A multi-technique appraisal of city-scale atmospheric pollution in Nigeria

by

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Declaration of originality

I, Yahaya Abbas Aliyu, declare that this thesis which I hereby submit in line with the requirements for the PhD Geoinformatics degree at the University of Pretoria is my own work and has not been previously submitted by me, for a degree at this or any other tertiary institution. Furthermore, I attest that the conceptualization, experimental exercises, results, analyses and conclusions, presented in the thesis are solely my individual effort, except otherwise stated and duly acknowledged. The chapter designs/drafts, methodical analyses, clarifications and refutations all through the peer-review process were carried out by my humble self.

………………………………………. 28 | FEBRUARY | 2019 ……………………………

Yahaya Abbas Aliyu **Date**

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Ethics statement

I, Yahaya Abbas Aliyu, whose name appears on the title page of this thesis, has obtained, for the research described in this thesis, the applicable research ethics approval. I declare that I have adhered to the ethical standards required in terms of the University of Pretoria's code of ethics for researchers and the policy guidelines for responsible research.

Disclaimer

This thesis mainly embraces the journal publication style of writing. The seven-chapter thesis has four specific objectives and it was intended that all the objectives would be published. Presently, four journal articles covering the four specific objectives of this thesis, have been accepted and published in various indexed peer-review journals. All the published articles are co-authored with my supervisor. The text in chapters 3 – 6, which adopts the journal publication style, is formatted as the published manuscript versions. However, contents such as numbering and reference style may have been re-formatted for consistency. Typographical errors were also amended.

Certification

I certify that I have read this thesis and that, in my opinion, it is adequate in scope and quality as a thesis for the award of the degree of Doctor of Philosophy in Geoinformatics.

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Dedication

This thesis is dedicated to my father; Wing Commander Dogara Abbas Aliyu (Retired).

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Abstract

This thesis is motivated by the Earth's environment taking serious hits, due to the propagation of varying atmospheric pollution across the cities of the globe. This propagation is driven mainly by the discharge of anthropogenic emissions such as; vehicular emissions, fossil fuel burning, industrial and biomass activities. Human exposure to alarming atmospheric pollution levels continues to be associated with a great number of adverse health effects. This challenge has resulted in air quality policymakers introducing globally adopted indices for air quality monitoring. The first task of this thesis was to review the existing air pollution status within the Nigerian territory. From the review of the available literature, the challenges were identified. A Nigerian city was adopted with the prospect of conducting a multi-technique appraisal of city-scale atmospheric pollution monitoring. Northern Nigeria's educational hub, Zaria, was spatially and temporally analysed for the period of December 2015 – November 2016. Considering Nigeria's limited technological resources, portable pollutant monitors were procured, validated and utilized for outdoor pollution measurement in this study. The results revealed alarming pollution levels, enough to rank Zaria amongst the World Health Organization's list of polluted cities. With the alarming pollution level in Zaria, respiratory wellness from population exposure was assessed. Certified health markers revealed that outdoor pollution contributed significantly to the respiratory well-being of the studied population. Satellite datasets have been a distinctive means for air quality monitoring over developing countries like Nigeria with limited ground pollution information. Using collocating ground measurements, we appraised the city-scale suitability of multi-satellite pollution measurements. The performance indicators adopted revealed that the Measurements of Pollution in the Troposphere Carbon Monoxide (MOPITT CO) estimates and the Moderate Resolution Imaging Spectroradiometer aerosol optical depth (MODIS AOD), as the suited satellite measurements. Another fundamental issue of this study was to identify if the existing Nigerian Global Navigation Satellite System Reference Framework (NIGNET) could be utilized for aerosol/particulate monitoring. This was achieved by appraising the effect of atmospheric aerosol optical depth (AOD) and ground particulate matter (PM) on the NIGNET derived-precipitable water vapour (PWV). A dual-comparison of the PWV estimates showed a significant correlation between the GPS PWV and MODIS PWV estimates. Analysing the ground particulate datasets, MODIS AOD measurements and GPS derived precipitable water vapour (PWV) estimates, the result of the collocating datasets showed good agreement. The findings of this study contribute immensely to policies on efficient air pollution monitoring in Nigeria.

Author's literature contributions

Peer-reviewed journals:

1. **Aliyu, Y.A.** & Botai, J.O. 2018. Appraising city-scale pollution monitoring capabilities of multi-satellite datasets using portable pollutant monitor. *Atmospheric Environment*, 179: 239-249. https://doi.org/10.1016/j.atmosenv.2018.02.034
2. **Aliyu, Y.A.** & Botai, J.O. 2018. Reviewing the local and global implications of air pollution trends in Zaria, Northern Nigeria. *Urban Climate*, 26: 51-59. https://doi.org/10.1016/j.uclim.2018.08.008
3. **Aliyu, Y.A.** & Botai, J.O. 2018. Appraising the effects of atmospheric aerosols and ground particulates concentrations on GPS-derived PWV estimates. *Atmospheric Environment*, 193: 24-32. https://doi.org/10.1016/j.atmosenv.2018.09.001
4. **Aliyu, Y.A.** & Botai, J.O. 2018. An exposure appraisal of outdoor air pollution on the respiratory well-being of a developing city population. *Journal of Epidemiology and Global Health*, 8(1): 91-100. DOI: 10.2991/j.jegh.2018.04.002

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List of abbreviations

AIRS	Atmospheric Infrared Sounder
AOD	Aerosol Optical Depth
AP	Attributable-risk Proportion
AQI	Air Quality Index
ATS	American Thoracic Society
AWOS	Automatic Weather Observing Stations
BMF	Biomass Fuel
CFR	Case Fatality Rates
CO	Carbon Monoxide
COPD	Chronic Obstructive Pulmonary Disease
CORS	Continuous Operating Reference Station
DLD	Division of Lung Disease
EOS	Earth Observing System
FEPA	Federal Environmental Protection Agency
GCO	Ground Carbon Monoxide
GNSS	Global Navigation Satellite Systems
GPM	Ground Particulate Matter
GPS	Global Positioning System
GPT	Global Pressure Temperature
HDF	Hierarchical Data Format
IGS	International GNSS Service
LST	Land Surface Temperature

MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NESREA	National Environmental Standards and Regulations Enforcement Agency
NetCDF	Network Common Data Form
NIGNET	Nigerian GNSS Network
NiMET	Nigerian Meteorological Agency
NPC	National Population Commission
NWP	Numerical Weather Predictions
OLI	Operational Land Imager
OMI	Ozone Monitoring Instrument
OSGOF	Office of the Surveyor General of the Federation
PER	Pollution Exposure Response
$PM_{2.5/10}$	Particulate Matter of less than 2.5/10 µm in aerodynamic diameter
PPP	Precise-Point Positioning
PWV	Precipitable Water Vapour
RINEX	Receiver Independent Exchange
RR	Relative Risk
SO_2	Sulphur Dioxide
UNEP	United Nations Environment Programme
USEPA	United States Environmental Protection Agency

USGS	United States Geological Survey
WHO	World Health Organization
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Tropospheric Delay
ZWD	Zenith Wet Delay

Chapter 1

Introduction

This chapter provides a succinct introduction to the research. First, it details the background to the subject matter 'atmospheric (air) pollution' in terms of the environment, public health risk and monitoring techniques. The chapter describes the status of air pollution highlighting the situation and initiatives, at the regional and local level. The main theme of this research is the portable cost-effective remote pollutant monitor. It is discussed conscientiously in each of the corresponding chapters. Further, this chapter elucidates the research motivation, research question and the specific objectives. The methodological framework adopted for the research, scope and limitations is also described. This chapter concludes with the thesis structure.

1.1. Air pollution and the environment

The atmosphere is said to be polluted if the concentration of elements within the earth's atmosphere is capable of interfering adversely with the physiological processes of man and his environment (UNEP, 2015). The severity of these adverse effects is mostly dependent on the concentration levels of these atmospheric elements. The atmospheric elements summarily comprise of gases (oxides of carbon, nitrogen, sulphur); particulates (fumes, aerosol); radioactive materials (barium, uranium) and so on (Heck et al., 1988). They are mainly discharged into the atmosphere through motor vehicle emissions, industrial activities, fossil fuel burning and biomass activities. They are grouped into primary or secondary pollutants. While the former is directly discharged into the atmosphere, the latter usually develops from the chemical interactions among the primary pollutants (Nazaroff and Weschler, 2004).

The environment contains various mechanisms necessary for life. The need for rapid industrialization of the environment is resulting in the discharge of harmful atmospheric pollutants, thus contributing to the atmospheric air pollution. This detrimental air pollution level within the earth's surface is becoming a key concern across the globe (Seinfeld and Pandis, 2016). The earth's atmospheric temperature is raising as a result of heat-trapping by carbon pollution. This anthropogenic-induced warmth is destroying the ecosystems since some of the species depend on the stable environment (Agarwal et al., 2017). The predominant environmental effects of air pollution include photochemical smog, acid rain deposits and land/water pollution.

The earth's ozone layer is responsible for protecting the ecosystem from the sun's ultraviolet radiations. However, man-induced chemicals like the chlorofluorocarbon (CFC) etc. continue to react with ozone particle thus depleting the layer and affecting the earth's environment (Ramanathan and Feng, 2009). Smog is created when gases mainly comprising of nitrogen oxides (NO_x), ozone (O_3) and peroxyacetyl nitrate (PAN) mix under the radiation of sunlight. This forms yellowish-brown haze which hampers visibility. It is referred to as brown air when the mixture occurs under intense sunlight. The incomplete smog formation resulting from less beaming solar radiation is referred to as grey air (Palliyaguru and Jayaweera, 2017). Acidic rain deposits do occur when dry and wet acidic components fall unto the earth surface under the influence of precipitation. They include rain, snow, fog, hail or even dust that is acidic. These deposits adversely corrode metal and deteriorate paints thus affecting cars and buildings, therefore increasing maintenance cost (Gerengi et al., 2016). The harmful elements released into the atmosphere are transported by air current over varying distances during dry and rainy seasons. In this process, some of the particles settle on the ground or in the water body. For the particles that would settle on the ground, some would be inhaled by living organism during the process. For the contaminated particles that would settle on water, it would upset the nutrients-balance in the rivers and coastal waters thus affecting the trees and forest soils (Nriagu and Pacyna, 1988).

The sensitivity between air pollution and the earth's environment is described in Figure 1.1. With the anticipation that earth's future environment will be more stagnant, researches are still utilizing various meteorological variables to comprehend the detrimental connection between atmospheric air pollution and environmental variables in polluted regions (Jacob and Winner, 2009; Maione et al., 2016).

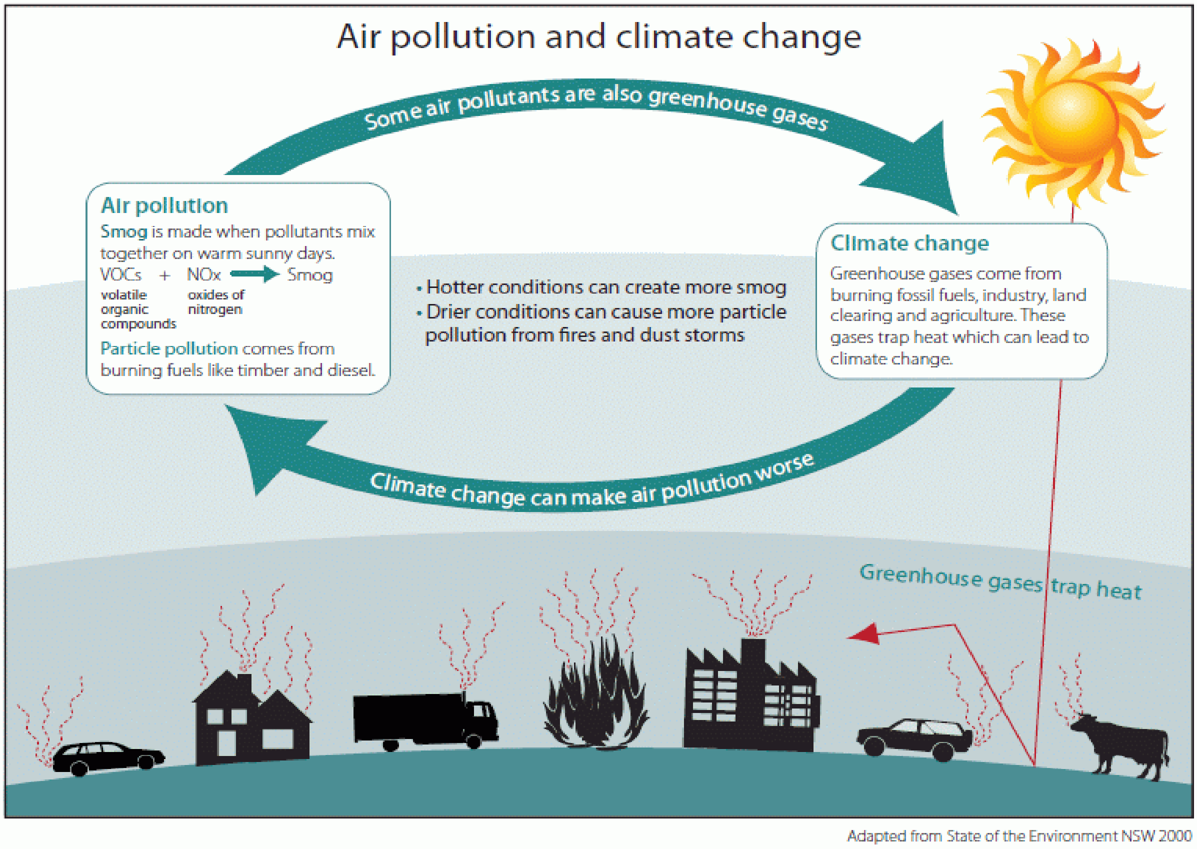


Figure 1.1. *The influence of air pollution on the environment (Source: EPA, 2000)*

1.2. Air pollution and public health

The human population exposure to critical atmospheric pollution concentration levels has been linked with numerous unfavourable health outcomes. The outcomes include, but are not limited to respiratory and cardiovascular illnesses. In severe situations, total mortality is inevitable (Vanos et al., 2014; Gray et al., 2015). According to the World Health Organization (WHO), there are quite a lot of processes that have been and are still being proposed in describing the harmful effects of air pollutants (WHO, 2005; WHO, 2014; WHO, 2017).

In air quality monitoring, there are major primary pollutants being monitored by various global environmental agencies. These primary pollutants, carbon monoxide, particulate matter, sulphur dioxide and volatile organic compounds (VOCs), are usually tagged as criteria pollutants. The ozone (O_3) is an example of the secondary pollutant (Arbex et al., 2012). Selected criteria pollutants, their origin and effects on the human respiratory systems are described as follows:

1.2.1. Carbon monoxide (CO)

Carbon monoxide is a lethal colourless, odourless and tasteless gas (Jang et al., 2017). It is a short-lived gas that plays a part in the development of ozone at ground-level. It is mainly generated from forest fires, partial fossil fuel combustion and road transportation. In the urban areas of developing cities, heavy traffic and biomass activities are the main anthropogenic contributors of CO emissions. Volcanic eruptions and chlorophyll decomposition are also organic sources of CO emissions. Human exposure to an excessive concentration of CO affects the alveoli and bloodstream of their respiratory system. This binds the haemoglobin interfering with oxygen distribution in the system. The results include headache and nausea. In pregnant women, CO exposure has been linked with low birth weight and foetal loss (Ocak et al., 2016; Jain, 2017).

1.2.2. Particulate matter (PM)

Particulate matter or particle pollution is the combination of solid elements and liquid precipitations found in the earth’s atmosphere. Some of these particles (e.g. dirt, smoke) are large or dark that they can be seen with the human eye, while the very small ones would require an electron microscope. The microscopic particles are mainly referred to as respirable particles that can easily be inhaled through the nostrils or throat. This causes critical health problems especially in children (Tecer et al., 2008). They impair the mucociliary flow and macrophage activity resulting in airway irritation. PM exposure creates a systemic imbalance between reactive oxygen species resulting in lung inflammation. Chronic exposure instigates chronic obstructive pulmonary disease (COPD), bronchial remodelling and cancer formation. They also cause reduced visibility. The respirable particulates include $PM_{2.5}$ (particles with a diameter of fewer than 2.5 micrometres) and PM_{10} (particles with a diameter of fewer than 10 micrometres) (Saxena and Bhargava, 2017). The particles less than 10 micrometres (μm) in diameter presents the bigger problem, as they are trapped in the nasal cavity thus affecting/contaminating the respiratory system (Upadhyay et al., 2014; Youn et al., 2016; Samek et al., 2017). The sources of particulate pollution include motor vehicles, biomass burning, sanitation activities, construction works, agricultural processes, pollen and volcanic ash (Kampa and Castanas, 2008). Table 1.1 highlights the exposure outcomes of air pollutants on the population.

1.2.3. Sulphur dioxide (SO_2)

Sulphur dioxide is a colourless gas characterized by a sharp irritating smell. The atmospheric sulphur dioxide results mainly from anthropogenic fossil fuel combustion, motor vehicle emissions and other industrial processing activities, e.g. oil and gas exploration, electricity generation using coal etc. This criteria air pollutant reacts easily with other substances creating harmful compounds, such as sulphuric acid and particles (Bernstein et al., 2008; Al-Haseen et al., 2015). Short-term exposures to SO_2 affect human health when it is breathed in through the upper airways, thus affecting the trachea, bronchi, and bronchioles of the human respiratory system. It irritates the mucous membrane that links the human eyes and the respiratory tract. This results in cough, wheeze, shortness of breath, increases bronchial reactivity and eventually facilitates bronchoconstriction (Künzli et al., 2010). In plants, high gaseous sulphuric oxide concentrations can harm plant vegetation by damaging their foliage thus hampering growth (USEPA, 2017).

Table 1.1. *Health outcomes of criteria pollutants on exposed population (modified after Künzli et al.,2010)*

Period of exposure	Effects on the respiratory system
Short-term (pollution level counting in days)	Raised symptoms for individuals with COPD or asthma; heightened frequency of respiratory infections (e.g. cough and wheeze); raised level of financial commitment for medical visits, medical dosage and hospital admissions; critical alterations in lung function; higher rates of occupational and academic non-appearance
Long-term (prolonged exposure over the years)	Increased mortality from cancer, pneumonia and other respiratory diseases; heightened prevalence of asthma and COPD; chronic changes in pulmonary functions; protracted decrease in FEV1 and FVC; compromised pulmonary development in children hampering their intellectual development; low birth weight; premature birth

1.3. Air pollution in Africa

For the last two decades, the hurried pace for development in numerous developing countries of the world has resulted in their air quality facing drastic degradation. During this process, the countries experienced measurable economic growth and sprawling urban populations generating excessive emissions from motor vehicles, factories and waste burning (Rai et al., 2011; Lindley et al., 2015).

Africa is one of the least developed and underperforming continents, especially in terms of monitoring intense atmospheric pollution activities (Lindley et al., 2015; Simos et al., 2017). Emissions in the African continent can be categorised into two (natural and anthropogenic) based on their sources. The natural sources include digestive tracts of animals, lightning, termites and vegetation. Anthropogenic emissions do result from human-related activities directly linked with energy-use in biomass, construction, industry, mining, and transportation (Knippertz et al., 2015). Africa's contribution to the global biomass burning activity still remains significant when compared to other regions (Vakkari et al., 2014; Marais and Chance, 2015; Ichoku et al., 2016).

In order to monitor air pollution in Africa, there are several established challenges that should be taken into consideration. The ground-level air pollution information varies as Africa is not a homogenous entity. The high-resolution emission inventories for regular monitoring are insufficient. More so, the countries have weak government institutions, high level of poverty, modest health care structures and inadequate social welfare, making it difficult for these countries to conform to the tenets of better air quality (Hanna and Oliver, 2016).

This nevertheless does not mean that the little available information should not be utilized by professionals to address the existing air pollution evidence (Knippertz et al., 2015; Roy, 2016). The African policymakers must make it a priority to push for trimming down of pollution emissions at least on the interim. During the process, the population should be counselled on adaptive procedures to minimize the exposure effects of air pollution.

1.4. Air pollution in Nigeria

Presently, Nigeria has the highest burden of fatalities from air pollution in Africa (Ogundipe, 2018). The rising population which would lead to increased anthropogenic activities seems to be not helping matters. Over the last six decades, the Nigerian state has experienced a steady increase in its human population, rising from 38 million in 1950 to 182 million in 2015. This increase has been as a result of the rural-urban migration, which accounts for 51 per cent of Nigeria's total population. The United Nations are optimistic that by 2030, Nigeria's human population would further rise to 263 million of which 80 per cent would be living in the urban areas (UNFPA, 2008; UNWPP, 2015). Figure 1.2 displays the population density map of Nigeria.

