairobi.

Lastly, much gratitude goes to my family members, for the love and support in coming up with this work. Thank you very much.

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LIST OF ABBREVIATIONS

APHA	American Public Health Association
ARI	Acute Respiratory Infection(s)
ASAL	Arid and semi-Arid Lands
ASAP	A Systems Approach to Air Pollution
AVHRR	Advanced Very High Resolution Radiometer
CDC	Centers for Disease Control and Prevention
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
DoH	Department of Health
eDEWS	Electronic Disease Early Warning System
EPA	Environmental Protection Agency
IHME	Institute of Health Metrics and Evaluation
IPCC	Intergovernmental Panel on Climate Change
KNBS	Kenya National Bureau of Statistics
LRI	Lower Respiratory Tract Infection
NCCAP	National Climate Change Adaptation Plan
NO_X	Nitrogen Oxides
$PM_{2.5}$	Particulate Matter (2.5)
RSV	Respiratory Syncytial Virus

SDG	Sustainable Development Goal
SO_2	Sulphur dioxide
UNICEF	United Nations Children Education Fund
URI	Upper Respiratory Tract Infection
VOCs	Volatile Organic Compounds
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

1.0 Introduction

This chapter contains the introduction of the study, from study background, problem statement, objectives, justification and significance.

1.1 Study Background

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as the 'change in the state of the climate that can be identified by changes in the mean or variability of its properties, extending for longer periods, due to either natural or anthropogenic changes' (IPCC, 2018).

In a special report of the IPCC (2018), it was observed that temperature had risen by 1^{o}C higher than the pre-industrial period, and that eight of the past ten years recorded the hottest years in the past decade, with main causes being fossil fuel combustion, industrialization, agriculture, land use and deforestation.

The IPCC's fourth and fifth assessment report noted that anthropogenic causes of climate change were one of the biggest social, environmental, and public health challenges the earth faced in this 21st century (IPCC, 2007; 2014). Impacts of the changing climate on health will differ globally mainly due to the underlying health differences globally, their socio-cultural distribution, economic development and their exposures to hazards which influence their capacity and ability to respond and adapt (Bennett and Friel, 2014). The most vulnerable groups to the effects of the changing climate (i.e. increased frequency of droughts, rising temperatures, et cetera) are children, affecting mostly those who come from lower socioeconomic status (UNICEF, 2008).

Several studies have been conducted across the globe to show that climate change can be directly linked to the health of people. Air pollution, driven by fossil fuels and enhanced by climate change, causes damage to the heart, lungs, and other vital organs, from adolescence to adulthood, accounting for over 7 million deaths globally (WHO, 2016).

Children are highly vulnerable to the effects of climate change as their bodies are still developing and sensitive to environmental hazards, such as heatwaves, droughts, floods, hurricanes, frost, forest fires, et cetera; and harm on them can result in life-long impacts. The Lancet (2019) warned that children born in this current age will experience a world that is four degrees warmer compared to the pre-industrial period, with the changing climate affecting their health from childhood to old age.

Children below the age of 5 years account for over 10 million deaths from diseases that can be prevented and cured, i.e. malaria, pneumonia, malnutrition, et cetera, that are highly influenced by the changing climate (WHO, 2006; Xu *et al*, 2012). The increasing atmospheric pollution levels from continued combustion of fossil fuels also threaten pediatric health, their quality of life and overall growth and development (UNICEF, 2008). Stern (2007) reported that, "climate change could cause an additional 40,000 to 160,000 children's death in South Asia and Sub-Saharan Africa under a baseline climate change scenario."

Children are highly sensitive to environmental hazards than adults, in terms of respiration, water intake, and metabolism (Pediatrics, 2004). A study by Landrigan, Sheffield and John (2010) found out that climate change increased morbidities and mortalities of respiratory diseases on children, mainly brought about by extreme weather events.

Acute Respiratory Infections (ARI) are the most common causes of morbidity and mortality in the world (Tosepu *et al*, 2020). As an effect of climate change, rising temperatures increases the dispersion of air pollutants, which aggravate these respiratory diseases through the spreading of these aerosols, affecting mostly infants and children in least developing nations who are exposed (AAFA, 2022).

Simoes *et al* (2006) found out that the proportion of mild to severe cases of Acute Respiratory Infections (ARI) varies between the developed and developing nations in children under five, with the severity of Lower Respiratory Tract Infections (LRIs) worsening in developing countries leading to higher fatality rates. Kamath *et al* (1969) identified that children under five experience an average of three to six episodes of ARIs no matter their location and economic status, with lowest rates reported during summer and highest rates reported during winter.

In a study conducted by The Lancet, LRIs were found out to be the second leading cause of death globally across all ages combined, compared to 2009 where it was third (Lancet, 2020). According to a World Health Organization study, developing countries reported an ARI incidence rate of 15 – 21% of children under five years, with greater than two-thirds of global prevalence in Africa (WHO, 2013; UNICEF, 2015).

The most common ARIs in children are pneumonia and bronchiolitis, which are the foremost causes of childhood deaths, accounting for about 2 million deaths among children below five years (Singh and Aneja, 2011). Pneumonia and bronchitis, being lower respiratory tract infections, had higher incidences during rainfall seasons in the tropics, where climate change would contribute to different mechanisms such as crowding due to floods and drought cases, contributing to an estimated 15% of all deaths below 5 years UNICEF, 2015).

Although mitigation of rising temperatures require global approaches, climate change caused by anthropogenic factors (combustion of fossil fuel and greenhouse gas emissions) is likely to lead to adverse effects on health, especially in low-income nations. Ayres *et al* (2009) observed that climate change impacts on people affected by respiratory infections will vary depending on several factors, such as: temperature increase levels, changes in air pollutants with shorter atmospheric lifetimes, risk of heatwaves, flooding and excess precipitation among other factors such as mold allergies.

Air pollution is regarded as the biggest environmental health risk worldwide, with most parts of the world recording higher levels of air pollution. People exposed to fine particles which are polluted in the atmosphere from both indoor and outdoor sources experienced respiratory and cardiovascular infections which generated diseases of the heart, respiratory illnesses, stroke and even cancer, affecting mostly low and middle income countries (WHO, 2018). Rapid urbanization coupled with increasing population and motorization in Kenya are paving way for air pollution problems, more-so in cities such as Nairobi and Mombasa (NCC, 2018).

A United Kingdom report on fine particulate matter found out that both $PM_{2.5}$ and PM_{10} caused additional hospital admissions and premature deaths for pediatric lower respiratory and cardiovascular cases, with $PM_{2.5}$ causing a 6% increase more than PM_{10} (AQEG, 2012). Particulate matter (2.5) is associated with long-range transboundary transport, which makes it travel from distances far away under favorable weather conditions contributing to the increased effect on health cases (AQEG, 2012).

In line with Sustainable Development Goal number three of: good health and well-being; and Vision 2030, the Government of Kenya is undertaking several interventions aimed at reducing child mortality and providing an efficient and high-quality health care system. However, as the changing climate poses huge threats to pediatric respiratory health, urban cities are more likely to be affected compared to rural areas due to the high chances of urban air pollution and heat waves from urban heat islands in cities (Oke, 1973). Most of these climate-sensitive diseases are borne by infants and young children, coming from developing countries with lower economic development and unsatisfactory health services (WHO, 2006).

In an economic survey report conducted by the Kenya National Bureau of Statistics, the total morbidities brought about by respiratory infections accounted for 39.3% of the total cases reported in 2018, with an increase from the previous year (KNBS, 2019). A special report on the state of global air (2020) found out that air pollution contributed to 27,700 deaths in Kenya, where 30% were associated with lower respiratory infections. This high number mainly came from children, brought about by ambient $PM_{2.5}$, household air pollution and ambient ozone which were the largest contributors to mortality, with variations brought about by seasons of the year (Health Effects Institute, 2020; Takaro *et al*, *2013*).

According to the Nairobi city county air quality action plan (2019-2023), respiratory infections are the leading illnesses of health among children, accounting for over 60% of hospital visits (NCC, 2018). The exposure of fine particles polluted from cook stoves and combustible fuels contribute to both indoor and outdoor pollution, which penetrate into the respiratory and cardiovascular systems causing diseases which affect children (NCC, 2018).

Climate change will act as an amplifier of these effects on the health and wellbeing of children across the globe, affecting most of the world's poorest and socially disadvantaged children, despite an improvement in healthcare, nutrition, and immunization (Bennett and Friel, 2014; UNICEF, 2007).

1.2 Problem Statement

Children are expected to grow healthier and live longer under a constant climate, free from the effects of anthropogenic forcing. However, as global warming continues due to human activities, temperatures keep on rising leading to extreme events which under the changing climate, cause numerous health issues on the respiratory system. Respiratory infections affect mostly children due to their lung structure which are still developing. In Kenya, the rapid urbanization and population growth enhanced by industrialization and motorization has increased air pollution with values exceeding the recommended limits by the WHO. Despite improvements in healthcare services offered by the government, the seasonal variation of respiratory diseases is not well understood. Temperature, precipitation, and humidity are thought to play an important part, where they tend to increase in tropical countries during winter months. Information and knowledge in the field of respiratory health and climate change is limited though based on substantial but informed speculation. There is very little information on pediatric respiratory infections brought about by atmospheric pollutants in the three cities under study. This study thus aimed to find out the impacts of air pollution on pediatric respiratory infections under the changing climate in Mombasa, Nairobi, and Nakuru, for children below 14 years.

1.3 Research Questions

The study sought to answer the following research questions:

i. How has air pollution changed in the study areas as a result of climate change?
ii. How has climate parameters (minimum temperature and rainfall) changed in the study areas as a result of climate change?
iii. How has this change of air pollution levels influenced the trends of pediatric respiratory infections?

1.4 Objectives of the Study

1.4.1 General Objective

The main objective of this study was to assess the impacts of air pollution on pediatric respiratory infections under the changing climate in Mombasa, Nairobi and Nakuru.

1.4.2 Specific Objectives

The specific objectives of the study were to:

i. Analyze the temporal patterns of air pollutants over Mombasa, Nairobi and Nakuru.

ii. Analyze the temporal patterns of climate parameters over Mombasa, Nairobi and Nakuru

iii. Determine the impacts of air pollutants on morbidity and mortality of pediatric respiratory infections for Nakuru, Nairobi and Mombasa cities.

1.4 Hypothesis of the study

The study considered the following hypothesis:

Null hypothesis (H_o): atmospheric pollutants do not contribute to any pediatric respiratory infections

Alternative hypothesis (H_1): the increase of air pollutants leads to increased cases of pediatric respiratory infections

1.5 Justification

Close to 88% of the disease burden directly related to climate change happens to fall on children (Philipsborn and Charn, 2018).

Watts *et al* (2018) in a review, estimated that between 2000 and 2016, outdoor productivity reduced by 5.3% globally. At the same time, there have been excess mortality peaks associated with extreme climate events such as the floods of Venezuela and mudslides of 1999, Bangladesh cyclone of 1991, and Myanmar cyclone of 2008, accounting for more than 300,000 deaths (Watts *et al*, 2018). Projections by the WHO estimate an additional 77,000 more deaths among children under 5 years as a result of natural disasters by 2030 if no strategies are put in place to mitigate the effects of such events.

Ayres *et al* (2009) further noted that respiratory infections will be affected by the changing climate through increasing morbidities and mortalities from heatwaves; and increasing the frequency of cardiovascular and respiratory from the presence of higher ground level ozone amongst other air pollutants, affecting those with existing conditions while causing occurrences and prevalence of ARIs to newer patients.

Childhood pneumonia for instance remains a significant cause of death and disability in lower and middle income countries, in as much as they have decreased in the developed world thanks to new vaccines and advanced monitoring techniques (Ebell, 2010). Gereige and Laufer (2013) found that pneumonia cases occurred throughout the year, with an increased number during colder months in temperate climates for unknown reasons, while occurring sporadically in tropical climate throughout the year.

These knowledge gaps observed on respiratory health and climate change need to be addressed through extensive research, and hope not to come too late for some situations as climate change advances (Ayres *et al,* 2009).

Additionally, through continuous measurement and assessment, model prediction can be improved so as to determine which exposures can influence respiratory health under the changing climate. Research focused on particular vulnerable groups, children in this case, should help evaluate the sensitivity and assist in identifying programs and activities that may be effective in reducing their vulnerability; taking into consideration the fact that the changing climate will likely alter the regions under risk (Ayres *et al*, 2009).

Bhore and Marimuthu (2016) notes that despite the denial of climate change by some, professionals and academia agree that it is real and a threat to the planet; further recommending for multi-sectorial efforts in addition to adaptation and resilience as defined by the Paris Climate Change Treaty.

Additionally, as climate change impacts on children cause disproportionate effects, Xu *et al* (2012) recommend strong advocacy on to exert pressure on governments and corporations in adopting mitigation strategies for climate change, and further research to help the children and families.

1.6 Significance

The relationship between climate change and health exists but needs further studies, especially on extreme events that pose additional stress and burden to health systems more so in developing nations that are already under pressure (Filho *et al*, 2018). Evidence suggests that increasing temperatures can amplify adverse effects of respiratory infections such as respiratory syncytial virus (RSV), by multiplying severe effects of bad air quality (Ayres et al, 2009).

Of the numerous studies conducted globally, few have been conducted in Africa as a continent. Adeboyejo *et al* (2012) discovered that climate change had wider implications to human health, and noted an increase in airborne and communicable diseases which affected mostly the children as they are most exposed and highly vulnerable to health hazards. They also noted that the effects are mostly felt on people from a lower socio-economic background.

The IPCC projects that climate change will adversely affect human health by: a) increasing mortality and morbidity caused by heatwaves and fires, and an increased risk in food and water-borne diseases, b) increasing undernutrition due to diminished food production, and c) increasing vector-borne diseases. This poses a risk to the future generation of children as 90% of climate-related health cases are experienced by children under 5 years in the developed and developing countries (WHO, 2018). A further challenge is the social status, where almost 20% of children across the globe live in extreme poverty (Zhang *et al*, 2007).

Despite everyone being affected, children are most vulnerable to the impacts as their bodies are growing, they have unique interactions with the world and are dependent on their caregivers (EPA, 2016). Climate change being a global challenge exposes children to allergens, extreme heat, insect-related diseases, and contaminated water mostly, which are brought about by the frequency of extreme events (EPA, 2016).

In a report by A Systems Approach to Air Pollution East Africa, Kenya is urbanizing rapidly where the population of Nairobi was estimated to have grown by 114% between 2000 and 2020, which is occurring at the expense of outdoor air quality (ASAP, 2020). With the Government of Kenya developing air quality regulations in 2014, policy implementation has been limited and fails to address air pollution issues in as much as levels remain higher despite high levels of awareness and action (ASAP, 2020).

This study can be useful in monitoring of respiratory health infections through identifying indicators, so as to adjust current and future programs in addressing preparedness for projected impacts of climate change. Furthermore, the information obtained may be useful in developing electronic disease early warning systems to improve surveillance and outbreak responses, such as the case of eDEWS in Yemen (Dureab *et al*, 2020).

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter contains literature that has been reviewed in this study. Several thematic issues pertinent to the study are the subject of the next questions.

2.1 General Overview

The Intergovernmental Panel on Climate Change (IPCC) defines air pollution as degradation of air quality with negative effects on human health or the natural or build environment due to the introduction, by natural or human activity, into the atmosphere of substances (gases, aerosols) which have a direct or indirect harmful effects (IPCC, 2018).

Air pollution is a global problem, affecting lower and middle income countries mostly, where it accounts to about 92% of deaths in these countries (Masekela and Vanker, 2020). Its impact on child health starts from before birth and progresses to adulthood causing lifelong health effects.