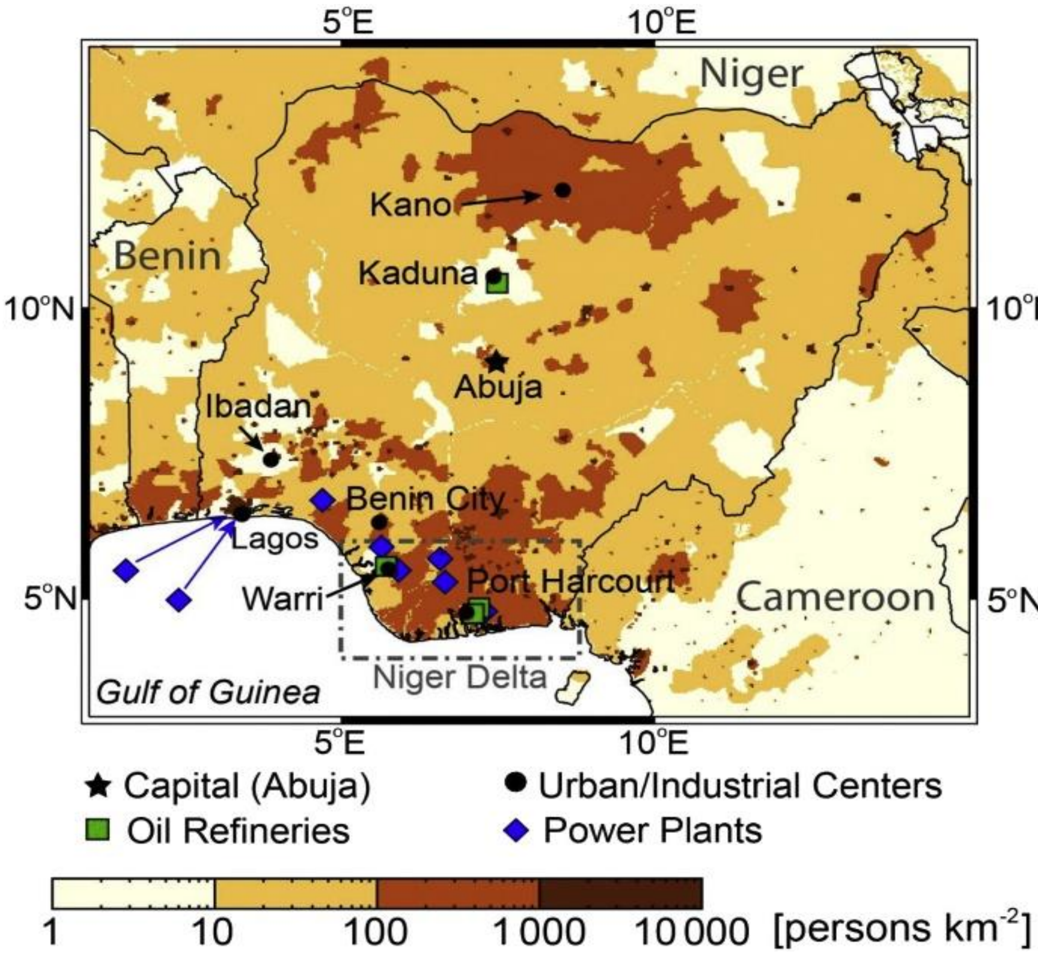


Figure 1.2. *Population density map of Nigeria highlighting major emission centres (Source: Marais et al. 2014)*

Selected studies in some of the major cities in Nigeria have confirmed the impacts of pollutants at *in situ* levels on the ambient air quality across the geopolitical zones in Nigeria. They have highlighted three main contributors to air pollution in Nigeria. These are the natural north-easterly harmattan dust (Dimari et al., 2008), roadside activities which include domestic combustion of solid fuels, wood etc. (Ndoke et al., 2006; Olowoporoku 2011) and industries (Nwaichi and Uzazabona, 2011). The industries are categorized as petroleum, non-petroleum and cottage.

The rapid population growth in Nigeria is yet to be coordinated with proper environmental planning, causing serious air quality concerns (Owoade et al., 2013; Marais et al., 2014). This lack of improper planning is resulting to unregulated use of time-worn vehicles, generators for personal and commercial energy supply, refuse and biomass burning (Assamoi et al., 2010; Orogade et al., 2016), thus elevating outdoor atmospheric pollution level.

From the industry sector, gas flaring (Osuji and Avwiri, 2005), frequent pipeline explosions (Fadeyibi et al., 2011) and illegal oil refining (USEIA, 2016) are also a source of worry for air pollution. The industries are mainly concentrated across 5 cities. They are Kaduna and Kano in the northern region; Lagos, Warri and Port Harcourt in the southern region. The oil and gas development are all situated in the Niger Delta of the southern region (Marais et al., 2014).

1.5. Air pollution monitoring techniques

There is a wide range of available techniques that can be employed for real-time monitoring of air pollutants. They extend from the professional to low-cost sensors for ground-level monitoring and also the remote sensing retrievals for top-bottom atmospheric estimates. These varieties do have their individual advantages as well as drawbacks. The selection of a pollution monitoring technique is mostly determined by the monitoring campaign objectives as well as the available budget (Gupta et al., 2006; Steinle et al., 2013).

The reference or professional instruments are designed and calibrated to accurately monitor pollutant properties either using a fixed or mobile approach. Majority of the available professional devices are usually adopted, validated and certified by the relevant governmental environmental agencies for official air quality measurements. They are however unsuitable for large-scale pollution monitoring due to their high cost (Budde et al., 2013). Spatial air pollution monitoring is attracting a growing interest across the globe especially for participatory monitoring (Patton et al., 2014; Van den Bossche et al., 2015). Presently, the portable lower-cost pollutant sensors are being utilized for high-time resolution and real-time spatial air pollution monitoring. The approach of these lower cost, portable pollutant monitors have totally changed the impression of mobile air quality assessment. Their lower-cost, low power demand and small dimensions are their main advantages, as it comfortably gives room for local air quality monitoring and also large-scale resolution mapping from several single measurements. While the public can be bothered by their limited accuracy, studies have demonstrated that their accuracy can be improved upon with the appropriate calibration and data optimization process (Budde et al., 2013; Gozzi et al., 2016).

In territories with limited technological resources, portable cost-effective devices are significant alternatives when we take into consideration the increasing rate of air pollution in developing countries. The portable sensors can be utilized for short/medium time monitoring inventory. Another available alternative for air quality monitoring in an environment with limited ground-level air pollution monitoring resources is the satellite remote sensing estimates.

For the remote sensing capabilities, there are existing atmospheric pollution monitoring satellites that were launched over two decades ago (Table 1.2). These satellites have continued to display better proficiency in observing atmospheric pollutants at high spatial and temporal resolutions as well as the conversion of raw satellite data retrievals to archived end user-friendly products (Streets et al., 2013).

Table 1.2. *Selected NASA satellite sensors, their specifications, and pollutants configuration (modified after Streets et al., 2013)*

Onboard Description					
Satellite platform	Terra	Terra	Terra	Aura	Aqua
Instrument	MODIS	MISR	MOPITT	OMI	AIRS
Operational period	2000-date	2000-date	2000-date	2004-date	2009-date
Orbital Specification					
Universal coverage	1 -2 days	9 days	3 days	daily	daily
Spatial resolution (Km)	˜1 × 1	17.6 × 17.6	22 × 22	13 × 24	50 × 50
Spectral portion	Visible – Infrared	Visible – Infrared	Infrared	Ultraviolet – Visible	Visible - Infrared
Spectral interval (µm)	0.4 – 14.4	0.44 – 0.87	2.2,2.3,4.6	0.27 – 0.5	3.7 – 15.4
Pollutants Retrieved					
CO	-	-	✓	✓	✓
PM (AOD)	✓	✓	-	✓	-

The large quantity of air pollution data from satellite measurements has proven beneficial to the decision-making process of environmental professionals. They can be utilized for ground-level pollution estimation, monitor/track exceptional events, assess regional trends and evaluate air pollution model output (Duncan et al., 2014). Satellite datasets are a distinctive means for air quality monitoring in a country like Nigeria with limited ground pollution information (Marais et al., 2014). Regulatory agencies, stakeholders and researchers are encouraged to make use of these satellite datasets to enrich the air quality decision support system. This will assist the scientists to improve the products to the varying requirements of the air quality community (Duncan et al., 2014).

1.6. Research motivation

In 2014, the WHO reported that air pollution exposure has resulted in approximately one in eight of the entire global deaths. The report did, as a matter of fact, double the WHO earlier projected estimates. This affirmed that the prevailing air pollution level is the world's major definite health threat (WHO, 2014). A breakdown of global mortality attributed to respiratory-related illnesses is highlighted in Figure 1.3.

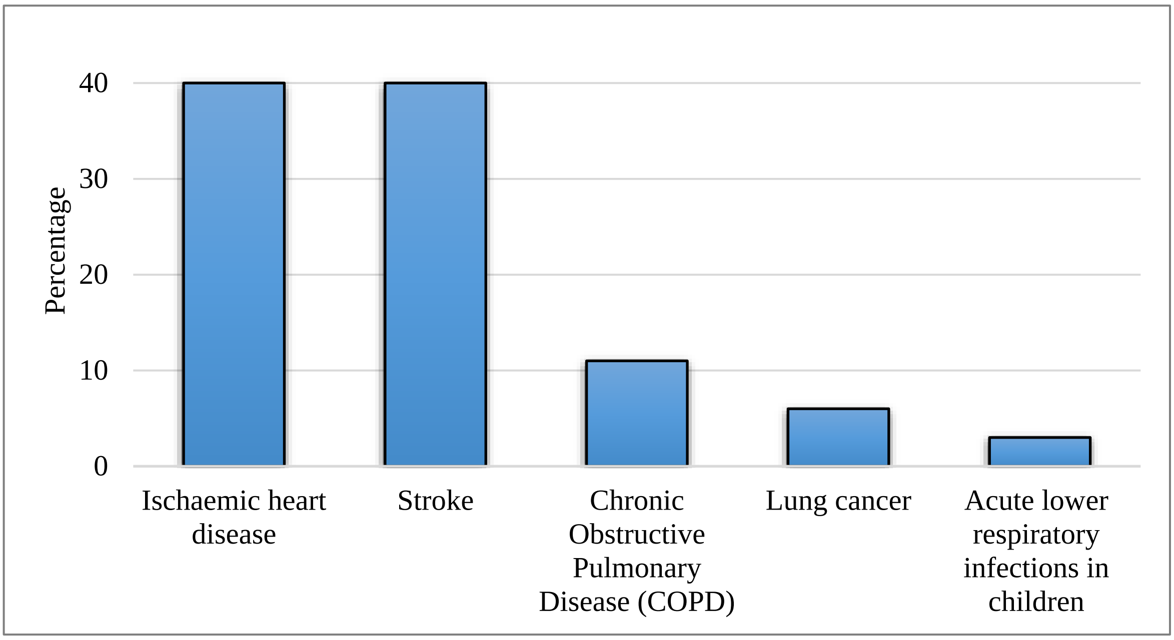


Figure 1.3. *Summary of specific respiratory diseases attributing to air pollution deaths (Source: WHO, 2014)*

Global policymakers continue to reflect on the need for nations to create emission inventories that are accurate and consistent so as to encourage continuous improvement of emission inventory compilation, to international standards (Francesco et al., 2014). In Africa in which Nigeria plays a major role, the increasing air pollution levels are raising serious concerns in line with the World's sustainable development goals (SDGs). These goals are aimed at harmonizing economic activities and revamping the public health system for sustainable urban development. For a country like Nigeria where its environmental policymakers appear unperturbed about the air quality status, this impact would not only expose its population to respiratory morbidity and mortality. It may blow out of proportion, escalating human and economic costs, making it further difficult to attain regional and global SDGs (Roy, 2016).

Atmospheric pollution has been a serious menace in most Nigerian urban cities (Hopkins et al., 2009). The Nigerian government is still yet to consider environmental legislation a priority as earlier reported (Akinlo, 2009). Mitigating the air pollution level in Nigeria would save millions of lives. Most individual researches within Nigeria have adopted portable pollutants monitoring devices. The reason for adopting this technique is mainly because Nigeria has no real-time reference air pollution monitoring station (Koku and Osuntogun, 2007; Abam and Unachukwu, 2009; NESREA, 2013; Jimmy et al., 2014; Njoku et al., 2016). The Nigeria Meteorological Agency (NiMET) did report that it had established five air pollution monitoring sites (UNEP, 2015). However personal inquiry did reveal that stations were not real-time functional, and are stationed at the city airports (Figure 1.4), which are at the outskirts away from the dense pollution urban activities. Additionally, this reveals that the majority of the air pollution studies reported using portable monitoring devices are not tied to any existing reference instruments. This is the main motivation for this research. This research seeks to develop the frontier by evaluating the functionality of these portable remote pollutant sensors using a multi-technique approach.

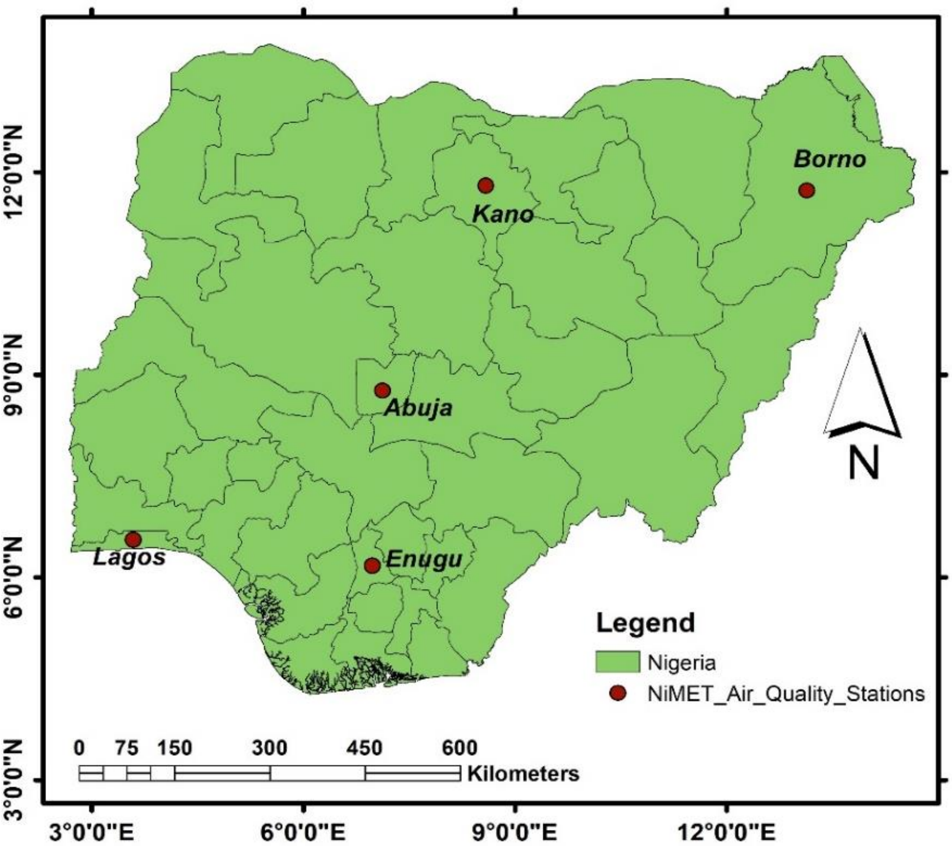


Figure 1.4. *The distribution of NiMET air monitoring stations situated at the city airports*

1.7. Research question

With the existing air pollution menace and the limited monitoring capabilities to effectively appraise atmospheric pollution effects within the Nigerian territory, this thesis provides answers to a far-reaching question, that is, how useful are portable pollutant sensors measurements for a multi-technique atmospheric pollution evaluation using an exposed Nigerian city? In answering this question, this thesis identifies specific objectives.

1.8. Research aim and objectives

The aim of this research is to appraise outdoor air pollution exposure in a Nigerian city with the view of integrating the retrieved pollutants variations with available environmental variables, for effective atmospheric pollution monitoring. The specific objectives of this research are described as follows:

1. Determine the ground-level seasonal distribution of the outdoor air pollutants in comparison to globally stipulated air quality indices
2. Evaluate the observed criteria pollutants' level for interim assessment of exposed population epidemiology
3. Appraise preferred satellite estimates using ground-level pollutant concentration as a city-scale bottom-top link analysis
4. Investigate the viability of the Nigerian GNSS signals as a pollution monitoring system for aerosol/particulates

1.9. Research methodology

First, ground measurements of selected criteria pollutants were obtained for the period of 1 December 2015 - 30 November 2016. These measurements were obtained across the various seasons over 19 appropriately selected sampling locations. The daily day-time samples were collected with devices positioned at 1.5m above the existing ground-level for peak morning (0730 – 0845 hrs), non-peak afternoon (1300 – 1415 hrs) and peak evening (1700 – 1815 hrs) periods daily (Bell and Davis, 2001; Yazdi et al., 2015). The ground measurements were restricted to day-time observations for the contributing anthropogenic activities as well as safety reasons.

Secondly, the population exposure appraisal assessed cross-sectional data on the lifestyle, household and medical histories by utilizing a standardized questionnaire survey modified after the ATS epidemiologic standardization project questionnaire for adults (Ferris, 1978) which has been successfully used in Liu et al. (2014). The respondents were identified across the selected sample sites in the area of study. The responses were analysed in comparison with observed criteria pollutant concentrations. The questionnaire was administered based on Krejcie and Morgan (1970) sample size determination for research. Respiratory health records were also obtained to determine population relative risk and baseline incidence. Study protocols were endorsed by the appropriate ethics committees.

Thirdly, we appraised the city-scale pollution monitoring capability of satellite pollution estimates with the available time-series ground pollution data. The satellite remote sensed pollutant estimates data were downloaded via NASA download portal. They are archived in a user-friendly format for applications covering a wide range of atmospheric problems.

Finally, we evaluated the effects of atmospheric aerosols and ground particulate matter on an existing Nigerian GNSS reference network (NIGNET) signals. The GNSS, the RINEX observation data, precise orbit data and site log information were retrieved over a GNSS/AWOS station with collocating aerosols and particulate matter datasets. The RINEX dataset was processed using the WaSoft software to obtain zenith tropospheric delay (ZTD) estimates at GNSS station for 2015 – 2016. Precipitable water vapour (PWV) estimates were obtained by interpolating meteorological parameters over the study GNSS station.

The methodology applied in this research is described using the flowchart in Figure 1.5.

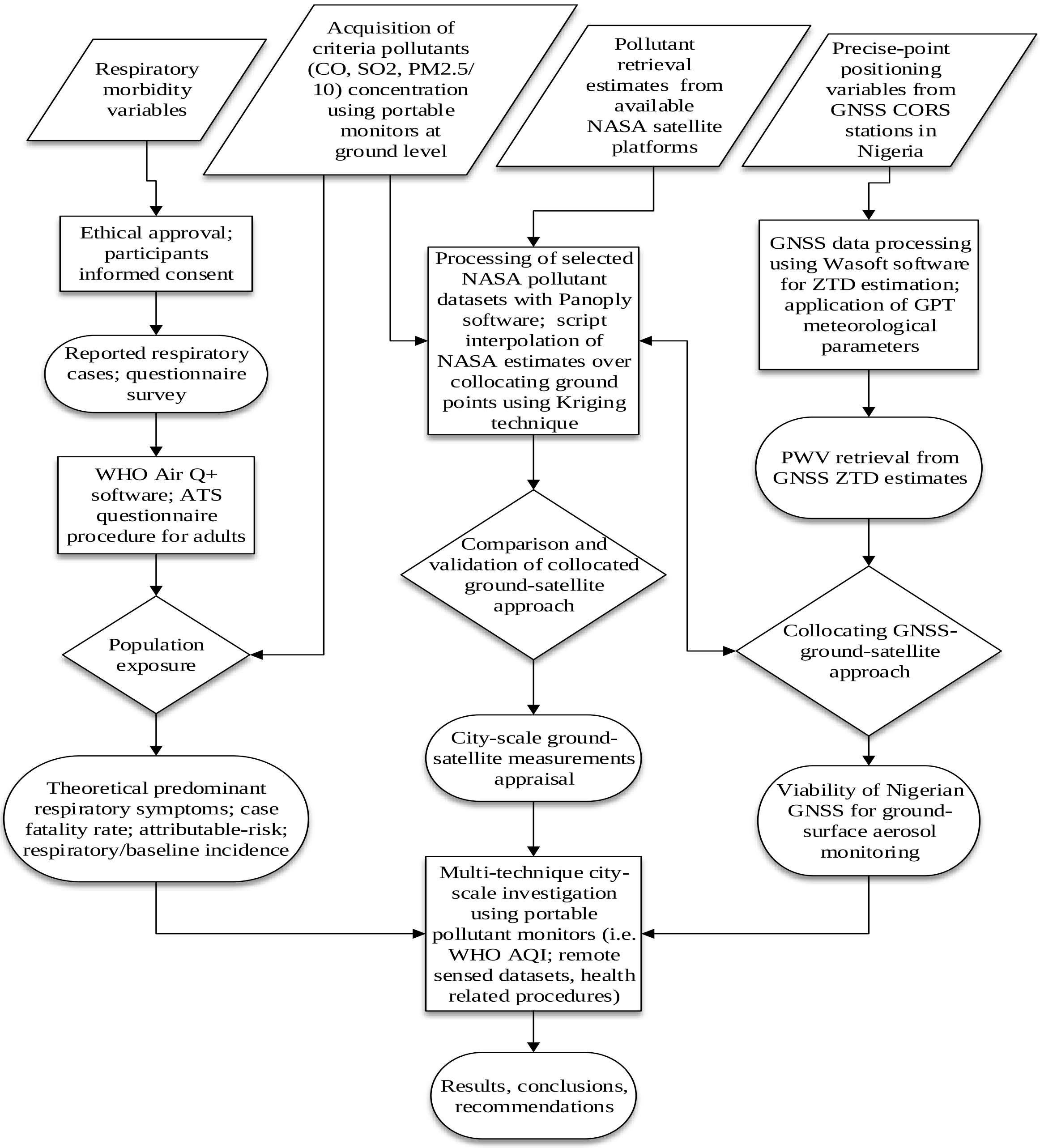


Figure 1.5. *Flowchart of the research methodological framework*

1.10. Scope and limitation of the research

The purpose of this research is to evaluate outdoor city-scale atmospheric pollution in Nigeria with the view of integrating the retrieved pollutants variations with available environmental variables, for effective atmospheric pollution monitoring. This includes the acquisition of ground-level selected criteria pollutants concentrations over a limited period of time (2015 – 2016). The portable devices utilized were obtained solely for the purpose of this research. In evaluating air pollution devices, much time and thought are given to evaluating data quality using reference stations. These devices are large, expensive and mostly unaffordable to most developing regions of the world. In most limited resource environments, the portable cost-effective sensors are being embraced. At present, studies are still formulating standards for the various types of portable pollutant sensors being used for air pollution monitoring. Their accuracy is the focus of this research.