Atmospheric pollution comes both indoor and outdoor sources as it affecting all population groups globally. Outdoor air pollution arises from both natural and anthropogenic sources, i.e. industrial processes, fuel combustion, agriculture, wildfires, dust storms and volcanic eruptions. Indoor air pollution arises as a result of the use of polluting fuels for cooking and heating, i.e. biomass, solid and fossil fuel. Incomplete combustion combined with insufficient ventilation results in formation of particulate matter, Sulphur dioxide, carbon monoxide, nitrogen dioxide and volatile organic compounds that are often inhaled, leading to extensive damage to the respiratory and cardiovascular systems (Masekela and Vanker, 2020).

Many countries in Africa still rely on polluting fuel for indoor use despite the access to cleaner fuels, while outdoor air pollution is poorly regulated due to lack of measurements and compliance from industries.

This increases the burden of pediatric respiratory infections where it remains the leading cause of childhood mortality, were outdoor air pollution deaths have increased by 60% from 1990 to 2017 (Masekela and Vanker, 2020; UNICEF, 2019). This has been brought about by the increasing importation of second-hand motor vehicles and two-stroke engines, rising population, industrialization and consumption growth, with statistics from the UN pointing out that the population of Africa is likely to double from its 1.1 billion citizens by 2050 (UNICEF, 2019).

McMichael (2012) noted that in as much as most researchers have studied the effects of climate change on public health, little has been written specifically about climate effects on child health. Steel *et al* (2011) also concluded on similar results, relating that very few studies have described the impacts of climate changes on ARIs in children. However, almost all studies agree on climate change and variability playing a huge role in child health, more so on ARIs. Climate affects disease patterns in various ways based on factors such as geographical location, patterns of land use, population, socio-cultural status, and the characteristics of human behavior.

A study by Prel *et al* (2009) found a positive correlation between Adenovirus, influenza type A and B and respiratory syncytial virus and temperature, and between rhinovirus and relative humidity, concluding that seasonal variations of ARIs could be explained by meteorological influences. Omer *et al* (2008) in a study found out that high relative humidity led to an increase in rhinovirus cases by 39% if humidity was moved from 1 to 6%. On the other hand, drops in temperature and particulate matter are related most with ARIs by the respiratory syncytial virus (Saulo *et al*, 2014).

The American Academy of Pediatrics Committee on Environmental Health, in a 2003 report, showed that children living in developing countries suffer a double or triple disease burden, referring to exposure, morbidity, and mortality from diseases such as ARI and diarrhea as well as threats from industrialization such as asthma and allergies. It further noted that children are more vulnerable to the effects of air pollution which was enhanced by rising temperatures (AAPCEH, 2003).

Moya (2003) further explained that metabolic rates in younger children are higher than that of adults as their bodies grow faster and have larger surface area per unit weight of the body. This leads to a higher demand for oxygen than adults, where any exposure to air pollutants would have a greater effect through irritation and obstruction of airways compared to adults.

2.2 Acute Respiratory Infection

Acute Respiratory Infection is a collection of diseases caused by a heterogeneous mix of organisms that affect the human airways (Simeos *et al*, 2006). ARIs contribute between 2 and 4% of mortalities in children below 5 years, in developed countries with attribution to air pollution among other climate factors such as temperature variation and humidity (Alemayehu *et al*, 2019). In the Eastern parts of the Mediterranean, Southeast Asia and Africa, it contributes to 19 to 21% of child death (Alemayehu *et al*, 2019). Although the prevalence of ARIs is similar in both the developed and developing nations, mortality from ARI is 10 – 50 times higher in developing countries (Broor *et al*, 2007). A quarter of all children admissions due to ARIs ranging from moderate to severe respiratory infections occur in nations with higher numbers of children (Woensel, 2003).

Simoes *et al* (2007) classifies ARIs into two groups: the upper respiratory tract infections which affects the airways, i.e. the nostrils, the larynx, and the middle ear; and lower respiratory tract infection which affect the rest of the respiratory system, i.e. the trachea, bronchioles and alveoli.

2.2.1 Upper Respiratory Tract Infections

URIs are the most common infectious diseases. They include: common cold, ear infection, pharyngitis, epiglottitis, and laryngitis, of which ear infections and pharyngitis cause severe complications such as deafness and rheumatic fever (Simoes *et al*, 2006). Denny, 1995, discovered that rhinoviruses accounted for 25-30% of URIs; respiratory syncytial viruses (RSV), influenza, and adenoviruses for 25-25 percent; coronaviruses for 10% and unidentified viruses for the remaining percentage.

Thomas and Bomar (2020) noted that URIs account for an estimated 10 million outpatient appointments in a year, where adults had about two or three cases a year while pediatrics had up to eight cases annually.

2.2.1.1 Acute Pharyngitis

Acute pharyngitis, commonly referred to as 'sore throat', is caused by viruses in more than 70% of cases in young children. It causes inflammation of the pharynx, leading to scratchiness of the throat and difficulty in swallowing. It is rare in children below 5 years and more on older children, especially in countries with crowded living conditions and populations that may be predisposed to the virus causing it (Simoes *et al*, 2006). Most cases of pharyngitis arise during colder seasons, causing adults to stay at home and miss work, while children miss schooling (Luo, 2020).

2.2.1.2 Acute Ear Infection

Acute ear infection occurs with up to 30% of URIs. They are caused by allergies, colds, sinus infections, excess mucus, changes in air pressure, et cetera (Normandin, 2019). It is very common in developing countries with inadequate health care, leading to perforated eardrums and chronic ear discharge that at times leads to hearing impairment (Berman, 1995). It affects 2-6% of children in developing countries, hindering their learning process. William *et al* (2002) notes that repeated ear infections may lead to mastoiditis and other complications, which account for about 5% of all ARI deaths worldwide.

2.2.1.3 Common Cold

Common cold is a viral infection of the throat and nose caused by several viruses, which poses the greatest risks to children below 6 years, even though healthy adults are also susceptible to contracting it (Mayo Clinic, 2019). The symptoms can last from two to 14 days before it goes away. It is caused by many types of viruses including rhinoviruses, which is the most common cause leading up to 80% of all respiratory infections during peak cold seasons (Heikkinen and Jarvinen, 2003). Symptoms appear one to three days after exposure and include: running nose, sore throat, cough, congestion, sneezing, wheezing for children, et cetera (Mayo Clinic, 2019).

2.2.2 Lower Respiratory Tract Infections

Lower respiratory infections are among the leading causes of morbidities and mortalities in children globally (Seidu *et al*, 2019). Almost all LRI cases occur in developing nations, especially in South Asia and Sub-Saharan Africa (UNICEF, 2016). They are brought about by bacteria, viruses and fungal infections.

LRIs show symptoms such as coughs, accompanied by short and rapid breathing which are commonly linked to death through co-morbidities with other pediatric illnesses such as pneumonia. Other symptoms include difficulty in breathing, pain when swallowing, wheezing sounds, exhaustion, discharge from the nose, fever and production of sputum (Seidu *et al*, 2019).

Simoes *et al* (2006) identified that the most common LRIs that occurred in children were pneumonia and bronchiolitis, who's most probable cause was RSVs which were seasonal in nature. Temperature and relative humidity had an almost direct relationship with LRIs where they showed an increase or decrease in cases reported, while rainfall varied on its effect depending on each location (Baharane *et al*, 2020).

2.2.2.1 Pneumonia

Pneumonia is a form of ARI which affects the lungs. In 2017 alone, it constituted of 15 percent of mortalities on children below 5 years, affecting families all over the world, but more prevalent in Asia and Africa (WHO, 2019). Pneumonia can be caused by bacteria, viruses, and even fungi (Normandin, 2019). Viruses account for 40 – 50% of hospitalized pediatric infections in developing nations, where they are mostly caused by measles virus, influenza type A and adenoviruses (Simoes *et al*, 2006). In addition to these causes, exposure to fine particles in air that is polluted can penetrate into the respiratory system leading to diseases including pneumonia (NCC, 2018).

From various studies, the death rate in children with viral pneumonia ranges from 1 to 7.3%, bacterial pneumonia from 10 to 14%, and mixed viral and bacterial infections from 16 to 18% (John *et al*, 1991; Ghafoor *et al*, 1990). It affects mostly children and infants, and older people, with symptoms such as: coughing, fever, chest pain, sweating, wheezing sound when breathing, and headaches, et cetera (Normandin, 2019).

2.2.2.2 Bronchiolitis

Bronchiolitis is a lower respiratory infection caused by viruses that affect the bronchioles, whose work is to control airflow to and from the lungs. It appears on children under the age of

2 year mostly due to a respiratory syncytial virus (RSV), and also in adults though rare and dangerous (Macon, 2017). RSVs are the major causes of bronchiolitis worldwide accounting up to 8% of LRIs during cold seasons (Simoes, 1999). Its signs and symptoms are almost similar to pneumonia, making it difficult in differentiating between the two by health workers.

Bronchiolitis poses a huge threat to children below 3 months as their lungs and immune systems aren't fully developed (Mayo Clinic, 2021). A study by Kelly (2021) found out that there is some evidence supporting ambient air pollution and bronchiolitis, which when exposed to children over longer times can lead to incidences and even mortalities of those affected.

2.3 Climate Change and Respiratory Diseases

The National Research Council defines an infectious disease as an illness caused by a specific infectious agent that is transmitted from an infected person, animal, or reservoir to a susceptible host (NRC, 2001). These agents cause diseases that emerge due to a variety of causes including the changing climate, which places people in contact with them through increasing proximity and/or enhancing conditions favorable for their multiplication (NRC, 2001).

Climate change poses a huge threat particularly to the most vulnerable groups, i.e. children, and persons with disabilities, by increasing extreme event cases, heat waves, blizzards, droughts, and floods. Extreme heat is projected to cause increased fatalities and lead to severe droughts. Floods on the other hand increase fungi and mold growth, accelerating asthma and allergies. People living with chronic conditions such as asthma, chronic obstructive pulmonary disease (COPD), ARIs, and lung cancer are at more risk from these changes (RHA, 2017).

The 4^{th} and 5^{th} IPCC assessment reports warned that economic and industrial growth has made air quality a major problem across the world, as higher concentrations of greenhouse gases especially CO_2, have warmed the planet greatly leading to extreme cases of heat waves, forest fires, variation in temperature patterns, droughts and floods, pollution, *et cetera,* all posing great risks to respiratory health (IPCC, 2007; IPCC, 2014).

Factors such as temperature, precipitation and radiation favor the growth, survival, movement and dissemination of these disease agents and their vectors. Each of these factors has different impacts in favor of the various infections. Climate enhances disease transmission directly through replication and movement, and indirectly through ecological impacts (NRC, 2001).

Climate change impacts the health of children both directly and indirectly. Direct impacts arise from the exposures of air pollution, floods, droughts and heatwaves, which lead to cardiovascular and respiratory diseases, fever, birth defects and death; while indirect impacts arise from exposures of decreased water, food shortage, and displacement of population, causing respiratory diseases as well, reproductive complications, cancer and death (Xu *et al,* 2012).

Nyiro *et al* (2018) in a study on the rural setting along Kenya's Coastal line found out that the most frequently detected virus was rhinovirus among children. Influenza, RSV, and coronavirus showed a seasonality pattern of occurrence, where RSV was predominant during the first quarter of the year (Nyiro *et al*, 2018). Rhinovirus and adenovirus appeared throughout the year; influenza type B occurred mostly between March and August (Nyiro *et al*, 2018). A similar study conducted by Feikin *et al* (2012) showed that acute respiratory infection cases were highest in June and July, and lower between October and December.

The climate in Kenya is already changing. The IPCC AR5 presented strong evidence that in Africa, surface temperatures have increased by 0.5 – 2^{0} C within the past 100 years, with extreme climate events increasing from 1950 in frequency and intensity (IPCC, 2014). Temperature rise has been observed across Kenya in all seasons, particularly on MAM season varying with location; while rainfall patterns have also changed, with longer rain seasons becoming shorter and drier and shorter rain seasons becoming longer and wetter (NCCAP, 2018).

The impacts of changing climate on health in Kenya has led to an increase in the number of ARI cases on ASAL areas, emergence and re-emergence of Rift Valley Fever and leishmaniosis, and malnutrition; whereas higher temperatures are projected to increase heat-related morbidity and mortality in children (NCCAP, 2018).

2.3.1 Temperature

Burning fossil fuels releases carbon dioxide, methane, nitrous oxides, which builds up in the atmosphere causing the earth's temperature to rise. This extra trapped heat disrupts the environment's inter-connected systems affecting health, and increasing the frequency and intensity of extreme heat events, leading to changes in wind, moisture, and heat circulation patterns hence contributing to extreme weather events (APHA).

Compared to the pre-industrial period, anthropogenic activities are estimated to have caused around 1.0^0 C rise in global surface temperature, with a likelihood of reaching 1.5^0 C between 2030 and 2052. This global warming is much greater across numerous regions and seasons, including two to three times more in the arctic (IPCC, 2018). The years 2015, 2016, 2017, and 2018 were recorded as the warmest years on records since the preindustrial baseline, with an upward trend of the long-term mean temperatures (WMO, 2019). At the same time, respiratory tract infections have increased across all ages for children except in infants (Hardelid *et al,* 2014).

Climate-related risks on health are expected to increase with global warming of 1.5^0C and further increase with 2^0 C, affecting most populations that are disadvantaged and vulnerable including dryland regions, small islands, and developing countries (IPCC, 2018). For this temperature increase, impacts are expected on heatwaves, causing heat-related morbidity and mortality, which are amplified by urban heat islands in cities (IPCC, 2018).

Boko *et al* (2007) noted that several studies conducted in Africa project that temperature increase has been consistent, resulting in extreme droughts and flood events. This can be elaborated by the fact that increasing mean temperatures enhance evapotranspiration which affects the availability of water resources regardless of possible increases in precipitation (SEI, 2009). These increased evaporation rates alongside other factors such as population and urbanization contribute to more severe drought cases.

A WHO report on climate change and health documented that incremental temperature changes may be lethal to disease-causing pathogens or cause them to incubate and replicate. This may in turn modify the growth of disease-carrying vectors, making them adapt to temperature changes through geographical changes and seasonal patterns through evolution (WHO, 2003).

2.3.2 Precipitation

The concept of the hydrological cycle and increasing temperatures is generally well understood. Higher temperatures allow for moisture to be stored in the atmosphere, which is later released as precipitation which can lead to intense downpour or flooding (Bell *et al*, 2018).

In many regions across the world, the changing patterns of precipitation and melting of snow and ice are changing hydrological systems, affecting water quality and quantity (IPCC, 2014). Human health is sensitive to any shifts in weather and climate patterns, with direct effects due to changes in precipitation, temperature, heat waves, droughts, floods, and fires (IPCC, 2014).

Since 1950, heavy precipitation events have become more frequent, with projections of more intense individual storms in the future, although it may vary from one region to another (IPCC, 2014). Thus, extreme precipitation is likely to lead to inland flooding, affecting large numbers of people in urban areas particularly those in informal settlements including the most vulnerable in this case children and the aged. On the other hand, the rising temperatures are likely to cause a rise in sea levels and flooding along coastal regions facilitating the loss of property, life, and reduced drinking water qualities, as well as the spread of communicable respiratory diseases (IPCC, 2014).

This variability in precipitation is likely to have direct and indirect consequences of infectious diseases, where they may expand their habitat creating new breeding environments (WHO, 2003).