This research is greatly dependent on the ground-level pollutant measurement datasets obtained using the MSA Altair 5x gas detector and the Chinaway CW-HAT200 particulate counter, and are limited to demonstration and evaluation of the criteria pollutants; carbon monoxide (CO), sulphur dioxide (SO_2) and particulate matter ($PM_{2.5}$ and PM_{10}). For the theoretical baseline incidence of the exposed city population, population estimates were adopted since the most recent population census for Nigeria was conducted in 2006.

1.11. Structure of the thesis

The introduction, reviews, analyses, results and conclusions of this thesis are structured in a total of seven chapters. The chapters 3 – 6 comprise of published peer-reviewed journal articles, that covers the four specific objectives of this thesis. The texts of Chapters 3 – 6 are formatted as the published manuscripts drafts, but the numbering and reference styles are reformatted for consistency. Typographic errors/mistakes were also corrected.

References

1. Abam, F.I. & Unachukwu, G.O. 2009. Vehicular emissions and air quality standards in Nigeria. *European Journal of Science and Research*, 34(4): 550-560.
2. Agarwal, P., Sharma, S., Sharma, M., Takshak, A. & Sharma, V. 2017. Isolation and characterization of Tyrosinase (a carbon trapping enzyme) producing microorganisms, in the agricultural soil of western Uttar Pradesh and the study of enzymatic activity of Tyrosinase produced. *Biochemistry and Molecular Biology Letters*, 3(1): 105.
3. Akinlo, A.E. 2009. Electricity consumption and economic growth in Nigeria: evidence from cointegration and co-feature analysis. *Journal of Policy Modelling*, 31: 681-693. https://doi.org/10.1016/j.jpolmod.2009.03.004
4. Al-Haseen, S.I., Al-Qarroni, E.H., Qassim, M.H., Al-Saad, H.T. & Al-Hello, A.Z. 2015. An experimental study on the determination of air pollutant concentrations released from selected outdoor gaseous emission sources in Basra city, Southern Iraq. *Journal of International Academic Research for Multidisciplinary*, 3(1): 88-98.
5. Arbex, M.A., Santos, U.D.P., Martins, L.C., Saldiva, P.H.N., Pereira, L.A.A. & Braga, A.L.F. 2012. Air pollution and the respiratory system. *Jornal Brasileiro de Pneumologia*, 38(5): 643-655. https://doi.org/10.1590/S1806-37132012000500015
6. Assamoi, E.M. & Liousse, C. 2010. A new inventory for two-wheel vehicle emissions in West Africa for 2002. *Atmospheric Environment*, 44(32): 3985-3996. https://doi.org/10.1016/j.atmosenv.2010.06.048
7. Bernstein, J.A., Alexis, N., Bacchus, H., Bernstein, I.L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., Oullette, J. & Reijula, K. 2008. The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*, 121(3): 585-591. https://doi.org/10.1016/j.jaci.2007.10.045
8. Budde, M., El Masri, R., Riedel, T. & Beigl, M. 2013. Enabling low-cost particulate matter measurement for participatory sensing scenarios. In: *Proceedings of the 12th International Conference on Mobile and Uxi Quitous Multimedia*, ACM, p. 19. https://doi.org/10.1145/2541831.2541859
9. Dimari, G.A., Hati, S.S., Waziri, M. & Maitera, O.N. 2008. Pollution synergy from Particulate Matter Sources: the harmattan, fugitive dust and combustion emissions in Maiduguri metropolis, Nigeria. *European Journal of Scientific Research*, 23: 465–473. https://doi.org/10.13140/2.1.3407.6160
10. Duncan, B.N., Prados, A.I., Lamsal, L.N., Liu, Y., Streets, D.G., Gupta, P., Hilsenrath, E., Kahn, R.A., Nielsen, E., Beyersdorf, A.J., Burton, S.P., Fiore, A.M., Fisherman, J., Henze, D.K., Hosteltler, C.A., Krotkov, N.A., Lee, P., Lin, M., Pawson, S., Pfister, S., Pickering, K.E., Bradley Pierce, R., Yoshida, Y. & Ziemba, L.D. 2014. Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. *Atmospheric Environment*, 94: 647-662. https://doi.org/10.1016/j.atmosenv.2014.05.061
11. EPA, 2000. *NSW State of the Environment 2000*, NSW Environment Protection Authority, Sydney.

12. Fadeyibi, I.O., Jewo, P.I., Opoola, P., Babalola, O.S., Ugburo, A. & Ademiluyi, S.A. 2011. Burns and fire disasters from leaking petroleum pipes in Lagos, Nigeria: an 8- year experience. *Burns*, 37: 145-152. https://doi.org/10.1016/j.burns.2010.06.012
13. Gerengi, H., Bereket, G. & Kurtay, M. 2016. A morphological and electrochemical comparison of the corrosion process of aluminum alloys under simulated acid rain conditions. *Journal of the Taiwan Institute of Chemical Engineers*, 58: 509-516. https://doi.org/10.1016/j.jtice.2015.05.023
14. Gozzi, F., Della Ventura, G. & Marcelli, A. 2016. Mobile monitoring of particulate matter: state of art and perspectives. *Atmospheric Pollution. Research*, 7(2): 228-234. https://doi.org/10.1016/j.apr.2015.09.007
15. Gray, D.L., Wallace, L.A., Brinkman, M.C., Buehler, S.S. & La Londe, C. 2015. Respiratory and cardiovascular effects of metals in ambient particulate matter: a critical review. In *Reviews of Environmental Contamination and Toxicology* (pp. 135-203). Springer International Publishing. https://doi.org/10.1007%2F978-3-319-10638-0_3
16. Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y.C. & Kumar, N. 2006. Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmospheric Environment*, 40(30): 5880-5892. https://doi.org/10.1016/j.atmosenv.2006.03.016
17. Hanna, R. & Oliva, P. 2016. Implications of climate change for children in developing countries. *The Future of Children*, 26(1): 115-132. https://doi.org/10.1353/foc.2016.0006
18. Heck, W.W., Taylor, O.C. & Tingey, D.T. 1988. *Assessment of crop loss from air pollutants*. London: Elsevier Applied Science.
19. Hopkins, J.R., Evans, M.J., Lee, J.D., Lewis, A.C., Marsham, J.H., McQuaid, J.B., Parker, D.J., Stewart, D.J., Reeves, C.E. & Purvis, R.M. 2009. Direct estimates of emissions from the megacity of Lagos. *Atmospheric Chemistry and Physics*, 9: 8471-8477. https://doi.org/10.5194/acp-9-8471-2009
20. Ichoku, C., Ellison, L.T., Willmot, K.E., Matsui, T., Dezfuli, A.K., Gatebe, C.K., Wang, J., Wilcox, E.M., Lee, J., Adegoke, J. & Okonkwo, C. 2016. Biomass burning, land-cover change, and the hydrological cycle in Northern sub-Saharan Africa. *Environmental Research Letters*, 11(9): 095005. https://doi.org/10.1088/1748-9326/11/9/095005/meta
21. Jacob, D.J. & Winner, D.A. 2009. Effect of climate change on air quality. *Atmospheric Environment*, 43(1): 51-63. https://doi.org/10.1016/j.atmosenv.2008.09.051
22. Jain, K.K. 2017. Carbon monoxide and other tissue poisons. In *Textbook of hyperbaric medicine* (pp. 131-154). Springer International Publishing. https://doi.org/10.1007/978-3-319-47140-2_13
23. Jang, D.H., Kelly, M., Hardy, K., Lambert, D.S., Shofer, F.S. & Eckmann, D.M. 2017. A preliminary study in the alterations of mitochondrial respiration in patients with carbon monoxide poisoning measured in blood cells. *Clinical Toxicology*, 55(6): 579-584. https://doi.org/10.1080/15563650.2017.1288912
24. Jimmy, E.O., Solomon, M.S., Peter, A.I. & Asuquo, C. 2014. Environmental health implications of motorcycles emitted gases in a metropolitan Nigeria. *American Journal of Environmental Protection*, 2(1): 7-10. https://doi.org/10.12691/env-2-1-2

25. Kampa, M. & Castanas, E. 2008. Human health effects of air pollution. *Environmental Pollution*, 151(2): 362-367. https://doi.org/10.1016/j.envpol.2007.06.012
26. Knippertz, P., Evans, M.J., Field, P.R., Fink, A.H., Liousse, C. & Marsham, J.H. 2015. The possible role of local air pollution in climate change in West Africa. *Nature Climate Change*, 5(9): 815-822. https://doi.org/10.1038/nclimate2727
27. Koku, C.A. & Osuntogun, B.A. 2007. Environmental-impacts of road transportation in southwestern states of Nigeria. *Journal of Applied Sciences*, 7(16): 2536-2560.
28. Krejcie, R.V. & Morgan, D.W. 1970. Determining sample size for research activities. *Educational Psychological Measurement*, 30: 607–610. https://doi.org/10.1177/001316447003000308?journalCode=epma
29. Künzli, N., Perez, L. & Rapp, R. 2010. *Air quality and health*. Lausanne: European Respiratory Society. ISBN: 978-1-84984-008-8
30. Lindley, S.J., Gill, S.E., Cavan, G., Yeshitela, K., Nebebe, A., Woldegerima, T., Kibassa, D., Shemdoe, R., Renner, F., Buchta, K. & Abo-El-Wafa, H. 2015. Green infrastructure for climate adaptation in African cities. In *Urban Vulnerability and Climate Change in Africa* (pp. 107-152). Springer International Publishing. https://doi.org/10.1007%2F978-3-319-03982-4_4
31. Liu, J. Man, Y. & Liu, Y. 2014. Temporal variability of PM_{10} and $PM_{2.5}$ inside and outside a residential home during 2014 Chinese spring festival in Zhengzhou, China. *National Hazards*, 73(3): 2149-2154. https://doi.org/10.1007%2Fs11069-014-1157-9
32. Maione, M., Fowler, D., Monks, P.S., Reis, S., Rudich, Y., Williams, M.L. & Fuzzi, S. 2016. Air quality and climate change: Designing new win-win policies for Europe. *Environmental Science and Policy*, 65: 48-57. https://doi.org/10.1016/j.envsci.2016.03.011
33. Marais, E.A. & Chance, K. 2015. A geostationary air quality monitoring platform for Africa. *Clean Air Journal*, 25(1): 40-45. http://dx.doi.org/10.17159/2410-972X/2015/v25n1a3
34. Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K. & Sauvage, B. 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space. *Atmospheric Environment*, 99: 32-40. https://doi.org/10.1016/j.atmosenv.2014.09.055
35. Nazaroff, W.W. & Weschler, C.J. 2004. Cleaning products and air fresheners: exposure to primary and secondary air pollutants. *Atmospheric Environment*, 38(18): 2841-2865. https://doi.org/10.1016/j.atmosenv.2004.02.040
36. Ndoke, P.N., Akpan, U.G. & Kato, M.E. 2006. Contribution of vehicular traffic to carbon dioxide emission in Kaduna and Abuja, northern Nigeria. *Leonardo Electronic Journal of Practices and Technologies*, 5: 81–90.
37. NESREA (National *Environmental* Standards and Regulations Enforcement Agency), 2013. *Air quality control monitoring in the FCT*. Available from: http://www.nesrea.gov.ng/news/air-quality.php. Last access: November 2015.
38. Njoku, K.L., Rumide, T.J., Akinola, M.O., Adesuyi, A.A. & Jolaoso, A.O. 2016. Ambient air quality monitoring in metropolitan city of Lagos, Nigeria. *Journal of Applied Sciences and Environmental Management*, 20(1): 178-185. http://doi.org/10.4314/jasem.v20i1.21

39. Nriagu, J.O. & Pacyna, J.M. 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. *Nature*, 333(6169): 134-139. https://doi.org/10.1038/333134a0
40. Nwaichi, E.O. & Uzazabona, M.A. 2011. Estimation of the CO_2 level due to gas flaring in the Niger Delta. *Research Journal of Environmental Sciences*, 5: 565–572. https://doi.org/10.3923/rjes.2011.565.572
41. Ocak, T., Tekin, E., Basturk, M., Duran, A., Serinken, M. & Emet, M. 2016. Treatment in carbon monoxide poisoning patients with headache: a prospective, multicenter, double-blind, controlled clinical trial. *The American Journal of Emergency Medicine*, 34(11): 2140-2145. https://doi.org/10.1016/j.ajem.2016.08.002
42. Ogundipe, S. 2018. *Air pollution: Nigeria ranks 4th deadliest globally*. Available from: https://www.vanguardngr.com/2018/09/air-pollution-nigeria-ranks-4th-deadliest-globally/ Last access: February 2019.
43. Olowoporoku, D. 2011. *How clean is the air Nigerians breathe?* A case for national air quality management framework. Nigeria World Feature Article 201. Available from: http://nigeriaworld.com/articles/2011/feb/012.html. Last access: October 2017.
44. Orogade, S.A., Owoade, K.O., Hopke, P.K., Adie, D.B., Ismail A. & Okuofu, C.A. 2016. Source apportionment for fine and coarse particulate matter in industrial areas of Kaduna, northern Nigeria. *Aerosol and Air Quality Research*, 16: 1179-1190. https://doi.org/10.4209/aaqr.2015.11.0636
45. Osuji, L.C. & Avwiri, G.O. 2005. Flared gases and other pollutants associated with air quality in industrial areas of Nigeria: an overview. *Chemistry and Biodiversity*, 2: 1277-1289. https://doi.org/10.1002/cbdv.200590099
46. Owoade, O.K., Fawole, O.G., Olise, F.S., Ogundele, L.T., Olaniyi, H.B., Almeida, M.S., Ho M.D. & Hopke, P.K. 2013. Characterization and source identification of airborne particulate loadings at receptor site-classes of Lagos Mega-City, Nigeria. *Journal of Air and Waste Management Association*, 63: 1026–1035. https://doi.org/10.1080/10962247.2013.793627
47. Palliyaguru, N.P.L. & Jayaweera, P.M. 2017. Investigation of photochemical smog formation after removal of water soluble organic and inorganic fractions in the diesel exhaust fume. In *Proceedings of International Forestry and Environment Symposium* (Vol. 21).
48. Patton, A.P., Perkins, J., Zamore, W., Levy, J.I., Brugge, D. & Durant, J.L. 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighbourhoods near an interstate highway. *Atmospheric Environment*, 99: 309-321. https://doi.org/10.1016/j.atmosenv.2014.09.072
49. Rai, R., Rajput, M., Agrawal, M. & Agrawal, S.B. 2011. Gaseous air pollutants: a review on current and future trends of emissions and impact on agriculture. *Journal of Scientific Research*, *55*(771): 1.
50. Ramanathan, V. & Feng, Y. 2009. Air pollution, greenhouse gases and climate change: Global and regional perspectives. *Atmospheric Environment*, 43(1): 37-50. https://doi.org/10.1016/j.atmosenv.2008.09.063

51. Roy, R., 2016. The cost of air pollution in Africa. https://doi.org/10.1787/5jlqzq77x6f8-en
52. Samek, L., Furman, L., Mikrut, M., Regiel-Futyra, A., Macyk, W., Stochel, G. & van Eldik, R. 2017. Chemical composition of submicron and fine particulate matter collected in Krakow, Poland. Consequences for the APARIC project. *Chemosphere*, 187: 430-439. https://doi.org/10.1016/j.chemosphere.2017.08.090
53. Saxena, N. and Bhargava, R. 2017. A review on air pollution, polluting agents and its possible effects in 21st century. *Advances in Bioresearch*, 8(2): 42-50.
54. Seinfeld, J.H. & Pandis, S.N. 2016. *Atmospheric chemistry and physics: from air pollution to climate change*. John Wiley and Sons. ISBN 0-471-17815-2
55. Simos, J., Naissem, F.B., Naissem, J., Sokona, F.M., de Dieu Konongo, J., Sani, A., Corburn, J., Karanja, I., Makau, J., Aikins, A.D.G. & Haroun, A. 2017. Healthy cities in Africa: a continent of difference. In *Healthy Cities* (pp. 89-132). Springer New York. https://doi.org/10.1007%2F978-1-4939-6694-3_6
56. Steinle, S., Reis, S. & Sabel, C.E. 2013. Quantifying human exposure to air pollution—moving from static monitoring to spatio-temporally resolved personal exposure assessment. *Science of the Total Environment*, 443: 184-193. https://doi.org/10.1016/j.scitotenv.2012.10.098
57. Streets, D.G., Canty, T., Carmichael, G.R., de Foy, B., Dickerson, R.R., Duncan, B.N., Edwards, D.P., Haynes, J.A., Henze, D.K., Houyoux, M.R. & Jacob, D.J. 2013. Emissions estimation from satellite retrievals: A review of current capability. *Atmospheric Environment*, 77: 1011-1042. https://doi.org/10.1016/j.atmosenv.2013.05.051
58. Tecer, L.H., Alagha, O., Karaca, F., Tuncel, G. & Eldes, N. 2008. Particulate matter (PM2. 5, PM10-2.5, and PM10) and children's hospital admissions for asthma and respiratory diseases: A bidirectional case-crossover study. *Journal of Toxicology and Environmental Health, Part A*, 71(8): 512-520. https://doi.org/10.1080/15287390801907459
59. UNEP (United Nations Environment Programme), 2015. *Fuel quality progress in Nigeria for Nigeria national air quality management programme*. Federal Ministry of Environment. Available from: http://staging.unep.org/Transport/new/PCFV/pdf/2015_Ecowas_FuelQualityProgress_Emmanuel.pdf. Last access: October 2017.
60. UNFPA (United Nations Population Fund), 2008. Annual report. ISBN 9780897149532, p. 20.
61. UNWPP (United Nations World Population Prospects), 2015. *World population prospects: the 2015 revision, highlights and advance tables*. Department of Economic and Social Affairs, Population Division. Working Paper No. ESA/P/WP.241. Available from: https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf. Last access: October 2017.
62. Upadhyay, S., Ganguly, K. & Stoeger, T. 2014. Inhaled ambient particulate matter and lung health burden. *European Medical Journal on Respiration*, 2: 88-95.

63. USEIA (US Energy Information Administration), 2016. Nigeria. Available from: https://www.eia.gov/beta/international/analysis_includes/countries_long/Nigeria/nigeria.pdf. Last access: September 2017.
64. USEPA (United States Environmental Protection Agency), 2017. Sulphur dioxide (SO_2) pollution: Sulphur dioxide basics. Available from: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects. Last access: October 2017.
65. Vakkari, V., Kerminen, V.M., Beukes, J.P., Tiitta, P., Zyl, P.G., Josipovic, M., Venter, A.D., Jaars, K., Worsnop, D.R., Kulmala, M. & Laakso, L. 2014. Rapid changes in biomass burning aerosols by atmospheric oxidation. *Geophysical Research Letters*, 41(7): 2644-2651. https://doi.org/10.1002/2014GL059396
66. Van den Bossche, J., Peters, J., Verwaeren, J., Botteldooren, D., Theunis, J. & De Baets, B. 2015. Mobile monitoring for mapping spatial variation in urban air quality: development and validation of a methodology based on an extensive dataset. *Atmospheric Environment*, 105: 148-161. https://doi.org/10.1016/j.atmosenv.2015.01.017
67. Vanos, J.K., Hebbern, C. & Cakmak, S. 2014. Risk assessment for cardiovascular and respiratory mortality due to air pollution and synoptic meteorology in 10 Canadian cities. *Environmental Pollution*, 185: 322-332. https://doi.org/10.1016/j.envpol.2013.11.007
68. WHO (World Health Organization), 2005. *Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulphur dioxide.* Copenhagen: Druckpartner Moser. Available from: http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf. Last access: August 2016.
69. WHO (World Health Organization), 2014. 7 million premature deaths annually linked to air pollution. World Health Organization News Release. Available from: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/. Last access: September 2017.
70. WHO (World Health Organization), 2017. *Evolution of WHO air quality guidelines. Past, present and future*. Available from: http://www.euro.who.int/__data/assets/pdf_file/0019/331660/Evolution-air-quality.pdf. Last access: September 2017.
71. Youn, J.S., Csavina, J., Rine, K.P., Shingler, T., Taylor, M.P., Sáez, A.E., Betterton, E.A. & Sorooshian, A. 2016. Hygroscopic properties and respiratory system deposition behaviour of particulate matter emitted by mining and smelting operations. *Environmental Science and Technology*, 50(21): 11706-11713. https://doi.org/10.1021/acs.est.6b03621

Chapter 2

Literature review

2.1. Introduction

Air pollution is the mixture of fume, dust and odour emissions in quantities that might negatively affect the human population and ecosystems (Powell, 2012). Air pollution sources can be categorized into a point, line, area or volume sources. A factory stack is an example of a point source. The stack point source component entails the gas emission volume, height and diameter of the stack. Mobile emission from vehicular activities characterises line sources. While the area or volume source can be described using the pollution distribution over the urban area. This merges all the available sources and criteria for area analysis (Beychok, 2005).

Figure 2.1. *The environmental atmosphere in a Nigerian city*

Many cities within the African continent do not have an existing and up-to-date air pollution database, which is the criteria for understanding the trend pattern of criteria pollutants (WHO, 2016). In Nigeria, atmospheric pollution is still a serious menace in many of its metropolitan cities. This is resulting from poorly managed vehicles, general use of the single-engine motor-cycles for shuttling commuters, traffic congestions (Figure 2.1) generating high levels of localized air pollution that can affect population health (Ite et al., 2017; Oluwole et al., 2017). To efficiently monitor the ambient air quality, there are various steps which include: identification of species pollutants, distribution of sample sites, regularity/period of sampling, sampling methods, infrastructural amenities, manpower and operation and maintenance costs (Schwela, 2010).

In 2013, five Nigerian Meteorological Agency (NiMET) air quality monitoring stations (Figure 1.4) were installed to monitor NO, NO_2, SO_2, CO and PM_{10} criteria pollutants (UNEP, 2015). However, there is no record online of any study/reports conducted using its datasets. The data is recorded at a temporal resolution of 15-minutes for NO, NO_2, SO_2, CO and 1-hour interval for PM_{10}. Unfortunately, these stations lack continuous data due to the poor electricity supply in Nigeria (NIMET, personal communication, 15 March 2016).