2.3.3 Humidity

A lot of pediatric respiratory infections are sensitive to changes in relative humidity. A study in Argentina showed that influenza and RSV positively correlated to the average monthly relative humidity on hospitalized children from acute LRIs (Viegas *et al*, 2004). Similar studies conducted in Jordan, Indonesia, Turkey, Mexico, Germany, New Zealand, and even Cameroon showed that high relative humidity led to an increase in hospitalization of children suffering from ARIs. However, a similar study in Singapore presented a negative correlation of both URIs and LRIs with relative humidity (Loh *et al*, 2011).

The effects of humidity on childhood respiratory infections are of concern as climate changes, noting that regional differences would produce different outcomes as geographical location determines weather factors (Gao *et al*, 2014).

2.3.4 Wind

Winds influence the dispersion of pollutants in the atmosphere, transporting them to other areas far from where they are emitted. Muthama *et al* (2015) in a study on coal miners in Kitui County found out that pollutants from mining activities affected the health of those who resided around emission zones, while dispersion enhanced by wind further affected those who lived along the direction which the wind carried the pollutants.

Temperature and precipitation influence the movement of air hence the movement of pollutants (UCAR, 2021). During JJA season, lower temperatures and available precipitation creates a calm environment which traps sulphur dioxide and carbon monoxide through thermal inversion, increasing their values in the atmosphere. Padmanabhamurty (1975) noted that the maximum concentration of pollutants mainly occurs under lower wind speeds and calmer conditions, whereas higher speeds improved the quality of air especially in cases of low pollution sources.

Nairobi and Mombasa were less calm compared to Nakuru during JJA season, which was over 50% calmer. Average wind speeds for Mombasa and Nairobi were higher as well, compared to those in Nakuru, which enhanced the concentration of pollutants in the atmosphere. Higher wind speeds and little calm conditions for Nairobi and Mombasa meant that air quality improved, as observed by Padmanabhamurty (1975), causing less harm from short-lived pollutants such as CO and SO_2.

A strategic environmental assessment for Olkaria and Eburru geothermal fields noted that emissions from geothermal activities in Nakuru resulted mainly to hydrogen sulphide (H_2S) emissions and other air emissions, i.e. SO_2, NO_2 and PM, from related activities. It further noted that the values measured for SO_2 were much smaller to cause any effects on health, though formation of acid rain was raised as a concern for key stakeholders. Despite getting measurements of H_2S, its impact on human health was minor in relation to human health, with challenges in monitoring certain concentration levels (KenGen, 2015).

2.4 Implications of air pollution on respiratory infections

Orru *et al* (2017) observed that climate change has two major effects on air quality, while directly and indirectly affecting human health: degrading the removal process through precipitation and dispersion, and amplifying atmospheric chemistry, affecting primary and secondary pollutants.

The Status of Global Air 2019 report ranks air pollution as the 5th leading cause of death worldwide, higher than road accident injuries or malaria (Health Effects Institute, 2019). Air pollution, both indoor and outdoor, contributes to breathing problems, chronic diseases, increased hospitalization, and premature mortality, mostly through the concentration of particulate matter which affects air quality. Air pollution results in short-term symptoms including nausea, chest pains, headaches, coughing, shortness of breath, URIs; and long-term effects of lung cancer, cardiovascular diseases, and LRIs (IAMAT, 2020).

The World Health Organization (WHO) notes that over 50% of premature deaths in children under 5 years are caused by particulate matter inhaled from indoor air pollution, translating to 3.8 million deaths (WHO, 2021). In 2014 alone, 92% of the global population lived in areas where air pollution thresholds were not met, both in cities and rural areas, where most of those affected came from low-and-middle income countries (WHO, 2021).

Household/indoor air pollution affects almost half of pneumonia mortality for children below 5 years old (WHO, 2021). Apart from pneumonia, indoor pollution contributes to chronic obstructive pulmonary disease (COPD), stroke, ischemic heart disease and lung cancer affecting mostly adults (WHO, 2021).

Outdoor air pollution affects everyone from both the developed and developing nations. There sources are beyond the control of individuals as they incorporate most important sectors of economies, i.e., industries, transport, power generation, agriculture, et cetera.

The climate and clean air coalition (2021) further noted that ozone worsens bronchitis, asthma and causes permanent damage to the lung tissue, affecting at least one million premature deaths each year. It further notes that children, the elderly and people with lung and cardiovascular diseases are at higher risks, with more effects felt on the Northern Hemisphere compared to the equatorial region.

Previous studies indicate that respiratory diseases have increased worldwide in the last decades due to urbanization and high emission levels, affecting most people living in urban areas compared to rural areas, with climatic factors enhancing air pollution (D'Amato and Cecchi, 2008).

Keats *et al* (2018) further found out that of all potential relationships of respiratory diseases in children, the mother's education, household wealth index and geographical location had a significant impact to deaths of children from LRIs in Kenya. Mortality rates were higher for women with less education and from poor backgrounds. Interestingly, Nairobi based families had higher chances of childhood deaths compared to most parts of the country, attributed to other sources such as outdoor and indoor air pollution et cetera (Keats *et al*, 2018).

The pollutants mainly considered under this study include: carbon monoxide, ozone, sulphur dioxide and particulate matter (2.5).

CHAPTER THREE

DATA AND METHODS

3.0 Introduction

This chapter consists of the study area, data types and sources, and methods used for analysis. This section explains how analysis was conducted to give results used in the study.

3.1 Study Area

Kenya as a country has a population of 47.5 million people, according to the 2019 census conducted by the Kenya National Bureau of Statistics (KNBS). Of the 47 counties within the country, this study focused on three major towns, i.e. Mombasa, Nakuru, and Nairobi.

Mombasa is a coastal town in Kenya that lies in Mombasa County at 4°03′S, 39°40′E, at an elevation of 54 meters. The region's climate is classified as tropical savanna under Köppen Classification, experiencing average temperatures of 26.1 degrees centigrade and a cumulative rainfall of about 1000 millimeters annually (Climate-data, 2021). In addition, humidity is relatively high in May, above 80%, and lowest in February, at about 71% (Climate-data, 2021). The total population as per KNBS 2019 census stands at 1.2 million people, where 47% of the population is comprised of youth, with an estimated 38.5% of the total county population under 15 years (DoH, 2018; KNBS, 2019).

Nairobi town lies in Nairobi County, at 1°17′S, 36°49′E, at an elevation of 1623 meters. It is classified a marine West Coast Climate under Köppen Climate Classification, where temperatures in winter happen to be mild and moderate in summer (Climate-data, 2021). Nairobi experiences average temperatures of close to 19 degrees centigrade, with an annual rainfall of about 700 millimeters; with relative humidity being highest in November, above 74%, and lowest in February, at about 53%. KNBS 2019 census showed that 4.7 million people live in Nairobi County, with a good number being children and youth.

Nakuru town lies in Nakuru County, at 0°18′S, 36°4′E, at an elevation of 1850 meters. It is classified as Mediterranean warm/cool summer climate under the Köppen-Geiger climate classification, with a mild, warm and temperate climate. Rainfall occurs mostly during winter, with relatively little rain in summer. Nakuru experiences rainfall of above 950 millimeters annually, with average temperatures of about 18 degrees centigrade; and relatively high humidity in November and low humidity in February (Climate-data, 2021). The 2019 national census by KNBS gave a total population of 2.16 million people for Nakuru County (KNBS, 2019; Climate-data, 2021).

3.2 Data

This study used historical secondary air pollution data, climate data and lower pediatric respiratory data from various sources ranging from 1990 to 2020. The data obtained was temporal and averaged monthly from the sources.

Climate data comprising of: minimum temperature, rainfall; and air pollution data comprising of: particulate matter ($PM_{2.5}$), Sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3); needed for this study were obtained from the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), at resolutions of 0.5^0 x 0.67^0. The data was gridded and bound in longitudes and latitudes of: Mombasa (39.375,-4, 39.375,-4), Nairobi (36.875,-1.5, 36.875,-1.5) and Nakuru (36.25,-0.5, 36.25,-0.5). MERRA-2 combines both bias and non-bias corrections from highly advanced radiometers (AVHRR) and moderate imaging spectroradiometer (MODIS) found in satellites and robotic ground-based network stations. MERRA-2 is widely used for studies as it provides diverse atmospheric data of high quality that is continuous based on spatial and temporal resolutions (Buchard *et al.,* 2017). This study simulated five major types of aerosols: black carbon (BC), sea salt (SS), dust, sulfates (SO_4) and organic carbon (OC). Particulate matter (2.5) concentrations from MERRA-2 were calculated by equation 1 below:

$$PM_{2.5} = 1.375 * SO_4 + 1.6 * OC + BC + Dust + SS \ \ldots\ldots \text{ Equation 1}$$

Equation 1 above lacks nitrate particulate matter which is mostly emitted from vehicles and industrial emissions, where it is assumed to be absorbed by NH_4 in the form of ammonium sulfate (Malm *et al.*, 1994).

Pediatric respiratory data was obtained from the Institute of Health Metrics and Evaluation (IHME) from the University of Washington, ranging from below 1 to 14 years for periods of 1990 to 2019, constituting of the number of morbidities and mortality cases for the three towns under study: Nairobi, Nakuru and Mombasa (IHME, 2020). The data was open source, grouped as: below 1, 1-4, 5-9 and 11-14 years, for all lower respiratory infections put together, accumulating to the total number required for the study. IHME obtains its data from a variety of sources, ranging from censuses to disease registries. Kenya supplies its data to IHME through the Kenya National Bureau of Statistics (KNBS), the Ministry of Health and also through the Kenya Medical Research Institute, where it then undergoes evaluation before publication (IHME, 2018).

3.2.1 Data Quality

A single mass curve was used to test the quality of climate data, where straight lines will indicated homogeneous records while curves showed heterogeneity.

This was achieved through arranging climate parameters, i.e. rainfall and minimum temperature, from 1990 to 2020 and their corresponding cumulative values. A graph of years against cumulative values of each parameter was then plotted, giving straight lines for all parameters in the three cities, showing homogeneity and consistency in the data.

3.3 Methodology

All the data used in this study was normalized before analysis to reduce redundancy and to ensure that only data which related was stored. This was considered appropriate due to the difference measures used for each parameter.

In order to achieve the first and the second specific objectives of the study, air pollutants, climate and pediatric data were analyzed using R statistical software version 4.0.3, through the Mann-Kendall test so as to detect trend patterns in the variables, as used in meteorology and hydrology (Wang *et al*, 2019). This is shown in equation 1 and 2 below.

$$S = \sum_{m=1}^{n-1} \sum_{p=m+1}^{n} sgn(x_p - x_m) \text{ ……………………… } \textit{Equation 2}$$

$$sgn(x_p - x_m) = \begin{cases} +1, if(x_p - x_m) > 0 \\ 0, if(x_p - x_m) = 0 \\ -1, if(x_p - x_m) < 0 \end{cases} \text{ …………. } \textit{Equation 3}$$

Where n is the length of the sample, x_m and x_p are from m=1, 2…, n-1, and p = m+1, …, n. if n is bigger than 8, S approximated to a normal distribution.

3.3.1 Regression analysis

The third specific objective was achieved through a multiple regression analysis, which was be performed between pediatric respiratory infections and air pollutants using Spearman correlation coefficients to give us time series plots. To ensure our model functions correctly, the study incorporated a Variance Inflation Factor (VIF) which tests the degree of multicollinearity, followed by a parametric multiple regression analysis as shown in equation 3 (Alexopoulos, 2010).

$$VIF_i = \frac{1}{1 - R_i^2} \text{ ………………………………… } \textit{Equation 4}$$

Where, R_i^2 represents the unadjusted coefficient of determination for regressing the i^{th} independent variable on the remaining ones. A VIF of 1 shows no correlation, between 1 and 5 shows moderate correlation and greater than 5 and less than 10 shows high correlation.

$$y = \beta 0 + \beta 1.x1 + \beta 2.x2 + \cdots + \beta n.xn \text{ .... } \textit{Equation 5}$$

Where n represents the number of independent variables, $\beta 0$~ βn represents the coefficients, and x1~xn the independent variable.

The degree of multicollinearity was tested between air pollutants and climatic parameters through correlation, to show which pollutant could be predicted from both rainfall and minimum temperature, across all three cities. Pollutants with weak correlation were then removed from further analysis. Pollutants with an almost exact linear relationship between them were then passed through standard multiple regression analysis, with morbidities and mortalities acting as independent variables while the pollutants themselves acted as dependent variables.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.0 Introduction

This chapter gives the results and discussions of analysis conducted on the data used for the study.

4.1 Analysis of Climatic Factors and Atmospheric Pollutants

4.1.1 Minimum Temperature

The study observed that minimum temperatures across all three cities had a bimodal structure for monthly averages, with peak seasons being March-April-May (MAM) and October-November-December (OND). Nakuru had the highest values of minimum temperature for the MAM season, while Nairobi was observed to have higher figures for OND season, as shown in *figure 1.*

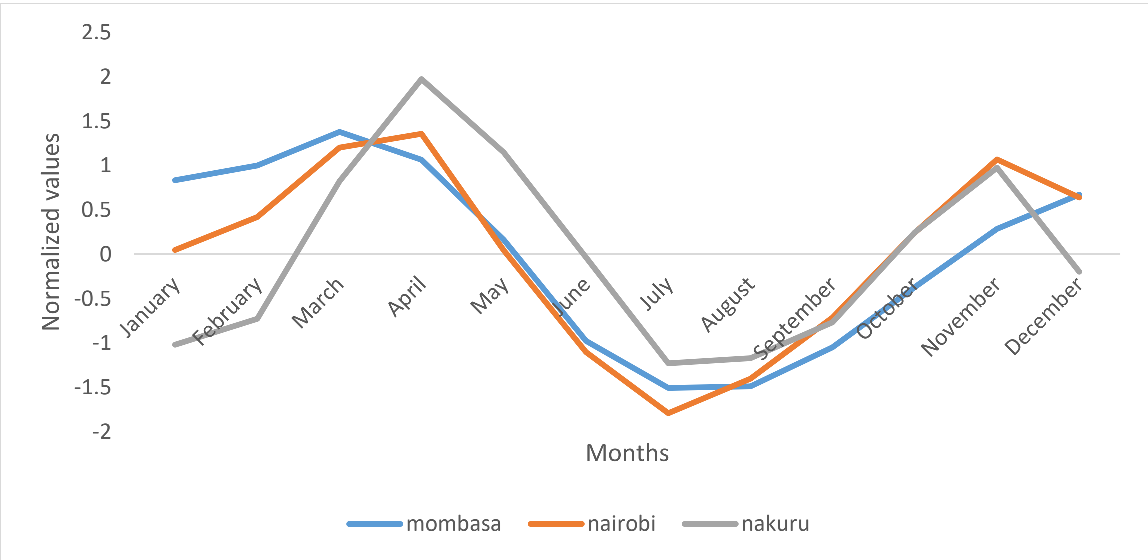


Figure 1: Average monthly minimum temperatures

Within the 30-year study period, minimum temperature, as shown in *figure 2,* was observed to have increased by 7.4% for Mombasa, 9.5% in Nairobi and 8.3% in Nakuru.

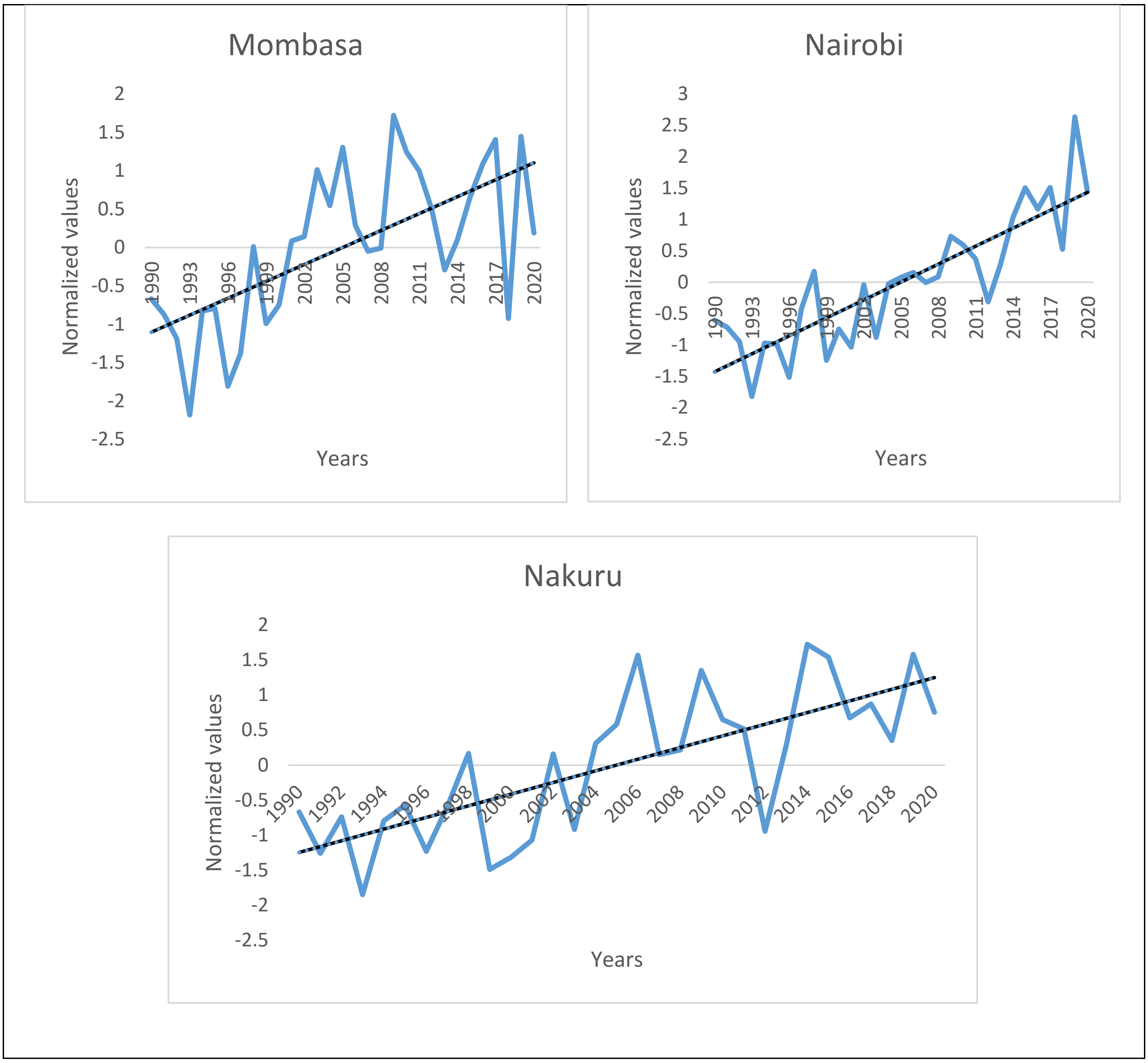


Figure 2: Annual minimum temperatures

4.1.2 Rainfall

The study found out a bimodal pattern for rainfall across the three cities, with high values observed during MAM and OND rainfall seasons. During the MAM rainy season, Nairobi and Nakuru showed higher peaks in April, while Mombasa peaked in May; in the OND season, Nairobi peaked highest in November, followed by Nakuru and Mombasa respectively, as shown in *figure 3.*

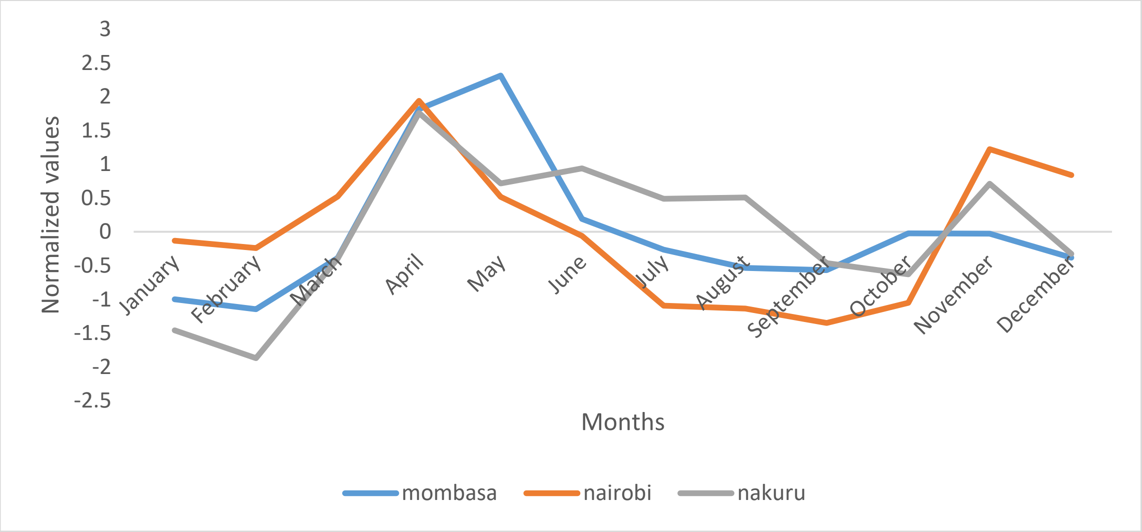


Figure 3: Average monthly rainfall

Rainfall was observed to have increased across the study period by 7.7% in Nairobi and 9.3% in Nakuru, while Mombasa showed a decreased amount by 2.8%, as seen in *figure 4.*

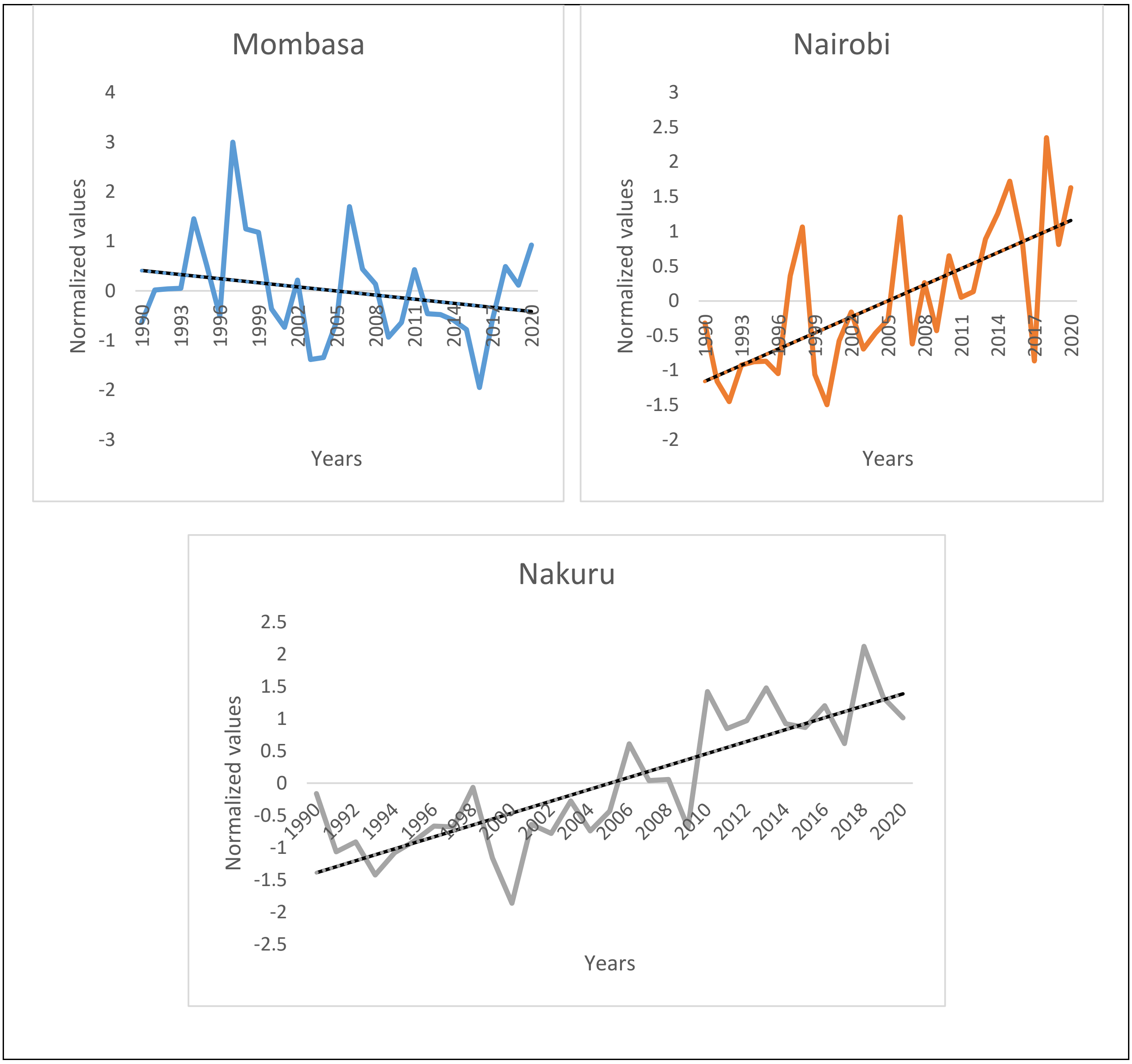


Figure 4: Annual rainfall patterns

4.1.3 Particulate Matter 2.5 ($PM_{2.5}$)

Over the 30-year study period, it was observed that $PM_{2.5}$ pollutants have been rising in all three cities, with Mombasa leading at 9.4% increase since 1990, followed by Nairobi at 7.8%, and Nakuru at 6.3%, as seen in *figure 5*. This is attributed to particulate matter components which all show an increase, i.e. sulphur dioxide, ozone, carbon monoxide, sea salt and black carbon.

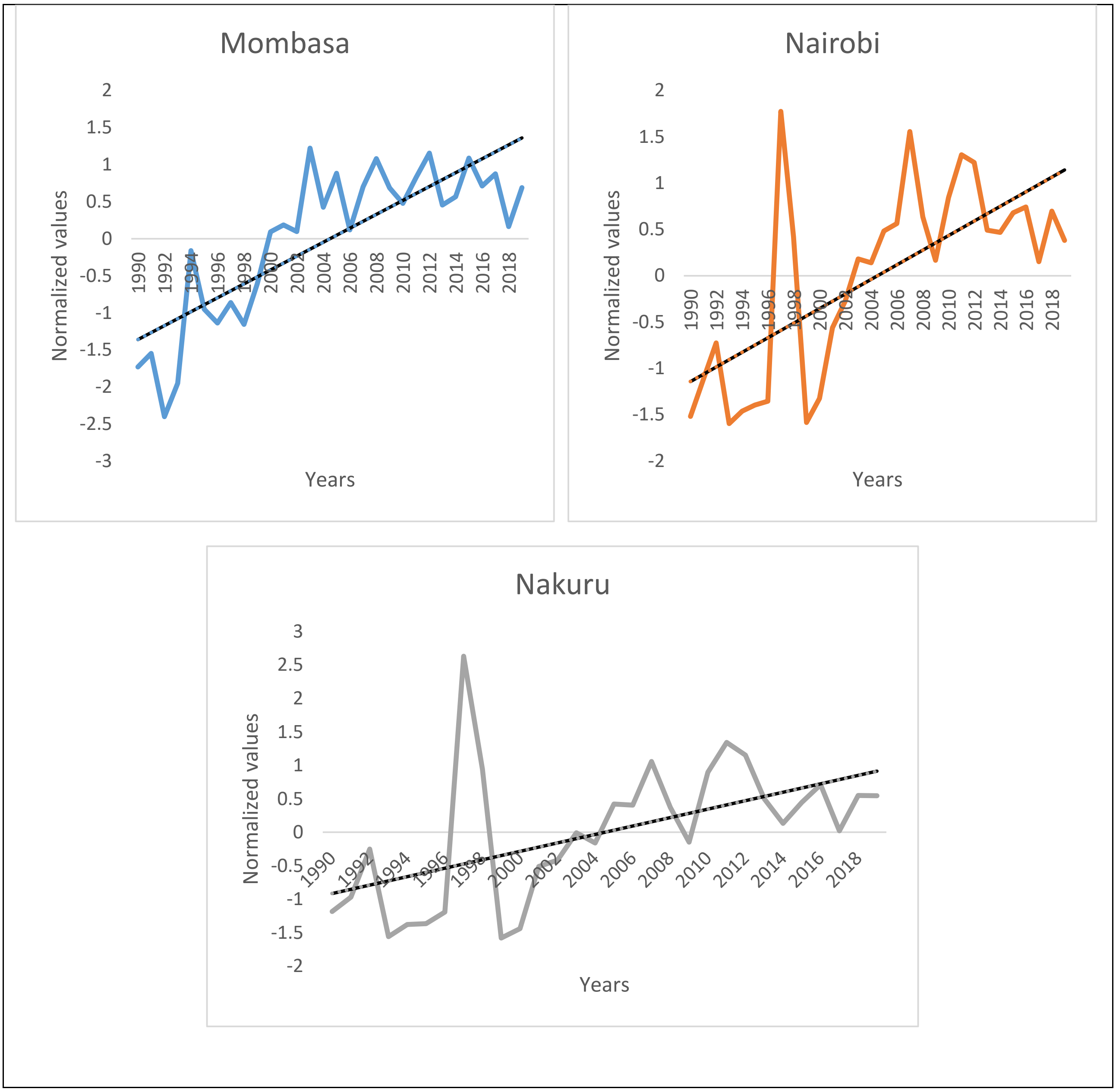


Figure 5: Annual particulate matter (2.5) values

Monthly variations of $PM_{2.5}$ was observed to have three peaks for Mombasa, i.e. January, May and December; two peaks for Nairobi in February and December; and two peaks for Nakuru, in February and July, as shown in *figure 6*. The peaks were observed mainly during periods of high minimum temperatures. Mombasa led on particulate matter (2.5) annually, with higher figures of up to 60 µg/m3 in January, followed by Nairobi with up to 25 µg/m3, and lastly Nakuru with around 15 µg/m3.