In the southern region of Nigeria, studies analysed the impact of road transportation emission on urban ambient air and reported pollutant concentrations to be above the Federal Environmental Protection Agency (FEPA) stipulated limit (Jerome, 2000) for Warri, Port Harcourt, Calabar and Uyo respectively (Abam and Unachukwu, 2009; Ediagbonya and Tobin, 2013; Olumayede and Okuo, 2013; Jimmy et al., 2014). In the south-west zone, air quality monitored within Ado-Ekiti, Ibadan and Lagos exceeded the stipulated limits (Koku and Osuntogun, 2007; Ana et al., 2013; Yusuf et al., 2013; Njoku et al., 2016), while Olotu community in Ondo recorded acceptable limits for observed pollutants (Akande et al., 2013). In the Northern region of Nigeria, pollutant levels contributed by automobile emissions were examined in some areas of Kaduna (Adewunmi et al., 2015; Mohammed et al., 2013; Orogade et al., 2016) and Abuja (Moen, 2008) in Northern Nigeria and concluded that the concentration impacted negatively on air quality. Okunola et al. (2012) evaluated the outdoor air pollution level in Kano with portable pollutant sensors and concluded that the observed concentration levels were above the United States Environmental Protection Agency (USEPA) threshold. Dimari et al. (2008) also reported a significant increase in pollution level across Maiduguri in North Eastern, Nigeria. The Nigerian environmental agency charged with ensuring an environmental-friendly environment for Nigerians monitored noise and criteria pollutants across selected sites within Abuja, Nigeria and revealed high levels of gaseous emissions with concentration levels above the USEPA and WHO standard limit except for SO_2 (NESREA, 2013).

2.2. Application of geoinformatics in atmospheric pollution monitoring

It is widely agreed that Geoinformatics has typical potential benefits in many environmental applications. It explores, visualizes and models spatial data. There is a growing increase in the adoption of Geoinformatics' remote sensing and geographic information system (GIS) capabilities for atmospheric pollution monitoring. This is mainly due to its ability to remotely collect pollution information for analysis and display (ESRI, 2007).

There is no doubt that air quality is vital to the health and environment. However, the process of monitoring the sources responsible for contamination remains challenging. The introduction of geoinformatics tools and technology through air pollution distribution, remotely sensed pollutants datasets and spatial statistics, continues to assist in describing the connection that links atmospheric pollution and other existing environmental variables. Geoinformatics also utilizes the process and interpretation of satellite remote-sensed data. This serves as a valuable mechanism for environmental aerosol analysis. An improved resolution from the satellite data would provide environmental managers with incredible geospatial research information. It would also serve as a data source for areas with limited or no ground related pollution information. In regions with ground field crews that mainly utilize mobile monitoring technology, the acquisition of air pollution and additional geographic data can be utilized by scientists to warn people residing in areas where hazardous pollution level is approaching to take precautions. Policymakers can also use environmental pollution analysis to stimulate control measures (ESRI, 2007).

Geoinformatics can process spatial data from a variety of air pollution sources for analysis, forecasting and integration into any mapping project. Many cities are embracing the concept of Geoinformatics for their day-to-day analysis, especially with governments encouraging public availability of spatial datasets. The global community is adopting this technique to collect all kinds of information in limited resource developing countries. For reliability, these techniques require that they are validated from time to time. Since the process of atmospheric pollution monitoring is thought-provoking due to its variability across locations, there is a need to spatially investigate the validity of remotely sensed data across every region. The techniques that are usually employed for a better understanding of air pollution pattern across a multiple of sampling locations are either the dispersion or interpolation models.

2.2.1. Interpolation models

Air pollution is a function of space. The majority of the existing air pollution monitoring approaches are designed in a way that the monitoring stations are usually positioned at intervals. The presence of spatial correlation in atmospheric pollutants provides the ideal interpolation for pollution mapping/prediction and valuable awareness on the structure of the air quality patterns (Moral et al., 2006). Interpolation models include Inverse Distance Weighting (IDW) and the Kriging technique (Shad et al., 2009).

The IDW interpolation model uses a simple mathematical computation to estimate the values of any point of interest. It interpolates the point of interest by assigning weights to values closer to that point of interest than values farther than the point of interest. This distance-dependent technique is usually achieved by introducing an inverse and non-linear weighting parameter (Equations 2.1 and 2.2) to the distance to a reference point (Syafei et al., 2013). These weights are computed by means of interpolation point distances.

$$\hat{Z}(S_o) = \left[\sum_{i=1}^{n} w(s_i) \times Z(s_i)\right] \div \sum_{i=1}^{n} w(s_i) \quad (2.1)$$

$$w(s_i) = Ps_i - s_o P^{-p} \quad (2.2)$$

The Kriging interpolation model estimates point values between available samples using a combined linear weighting system (Diem and Comrie, 2002). The technique has been used extensively for air quality data management due to its spatial continuity. Amongst these two models, the Kriging technique is the most adopted due to its ability to estimate the optimal values of its weights. A regular form of Kriging is the Ordinary Kriging (OK) described as follows:

$$Z(s) = \mu + \varepsilon'(s) \quad (2.3)$$

where μ denotes the fixed function (global mean) which is constant and $\varepsilon'(s)$ represents the stochastic part of variation which is spatially correlated.

The collective idea is that the predicted value Z(s) (e.g. pollutant concentration), at any location, will be attained as a weighted average of the nearest value (Bailey and Gatrell, 1996).

$$Z_{OK}(s_o) = \sum_{i=1}^{n} w_i(s_o) \times Z(s_i) = \lambda_o^T \times z \qquad (2.4)$$

λ_o denotes the vector of Kriging weights (w_i), Z represents the vector of sample observations (n) at primary locations.

The contrast of the Kriging to the IDW can be attributed to the fact that the Kriging technique generates interpolation errors and confidence intervals. This is achieved because it adopts the semi-variogram distance sample, the point difference of the observed values to describe interpolation weights and develop spatial correlations (Robinson and Metternicht, 2006). This is described in Equation 2.5 below.

$$\gamma(h) = \frac{1}{2} E\left[(z\,(s_i) - z\,(s_i + h))^2\right] \qquad (2.5)$$

where $z\,(s_i)$ represents the measured variable at selected sampled location assuming the variance of Z is constant, $z\,(s_i+h)$ represents the neighbouring value at distance h from s_i, h is the mean squared difference between observed values at z (s_i) and the observation value at z (s_i+h), all divided by half.

2.2.2. Multivariate statistical analysis

Outdoor air pollution investigation is a diverse area that has experienced a range of multivariate analysis applications. For the appraisal and prediction evaluation of the atmospheric pollution effects, this study adopted extensive forms of discrimination analysis. The statistical approaches include bias (Zeger et al., 2000), correlation coefficient (Statheropoulos et al., 1998), root mean squared error (Chai and Draxler, 2014), model efficiency (McCuen et al., 2006), linear regression (Zeger et al., 2000) and test of dataset normality (Leiva et al., 2010). Multivariate interpolation is another branch of multivariate analysis. It is useful for prediction and forecasting measured outdoor pollutants (Araki et al., 2015).

2.3. Atmospheric pollution monitoring procedure

2.3.1. Air pollution data quality

To efficiently monitor air pollution, the datasets to be acquired and utilized should be able to guarantee that it is of high standards. To make certain the amount of confidence in the datasets, statistical analysis is usually performed from which conclusions can be drawn. Most methodologies adopted when trying to enhance the quality of air pollution data across the monitoring networks are tasked with picking the ideal sampling frequency/resolution and ensuring the appropriate distribution of sampling locations. Exploratory techniques for probing the quality of any dataset include descriptive statistics and a host of other time-series assessment (Shumway and Stoffer, 2000). These methods can be utilized to evaluate the spatial and temporal correlation of air pollution datasets, especially during an experimental phase.

2.3.2. Ground-based data retrieval

The present state of awareness on urban pollution assessment shows a rising emphasis on anthropogenic emissions, which occurs at ground-level, resulting in significant population exposure. Due to the severity of this menace in the developing world, there is the need to embrace available cost-effective mobile pollution sensors. These devices assist in the measurement of air pollution level, that remains key, for any atmospheric pollution mitigation plan. These pollutant measurements also help in conducting high spatial and temporal variability feasibility studies on pollutant concentrations (Kumar et al., 2015). The paradigm of monitoring air pollution is changing from the conventional use of expensive, complex, equipment/laboratories to inexpensive, user-friendly, and handy air pollution sensors that provide efficient near-real-time resolution data, that will better safeguard of public health at an affordable cost (Snyder et al., 2013). Available portable gas monitors for air pollution studies include: MSA Altair gas detector (Shibata et al., 2015), Crowcon gasman (Kaur, 2007), MultiRAE gas monitor (Devi et al., 2013), BW Technologies GasAlert (Chai et al., 2010) and the Chinaway CW-HAT200 particulate counter (Liu et al., 2014). Multiple ground-based retrieval stations are assumed to represent a spatial exposure/pattern of pollutants (Engel-Cox et al., 2013). Spatial and temporal distribution of pollutants with sufficient accuracy is the key step for identifying pollution hot spots (Jiang et al., 2012), assessing human health risks, seasonal trend analysis and evaluating the air quality policy quantitatively (Araki et al., 2015).

2.3.3. Remote sensing (satellite) based data retrieval

For the past two decades, Earth-observing satellites have been designed for the purpose of detecting atmospheric air pollution at increased spatial and temporal scales (Streets et al., 2013). In this section, a concise review of the latest relevant satellite instruments designed by the United States National Aeronautical Space Agency (NASA) that have helped to improve the monitoring of atmospheric air pollution.

The NASA Earth Observation System (EOS) programme commenced in December 1999 with the launching of the Terra platform. In May 2002, the second EOS platform (Aqua) was launched. Two years later, the Aura satellite platform hosting the Ozone Monitoring Instrument (OMI) and the Tropospheric Emission Spectrometer (TES) was launched (Martin, 2008). The Terra platform featured three onboard sensors. They are The Measurements of Pollution in the Troposphere (MOPITT), the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging SpectroRadiometer (MISR) instruments. The MODIS and MISR measure PM and its optical effects (Kumar et al., 2015; Xiong et al., 2014) while the MOPITT sensor measures Carbon monoxide (Buchholz et al., 2017). The Aqua platform carried a second MODIS sensor and the Atmospheric Infrared Sounder (AIRS) sensor which collects CO emissions (Elliott et al., 2015). On the Aura platform, the OMI and TES instruments measure PM (Levelt et al., 2014) and CO (Luo et al., 2015) respectively.

2.4. Review of air pollution studies in Nigeria

2.4.1. Review methods

The search for literature was done in the English language using the Google Scholar database. The search keywords utilized include air pollution, air quality, air monitoring, respiratory health and Nigeria. A total of 318 journal articles were identified and retrieved. All the retrieved publications were vetted to eliminate duplicates. The relevant articles were manually sorted from the ensuing list. Three criteria were utilized for the selection: (1) internet available peer-reviewed articles in English language journals; (2) publications conducting air pollution and respiratory-related studies within Nigeria containing criteria air pollutants monitoring data and (3) additional literature were also obtained from the bibliographies of the chosen literature. All articles with the indistinct methodology or data analysis were excluded from the selection. We do note that some of the air pollution studies conducted within Nigeria may have not been electronically indexed.

2.4.2. Main findings of the reviewed air pollution studies in Nigeria

A total of 174 peer-reviewed journal articles were utilized in this review of air pollution studies within Nigeria. The search revealed that the first peer-reviewed article on air pollution studies in Nigeria was authored by Oluwande (1977). The literature revealed that air pollution studies became prominent in this millennium, with the majority conducted less than a decade ago (Figure 2.2).

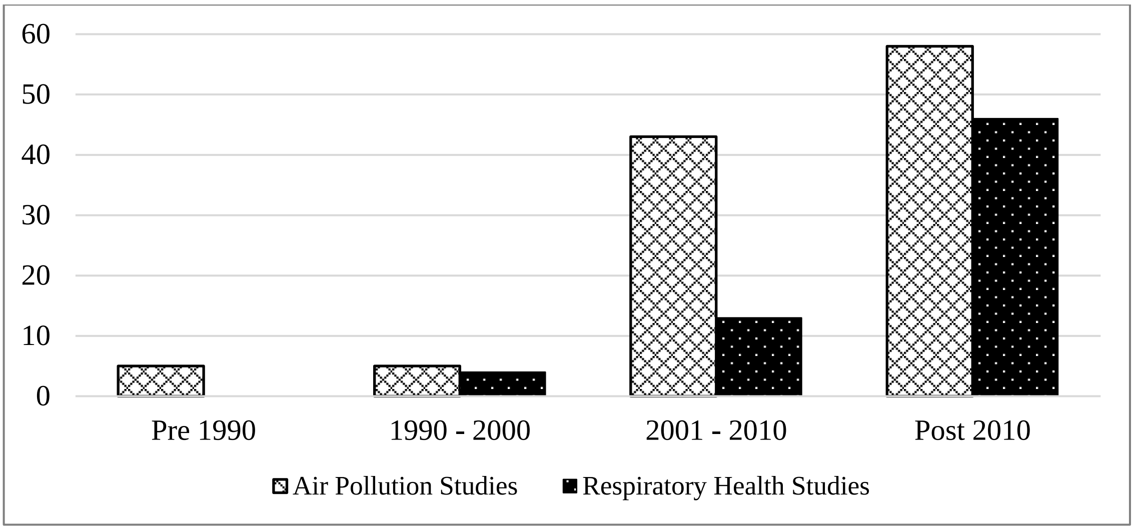


Figure 2.2. *Air pollution studies in Nigeria spanning the period of pre-1990 – post-2010*

The overall prevalence of air pollution studies in Nigeria across the 36 states of the country is displayed in Figure. 2.3. Seven states were identified to have no record of any air pollution study. A further breakdown (Figure 2.4) reveal that the South-West (SW) region recorded the highest number of researches for air pollution and respiratory-related studies with 44 per cent. It is followed by the South-South (SS) geopolitical zone with 27 per cent (Figure 2.4).

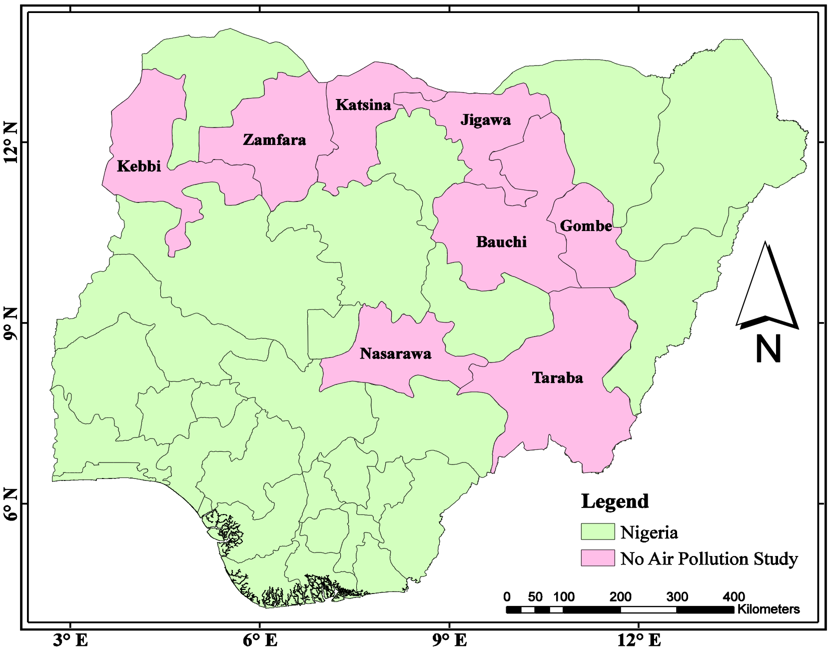


Figure 2.3. *Map of Nigeria showing the states with no review record of air pollution studies*

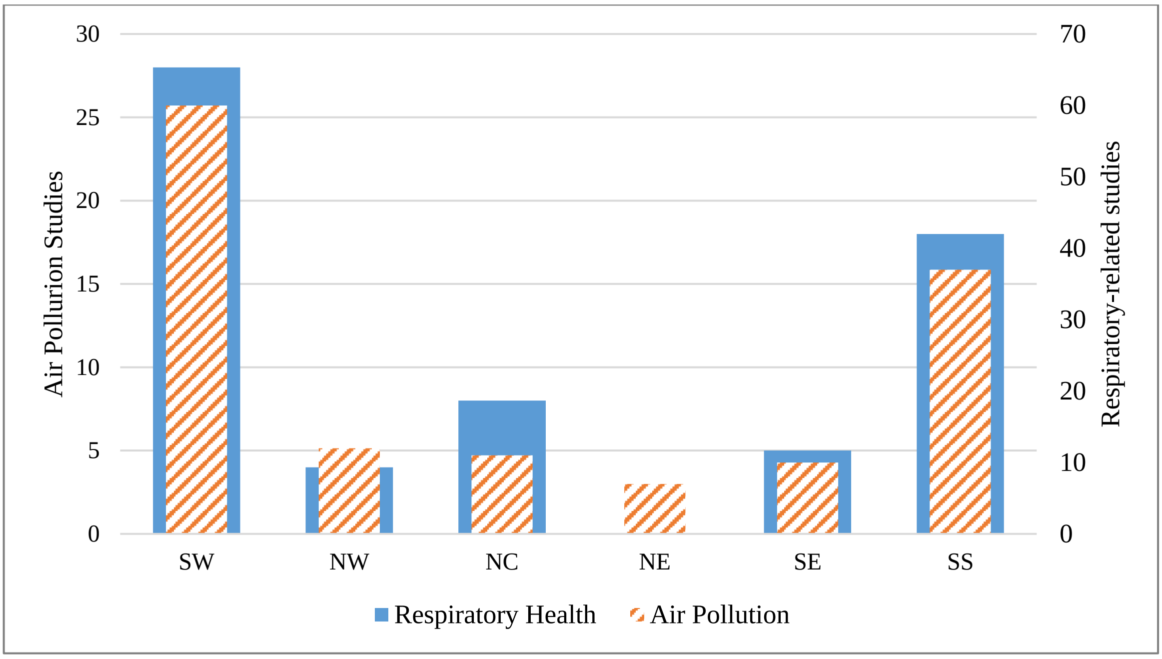


Figure 2.4. *Distribution of air pollution studies across Nigeria's geopolitical zones*

From the available literature, the air pollutants sampling techniques utilized are categorized into two. They are the ground mobile sampling (which accounts for 90.1 per cent of the entire literature) and the satellite remote sensing technique. The ground sampling technique is further sub-divided into direct reading and mobile indirect reading. Direct and indirect reading techniques signify that the pollutant concentration was observed directly on-site with the sampling instrument while for the indirect, pollutant samples were retrieved and returned to the laboratory for post-sampling processing. The direct reading technique accounted for 51.5 per cent. The literature review revealed that the majority of the sampling duration fell within the sampling duration of ≤1 month (Figure 2.5).

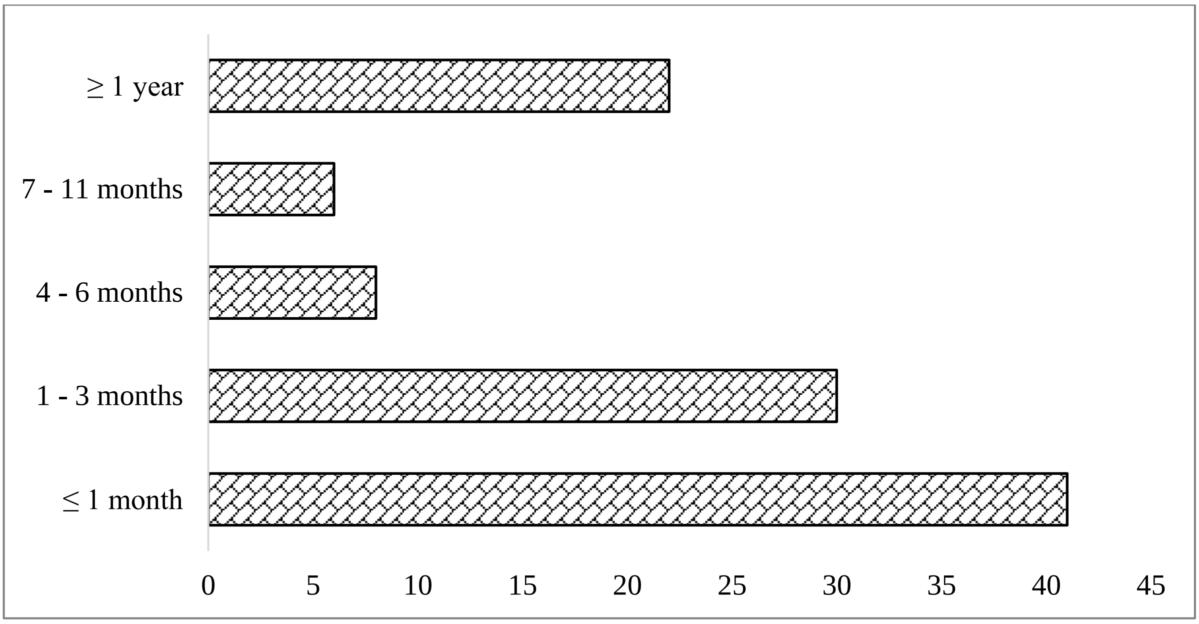


Figure 2.5. *Sampling time frequency of the air pollution studies*

The majority of the studies that covered a one-year period or more utilized the satellite remote sensing technique. No literature utilized the direct reading technique for a 1 year or more sample period. For the air pollution studies that took into consideration respiratory-related issues, literature revealed that cross-sectional questionnaires, health records, respondent blood samples, forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC) assessment techniques were adopted. While 61.9 and 30.2 per cent of the study population are adults and children, respectively. The remainder utilized a combination of both. For respiratory illness assessment, most of the literature utilized the cross-sectional questionnaire approach (Figure 2.6). The researches that utilized health records data were low and can be attributed to the tedious procedure of collating health record data since the majority of the health facilities store them away in hard copies.