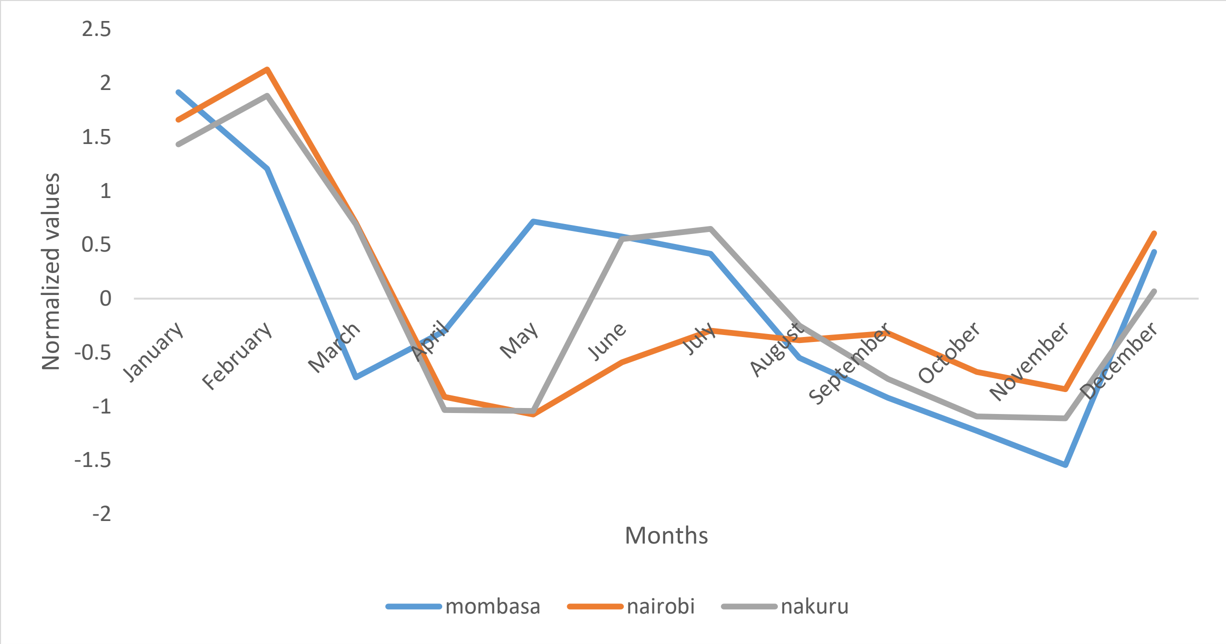


Figure 6: Average monthly particulate matter (2.5) values

MAM and OND seasons were observed to have lower values of particulate matter (2.5) in all three towns. This was due to the 'wash effect' in which rainfall during that season washes down these pollutants in the atmosphere and removes them.

The higher values in January follow short rain seasons of OND experienced throughout the country, which through the cool air it brings, carries these pollutant along with it. However, as most parts experience a cooler season, stagnant air conditions are created which are witnessed during night time, causing these pollutants to be suspended closer to their emission sources in a phenomenon known as radiative inversion (Asian Institute of Technology, 2019).

Mombasa had the highest $PM_{2.5}$ which came from the presence of sea salt, from the Indian Ocean. Nairobi and Nakuru also had small amounts of sea salt, which contributed to the number of particulate matter in the atmosphere (*figure 7)*.

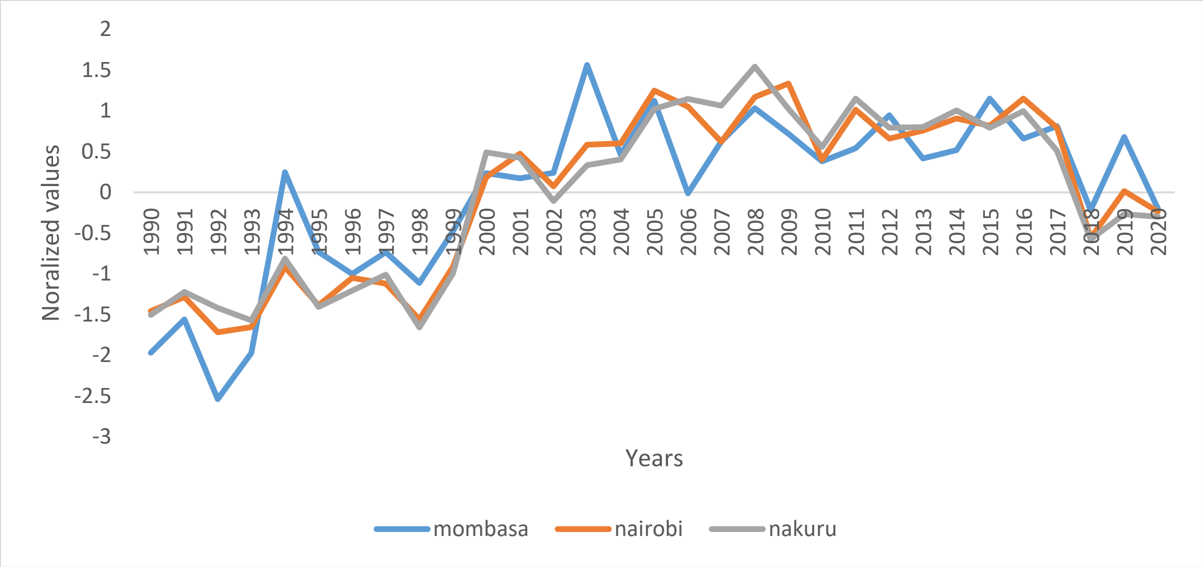


Figure 7: Average annual sea salt patterns

Sea salt came from the evaporation of the water bodies, i.e. the Indian Ocean and lake waters, in which the rising temperatures facilitated higher rates of evaporation, increasing salt aerosols in the atmosphere.

In Mombasa, the high amount of sea salt from the Indian Ocean evaporation was pushed further inland through sea breeze. Temperatures rising made the particles lighter and rise more, while the decreasing rainfall over the study period meant that the concentration of sea salt as part of $PM_{2.5}$ experienced a lessening 'washing effect' hence increasing in the atmosphere. However, as the winds blew inwards towards land, their effect was not felt at the coastal city. A study by Liu *et al* (2020) showed that the lower the precipitation, the higher the concentration of $PM_{2.5}$, where wind played a huge role in pushing the pollutants.

Black carbon is a climate forcing with a shorter lifespan in the atmosphere despite being up to 5000 times more than carbon dioxide (Bachmann, 2009). The increasing number of motor vehicles in the country, especially in the three cities means a higher value of black carbon is observed in them, with Nairobi leading, followed by Nakuru and finally Mombasa; as well as the carbonization of organic matter (*figure 8*). Cruz *et al* (2014) in a study on carbon emissions found out that organic carbon emissions were ten times higher compared to black carbon emissions.

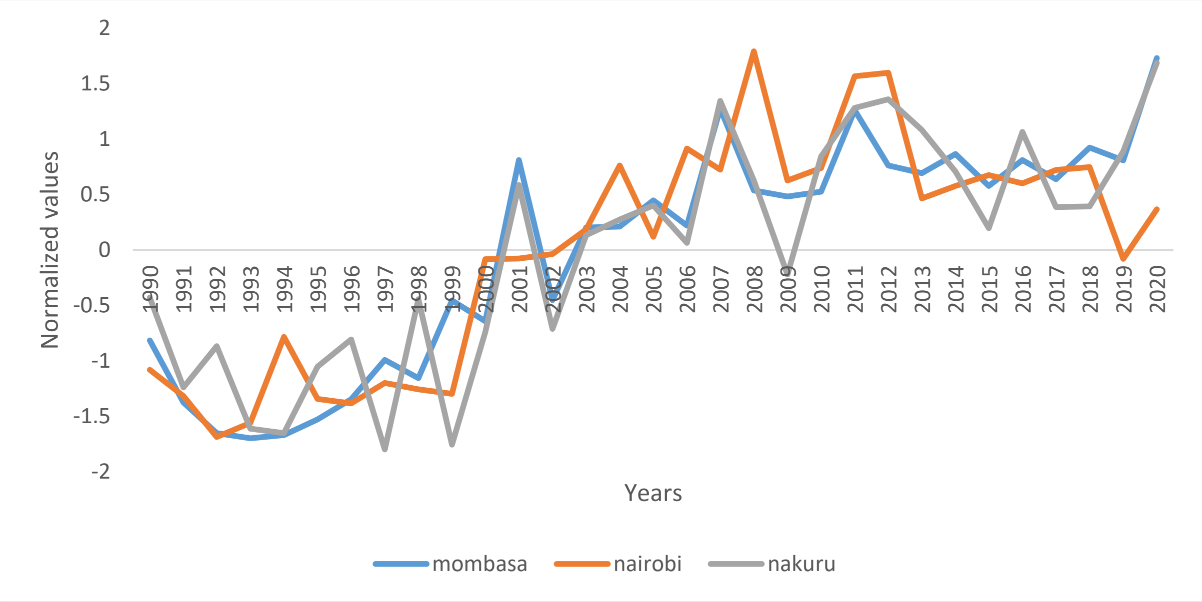


Figure 8: Average annual black carbon patterns

Organic carbon in all cities was found to be the third highest contributor of particulate matter, with sources from the soil surface and sediments where waste was deposited, including impervious surfaces. A 2019 policy by the Ministry of Environment and Forestry noted that Kenya generates an estimated 22,000 tons of waste per day, where 40% of it came from cities, with a national average of up to 70% being organic waste.

In a study by the department of agriculture and food in Australia, organic matter contains at least 58% organic carbon, while the rest generates methane gas, depending on the soil type and depth (Pluske *et al*, *2021*). This confirms the results of our study, where we found out that organic carbon was higher than black carbon in particulate matter.

The study observed higher values of black carbon in Nairobi and Nakuru towns over the study period, and rising highest from 2019 in all three towns, as shown in *figure 9*.

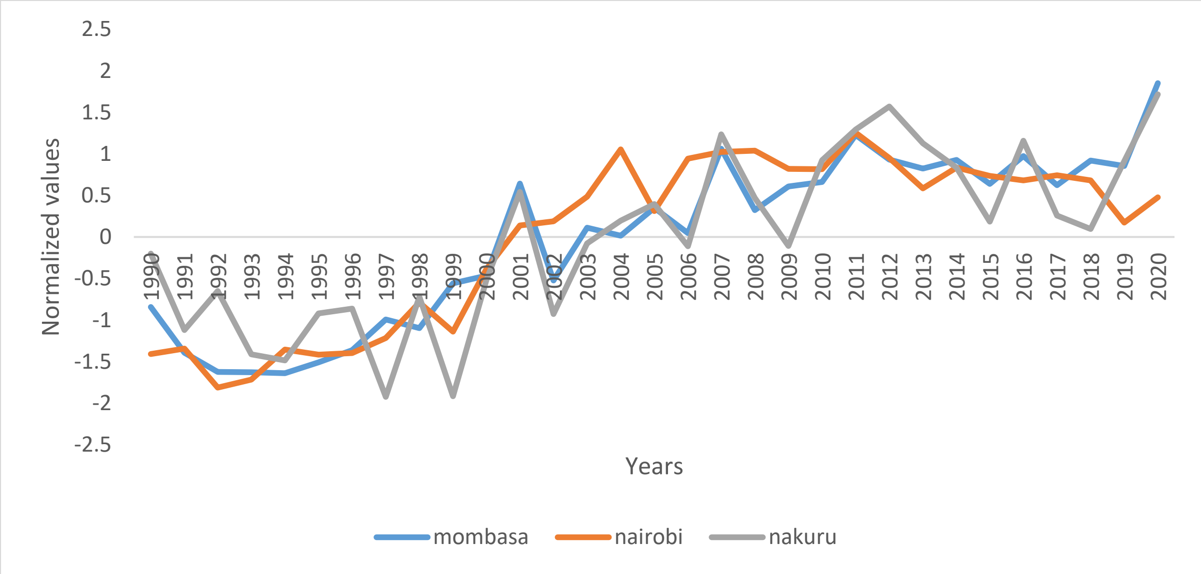


Figure 9: Average annual organic carbon patterns

Atmospheric dust was observed to be increasing in all three towns over the study period, as shown in *figure 10.* Mombasa and Nakuru showed higher values while Nairobi had the least values over the 30-year period. Dust particles were generated mainly from vehicular traffic, industrial emissions, deforestation, construction and combustion processes for man-made sources, and from spores, pollen and soil erosion for natural sources.

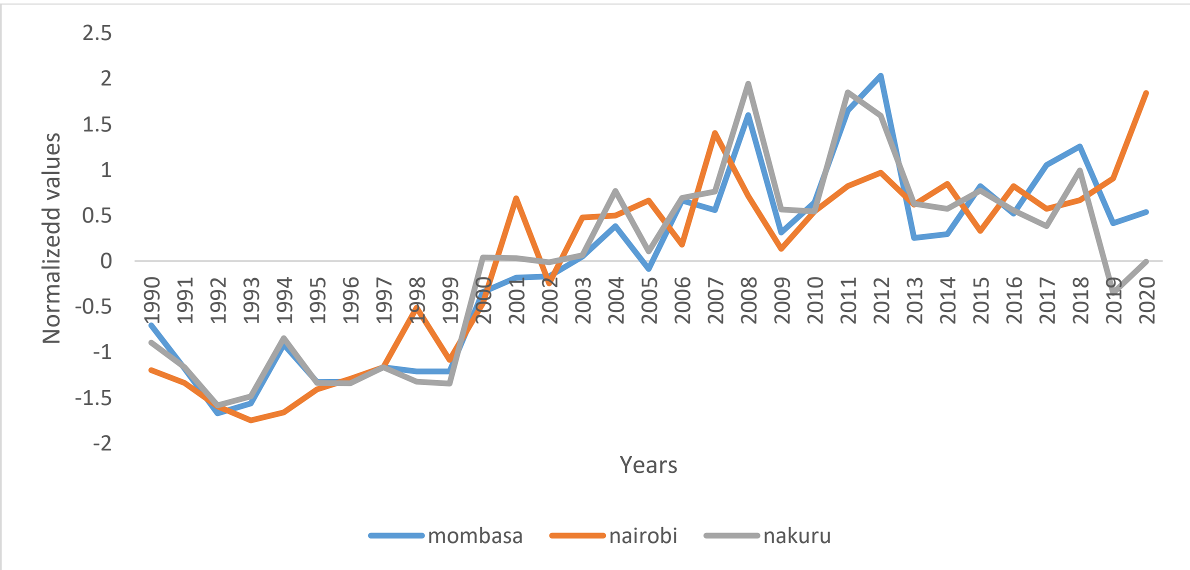


Figure 10: Average annual dust patterns

Sulfates result from fossil fuel and biomass combustion mostly. Over the study period, sulfates were observed to be increasing in all towns, peaking highest in 2011 for Nakuru town, 2018 for Mombasa and rising from 2019 for Nairobi town (*figure 11*).

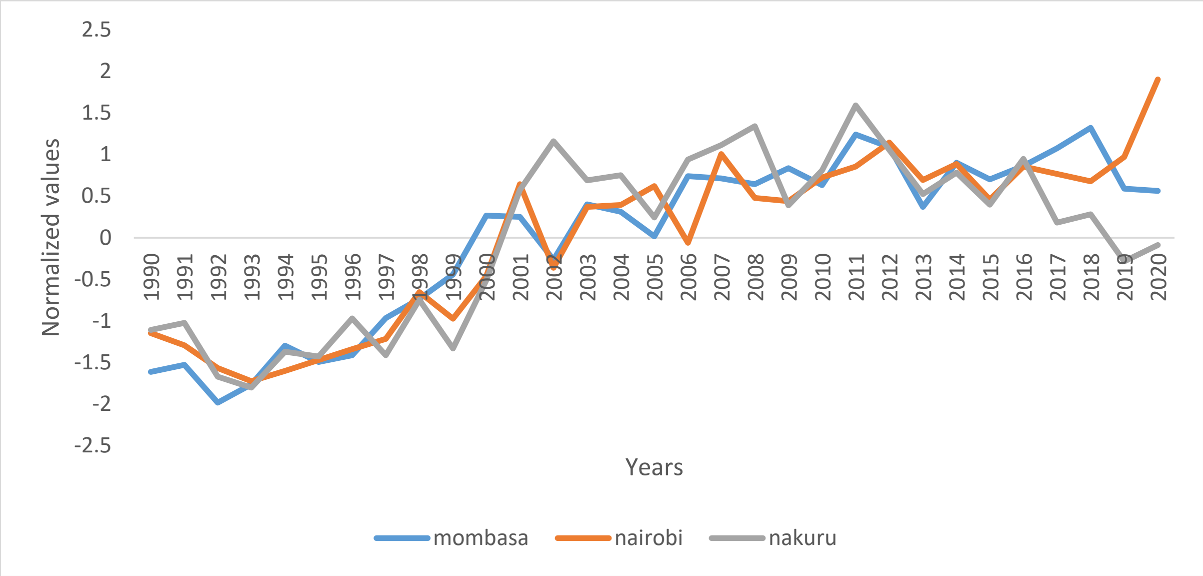


Figure 11: Average annual sulfate patterns

4.1.4 Sulfur Dioxide (SO_2)

Results from analysis of this study showed that Sulphur dioxide has been increasing in all three towns over the study period, as shown in *figure 12*. Mombasa and Nairobi SO_2 emissions increased highest by 10.4%, while Nakuru had an 8.4% increase over the 30-year period. Monthly values were observed to have a bimodal structure, peaking at the start of MAM and mid OND seasons for Mombasa; in February and August for Nakuru, and peaking only in February for Nairobi city, as shown in *figure 13*.

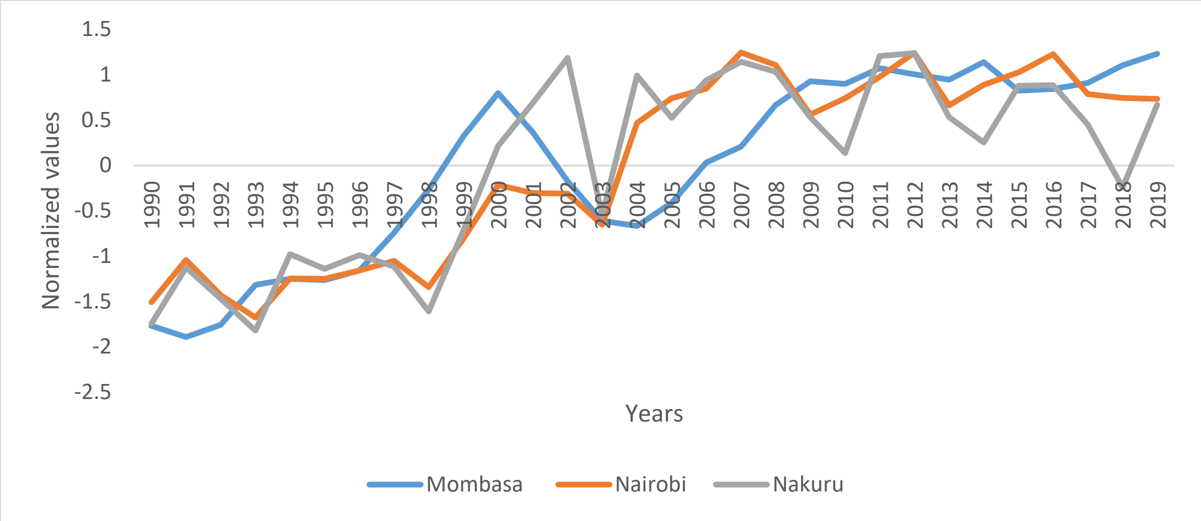


Figure 12: Average annual SO_2 patterns

In comparison to the climate factors observed, SO_2 emissions were lowest during periods of higher rainfall and minimum temperature observed on MAM and OND seasons. However, Mombasa exhibited higher values of SO_2 pollutants during OND season, as shown in *figure 13.*

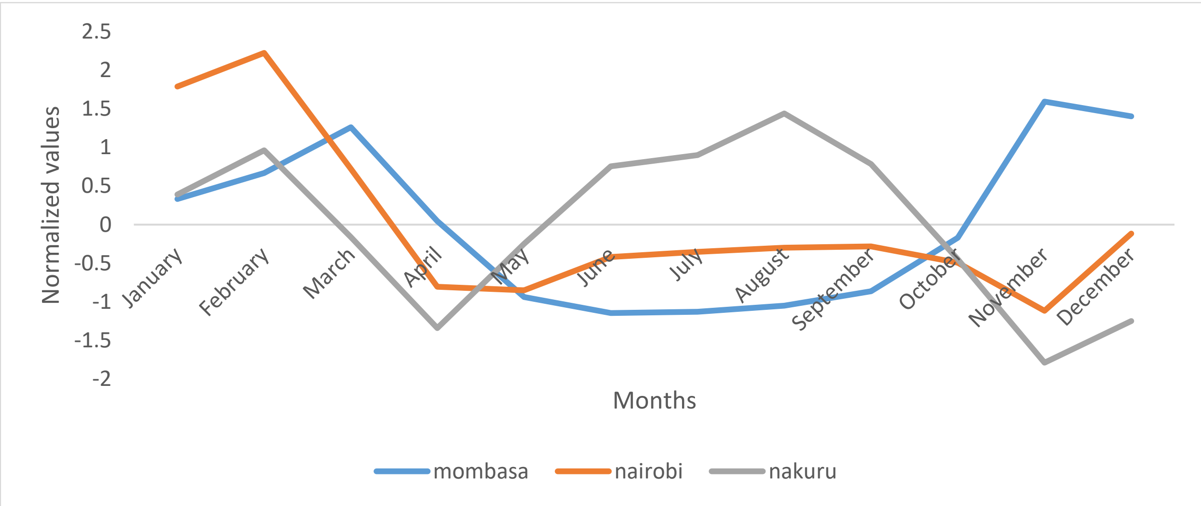


Figure 13: Monthly SO_2 patterns

Climate on the other hand plays a huge role in dispersion of sulfur dioxide in the atmosphere. The high values of SO_2 observed in Mombasa during OND season was seen to directly correlate with the higher minimum temperatures observed in *figure 1*, which increased the presence of these pollutants in the atmosphere. This meant that SO_2 aerosols in Mombasa emitted from various sources such as trains, ships, industries, power plants and many others, stayed in the atmosphere for longer periods and dispersed widely from the effect of wind and breezes in that city. Nakuru had higher values for the colder season of June-July-August (JJA) which experienced lower rainfall quantities and minimum temperature values, which meant that the concentration of SO_2 aerosols in the atmosphere stagnated, not spreading across or being washed away, with the calm conditions.

4.1.5 Carbon Monoxide (CO)

As seen in *figure 14, i*t was observed that CO was highest in Mombasa at the start of the study period until 2007 where Nairobi and Nakuru had the highest values afterwards. Mombasa had the least increment of carbon monoxide emissions over the study period, having risen by only 3.4% since 1990. Nairobi CO emissions increased highest, by 7.8% while Nakuru by 6.3% over the study period.

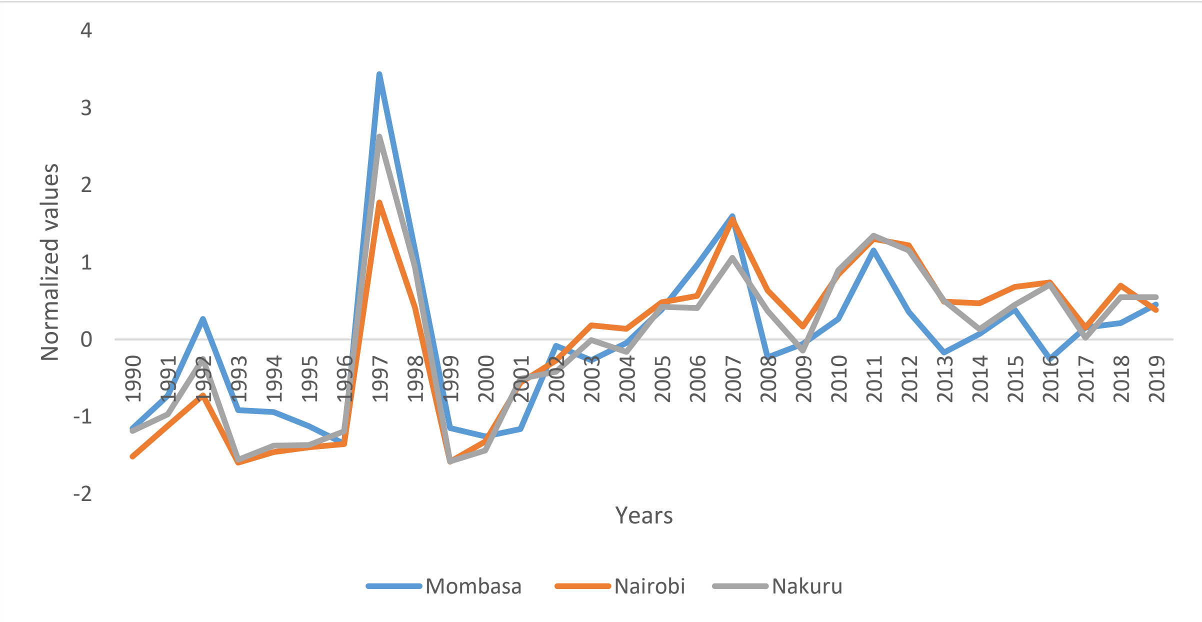


Figure 14: Average annual CO patterns

Monthly variations of carbon monoxide was seen to be reducing during MAM long rains season, and increasing all the way towards the end of the year, with high values observed between June and August for Nakuru (*figure 15*). All three towns portrayed a bimodal structure with at least two peaks in a year, recording lower values during the OND rainfall season as compared to January and February.

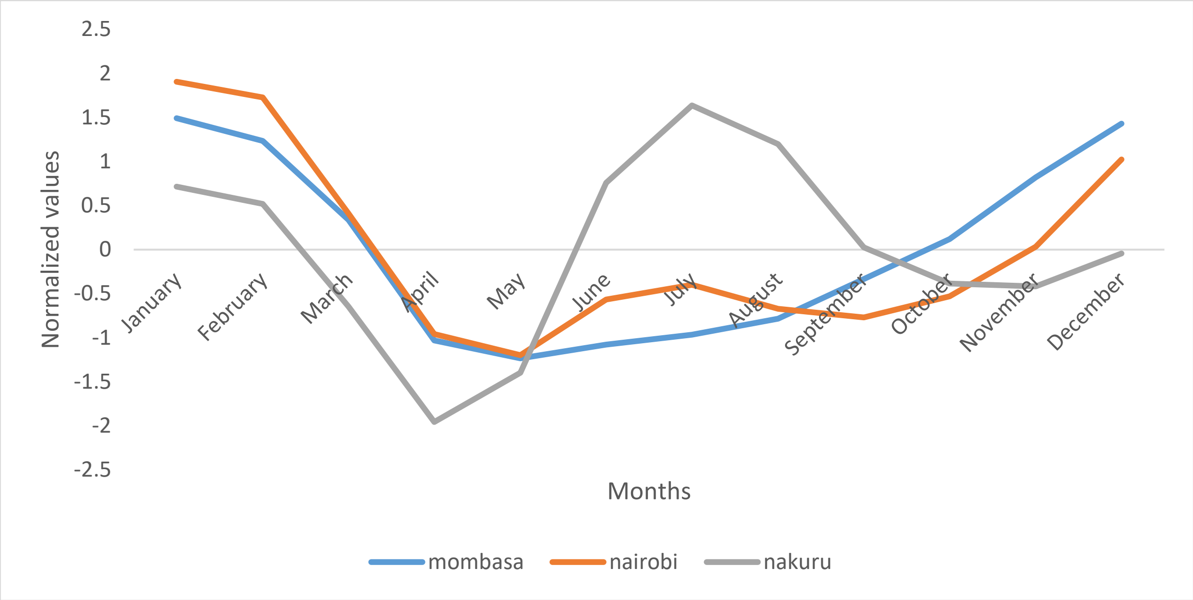


Figure 15: Monthly CO patterns

Figure 15 also observed higher peaks of carbon monoxide values during the colder JJA season for Nakuru, where we observed lower rainfall quantities and minimum temperature values in *figures 1 and 3*, hence suspension of these aerosols in the atmosphere, contributing to the large numbers witnessed. These aerosols from various sources such as motor vehicles, wood stoves, fireplaces, and many others, stayed in the atmosphere for longer periods during the colder season. Additionally, wind patterns were generally calm over Nakuru during JJA cold season, contributing to suspension of these pollutants in the atmosphere.

4.1.6 Ozone

Tropospheric ozone gas was observed to have an almost similar trend for all cities over the study period, as shown in *figure 16.* Between 1990 and 2019, ozone gas increased highest in Mombasa by 15.5%, followed by Nakuru with 12.1% and Nairobi with 10.8%.

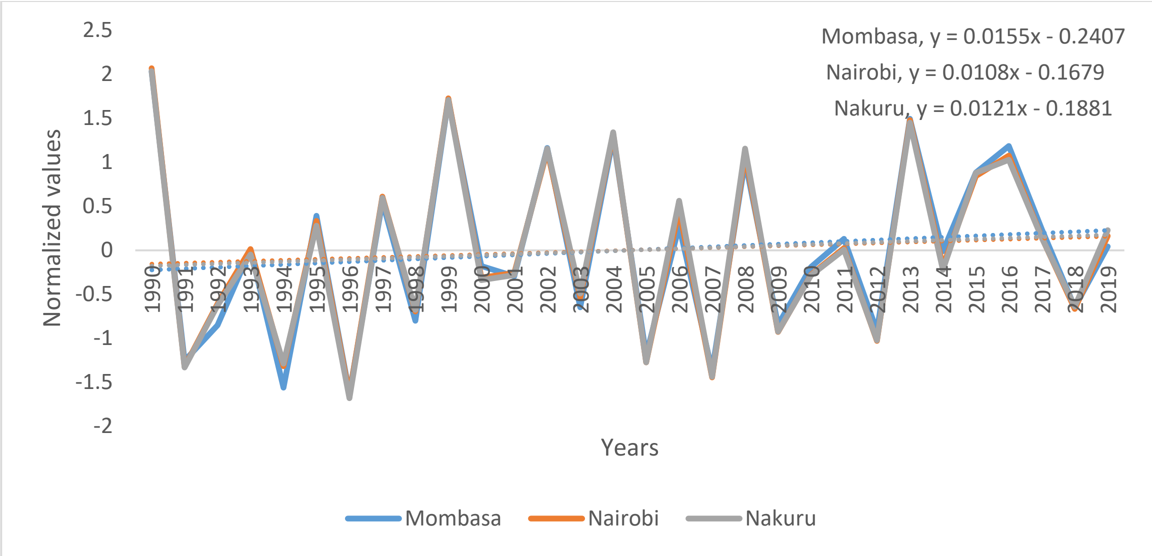


Figure 16: Average annual ozone patterns

Monthly variations over the study period was observed to have a bimodal structure, with peaks in April and September in all three cities. Nakuru had the highest peak in April while Mombasa had the highest peak in September (*figure 17)*.