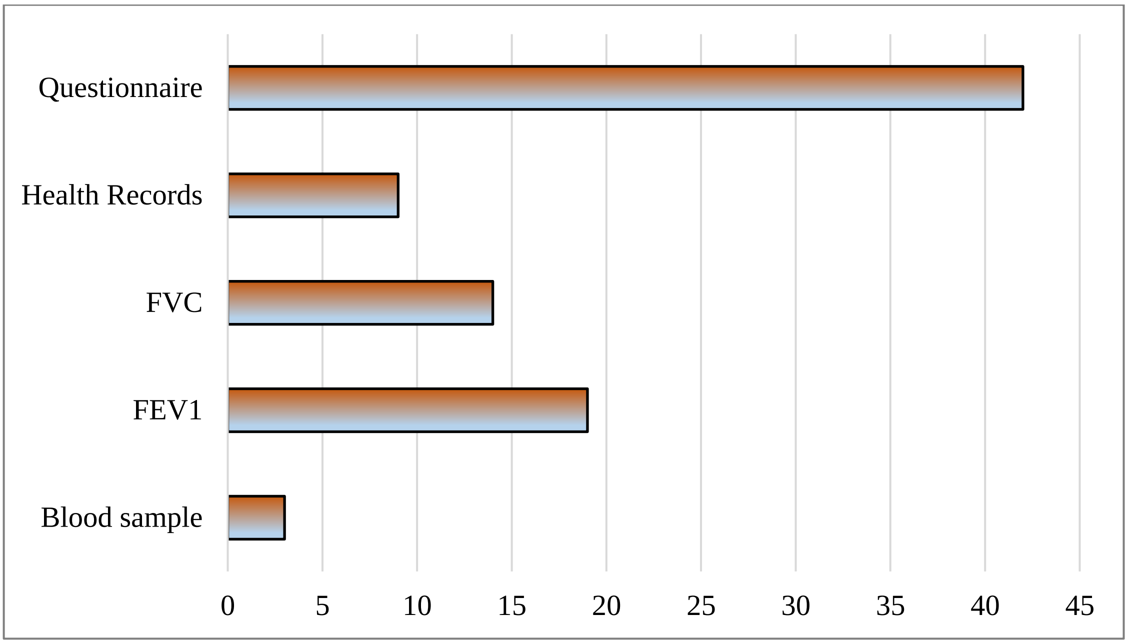


Figure 2.6. *Respiratory health assessment technique utilized in the literature*

2.5. Gaps in the present knowledge

The broader research area considered during this literature review was conceived from a goal to contribute towards solving the challenge of atmospheric pollution and climate change activities in the 21st century most especially for a limited resource country like Nigeria. From the review, we can evidently conclude that there was no electronically indexed study that utilized the NiMET reference station data, thus no validation ground monitoring techniques utilizing the NiMET stations. We also observed that the northern region of Nigeria had a lower count of atmospheric pollution studies, across the country. The gaps in the literature are:

i. There are limited time-series ground pollutant measurements for efficient air pollution appraisal across most Nigerian cities

ii. The contributory level of atmospheric pollutants in appraising the respiratory well-being of the exposed population has not been ascertained

iii. There is no attempt to evaluate the atmospheric relationship between ground pollutant measurements and collocating satellite retrieval estimates

iv. Finally, no attempt has been made to appraise the ability of signals from the available Nigerian GNSS network (NIGNET) for atmospheric pollution monitoring

2.6. Conclusions

The literature review outcome reveals that mitigation of air pollution remains a challenge in many Nigerian cities. This may perhaps be partly due to non-existent reference air monitoring facilities as well as minimal collaborative efforts among environmental policy makers, academic and research institutes leading to low research output on the collective use of modern pollution monitoring technologies. Additionally, the majority of the literature revealed that pollution sampling at ground-level did not go beyond 3 months. On the other hand, literature showed that mobile pollution sensor deployment is on the rise, thus critical as it affects the quality of data being collected. Since the deployment methods are most likely based on optimising a constrained cost role, global researches have revealed that there are available multi-satellite datasets that offer valuable atmospheric pollution information in high spatial and temporal resolutions. The majority of available literature that utilized the modern satellite pollution monitoring technology clearly highlighted the minimal availability of ground pollution data. Attempts to determine the association between ground-level pollutants and satellite predicted estimates in Nigerian cities have not been reported, thus should be encouraged. A comprehensive ground-level time-series pollution data can be integrated with population socio-economic factors and remotely sensed estimates to serve as background to guide Nigeria policymakers on the need to adopt and implement of a functional air pollution monitoring system across its cities.

References

1. Abam, F.I. & Unachukwu, G.O. 2009. Vehicular emissions and air quality standards in Nigeria. *European Journal of Science and Research,* 34(4): 550-560.
2. Adewunmi, R, Adewunmi, R., Obi, P. & Odumosu, A. 2015. P15 assessment of cumulative exposures of traffic wardens to vehicular emissions in Zaria, Nigeria. *Journal of Transport and Health,* 2(2): S71. https://doi.org/10.1016/j.jth.2015.04.474
3. Akande, J.M., Ajaka, E.O., Omosogbe, F.M. & Lawal, A.I. 2013. Environmental effects of processing marine clay in Olotu, Ondo State, Nigeria. *Civil and Environmental Research,* 3(2): 82-86.
4. Ana, G., Adeniji, B., Ige, O., Oluwole, O. & Olopade, C. 2013. Exposure to emissions from firewood cooking stove and the pulmonary health of women in Olorunda community, Ibadan, Nigeria. *Air Quality Atmosphere and Health,* 6(2): 465-471. https://doi.org/10.1007/s11869-012-0183-6
5. Araki, S., Yamamoto, K. & Kondo, A. 2015. Application of regression kriging to air pollutant concentrations in Japan with high spatial resolution. *Aerosol and Air Quality Research,* 15: 234-241. https://doi.org/10.4209/aaqr.2014.01.0011
6. Bailey, T.C. & Gatrell, A.C. 1996. Interactive spatial data analysis in medical geography. *Social Science and Medicine*, 42(6): 843-855. https://doi.org/10.1016/0277-9536(95)00183-2
7. Beychok, M.R. 2005. *Fundamentals of Stack Gas Dispersion* (4th Edition). Author-published. ISBN: 0-9644588-0-2
8. Buchholz, R.R., Deeter, M.N., Worden, H.M., Gille, J., Edwards, D.P., Hannigan, J.W., Jones, N.B., Paton-Walsh, C., Griffith, D.W., Smale, D. & Robinson, J. 2017. Validation of MOPITT carbon monoxide using ground-based Fourier transform infrared spectrometer data from NDACC. *Atmospheric Measurement Techniques*, 10(5): 1927-1956. https://doi.org/10.5194/amt-10-1927-2017
9. Chai, T. & Draxler, R.R. 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscience Model Development*, 7(3): 1247-1250. https://doi.org/10.5194/gmd-7-1247-2014
10. Diem, J.E. & Comrie, A.C. 2002. Predictive mapping of air pollution involving sparse spatial observations. *Environmental Pollution,* 119: 99-117. https://doi.org/10.1016/S0269-7491(01)00308-6
11. Dimari, G.A., Hati, S.S., Waziri, M. & Maitera, O.N. 2008. Pollution synergy from particulate matter sources: The Harmattan, fugitive dust and combustion emissions in Maiduguri Metropolis, Nigeria. *European Journal of Scientific Research*, 23(3): 465-473. https://doi.org/10.13140/2.1.3407.6160
12. Ediagbonya, T.F. & Tobin, A.E. 2013. Air pollution and respiratory morbidity in an urban area of Nigeria. *Greener Journal of Environmental Management and Public Safety*, 2(1): 10-15.
13. Elliott, D.A., Pagano, T.S., Aumann, H.H. & Broberg, S.E. 2015. Performance status of the AIRS instrument thirteen years after launch. In *SPIE Optical Engineering+ Applications* (pp. 961109-961109). International Society for Optics and Photonics.

14. ESRI (Environmental Systems Research Institute), 2007. GIS for Air Quality. Available from: https://www.esri.com/library/bestpractices/air-quality.pdf. Last access: November 2017.
15. Ite, A.E., Ogunkunle, C.O., Obadimu, C.O., Asuaiko, E.R. & Ibok, U.J. 2017. Particulate matter and staff exposure in an air-conditioned office in Akwa Ibom State University–Nigeria. *Journal of Atmospheric Pollution*, 5(1): 24-32.
16. Jerome, A. (2000). *Use of economic instruments for environmental management in Nigeria*. Paper presented at workshop on Environmental Management in Nigeria and Administration (NCEMA), 2000.
17. Jimmy, E.O., Solomon, M.S., Peter, A.I. & Asuquo, C. 2014. Environmental health implications of motorcycles emitted gases in a metropolitan Nigeria. *American Journal of Environmental Protection*, 2(1): 7-10. https://doi.org/10.12691/env-2-1-2
18. Koku, C.A. & Osuntogun, B.A. 2007. Environmental-impacts of road transportation in southwestern states of Nigeria. *Journal of Applied Sciences*, 7(16): 2536-2560.
19. Kumar, K.R., Yin, Y., Sivakumar, V., Kang, N., Yu, X., Diao, Y., Adesina, A.J. & Reddy, R.R. 2015. Aerosol climatology and discrimination of aerosol types retrieved from MODIS, MISR and OMI over Durban (29.88 S, 31.02 E), South Africa. *Atmospheric Environment*, 117: 9-18. https://doi.org/10.1016/j.atmosenv.2015.06.058
20. Leiva, V., Vilca, F., Balakrishnan, N. & Sanhueza, A. 2010. A skewed sinh-normal distribution and its properties and application to air pollution. *Communications in Statistics—Theory and Methods*, 39(3): 426-443. https://doi.org/10.1080/03610920903140171
21. Levelt, P., Veefkind, J.P., Bhartia, P.K., Joiner, J. & Tamminen, J. 2014. Ten Years of OMI Observations: A Unique Contribution to Air Quality, Ozone Layer and Climate Research from Space. In *AGU Fall Meeting Abstracts*.
22. Luo, M., Shephard, M.W., Cady-Pereira, K.E., Henze, D.K., Zhu, L., Bash, J.O., Pinder, R.W., Capps, S.L., Walker, J.T. & Jones, M.R. 2015. Satellite observations of tropospheric ammonia and carbon monoxide: Global distributions, regional correlations and comparisons to model simulations. *Atmospheric Environment*, 106: 262-277. https://doi.org/10.1016/j.atmosenv.2015.02.007
23. Martin, R.V. 2008. Satellite remote sensing of surface air quality. *Atmospheric Environment* 42: 7823-7843. https://doi.org/10.1016/j.atmosenv.2008.07.018
24. McCuen, R.H., Knight, Z. & Cutter, A.G. 2006. Evaluation of the Nash–Sutcliffe efficiency index. *Journal of Hydrologic Engineering*, 11(6): 597-602.
25. Moen, E. 2008. *Vehicle emissions and health impacts in Abuja, Nigeria*, [B.Sc. Dissertation] Rhodes Island, Browns University, Rhodes Island. Available from: http://envstudies.brown.edu/theses/archive20072008/ericamoenthesis.pdf. Last access: January 2012.
26. Mohammed, Y., Uzairu, A. & Ujoh, J.O. 2013. Determination of sulphur dioxide concentrations in ambient air of some selected traffic areas in Kaduna metropolis. *Research Journal of Applied Science Engineering Technology*, 6(16): 2923-2930.

27. Moral, F.J., Ivarez, P.A. & Canito, J.L. 2006. Mapping and hazard assessment of atmospheric pollution in a medium sized urban area using the Rasch model and geostatistics techniques, *Atmospheric Environment*, 40: 1408–1418. https://doi.org/10.1016/j.atmosenv.2005.10.054
28. NESREA (National *Environmental* Standards and Regulations Enforcement Agency), 2013. *Air quality control monitoring in the FCT*. Available from: http://www.nesrea.gov.ng/news/air-quality.php. Last access: November 2015.
29. Njoku, K.L., Rumide, T.J., Akinola, M.O., Adesuyi, A.A. & Jolaoso, A.O. 2016. Ambient air quality monitoring in metropolitan city of Lagos, Nigeria. *Journal of Applied Sciences and Environmental Management*, 20(1): 178-185. http://doi.org/10.4314/jasem.v20i1.21
30. Okunola, O.J., Uzairu, A., Gimba, C.E. & Ndukwe, G.I. 2012**.** Assessment of gaseous pollutants along high traffic roads in Kano, Nigeria. *International. Journal of Environmental Sustainability*, 1(1): 1-15.
31. Olumayede, E.G. & Okuo, J.M. 2013. Ambient air pollution and assessment of ozone creation potential for reactive volatile organic compounds in urban atmosphere of southwestern, Nigeria. *African Journal of Environmental Science and Technology*, 7(8) 815-823. https://doi.org/10.5897/AJEST11.167
32. Oluwande, P.A. 1977. Automobile traffic and air pollution in a developing country: an example of affluence-caused environmental problems. *International Journal of Environmental Studies*, 11(3): 197-203. https://doi.org/10.1080/00207237708737353
33. Oluwole, O., Arinola, G.O., Huo, D. & Olopade, C.O. 2017. Household biomass fuel use, asthma symptoms severity, and asthma under diagnosis in rural schoolchildren in Nigeria: a cross-sectional observational study. *BMC Pulmonary Medicine*, 17(1): 3. http://doi.org/10.1186/s12890-016-0352-8
34. Orogade, S.A., Owoade, K.O., Hopke, P.K., Adie, D.B., Ismail A. & Okuofu, C.A. 2016. Source apportionment for fine and coarse particulate matter in industrial areas of Kaduna, northern Nigeria. *Aerosol and Air Quality Research*, 16: 1179-1190. https://doi.org/10.4209/aaqr.2015.11.0636
35. Powell, H.L. 2012. *Estimating air pollution and its relationship with human health* (Doctoral dissertation, University of Glasgow).
36. Robinson, T.P. & Metternicht, G. 2006. Testing the performance of spatial interpolation techniques for mapping soil properties. *Computer and Electronics in Agriculture,* 50: 97-108. https://doi.org/10.1016/j.compag.2005.07.003
37. Schwela, D. (2010). *Global atmospheric pollution forum air pollution monitoring manual*, [online] Stockholm Environment Institute (SEI). Available from: http://www.sei-international.org/rapidc/gapforum/html/technical/monitoring/GAP_Forum_Monitoring_Manual_2010.pdf. Last access: November 2015.
38. Shad, R., Mesgari, M.S. & Shad, A. 2009. Predicting air pollution using fuzzy genetic linear membership kriging in GIS. *Computer Environment and Urban Systems,* 33(6): 472-481. https://doi.org/10.1016/j.compenvurbsys.2009.10.004
39. Shumway, R.H. & Stoffer, D.S. 2000. *Time series analysis and its applications*. Springer Verlag.

40. Statheropoulos, M., Vassiliadis, N. & Pappa, A. 1998. Principal component and canonical correlation analysis for examining air pollution and meteorological data. *Atmospheric Environment*, 32(6): 1087-1095. https://doi.org/10.1016/S1352-2310(97)00377-4
41. Streets, D.G., Canty, T., Carmichael, G.R., de Foy, B., Dickerson, R.R., Duncan, B.N., Edwards, D.P., Haynes, J.A., Heinze, D.K., Houyoux, M.R., Jacob, D.J., Krotkov, N.A., Lamsal, L.N., Liu, Y., Lu, Z., Martin, R.V., Pfister, G.G. Pinder, R.W., Salawitch, R.J. & Wecht, K.J. 2013. Emissions Estimation from Satellite Retrievals: A Review of Current Capability. *Atmospheric Environment*, 77: 1011-1042. https://dx.doi.org/10.1016/j.atmosenv.2013.05.051
42. Syafei, A.D., Fujiwara, A. & Zhang, J. 2013. A comparative study on NO concentration interpolation in Surabaya city. *Proceedings of the Eastern Asia Society for Transportation Studies*, 9: 1-13.
43. UNEP (United Nations Environment Programme), 2015. *Fuel Quality Progress in Nigeria for Nigeria National Air Quality Management Programme*. Federal Ministry of Environment. Available from: http://staging.unep.org/Transport/new/PCFV/pdf/2015_Ecowas_FuelQualityProgress_Emmanuel.pdf. Last access: October 2017.
44. WHO (World Health Organization), 2016. WHO's urban ambient air pollution database–update. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/AAP_database_summary_results_2016_v02.pdf. Last access: November 2017.
45. Xiong, X., Angal, A., Madhavan, S., Link, D., Geng, X., Wenny, B., Wu, A., Chen, H. & Salomonson, V. 2014. MODIS instrument operation and calibration improvements. In *Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International* (pp. 1385-1388). IEEE.
46. Yusuf, K.A., Oluwole, S., Abdulsalam, I.O. & Adewusi, G.R. 2013. Spatial patterns of urban air pollution in an Industrial estate, Lagos, Nigeria. *International Journal of Engineering Inventory*, 4: 1-9.
47. Zeger, S.L., Thomas, D., Dominici, F., Samet, J.M., Schwartz, J., Dockery, D. & Cohen, A. 2000. Exposure measurement error in time-series studies of air pollution: concepts and consequences. *Environmental Health Perspectives*, 108(5): 419. https://doi.org/10.1289/ehp.00108419

Chapter 3

Reviewing the local and global implications of air pollution trends in Zaria, northern Nigeria**

Abstract

Air pollution is an unnoticed problem in many Nigerian urban cities. This is mainly attributed to the usage of power generating sets, indiscriminate refuse burning, biomass consumption and import/recycle of timeworn automobiles, which dominates the Nigerian automobile fleet. Reduced economic infrastructure and the Nigerian climate, are a major factor for dense outdoor population activities. This is contributing to the increasing population health risk resulting from pollution exposure. The literature on the seasonal spatial-temporal distribution of air pollutants within Nigerian urban cities is presently scanty. This study evaluates the local and global implications of air pollution trends in northern Nigeria's educational hub. The study utilized validated cost-effective devices (MSA Altair 5x gas detector and the CW-HAT200 particulate counter) to assess the outdoor air quality in Zaria. The findings revealed the one-year day-time weighted average concentration level for CO, SO_2 $PM_{2.5}$ and PM_{10} as 29.22 ppm, 0.32 ppm, 219.73 μgm^{-3} and 451.96 μgm^{-3} respectively. These concentration levels were above the locally and globally stipulated air quality indices. In particular, the concentration levels of particulate matter pollutants ($PM_{2.5}$ and PM_{10}) were high enough to place Zaria amongst the World Health Organization's list of polluted cities. We are optimistic that these findings would instigate Nigerian policymakers to take decisive steps for air quality management across its cities.

***Keywords**: Air pollution; Air quality index; MSA Altair 5x gas detector; Chinaway CW-HAT200 particulate counter; Nigeria*

***This chapter is a formatted text of a peer-reviewed journal article described as follows:*

Aliyu, Y.A. & Botai, J.O. 2018. Reviewing the local and global implications of air pollution trends in Zaria, northern Nigeria. *Urban Climate*, 26: 51-59. https://doi.org/10.1016/j.uclim.2018.08.008

3.1. Introduction

Urban air pollution is a major ecological threat in most developing countries (Gorai et al., 2017). The consistent rise in greenhouse gas emissions is also intensifying and therefore affects the earth's climate system (Nsubuga et al., 2013). Studies have expressed concerns over outdoor air pollution especially since the anthropogenic sources in urban cities are positioned at ground level, thus aggregating the exposure profile of the population within (Aliyu et al., 2014; Patton et al., 2016).

In Africa, air quality studies are very challenging especially when it comes to accessing observed station series data. This is due to difficulties regarding the availability, accessibility and consistency of pollution datasets. Some of the cited studies revealed that they depended on remote sensing re-analysis data (e.g. top-down estimates), to fill this gap (DeMott et al., 2003; Hopkins et al., 2009; Marais et al., 2014; Marais and Chance, 2015). Proper management of city-scale air pollution can be complex, especially when there is no accurate and organized geospatial data for up-to-date identification of species pollutants, distribution of sample sites, regularity/period of sampling, sampling methods, infrastructural amenities, manpower and maintenance expenditures (Al-Awadi et al., 2015).

Nigeria is Africa's leading economy. It has a rapidly growing population with little information available about its air quality (Marais et al., 2014). Air pollution is a serious threat to public health in most Nigerian urban cities resulting from poorly managed private/commercial vehicles, unregulated recreational activities, trash burning, traffic congestion and biomass consumption. These often lead to high air pollution from unproductive fuel combustion in the socio-economical scheme (Hopkins et al., 2009; Aliyu et al., 2014). The challenges with urban air pollution across Nigerian urban cities are well-known, however, the attitude towards tackling it remains uncertain. Air quality studies across Nigerian cities demonstrate that pollution measurements are collected on a makeshift basis and in most cases, the monitoring network is scantily distributed. With such a situation, it is therefore difficult to develop an air quality management plan for its cities. To instigate this process, we appraise the ramifications of air quality for northern Nigeria's educational hub, Zaria.

The Intergovernmental Panel on Climate Change (IPCC) guideline continues to reflect on the need for policymakers to create emission inventories that are accurate and consistent. This will encourage continuous improvement of emission inventory compilation to international standards (Francesco et al., 2014). For effective air pollution management, there must be a collaboration between various key sector players including transportation, energy, water resources, urban planning and health (Hasenfratz et al., 2015). In addition, air pollution is usually regulated by air quality guidelines. Presently, organizations and countries e.g. World Health Organization (WHO); South African National Standards (SANS); Nigeria's Federal Environmental Protection Agency (FEPA), have adopted varying air quality indices (AQIs) (Table 3.1). These AQIs are centred on the ambient concentrations of criteria pollutants including, but not limited to – CO (Carbon Monoxide), PM_{10} (Particulate Matter of less than 10 µm in aerodynamic diameter) and SO_2 (Sulphur Dioxide), while in some cases $PM_{2.5}$ (less than 2.5 µm in aerodynamic diameter) is taken into consideration (Cairncross et al., 2007).

Table 3.1. *Guidelines/standards of selected air pollutants, modified after (FEPA, 1999; SANS, 2011; WHO, 2017)*

Pollutants	AQIs		
	WHO[a]	SANS[a]	FEPA[b]
CO	9 ppm	9 ppm	20 ppm
$PM_{2.5}$	25 µgm^{-3}	40 µgm^{-3}	-
PM_{10}	50 µgm^{-3}	75 µgm^{-3}	150 µgm^{-3}
SO_2	0.01 ppm	0.04 ppm	0.1 ppm

[a]24-hour average period for listed pollutants except for CO (8-hour); [b]time average is not indicated; ppm (parts per million); µg.m^{-3} (microgram per meter cube)

3.2. Materials and methods

3.2.1. Study area

Zaria metropolis is the educational hub of Northern Nigeria (Figure 3.1). It occupies an area of approximately 296.04 km^2. It has an estimated population of 938, 521 from the 2006 census considering its growth rate of 3.0 per cent per year. The study area is stationed at an altitude of mainly about 670 m above mean sea level (MSL) (NPC, 2010). Its climate is characterized by 2 seasons: dry (October – May) and rainy (June – September). The respective seasonal average values for dry and rainy seasons are precipitation (24.6 mm and 213.8 mm), minimum temperature (14.1°C and 19.5°C) and maximum temperature (35.2°C and 28.9°C) (Grace et al., 2015).

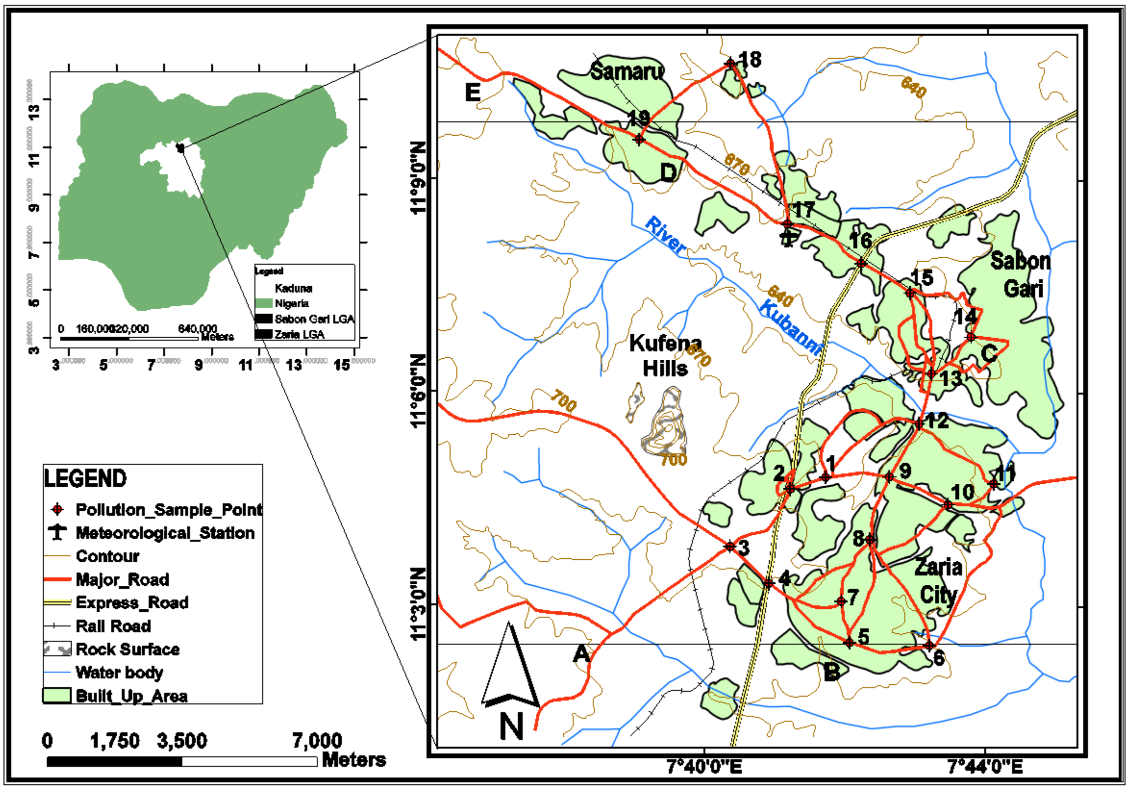


Figure 3.1. The study area highlighting the distribution of pollution sample sites. The sampling sites are described in Table 3.2.

***Table 3.2**. Description of pollution sample sites*

S/No	Description	Longitude (deg.)	Latitude (deg.)	Dense population activity
1	Kofar Kibo	7.695	11.080	Yes
2	Danmagaji, Wusasa	7.686	11.078	Yes
3	Madaci, Saye	7.673	11.064	No
4	Gwargwaje	7.682	11.054	Yes
5	Kofar Gayan	7.701	11.044	Yes
6	Kofar Kona	7.720	11.041	No
7	Zaria City Market	7.699	11.051	Yes
8	Babban Dodo	7.706	11.066	Yes
9	Kofar Doka	7.710	11.081	Yes
10	Banzazzau	7.725	11.074	Yes
11	FCE/Ungwan Kaya	7.735	11.079	Yes
12	Agwaro, Tudun Wada	7.717	11.093	Yes
13	PZ	7.721	11.104	Yes
14	Sabon Gari Market	7.730	11.113	Yes
15	MTD	7.715	11.124	Yes
16	Kwangila Bridge	7.703	11.130	Yes
17	Aviation by NITT Road	7.686	11.139	Yes
18	Basawa by Hayin Dogo	7.672	11.177	No
19	Samaru Market	7.651	11.159	Yes

3.2.2. Method and instrumentation

The nineteen sampling sites were identified across the study area (Table 3.2). All the sites are located along major road intersections. 16 sites are positioned within dense population activities which cut across the residential and commercial settlements, while the remaining 3 control sites are positioned strategically in the outskirts of the city with minimal population activity. The control sites were used to aid in result comparison. The most convenient route across the 19 sample stations for effective cost and timing was identified and tagged serially as 1 – 19 (Figure 3.1). This covers a distance of 42.8 km.

Four criteria air pollutants CO, SO_2, $PM_{2.5}$, and PM_{10} were monitored to achieve study objectives. The MSA Altair 5x gas detector (Figure 3.2a) and CW-HAT200 particulate counter (Figure 3.2b) were used to collect ground-level criteria pollutant concentrations, for December 2015 – November 2016. Ground in-situ samples were retrieved daily across three epochs. They are morning (0730 – 0845 hrs), afternoon (1300 – 1415 hrs) and evening (1700 – 1815 hrs). The reason for adopting these epochs is to ensure adequate representation of pollution-related activities at peak (morning and evening) and less peak (afternoon) periods (Pattinson et al., 2014; Wang et al., 2014; Yazdi et al., 2015). The observed concentration levels for the criteria pollutants were recorded based on instrument configuration (Table 3.3). To ensure assurance and control of data quality, detectors were calibrated using the procedures described in the producer manual. The instrument background and pump flow were also examined prior to conducting each monitoring session. Pollutant concentration levels for CO and SO_2 were obtained using the MSA Altair 5x in parts per million (ppm) units, while the CW-HAT200 collected particulate matter ($PM_{2.5}$ and PM_{10}) in microgram per meter cube (μg m^{-3}). The day-time observations were collected with devices positioned at 1.5m above ground-level (the average height of an adult).

(a) (b)

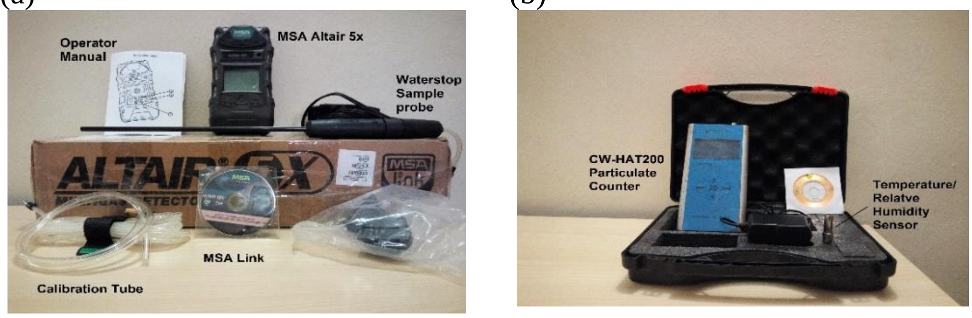


Figure 3.2. *Portable air pollutant detectors (a) MSA Altair 5x gas detector; (b) Chinaway CW-HAT200) particulate counter*

Table 3.3. *Specifications of portable pollutant monitors utilized for the study*

Specifications	MSA Altair 5x gas detector[a]	Chinaway CW-HAT200 particle counter
Dimension (cm)	17 (H) x 8.94 (W) x 4.88 (D)	18 (H) x 9.3 (W) x 4.8 (D)
Weight (kg)	0.45	0.60
Measuring method	Internal pump; Catalytic/electrochemical sensor	Internal pump; laser light scattering
Pollutant measured	CO; SO_2; H_2S; LEL (Combustible)	$PM_{2.5}$, PM_{10}
Concentration range	CO (0 - 500 ppm) SO_2 (0 - 25 ppm) H_2S (0 - 100 ppm) LEL (0 - 100 %)	$PM_{2.5}$ (0 - 500 µgm^{-3}) PM_{10} (0 - 1000 µgm^{-3})
Sample/response time	CO (15 secs) SO_2 (20 secs) H_2S (15 secs)	$PM_{2.5}$ (60 secs) PM_{10} (60 secs)
Accuracy	±10% of reading	±5% of reading
Operating temperature	-10 °C to 40 °C	5 °C to 45 °C
Operating humidity	15 - 90% RH	<90% RH
Calibration due	6 months	1 year
Battery	Rechargeable lithium-ion	Rechargeable lithium-ion polymer
Display	Monochrome	LCD
Certification	CE, UL, CSA, IEC, IP	CE

[a]Instrument re-calibration was carried out in January 2016 and June 2016 (6 months' intervals after factory calibration) using span calibration mixed gas specifications: CO – 50 ppm; SO_2 – 5 ppm; H_2S – 15 ppm; LEL – 58 %.

3.2.3. Statistical analysis

The observed data were entered and analysed in Microsoft Excel 2013, SPSS version 18 and Matlab. The geostatistical analysis was conducted using the Surfer 8 software. The day-time weighted average (Llanes, 2016) for criteria pollutants concentrations were adopted to compute the 1-year running average. The outdoor pollution exposure categories were determined using the WHO, FEPA and SANS stipulated limits.

3.3. Results and discussion

The results highlight the weighted day-time average of criteria pollutants (CO, SO_2, $PM_{2.5}$ and PM_{10}) obtained in Zaria from December 2015 - November 2016. Table 3.4 presents the descriptive statistics of criteria pollutants concentrations averaged across the various seasons of the study period. The 1-year averaged concentration values of criteria pollutants reveal that CO, SO_2, $PM_{2.5}$ and PM_{10} recorded 29.22 ppm, 0.32 ppm, 219.73 μgm^{-3} and 451.96 μgm^{-3} respectively. The concentration level for observed criteria pollutants was lowest during the December-January-February (harmattan) season. This can be attributed to the restricted outdoor activities due to low ambient temperature, especially during morning and evening periods. Another factor is the windy harmattan season which quickly disperses pollutant emissions. Correlation values between the observed criteria pollutants averaged 0.985, 0.988, 0.988 and 0.986 for CO, SO_2, $PM_{2.5}$ and PM_{10}. They were all significant at the 0.01 level.

Table 3.4. *Descriptive statistics of criteria pollutants: CO, SO_2, $PM_{2.5}$ and PM_{10} in Zaria metropolis in 2015 – 2016 (N = 19, 104)*

Criteria Pollutants		Mean	SD	Median	Q1	Q3	Min[a]	Max
CO (ppm)	Whole Year	29.22	28.28	23.0	12.0	38.0	0.0	413.0
	DJF	20.34	20.09	16.0	6.0	29.0	0.0	269.0
	MAM	34.33	30.20	28.0	17.0	42.0	0.0	407.0
	JJA	34.20	32.24	27.0	14.0	44.0	0.0	386.0
	SON	28.00	27.14	23.0	12.0	36.0	0.0	413.0
SO_2 (ppm)	Whole Year	0.32	0.26	0.20	0.10	0.40	0.0	3.50
	DJF	0.28	0.25	0.10	0.10	0.30	0.0	1.70
	MAM	0.21	0.17	0.20	0.10	0.40	0.0	3.50
	JJA	0.37	0.30	0.30	0.10	0.50	0.0	3.20
	SON	0.42	0.27	0.40	0.20	0.60	0.1	2.80
$PM_{2.5}$ (μgm^{-3})	Whole Year	219.73	123.46	197.0	127.0	304.0	6.0	500.0[b]
	DJF	196.15	103.95	173.0	118.0	250.5	11.0	500.0[b]
	MAM	216.36	122.09	197.0	123.0	300.0	9.0	500.0[b]
	JJA	190.40	123.42	181.0	106.0	277.0	6.0	500.0[b]
	SON	276.01	130.64	261.0	172.0	371.0	7.0	500.0[b]
PM_{10} (μgm^{-3})	Whole Year	451.96	251.42	403.0	259.0	615.0	12.0	1000.0[b]
	DJF	401.82	213.45	350.0	243.0	505.0	16.0	1000.0[b]
	MAM	442.45	248.13	405.0	250.0	608.0	17.0	1000.0[b]
	JJA	405.72	250.98	363.0	214.0	561.0	12.0	1000.0[b]
	SON	557.58	265.89	529.0	349.3	758.0	18..0	1000.0[b]

[a] values recorded mostly at control sites, [b] maximum concentration range for CW-HAT200 particulate counter

Figure 3.3 displays the time-series plots of criteria pollutants for control site 6 and two other sites (9 and 15). The FEPA/SANS/WHO standards/guidelines are introduced to compare the range of ground pollutant measurements across the 19 sampling sites (Figure 3.4). Acknowledging the discrepancies, this aims to enlighten Nigeria's policymakers on how the range of observed pollutant measurements within its territory, fares with recognized guidelines/standards. Site 14 recorded the highest concentration levels for the criteria pollutants studied. This could be attributed to the site being positioned at the study area's main market. The average concentration of CO measured was above WHO stipulated limit in 16 of the 19 sample sites; FEPA limit (in 15 sample sites) and 10 sites exceeded the SANS limit. The averaged SO_2 and PM_{10} levels were above WHO, FEPA and SANS limit in all the sampling sites. Averaged $PM_{2.5}$ concentrations were also above WHO limit in all the sample sites (Nigeria's FEPA and South Africa's SANS guidelines do not have specified threshold for $PM_{2.5}$); PM_{10} was above WHO, FEPA and SANS limit in all the sites (Figure 3.4). The predicted spatial distribution of criteria pollutants from the network relationship over the 19 sample sites is also displayed in Figure 3.4. The pollution map process was achieved by averaging the spatiotemporal pollutant concentrations based on the Kriging function (Araki et al., 2015). This spatial pollution distribution is often used for predicting air pollutant measurements over unmeasured locations (Contreras and Ferri, 2016).

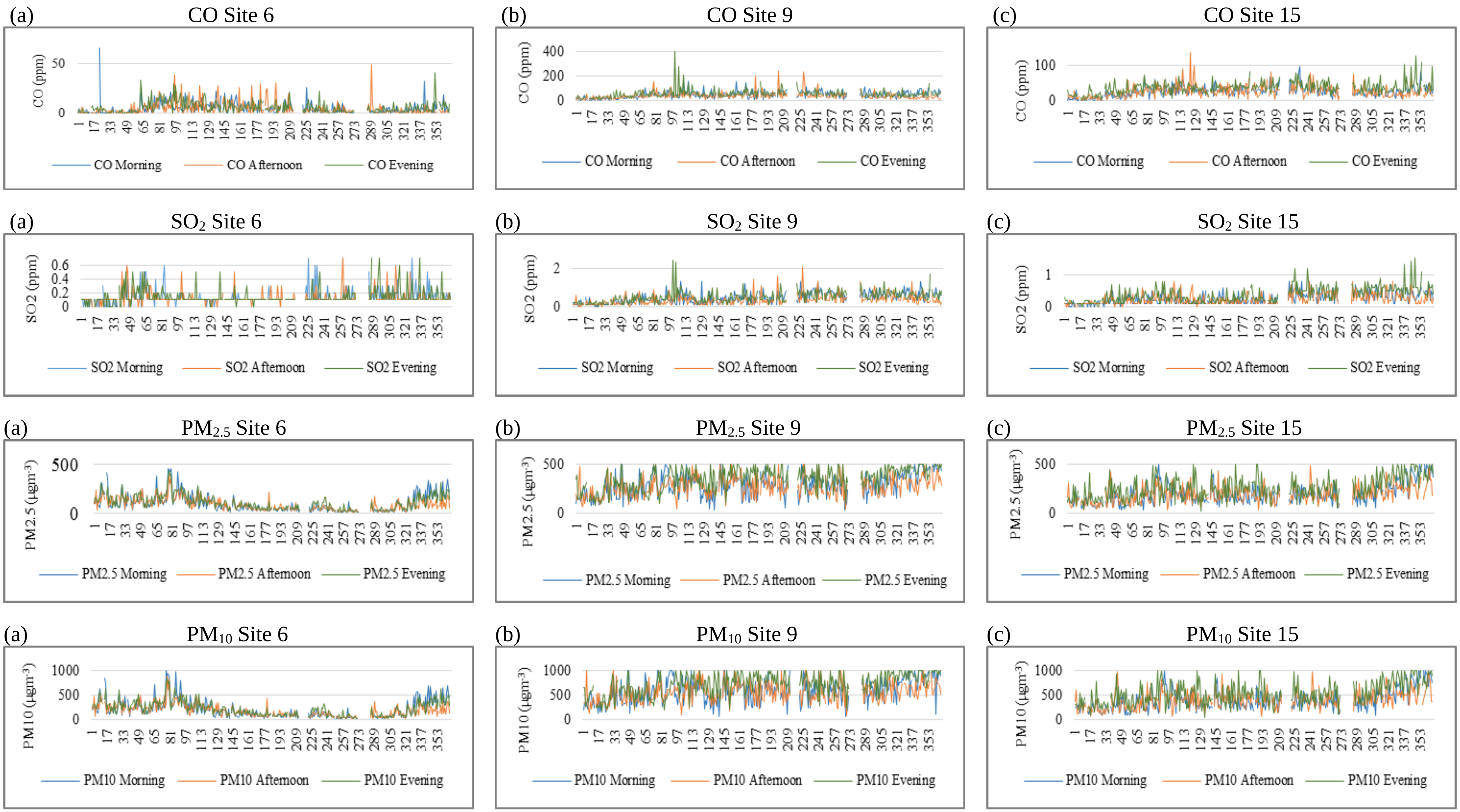


***Figure 3.3**. Time-series of criteria pollutants (CO, SO_2, $PM_{2.5}$ and PM_{10}) concentrations for randomly selected (a) site 6 (b) site 9 and (c) site 15 for the 366 days of the study period*