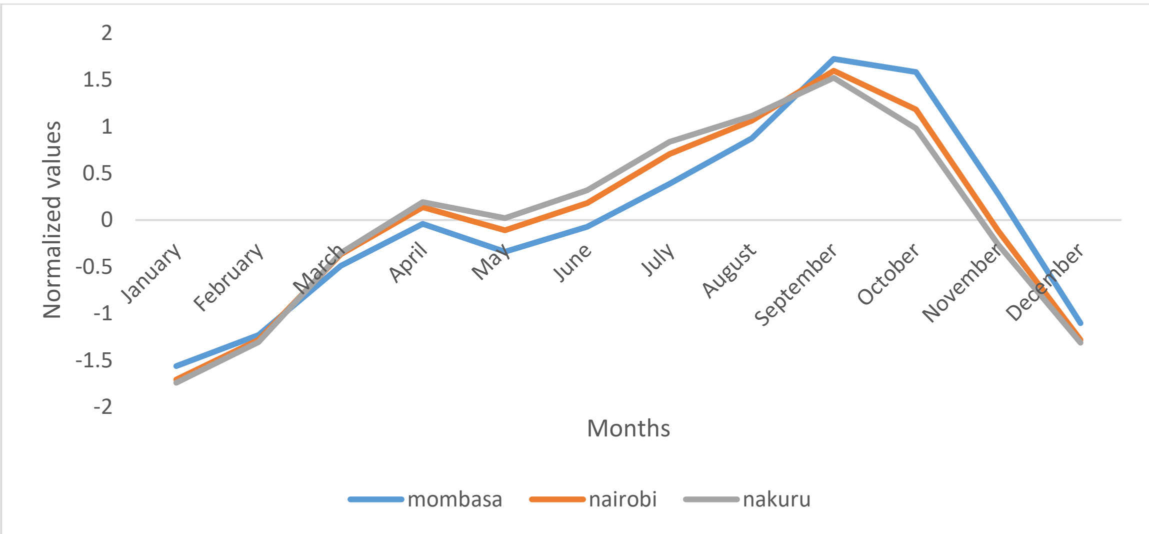


Figure 17: Monthly ozone patterns

The slightly above average ozone values observed in April came as a result of higher temperatures shown in *figure 1*. However, the presence of rainfall at that season meant that a good percentage of ozone particles in the atmosphere were washed away, not allowing for much of its presence in the air. Higher values observed in September came at a time when the weather experienced across all cities was dry, having average minimum temperatures and no rainfall witnessed. This dry weather was more conducive for the formation of ozone, having the right temperatures and emissions of nitrogen oxides and volatile organic compounds (VOC) from sources such as industrial emissions, motor vehicles, airplanes, ships and several others, facilitating its high values in the atmosphere.

Tropospheric ozone production, which occurs at the surface, is accelerated by higher temperatures which are accompanied by weak winds that cause the atmosphere to stagnate, thus building up ozone levels.

4.1.7 Relationship between atmospheric pollutants and climate factors

It was observed that even though tropospheric ozone correlated to minimum temperature and rainfall, it gave a lower degree of correlation in all cities, compared to the other pollutants which showed moderate to high degrees of correlation (*Table 1)*.

Table 1: Correlation values between atmospheric pollutants and climate factors

		Rainfall		
	PM2.5	Ozone	SO2	CO
Mombasa	-0.3515	-0.0732	-0.20479	0.470133
Nairobi	0.421756	0.21602	0.534072	0.626931
Nakuru	0.597245	0.127326	0.450118	0.614399
		Minimum temperature		
	PM2.5	Ozone	SO2	CO
Mombasa	0.773912	0.049342	0.595369	0.234001
Nairobi	0.620506	0.159715	0.721915	0.608755
Nakuru	0.598521	0.153546	0.577898	0.510547

Compared to particulate matter, sulphur dioxide and carbon monoxide which had moderate to very high relationships with the climate parameters, the three cities could not show any strong connections between ozone and these parameters. Their relationship was very weak to make any conclusive results. This was mainly due to the heavy variations of ozone aerosols over the study period which did not show enough consistency to relate with climate parameters that did not vary as much.

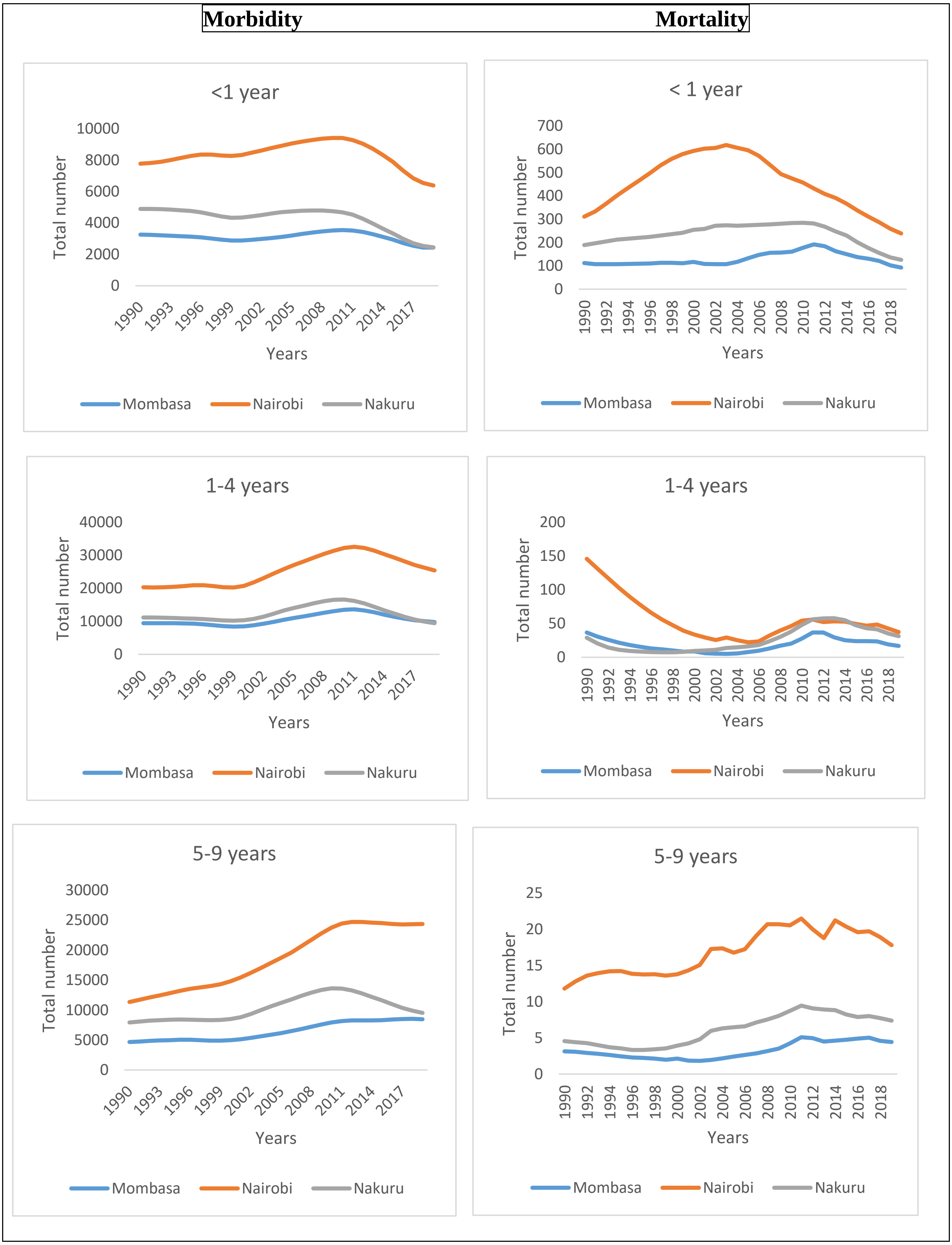
4.2 Patterns of Lower Pediatric Respiratory Infections

Figure 18 above shows the temporal patterns of morbidities and mortalities of lower respiratory infections, consisting mainly of pneumonia and bronchitis, for children ranging from below 1 to 14 years.

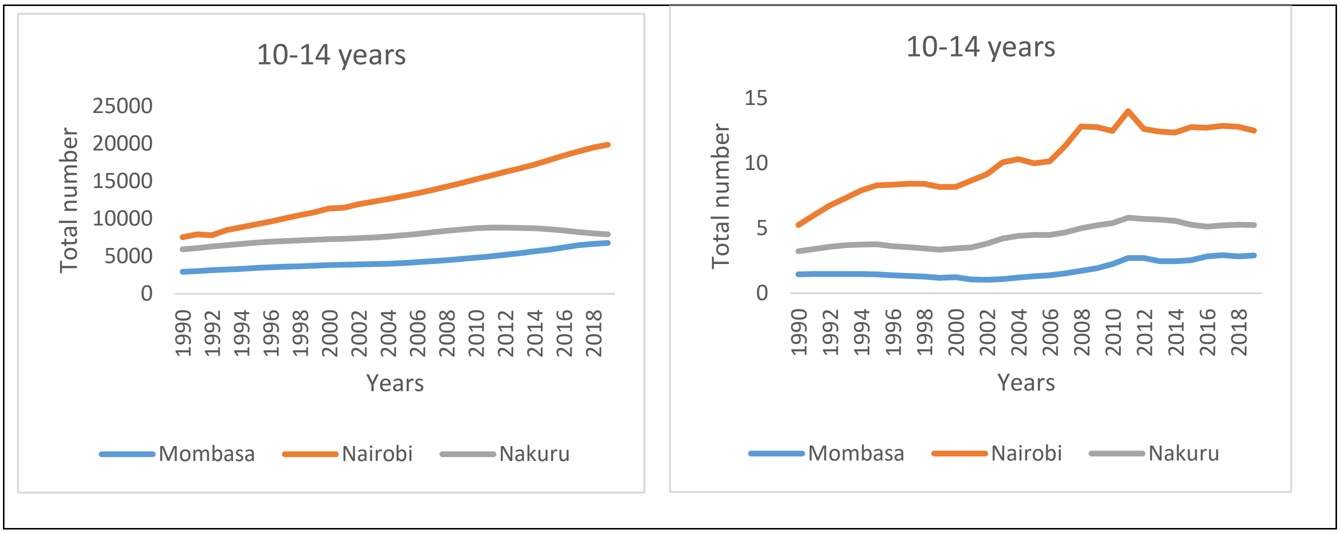
Figure 18: Morbidities (left) and Mortalities (right) of LRI's in children

For children below 1 year, and those between 1 and 4 years, it was observed that morbidities of lower respiratory infections were highest in Nairobi, followed by Nakuru and finally Mombasa. The numbers increased from 1990 to 2010, then started decreasing towards the end of the study period. This can be attributed to the fact that there was little information and support by the government on respiratory infections in children. The United Nations, through its millennium development goals and later sustainable development goals promoted awareness on health, more so to infants and young children who were affected most by lower respiratory infections, especially in lower to middle income countries. As such, awareness was created, pushing governments to coming up with programmes such as 'Malezi bora strategy' witnessed from 2002 onwards (UNDP, 2021).

From ages 5 – 14, morbidities of lower respiratory infections showed an increasing number for all genders over the study period of 30 years, with Nairobi leading followed by Nakuru and



Mombasa respectively, witnessed by the outdoor exposure of growing children eager to learn more about the world



Mortality rates for LRI cases in all children between <1 and 14 years of age was found to be highest in Nairobi, followed by Nakuru and Mombasa. A decrease for mortality was observed in children below 1 year and those between 1 and 4 years over the study period, while an increase for children between 5 to 14 years despite the numbers being smaller. This came about as a result of children of 4 years and below had a limited exposure to any contributors of respiratory diseases due to more care and concern, compared to those between 5 and 14 years, who spent most time outdoors.

In as much as exposure to the causes of lower respiratory infections in children was a key issue, other factors such as education, economic status and medical cover contributed to mortalities and morbidities as well. Families that were well off in societies had easy access to medical care and limited exposure to any underlying causes of lower respiratory infections, compared to those from not well off backgrounds.

4.3 Air pollutants and pediatric respiratory infections

As observed in *table 1*, tropospheric ozone was left out in this section due to its low correlation with climatic factors. It had a very low relationship with minimum temperatures and rainfall due to its heavy variability, thus not a strong factor in this study.

Table 2: Regression results between PM2.5, morbidities and mortalities

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.31125E-15	0.120906496	-1.1E-14	1	-0.2480796	0.24807964
morbidities	1.0595318	0.195484704	5.420024	9.87E-06	0.65843032	1.46063328
mortalities	-0.413205348	0.195484704	-2.11375	0.043918	-0.8143068	-0.0121039

Mombasa

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-5.38862E-16	0.065065099	-8.3E-15	1	-0.1335026	0.13350256
morbidities	1.032767284	0.071935906	14.35677	3.7E-14	0.885167	1.18036757
mortalities	0.325988432	0.071935906	4.531651	0.000107	0.1783881	0.47358872

Nairobi

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	7.51902E-16	0.110492852	6.8E-15	1	-0.22671261	0.226712606
morbidities	1.08970422	0.23718116	4.594396	9.06E-05	0.603048678	1.576359761
mortalities	-0.321849093	0.23718116	-1.35698	0.186026	-0.80850463	0.164806449

Nakuru

Table 2 above shows results from the multiple regression analysis conducted between $PM_{2.5}$, lower respiratory morbidities and mortalities for all three cities. It was observed that Mombasa and Nairobi had a *p-value* of <0.05 for both morbidities and mortalities, showing statistical significance; while Nakuru had a *p-value* of >0.05 for mortalities, showing a lack of statistical significance. This meant that $PM_{2.5}$ had strong influence on morbidities and mortalities in Mombasa and Nairobi, being <0.05, but no influence on the mortalities of Nakuru which had >0.05.

The coefficients of $PM_{2.5}$ against morbidities and mortalities of LRIs in children indicated the following: in Mombasa, as $PM_{2.5}$ increased, morbidities of LRIs in children increased while mortalities decreased; in Nairobi, as $PM_{2.5}$ increased over the study period, both morbidities and mortalities of LRIs in children increased; and in Nakuru, as $PM_{2.5}$ increased, morbidities of LRIs in children increased, while mortalities decreased. As $PM_{2.5}$ increased, morbidities of LRIs in children was also found to be increasing for all ages, mostly between 5-14 years, in all three cities. Nairobi had the highest effect due to black carbon from vehicles and organic carbon from waste as these children were more exposed to these particles more, especially when schools were open. During rainy seasons of MAM and OND, $PM_{2.5}$ values reduced as rainfall removed the pollutants in the atmosphere, i.e. scavenged pollutants as put by Liu *et al* (2020).

In Mombasa, the high levels of particulate matter was mainly attributed to sea salt from the ocean. The high temperatures observed within the study period creates a pressure gradient, which causes winds to transport sea salt further inland increasing the pollutants. This in turn causes LRIs in children, but in smaller numbers alongside other factors such as weather, environment, et cetera. Pressure differences from temperature variations also causes winds to increases, which enhance dust particles in the atmosphere for both cities.

Nakuru had moderate cases for both LRI morbidities and mortalities of all three cities. Particulate matter showed a direct relationship with morbidities, where as one increased, the other also increased, and brought about mainly by black carbon, organic carbon and SO_4. On the contrary, as we saw in *table 2*, the *p-value* which was >0.05 showed no statistical significance on mortality cases, meaning that other factors played a role in the decreasing numbers, which may not have been identified in this study. Paytner *et al* (2010) further noted that the changing climate would lead to more LRI morbidities in children. The increasing precipitation amounts in Nairobi and Nakuru are likely to contribute to the increase of LRI in children since the bacteria and viruses causing them survive well in higher humidity.

Table 3 below showed the results of multiple regression between carbon monoxide, morbidities and mortalities of LRI in children below 14 years. It was observed that Mombasa had a *p-value* of >0.05 for all morbidities and mortalities, showing no statistical significance, while Nairobi and Nakuru had a *p-value* of <0.05 for morbidities only indicating some statistical significance.

Table 3: Regression results between CO, morbidities and mortalities

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-9.00972E-16	0.18305193	-4.9E-15	1	-0.3755915	0.37559154
morbidities	0.286973197	0.295963025	0.969625	0.34084	-0.3202928	0.89423916

mortalities	0.027047791	0.295963025	0.091389	0.927858	-0.5802182	0.63431376

Mombasa

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.55077E-15	0.124930978	1.24E-14	1	-0.2563372	0.25633719
morbidities	0.822122395	0.13812356	5.952079	2.4E-06	0.5387163	1.10552853
mortalities	0.190476251	0.13812356	1.379028	0.179204	-0.0929299	0.47388239

Nairobi

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.15297E-15	0.164140238	1.31E-14	1	-0.33678795	0.33678795
morbidities	0.888791195	0.35233928	2.522544	0.017851	0.165850708	1.611731682
mortalities	-0.468449813	0.35233928	-1.32954	0.194794	-1.1913903	0.254490674

Nakuru

This meant that carbon monoxide had its effect only on the morbidities of lower pediatric respiratory infections in Nairobi and Nakuru cities but not Mombasa. It also did not have any effect on mortalities across all cities.

Carbon monoxide coefficients for Nairobi and Nakuru indicated that as CO increased in the atmosphere, incidence cases of lower respiratory infections increased.

Due to the high number of motor vehicles in Nairobi and Nakuru, carbon monoxide is expected to rise faster than values in Mombasa. Young children are at more risk from CO poisoning which occurs when they are exposed more to it. According to Olson and Smollin (2008), unborn babies are at the highest risk of CO poisoning as their fetal hemoglobin mixes more readily with CO than that of an adult. Additionally, as they breathe faster than adults and have higher metabolic rates, they inhale two times more air than adults, risking permanent organ damage due to the higher exposure. On the other hand, carbon monoxide deprives oxygen to the blood cells resulting to shortness of breath, especially on physical activities. These results concur with recent studies including Wang *et al* (2019), who noted that CO increased the total outpatient visits in Yichang, China.

The increasing amounts of CO in Nakuru and Nairobi can also be attributed to the climate observed as seen in *figure 3,* where rainfall was found to be highest in Nakuru and Nairobi. Increasing amounts of precipitation over a region implies that emitted carbon monoxide from vehicle emissions, industries and other sources will not only be 'washed' down, but will also disperse less compared to drier areas. Thus, Nakuru and Nairobi will also note an increase in the morbidities of pediatric respiratory infections where weather plays a role in influencing its occurrence.

A multiple regression analysis as shown in *table 4* revealed that the *p-value of* SO_2 was <0.05, which was statistically significant for morbidities of pediatric LRIs for both three cities.

Table 4: Regression results between SO2, morbidities and mortalities

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.95203E-15	0.112131486	-1.7E-14	1	-0.2300748	0.23007481
morbidities	1.051376048	0.181297045	5.79919	3.6E-06	0.67938524	1.42336686
mortalities	-0.33865189	0.181297045	-1.86794	0.07266	-0.7106427	0.03333892

Mombasa

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.48998E-15	0.062266808	-2.4E-14	1	-0.1277609	0.12776094
morbidities	0.985739311	0.068842118	14.31884	3.94E-14	0.844487	1.12699167
mortalities	0.103580071	0.068842118	1.504603	0.144035	-0.0376723	0.24483243

Nairobi

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-4.3838E-16	0.144514157	-3E-15	1	-0.29651856	0.296518557
morbidities	0.796285169	0.310210431	2.566919	0.016121	0.15978594	1.432784399
mortalities	-0.15823569	0.310210431	-0.51009	0.614132	-0.79473492	0.47826354

Nakuru

This meant that sulfur dioxide influenced only morbidities of lower pediatric respiratory infections across all cities but not mortalities.

The coefficients obtained, being positive, showed that as sulfur dioxide increased in the atmosphere, morbidities of LRIs in children increased in all cities, translating to more cases expected in hospitals within those cities. Similar results were also obtained on a Kenyan policy brief on *towards realization of vision 2030,* on air pollution within Nairobi, noting an annual increase of sulfur dioxide over a 37 year study period (Muthama, 2021).

Short term exposures to sulfur dioxide harms the respiratory system particularly of children, making breathing difficult. Additionally, the formation of sulfur oxides can contribute to acid rain, and even formation of particulate matter which penetrates deep in the lungs increasing health problems.

4.4 Discussion

Patterns of climatic factors and atmospheric pollutants

Minimum temperatures observed in all three cities was found to be increasing at different rates, with Nairobi leading followed by Nakuru and Mombasa respectively; while MAM and OND seasons had higher minimum temperature values. The National Climate Change Response Strategy (2010) also noted similar results, stating that the trends over inland areas of the country showed a steeper increase in minimum temperatures than maximum temperatures since early 1960s. The national climate change action plan (2018) observed a decrease of colder nights and increase of warmer nights in the country across all seasons since 1960, particularly during MAM long rain season, with slight variations depending on the location, agreeing with our study results.

Rainfall patterns in the country were found to be changing, with observed increment in Nairobi and Nakuru and a decrease in Mombasa city; while seasonal variations showed still higher rainfall amounts over MAM season compared to OND season. Rainfall amounts observed in the recent years are relatively lower compared to the 1960s, with trends of decreasing amounts in most parts of the country hence increasing desertification and aridity. Long rainy seasons are becoming shorter and drier while short rainy seasons become longer and wetter. However, most seasons depict the same patterns of rainfall observed, with increased frequency of droughts and heavy rainfall (Government of Kenya, 2018).

Regional climate models also suggest that the proportion extreme events of rainfall are likely to increase, while most areas of the country experience drying and rainfall reduction (Government of Kenya, 2018). As shown in this study, rainfall is found to be increasing in Nairobi and Nakuru but decreasing in Mombasa, concurring with results from regional climate models.

The increasing amount of air pollutants in the three cities poses a serious threat to respiratory health of children. Through emission sources such as transport, industries, electricity generation among others, these air pollutants are expected to keep on rising. This finding agrees to results found by the Nairobi County air quality action plan (2019-2023), which notes that rapid urbanization and increasing motorization enhances air pollution in most cities, with limitations in air quality monitoring which do not provide a favorable environment for air quality control (NCC, 2019).

Particulate matter (2.5) was found to be increasing across all three cities, with higher values in Mombasa which was mainly attributed to the high amount of sea salt present in the area. In a hypothetical case where sea salt was eliminated from the equation, Nairobi and Nakuru would have higher values of particulate matter from other contributors such as black carbon. Seasonal variations of particulate matter (2.5) however showed that these pollutants decreased during rainfall seasons of MAM and OND. Liu *et al* (2020) and Zhou *et al* (2019) in separate studies pointed out that precipitation mainly enhances the removal of aerosol particles of sizes $<1\mu m$ and 2.5-10 μm, agreeing to the results obtained in this study. Hong *et al* (2019) in another study found out that rising temperatures led to an increase in evaporation, which increased precipitation amounts that washed air pollutants in the atmosphere; while extreme climate events increased greatly $PM_{2.5}$ values.

The State of Global Air (2020) report, in agreement with our study, observed that least developed countries, particularly those in Africa, Asia and the Middle East, showed increases in particulate matter (2.5) exposure compared to the developed nations, which were mainly driven by strict air quality policies.

Particulate matter (2.5) components, i.e. black carbon, organic carbon, sea salt, dust and sulfates, all showed an increase over the study period. The increasing motorization in the three cities, more-so private cars, increases vehicular emissions which contributes to black carbon rising in the atmosphere. Higher values were mainly attributed to rush hour times in cities as well as traffic congestion and poorly maintained and older vehicles, and decreased as one moved away from the cities (NCC, 2019).

The rising levels of particulate matter (2.5) and its components translates to a long term exposure of these pollutants which are increasing the disease burden and mortality more-so in Asia and Africa. The State of Global Air (2020) reports that $PM_{2.5}$ contributes to a large percentage of deaths globally, ranging from cardiovascular to respiratory diseases, affecting the most vulnerable who constitute of children. Prolonged exposure to $PM_{2.5}$ accounted for 62% of all air pollution mortalities, concurring with this study. (Health Effects Institute, 2020).

Sulfates, dust and organic carbon levels also increased over the study period for all three cities, enhanced by the rising temperature values observed previously, concurring to a study conducted by the Nairobi City County, which identified the sources of these aerosols from traffic congestion, mineral dust, and construction of roads going on across the cities, industrial emission and soil erosion (NCC, 2019).

The study also found out that other atmospheric pollutants, i.e. Sulphur dioxide, carbon monoxide and ozone increased in the three cities, agreeing to studies conducted previously. Birgen *et al* (2017) in a study on sulphur dioxide levels in Athi River found out that SO_2 values increased in the area, mainly attributed to industries around such as Bamburi and Mombasa cement factories and fuel combustion from vehicles passing along Namanga-Mombasa highway. Additionally, higher temperatures and lower precipitation periods led to the increase of SO_2 concentration in the area due to the lack of natural washout processes that precipitation offers.

A study by Shilenje *et al* (2016) found out that ozone levels in Nairobi peaked during periods of maximum temperature during the day as ozone is formed through a photochemical oxidation of CO, CH_4 and non-methane volatile organic carbons in the presence of NO_X. This was in agreement with our study where we observed rising concentrations of ground level ozone, which pose several respiratory problems.

A further analysis pointed out that pollutants such as ozone had very little influence on lower pediatric respiratory infections. On the other hand, carbon monoxide, sulfur dioxide and $PM_{2.5}$ had more impact on pediatric morbidities and mortalities of lower respiratory infections.

Patterns of pediatric lower respiratory infections.

Our study found out that children below 5 years showed declines in both morbidities and mortalities from 2010 onwards, despite their numbers being higher. Ritchie and Roser (2018) observed that deaths from communicable diseases such as respiratory infections, accounted for more than 73% of global deaths. They further noted that, compared to the early 90's where a quarter of all deaths were in young children, fewer deaths were observed in 2017 on children, accounting to only 10% of all deaths, agreeing to the results we obtained in this study. The fewer numbers for both morbidities and mortalities could also be attributed to the less exposure to cold weather and pollution that these children face, hence reducing such infections.

Children between 5 – 14 years showed an increase in lower respiratory morbidities and deaths over the study period for both three cities. Despite their global deaths ranking between 1 and 2%, LRIs rank as the third cause of death in Kenya, amounting to roughly 580 deaths per year (Ritchie and Roser, 2018).

Improved healthcare services and affordability offered by the government in the past two decades have helped reduce mortalities of children, including most Sub-Saharan countries, compared to the 1990s where healthcare services were scarce and expensive. In Kenya, the total health spending doubled between 2001 and 2013, while insurance cover grew with support from external donor financing, increasing health access to most families through both private and public hospitals (Keats *et al*, 2018).

Furthermore, under the Millennium Development Goal 4 (reducing child mortality), the Kenyan government launched a *Child Survival and development Strategy* as an effort to accelerating child survival and provide a framework for children. The strategy guided by the National Health Sector Strategic Plan 2 and Vision 2030, together with *Malezi Bora Strategy* helped in infant and childhood mortality declines in the country (UNDP, 2021). This can be witnessed in the results where we found out lower and reducing values of lower pediatric respiratory cases for children of 4 years and below.

Relationship between air pollutants and lower pediatric respiratory diseases

Climate change is linked to air pollution both as a cause and its effect. It is most likely to have greater effects on children with respect to air pollution since their lungs are still growing, and any exposures will affect them for longer durations of time. In this study, the number of morbidities and mortalities for LRIs in children are increasing in the three cities, especially for children above 5 years, which may result from spending more time outdoors where the concentration of air pollution is higher.

Increasing temperatures play a huge role in the dispersion of pollutants, and with the changing climate, we expect the rising temperatures to enhance dispersion further causing more harm even to places that had fewer cases of pediatric respiratory infections. The increase in precipitation over certain areas will assist in the reduction of certain pollutants while increasing the effects of other pollutants, although delayed short and long rains periods will have an influence on the spread. This is because precipitation may wash down the pollutants available after emissions in the atmosphere, while also acting as a blanket for emitted pollutants such as SO_2 increasing their effects on that locality.

CO and SO_2 have relatively shorter life spans in the atmosphere, and if distributed equally, their harmful effects will be smaller. However, the concentration of these pollutants in localized areas influenced by climate change and variability, as well as topographical factors influencing respiratory health effects, as witnessed to our results, agreeing with the results of Speight (2020). This can be witnessed on how carbon monoxide, sulphur dioxide and particulate matter (2.5) have much impact during JJA season for Nakuru compared to Nairobi and Mombasa.

Ritchie and Roser (2019) found out that outdoor air pollution worsens for countries which industrialize in order to transform from low to middle incomes, and that the two key local air pollutants with more diverse health impacts happen to be ozone and particulate matter. Furthermore, deSouza (2020) in a study found out that motor vehicles contributed majorly to pollution in Nairobi, compared to other cities in the country, agreeing with our findings where we saw higher cases of morbidities and mortalities of lower pediatric respiratory infections in the same city.

The State of Global Air (2020) report ranked Kenya among the top ten countries in Sub-Saharan Africa with the highest burden of $PM_{2.5}$ deaths, affecting mostly young children and the elderly (IHME, 2020). This concurred with our study which found out similar results, agreeing to the report on increases of $PM_{2.5}$, where it also observed its influence on pediatric LRIs morbidities and mortalities across the three cities.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter consists of conclusions and recommendations from the study.

5.1 Conclusions

From this study, minimum temperatures in all three cities are increasing at different rates, while rainfall increases in Nairobi and Nakuru but declines in Mombasa. Increasing temperatures enhance dispersion of atmospheric pollutants which in turn increases morbidity and mortality cases of lower pediatric respiratory infections. On the other hand, increasing rainfall produces the 'wash effect' which cleans the atmosphere from air pollutants, reducing their concentration on respective localities, which in turn reduces lower respiratory morbidity and mortality cases.

As children grow, they tend to spend more time outdoors in which the atmosphere is composed of numerous pollutants, especially between the ages of 5 to 14 years. Atmospheric pollutants that affect most all three cities in terms of both morbidities and mortalities of lower pediatric respiratory infections is particulate matter (2.5). Sulphur dioxide and carbon monoxide only have effects on morbidities of pediatric LRIs, and not on mortalities across all cities. The exposures to these harmful pollutants, mainly particulate matter (2.5), is likely to worsen their respiratory health across all three cities, even though carbon monoxide does not affect children in Mombasa. For cases of 4 years and below, programmes initiated by the government and non-governmental bodies has created awareness on lower respiratory diseases, which will reduce their exposures to aerosols thus having fewer cases of these children reported on both morbidities and mortalities.

Climate change and variability has been seen to greatly influence the behavior of pollutants and respiratory infections. Meteorological factors such as the rising minimum temperatures, which is one of climate change indicators, enhance the increase of pollutants such as tropospheric ozone, carbon monoxide, particulate matter, sulphur dioxide and many others, which causes inflammation and damage to a child's respiratory system increasing their cases on both morbidities and mortalities. Additionally, increasing temperatures affect the movement of wind, which carries along with it the air pollutants from a source to other areas while cold weather causes thermal inversion, which holds the pollutant at one point, saturating them at that area. The variations of rainfall patterns will mostly have strong effects in reducing air pollutants on the long rain season of MAM, with fewer cases of pediatric respiratory infections, but OND season will not have much impact especially in removing them from the atmosphere.

Understanding the influence of climate change through air pollution will offer better results in assessing and tackling lower respiratory diseases in children within the country. This study thus, has produced more insight on pediatric respiratory diseases and air pollution under the changing climate, aiming in formulation and strengthening of policy development and monitoring of LRIs in the health sector while helping the country achieve Vision 2030 and the Sustainable Development Goals on health.

5.2 Recommendations

This study recommends:

a) Set up of equipment and sites to assist in monitoring air pollutant levels in cities mainly, from both private and public sectors.

b) The study also recommends storage and archiving of health data by governments and private sectors, which will assist in research and policy making.

c) More research on linking climate change, air pollutants and respiratory infections across all ages, which will assist in strengthening existing policies on health, transport and other related sectors.

This study had several limitation, i.e. potential confounders were not included in the models used, and the effects of other weather elements were not considered.

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