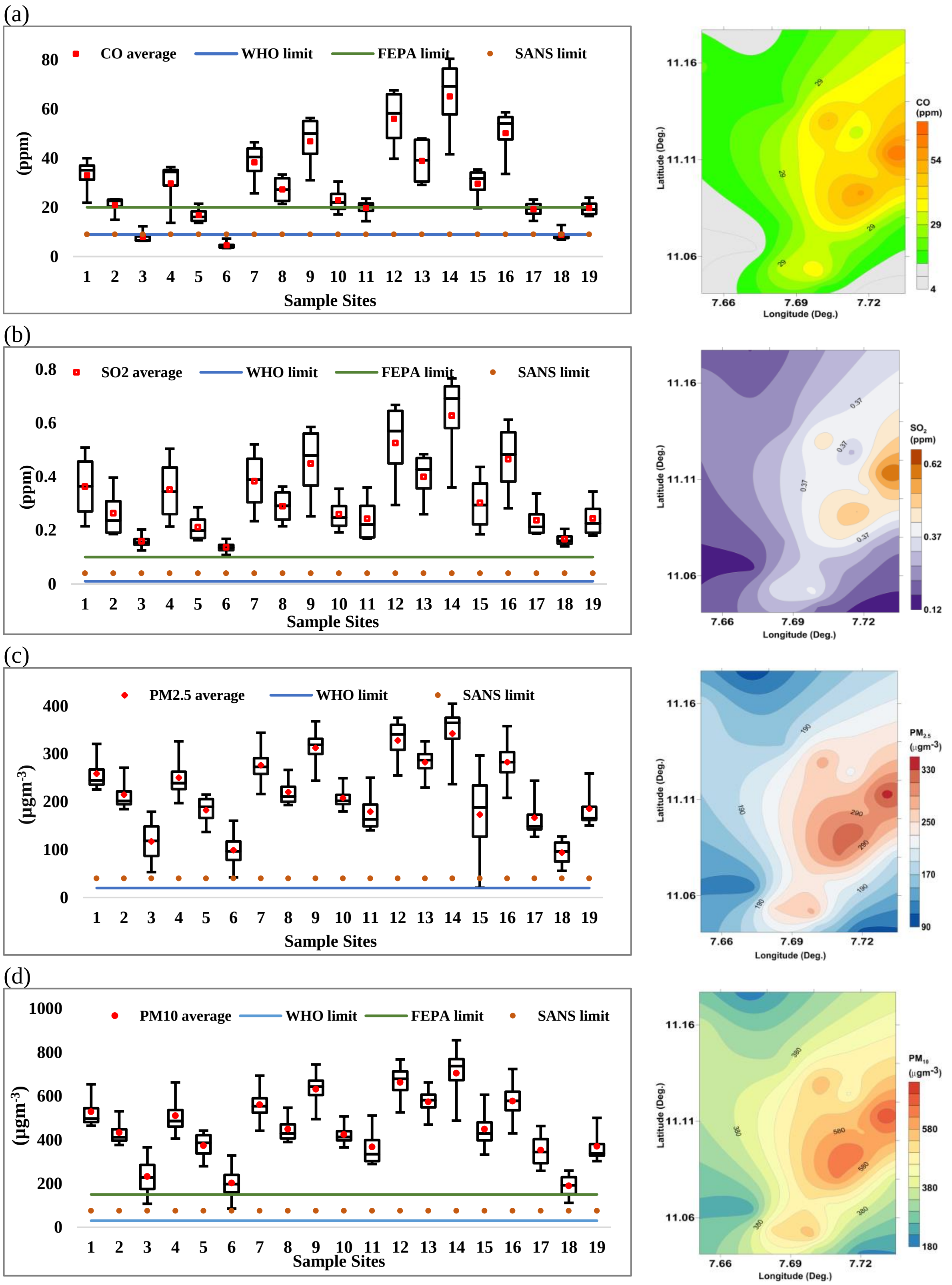
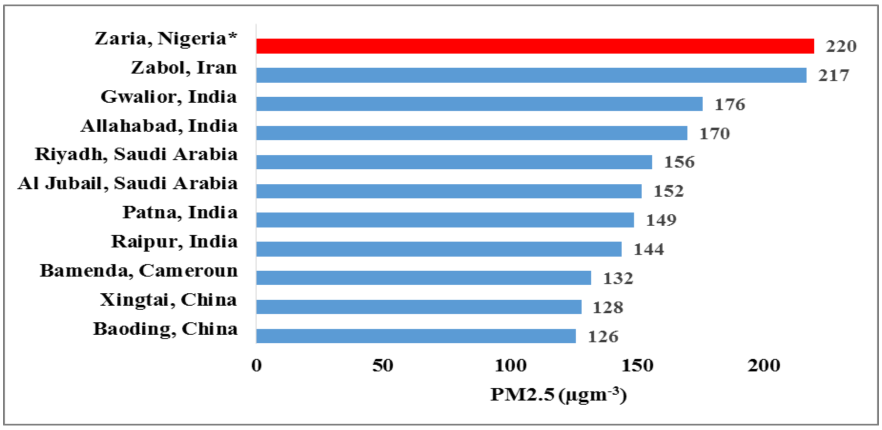


Figure 3.4. *Box plots of pollutant concentrations from the 19 sample sites showing the performance against the WHO/FEPA/SANS stipulated limits and the predicted exposure maps in 2015 – 2016 (a) CO (b) SO_2 (c) $PM_{2.5}$ (d) PM_{10} (Sites 3, 6 and 18 are control sites)*

Taking into consideration, the global ambient air pollution update (WHO, 2016) in addition to the observed yearly day-time average concentration level for $PM_{2.5}$ and PM_{10} as 219.73 µgm^{-3} and 451.96 µgm^{-3} respectively revealed by our study, we can categorically report that the study area, Zaria metropolis, is a major contender for the World's top 5 polluted cities (Figures 3.5a and b).

(a)



(b)

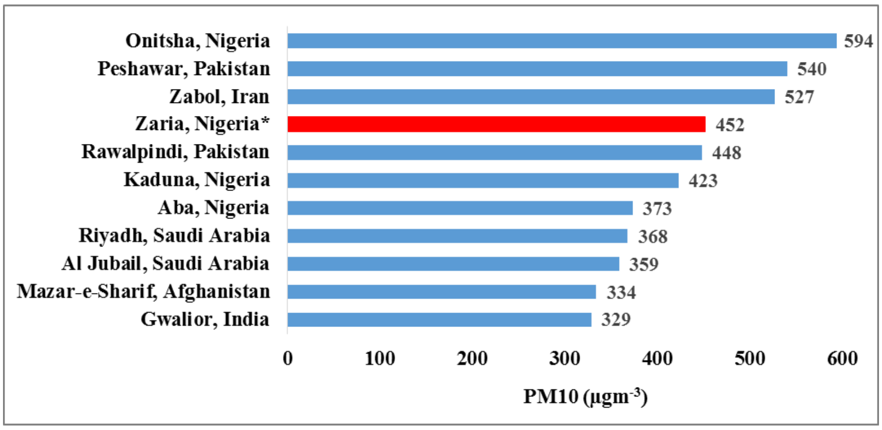


Figure 3.5. *The 1-year weighted average of measurement $PM_{2.5}$ (a) and PM_{10} (b) for Zaria, in contrast with the 10 most polluted cities of the World. This is modified after the (WHO 2016). *Zaria is placed in the 1st and 4th position respectively.*

3.3.1. Instrument reliability

Owing to the unavailability of real-time reference air pollution monitors within the study region, the devices were validated the portable pollutants monitors using the WHO air filter sampling model (Equation 3.1). To validate the portable devices, total suspended particulates were collected at two distinct sample test stations at 1.5m above existing ground-level. One of the sample sites had dense outdoor traffic/population activity and the other had minimal traffic/population activity (control site). The validation samples and synchronized portable monitor measurements were obtained on Mondays, Wednesdays, Fridays and Sundays in November 2015 across three periods, that are, morning, afternoon and evening. Total suspended particulates are described as particulate fraction ranging from 0.1 µm to about 100 µm in size (diameters). Particulates matter $PM_{2.5}$ (diameter less than 2.5 µm) and PM_{10} (diameter less than 10 µm) fall within the specified range. Based on Brook et al. (1997) which identified significant relationship between total suspended particulates, PM_{10} and $PM_{2.5}$ and Guo et al. (2017) which reported that there is a significant correlation among pollutant emissions resulting from common source, the study adopted the WHO air sampling filter technique for the validation of the CW-HAT200 particulate counter and MSA Altair 5x multi-gas detector measurements. Equation 3.1 describes the WHO air sample model technique (Efe and Efe 2008).

$$Total\ Suspended\ Particulates\ (\mu gm^{-3}) = \frac{M_S - M_O}{V} \quad (3.1)$$

Where *Mo* is the mass of filter paper prior to sampling, *Ms* is the mass filter paper after sampling, *V* is the TSP volume. To determine the concentration (μgm^{-3}), model equation 1 was divided by the sample time (in hours).

Using the WHO air filter sample model, validation samples were collected individually on filter papers and collocating pollutant measurements with the portable device over the sample duration. The particulate filter samples were processed in the laboratory to obtain their individual concentrations using Equation 3.1. The 102 filter papers had an equal dimension (5in x5in). The gravimetric mass was obtained using a semi-micro analytical balance. A graduated 20mL test-tube was utilized to determine the volume. the TSP samples were mixed with 10mL of water and the resulting rise in volume was recorded.

The filter sample results were then analysed with the separately recorded collocating pollutant measurements from the portable devices. The collocating measurements were then analysed using linear regression and bias, for the validation of the portable monitors. The analysis is described in Figures 3.6 and 3.7 below. The observed measurements for the validation procedure were normal distributed [skewness (-0.334); kurtosis (0.301)].

The study adopted two performance indicators for the purpose of validating the portable pollutant instrument. The performance indicators are the Bland-Altman agreement plot and the coefficient of determination (R^2). The Bland-Altman plot evaluates the systematic bias between the two measurements techniques while the coefficient of determination indicates how strongly related the pair(s) of variables are. The Bland-Altman agreement plot can be seen in Figure 3.6.

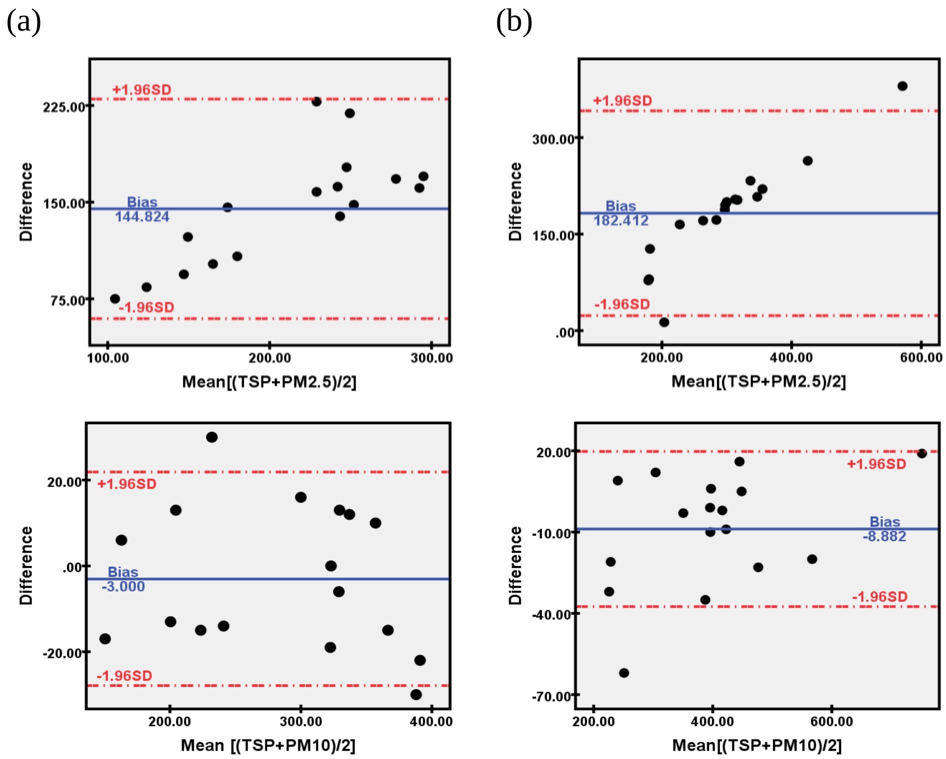
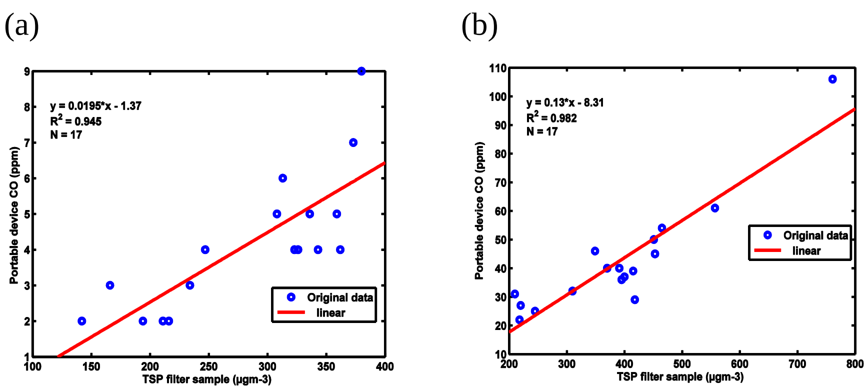


Figure 3.6. *Bland-Altman bias plot highlighting the agreement of observed validation measurements ($PM_{2.5}$ and PM_{10}) within the 95% confidence interval. (a) a control site (b) densely populated site*



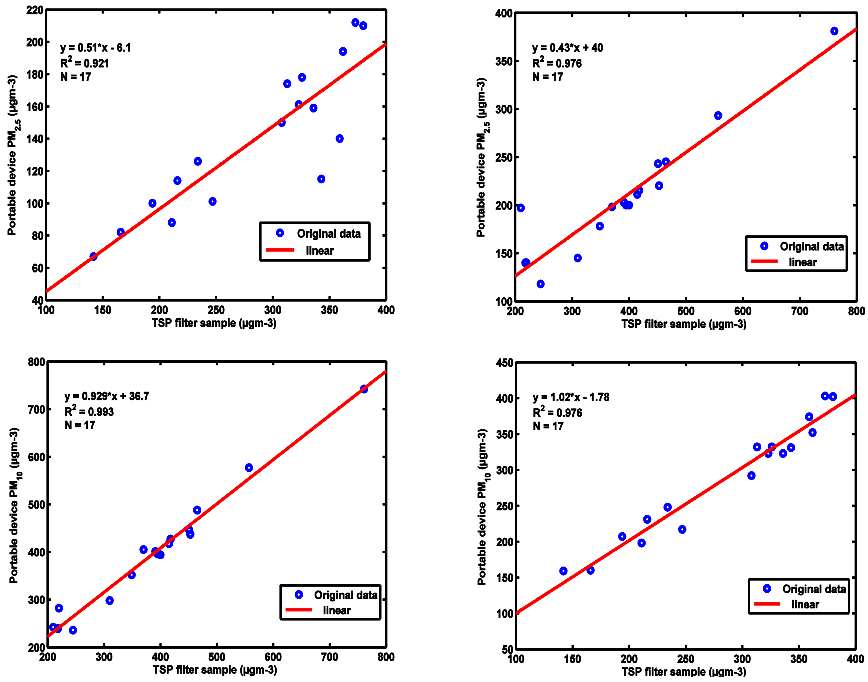


Figure 3.7. *Scatter plots showing the linear regression and coefficient of determination between the TSP and the portable monitor samples, (a) control site, (b) densely populated site*

Additionally, studies have evaluated the reliability of this low-power and relatively low-cost pollutant sensors for air pollution monitoring application. They have been adjudged to have acceptable potential when compared to reference monitoring instruments (Walker, 2012; Lin et al., 2015; Liu et al., 2014; Mishra et al., 2015; Shibata et al., 2015; Li and Biswas, 2017). However, considering that the study area has no existing reference pollution monitoring stations, we decided to adopt validated theories on air pollution contributes to global warming (Hansen et al., 2000; Duan et al., 2017). We utilized the retrieved criteria pollutant concentrations for analysis with the independent collocating ground air temperature and land surface temperature (LST) data for the study period. The ground air temperature data are collected using the Casella and Co. wall thermometer stationed at the Nigerian Meteorological Agency (NiMET) Zaria office, while the LST were extracted from Landsat 8. This is a unique approach. For the LST, the Landsat 8 at Path/Row 189/52 (which collocates with image tile covering the area of interest) was downloaded from the USGS website (https://earthexplorer.usgs.gov/). The criterion of Landsat 8 image file was set at cloud cover of less than 10 per cent. The Landsat scene information is described in Table 3.5.

Table 3.5. *Landsat image parameters which fulfilled the criteria for the study period of interest*

Acquisition date	Scene ID	Scene centre time (GMT)	Cloud cover (%)	Sun Azimuth (deg.)	Sun elevation (deg.)
10-Dec-15	LC81890522015344LGN00	09:49:29	4.41	146.47	48.65
11-Jan-16	LC81890522016011LGN00	09:49:27	0.01	141.42	47.28
12-Feb-16	LC81890522016043LGN00	09:49:20	0.03	130.87	51.81
28-Feb-16	LC81890522016059LGN00	09:49:16	0.01	129.59	55.58
31-Mar-16	LC81890522016091LGN00	09:49:02	7.56	103.26	62.99
16-Apr-16	LC81890522016107LGN00	09:48:57	0.50	90.34	65.17
02-May-16	LC81890522016123LGN00	09:49:00	5.10	77.74	65.76
25-Oct-16	LC81890522016299LGN00	09:49:44	0.01	138.01	58.21
10-Nov-16	LC81890522016315LGN00	09:49:42	0.00	143.79	54.37
26-Nov-16	LC81890522016331LGN00	09:49:43	0.89	146.36	50.87

The LST extracted from Landsat 8 OLI and TIRS images was achieved using thermal bands 10 and 11, which retrieve information at 100-meter resolution but are resampled to 30-meter for data delivery. LST was retrieved from thermal bands 10 and 11 using ArcGIS 10.2.2 software with Equations (3.2 - 3.4) below.

$$LST = [T / 1 + w \times (T / p) \times \ln(e)] \tag{3.2}$$

where T is satellite brightness temperature derived from inversion of Planck's Law (Equation 3.3); w is the wavelength of emittance (11.5 µm); p is 14380 and e is the land surface emissivity derived from normalized vegetation difference index (NDVI).

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \tag{3.3}$$

where K_2 and K_1 are the band specific thermal conversion constant for thermal bands, 1321.0789 and 774.8853 respectively; L_λ is top of atmosphere radiance described in Equation 3.4.

$$L_\lambda = M_L \times Q_{CAL} + A_L \tag{3.4}$$

where L_λ is top of atmosphere radiance; M_L is 0.0003342 (radiance multiplicative scaling factor for thermal bands); Q_{CAL} is the quantized digital number; A_L is 0.1 (radiance additive scaling factor for thermal bands).

For improvement of reliability, the 10 LSTs days derived from the Landsat 8 thermal bands were first correlated with collocating day-time ground air temperature data and then the weighted averaged pollutant measurements. The correlation coefficient revealed a compelling relationship between the Landsat 8 retrieved LST with ground air temperature and pollutant concentration (Figure 3.8). The analysis showed that ground air temperature and Landsat LST correlated highest as expected (R = 0.94), then followed by PM_{10} (R = 0.91) in Figure 3.8b. Considering the limitations within the study area, this approach to utilize independent datasets was adopted to further give confidence in the reliability of the sensor measurements. These coefficient values certified the reliability of the portable pollutant monitors.

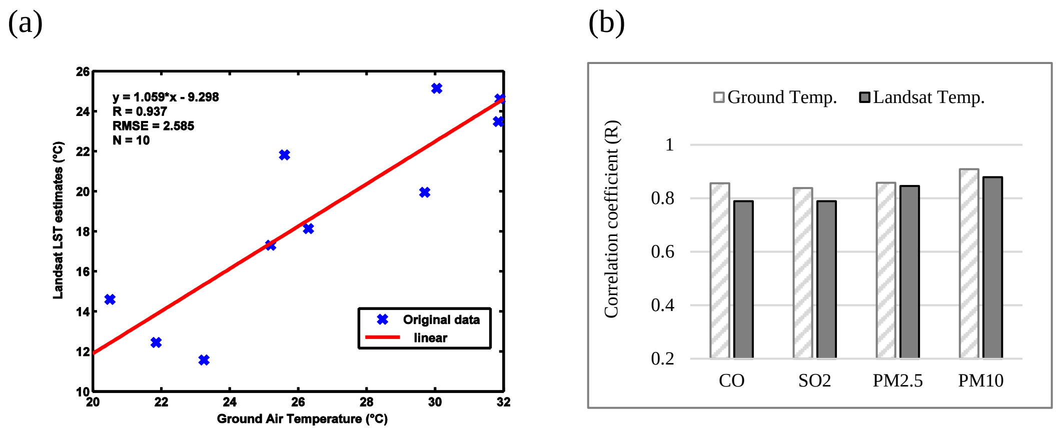


Figure 3.8. *The correlation coefficient between (a) ground air temperatures with Landsat LST estimates; (b) observed ground pollution measurements and ground temperature/Landsat LST confirming instrument reliability*

3.4. Conclusions

There is a need for Nigeria to improve its management of air pollution. This conclusion is based on the alarming results revealed by this study. The study revealed a one-year day-time weighted average of 29.22 ppm for CO, 0.32 ppm for SO_2, 219.73 μgm^{-3} for $PM_{2.5}$ and 451.96 μgm^{-3} for PM_{10}. The recorded $PM_{2.5}$ and PM_{10} pollutants sadly predict Zaria metropolis, as a major contender for the top five of the World Health Organization's most polluted cities (Figure 3.5). Measured concentration levels of CO were above WHO, FEPA and SANS stipulated limit in most of the sample sites; SO_2, $PM_{2.5}$ and PM_{10} concentration levels were above WHO, FEPA and SANS limit in all the sites. The need for in-situ pollution data in Nigerian cities cannot be over-emphasized. With the disturbing findings of this study, other fields of study that should be explored include the population health risk due to air pollution exposure and existing remote sensing capabilities for air pollution monitoring.

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References

1. Al-Awadi, L.T., Popov, V. & Khan, A.R. 2015. Seasonal effects of major primary pollutants in Ali Sabah Al-Salem residential area in Kuwait. *International Journal of Environmental Technology and Management,* 18(1): 54-82. https://doi.org/10.1504/IJETM.2015.068417
2. Aliyu, Y.A., Musa, I.J. & Jeb, D.N. 2014. Geostatistics of pollutant gases along high traffic points in urban Zaria, Nigeria. *International Journal of Geomatics Geosciences,* 5(1): 19-31.
3. Araki, S., Yamamoto, K. & Kondo, A. 2015. Application of regression kriging to air pollutant concentrations in Japan with high spatial resolution. *Aerosol and Air Quality Research,* 15: 234-241. https://doi.org/10.4209/aaqr.2014.01.0011
4. Brook, J.R., Dann, T.F. & Burnett, R.T. 1997. The relationship among TSP, PM10, PM2. 5, and inorganic constituents of atmospheric participate matter at multiple Canadian locations. *Journal of the Air and Waste Management Association,* 47(1): 2-19. https://doi.org/10.1080/10473289.1997.10464407
5. Cairncross, E.K., John, J. & Zunckel, M. 2007. A novel air pollution index based on the relative risk of daily mortality associated with short-term exposure to common air pollutants. *Atmospheric Environment,* 41: 8442–8454. https://doi.org/10.1016/j.atmosenv.2007.07.003
6. Contreras, L. & Ferri, C. 2016. Wind-sensitive interpolation of urban air pollution forecasts. *Procedia Computer Science,* 80: 313-323. https://doi.org/10.1016/j.procs.2016.05.343
7. DeMott, P.J., Sassen, K., Poellot, M.R., Baumgardner, D., Rogers, D.C., Brooks, S.D., Prenni, A.J. & Kreidenweis, S.M. 2003. African dust aerosols as atmospheric ice nuclei. *Geophysical Research Letters,* 30(14). https://doi.org/10.1029/2003GL017410
8. Duan, K., Sun, G., Zhang, Y., Yahya, K., Wang, K., Madden, J.M., Caldwell, P.V., Cohen, E.C. & McNulty, S.G. 2017. Impact of air pollution induced climate change on water availability and ecosystem productivity in the conterminous United States. *Climatic Change,* 140(2): 259-272. https://doi.org/10.1007/s10584-016-1850-7
9. Efe, S.I. & Efe, A.T. 2008. Spatial distribution of particulate matter (PM10) in Warri metropolis, Nigeria. *The Environmentalist,* 28(4): 385-394. http://doi.org/10.1007/s10669-007-9154-0
10. FEPA (Federal Environmental Protection Agency), 1999. *Nationale Environmental (Effluent Limitation) Regulations*. http://www.placng.org/new/laws/F10.pdf. Last access: September 2016.
11. Francesco, N., Tubiello, R.D., Cóndor-Golec, M., Salvatore, A.P., Sandro, F., Alessandro, F., Simone, R., Alessandro, F., Paola, C., Riccardo, B., Heather, J., Paulina, P. & Paolo, P. 2014. *Estimating Greenhouse Gas Emissions in Agriculture. A Food and Agriculture Organization (FAO) of the United Nations manual to Address Data Requirements for Developing Countries* http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Glossary_Acronyms_BasicInfo/Glossary.pdf. Last access: March 2015.

12. Gorai, A.K., Tchounwou, P.B. & Mitra, G. 2017. Spatial variation of ground-level ozone concentrations and its health impacts in an urban area in India. *Aerosol and Air Quality Research,* 17(4): 951-964. https://doi.org/10.4209/aaqr.2016.08.0374
13. Grace, U.M., Sawa, B.A. & Jaiyeoba, I.A. 2015. Multi-temporal remote sensing of landuse dynamics in Zaria, Nigeria. *Journal of Environment and Earth Science*, 5(9): 121-138.
14. Guo, H., Wang, Y. & Zhang, H. 2017. Characterization of criteria air pollutants in Beijing during 2014–2015. *Environmental Research*, 154: 334-344. https://doi.org/10.1016/j.envres.2017.01.029
15. Hansen, J., Sato, M., Ruedy, R., Lacis, A. & Oinas, V. 2000. Global warming in the twenty-first century: An alternative scenario. *Proceedings of the National Academy of Sciences*, 97(18): 9875-9880. https://doi.org/10.1073/pnas.170278997
16. Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., Arn, T., Beutel, J. & Thiele, L. 2015. Deriving high-resolution urban air pollution maps using mobile sensor nodes. *Pervasive and Mobile Computing*, 16: 268-285. https://doi.org/10.1016/j.pmcj.2014.11.008
17. Hopkins, J.R., Evans, M.J., Lee, J.D., Lewis, A.C., Marsham, J.H., McQuaid, J.B., Parker, D.J., Stewart, D.J., Reeves, C. & Purvis, R.M. 2009. Direct estimates of emissions from the megacity of Lagos. *Atmospheric Chemistry and Physics*, (9): 8471-8477. https://doi.org/10.5194/acp-9-8471-2009
18. Li, J. & Biswas, P. 2017. Optical characterization studies of a low-cost particle sensor. *Aerosol and Air Quality Research*, 17(7): 1691-1704. https://doi.org/10.4209/aaqr.2017.02.0085
19. Lin, C., Gillespie, J., Schuder, M.D., Duberstein, W., Beverland, I.J. & Heal, M.R. 2015. Evaluation and calibration of Aeroqual series 500 portable gas sensors for accurate measurement of ambient ozone and nitrogen dioxide. *Atmospheric Environment*, 100: 111-116. https://doi.org/10.1016/j.atmosenv.2014.11.002
20. Liu, J., Man, Y. & Liu, Y. 2014. Temporal variability of PM_{10} and $PM_{2.5}$ inside and outside a residential home during 2014 Chinese spring festival in Zhengzhou, China. *Natural Hazards*, 73(3): 2149-2154. https://doi.org/10.1007/s11069-014-1157-9
21. Llanes, S. 2016. How to calculate time-weighted average (TWA). 26th Annual California Industrial Hygiene Council (CIHC) Conference, San Diego, http://www.thecohengroup.com/article/calculate-time-weighted-average-twa/. Last access: October 2017.
22. Marais, E.A. & Chance, K. 2015. A geostationary air quality monitoring platform for Africa. *Clean Air Journal*, 25(1): 40-45. https://doi.org/10.17159/2410-972X/2015/v25n1a3
23. Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K. & Sauvage, B. 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space. *Atmospheric Environment*, 99: 32-40. https://doi.org/10.1016/j.atmosenv.2014.09.055

24. Mishra, R.K., Joshi, T., Goel, N., Gupta, H. & Kumar, A. 2015. Monitoring and analysis of PM10 concentration at Delhi Metro construction sites. *International Journal of Environment and Pollution*, 57(1-2): 27-37. https://doi.org/10.1504/IJEP.2015.072111
25. NPC (National Population Commission), 2010. *Population distribution by sex, state, LGA, senatorial district, 2006 population and housing census*. http://www.population.gov.ng/images/NPCNEW/Pr%20Vol%203%20Pop%20by%20State%20&%20Senatorial%20District.zip. Last access: December 2016.
26. Nsubuga, F.N.W., Olwoch, J.M. & Rautenbach, H. 2013. Variability procedures for daily and monthly observed near-surface temperatures in Uganda. *International Journal of Climatology*, 34(2): 303-314. https://doi.org/10.1002/joc.3686
27. Pattinson, W., Longley, I. & Kingham, S. 2014. Using mobile monitoring to visualise diurnal variation of traffic pollutants across two near-highway neighbourhoods. *Atmospheric Environment*, 94: 782-792. https://doi.org/10.1016/j.atmosenv.2014.06.007
28. Patton, A.P., Laumbach, R., Ohman-Strickland, P., Black, K., Alimokhtari, S., Lioy, P.J. & Kipen, H.M. 2016. Scripted drives: A robust protocol for generating exposures to traffic-related air pollution. *Atmospheric Environment,* 143: 290-299. https://doi.org/10.1016/j.atmosenv.2016.08.038
29. SANS (South African National Standards), 2011. *Ambient air quality — limits for common pollutants*, https://archive.org/download/za.sans.1929.2011/za.sans.1929.2011.pdf. Last access: February 2019.
30. Shibata, T., Wilson, J.L., Watson, L.M., Nikitin, I.V., La Ane, R. & Maidin, A. 2015. Life in a landfill slum, children's health, and the millennium development goals. *Science of the Total Environment*, 536: 408-418. https://doi.org/10.1016/j.scitotenv.2015.05.137
31. Walker, S. 2012. Keeping Mineworkers Safe. *Engineering and Mining Journal*, 213(2): 42.
32. Wang, Y., Li, J., Cheng, X., Lun, X., Sun, D. & Wang, X. 2014. Estimation of PM10 in the traffic-related atmosphere for three road types in Beijing and Guangzhou, China. *Journal of Environmental Science*, 26(1): 197-204. https://doi.org/10.1016/S1001-0742(13)60398-8
33. WHO, (World Health Organization), 2016. *Global urban ambient air pollution database update*, http://www.who.int/phe/health_topics/outdoorair/databases/WHO_AAP_database_May2016_v3web.xlsx?ua=1. Last access: September 2016.
34. WHO (World Health Organization), 2017. *Evolution of WHO air quality guidelines. Past, present and future*, http://www.euro.who.int/__data/assets/pdf_file/0019/331660/Evolution-air-quality.pdf. Last access: September 2017.
35. Yazdi, M.N., Delavarrafiee, M. & Arhami, M. 2015. Evaluating near highway air pollutant levels and estimating emission factors: Case study of Tehran, Iran. *Science of the Total Environment*, 538: 375-384. https://doi.org/10.1016/j.scitotenv.2015.07.141

Chapter 4

An exposure appraisal of outdoor air pollution on the respiratory well-being of a developing city population[††]

Abstract

Zaria is the educational hub of Northern Nigeria. It is a developing city with a pollution level, high enough to be ranked amongst the WHO most polluted cities. The study appraised the influence of outdoor air pollution on the respiratory well-being of the population in a limited resource environment. With the approved ethics, the techniques utilized are portable pollutant monitors, respiratory health records, the World Health Organization (WHO) AirQ+ software and the American Thoracic Society (ATS) questionnaire. They were utilized to acquire day-time weighted outdoor pollution levels, health respiratory cases, assumed baseline incidence (BI) and exposure respiratory symptoms among selected study participants respectively. The study revealed an average respiratory illness incidence rate of 607 cases per 100, 000. Findings showed that an average of 2, 648 cases could have been avoided if the theoretical WHO threshold limit for the particulate matter with a diameter of less than 2.5 micron/10 micron ($PM_{2.5}$/PM_{10}) were adhered to. Using the questionnaire survey, phlegm was identified as the predominant respiratory symptom. A regression analysis showed that the criteria pollutant $PM_{2.5}$ was the most predominant cause of respiratory symptoms among interviewed respondents. The study logistics revealed that outdoor pollution is significantly associated with the respiratory well-being of the study population in Zaria, Nigeria.

Keywords: *Air pollution; Respiratory health; Zaria*

[††]*This chapter is a formatted text of a peer-reviewed journal article described as follows:*

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4.1. Introduction

Clean air is extremely essential for human well-being (Gong et al., 2016). Ambient air quality remains a major concern in developing cities with limited pollution monitoring capabilities (Marais et al., 2014). The spatial and temporal classification of city-scale ambient air quality is vital from any respiratory epidemiological standpoint (Dash, 2016). Estimates have put respiratory infections as the cause of nearly 20 per cent of mortality in children under 5 years, with a sizeable portion of the dilemma experienced by populations in Africa and Asia (Mehta et al., 2013). Managing air pollution can be very complex, especially as it revolves around the intricacy of emission sources, implementation strategy concerns and scarce means for regulating and pursuance (Krupnick, 2008). These difficulties, combined with the hurried demand for technological advancement in many countries, have resulted to a global concern on possible vulnerability from air pollution (Evans et al., 2013; Miranda et al., 2016).

Anthropogenic emissions are the largest contributors of urban outdoor air pollution as they emit various kinds of petrochemical gases into the atmosphere (Svendsen et al., 2012; Ana et al., 2014; Obaseki et al., 2014). The atmospheric air quality plays a crucial role in population health as its pollution is projected to be responsible for 3.2 per cent of the worldwide burden of diseases (WHO, 2016). Other than conventional respiratory illnesses, poor air quality is also reported to be linked with non-respiratory health conditions such as diabetes (Thiering et al., 2015), stroke (Maheswaran, 2016) and infertility (Vizcaíno et al., 2016).

Strategies are being identified for reducing population exposure to air pollution. They include: restricting air pollution emitters, technological upgrade on emitters to cut or eradicate emissions, and creating health risks alertness of pollution exposure to population (Oltra and Saint Jean, 2009; Plaia and Ruggieri, 2010; Wolff, 2014). The idea of restriction or technological upgrades of air pollution sources can be strenuous to enforce or probably not in line with the paradigms of the state, such as restrictions that may end up minimizing economic output (Abbasi, 2012). Providing health hazard awareness on air pollution is a concrete first step for policies that find it tasking to revolutionize their present emission status. And if executed properly, it will provide health benefits (Adams and Kanaroglou, 2016).

In Nigeria, atmospheric pollution and its burden of respiratory diseases is still a serious menace in many of its metropolitan cities. This is mainly due to expended vehicles, general use of the single-engine motorcycles for shuttling commuters, traffic congestions and the natural north-easterly harmattan which all combine to generate high levels of localized air pollution that can affect population health (Oluwole et al., 2017). With Nigerian cities now beginning to rank among the top most polluted in the world (WHO, 2016), it is worth noting that researches are identifying increased occurrence of respiratory disease symptoms in individuals exposed to this pollution (Sarnat et al., 2014; Peters et al., 2015; Patton et al., 2016).

This study is a step in confronting public concerns as it aims to evaluate the influence of outdoor air pollution on interim respiratory well-being within a limited resource environment. To achieve this, it is necessary to first assess the present air pollution levels within the study population. Secondly, to determine the theoretical attributable risk proportion using the available respiratory health outcome information and the measured exposure level. Thirdly, establish whether outdoor air pollutants exposure is significantly associated with the respiratory symptoms within the study population. For reliable theoretical influence, pollution epidemiology studies require pollution and health outcome data covering a reasonable time-frame. This study hopes to provide a scientific basis for air pollution regulation in a local metropolis of Nigeria.

4.2. Methods

4.2.1. Study area

This study was conducted in Zaria metropolitan area, northern Nigeria (Figure 4.1). Zaria metropolis consists of two local government areas (Zaria and Sabon-Gari) and occupies an area of about 296.036 km^2. It is the educational hub of northern Nigeria. The topography is mainly flat with a mean height of 670 m above mean sea level (MSL). The climate comprises of the dry (October – May) and wet (June – September) seasons. The lowest temperature is 14.1°C and maximum average = 35.2°C during the harmattan (January) and heat (April) seasons. It has a 2016 population estimated to be 938, 521 using the 2006 population census and a 3-per cent growth rate (NPC, 2010). The western areas are sparsely vegetated around the Kufena Hills. The main water body in the study area is the River Kubanni.

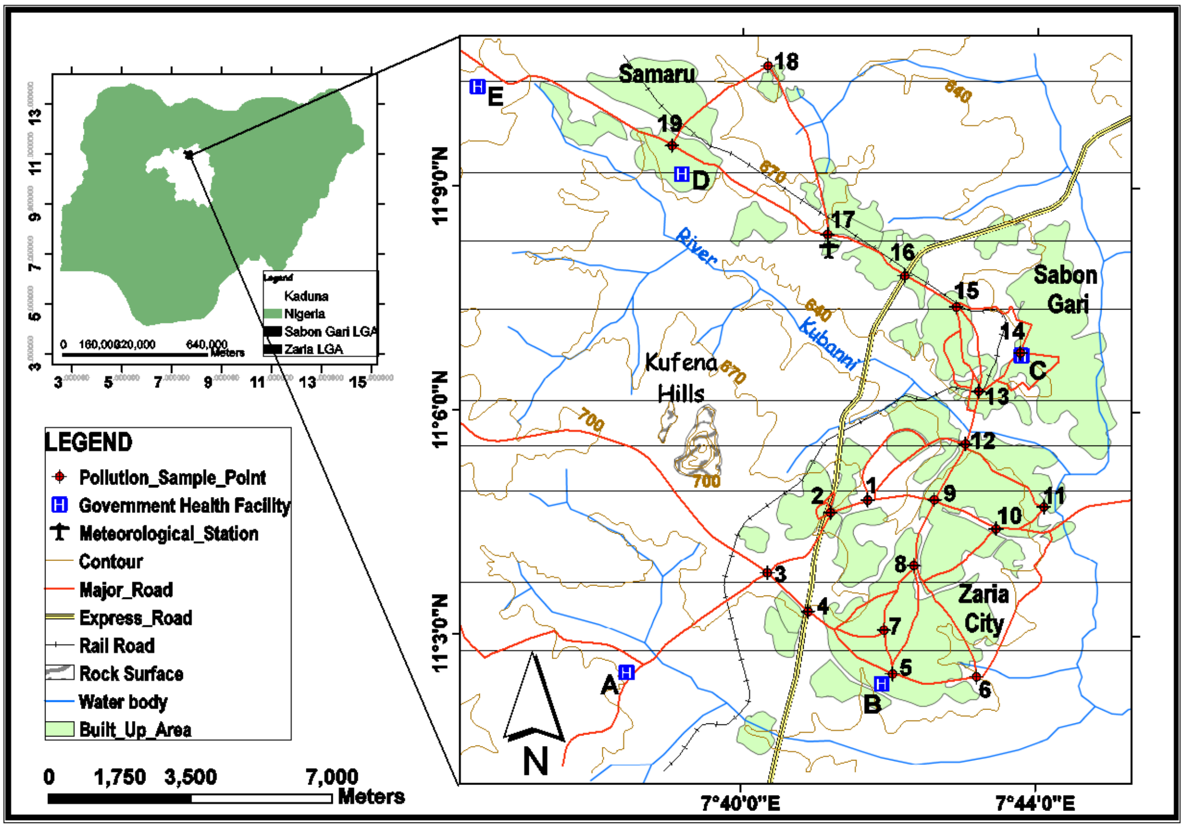


Figure 4.1. *The study area showing the distribution of pollution sample sites and government health facilities from which respiratory health records were obtained*

4.2.2 Ethics

Research protocols were endorsed by the Kaduna State Ministry of Health Research Ethics Committee (MOH/ADM/744/VOL.1/448); Ahmadu Bello University Teaching Hospital Health Research Ethics Committee (ABUTH/HREC/CL/05) within the study area and the Faculty of Natural and Agricultural Sciences Ethical Committee at the University of Pretoria, South Africa (EC170124-092).

4.2.3 Data collection

To appraise the influence of outdoor air pollution on respiratory well-being within the study area, four categories of datasets were obtained. They are described as follows:

4.2.3.1. Outdoor pollution data

With the design of numerous handy cost-effective devices for monitoring airborne contaminants (Moltchanov et al., 2015; Deary et al., 2016; Thompson, 2016), this study utilized portable air quality monitors to collect pollution data. The sample monitors are the MSA Altair 5x gas detector and the Chinaway CW-HAT200 particulate counter (Figures 4.2a and b). The devices are manufactured by the Mine Safety Appliances Company, Pennsylvania, USA and the Shenzhen Environmental Technologies Co. Ltd, Guangdong, China respectively. The MSA Altair collects criteria pollutants: carbon monoxide (CO) and sulphur dioxide (SO_2), measured in parts per million (ppm) while the CW-HAT200 collected particulate matter $PM_{2.5}$ and PM_{10} in micrograms per cubic meter (μgm^{-3}). The portable pollutant devices were validated (R > 0.96) before the commencement of proper sampling. The World Health Organization (WHO) filter sampling procedure, described in Efe and Efe (2000), was adopted to validate the portable devices used in this study. 19 sample sites distributed across the study area, were utilized to routinely observe air pollution concentrations, 3-epochs daily (Bell and Davies, 2001; Yazdi et al., 2015). The duration of the outdoor sampling was 1 December 2015 – 30 November 2016. The sites were situated along the major road intersections. 16 sites are positioned within dense population activities which cut across the residential and commercial settlements, while the remaining 3 control sites are positioned strategically at the outskirts of the city with minimal population activity. The control sites were embraced to aid in the result comparison.

(a) (b)

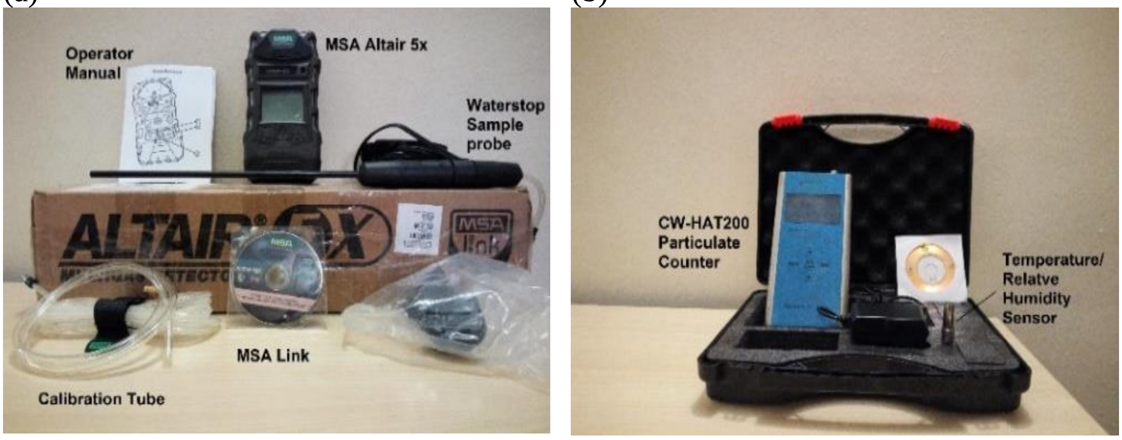


Figure 4.2. *Portable air pollutant detectors (MSA Altair 5x/ Chinaway CW-HAT200)*

4.2.3.2. Attributable risk data

The health records of respiratory illnesses utilized in this study were restricted to the five major government-owned health facilities in the study area. This is because they are the most medically equipped thus most likely to handle referrals cases. They are also cost-effective for all patients to access medical treatment. The facilities are National Tuberculosis and Leprosy Training Centre, Hajiya Gambo Sawaba General Hospital, Major Ibrahim A. Abdullahi Memorial Hospital, Ahmadu Bello University Medical Centre and Ahmadu Bello University Teaching Hospital (They are tagged A – E in Figure 4.1). The data obtained comprised of reported cases from the health facility records, for varying age brackets and death occurrences for case fatality rates (CFR) computations. The obtained data were used to determine the attributable proportion using the WHO AirQ+ software designed by the WHO, Europe regional office.

To ascertain the theoretical attributable risk proportion (AP) of respiratory illnesses on the Zaria population, we adopted the input files embedded into the WHO air quality software AirQ+. The inputs adopted include peer-reviewed relative risks (RR) estimates, mathematical formulae and WHO stipulated limits, The WHO encourages the use and dissemination of information using the software. Several studies have corroborated the use of the software (Fattore et al., 2011; Nagpure et al., 2014; Miri et al., 2016; Khaniabadi et al. 2017). The validated AirQ+ software quantifies possible respiratory health effects resulting from exposure to pollutant within any study area. This is achieved by computing the ratio of traceable health outcomes resulting from exposure to atmospheric pollutant(s), for a defined population. It hypothesizes the relationship between exposure and health consequence, with no significant discountenance. The assumed AP can be derived using the formulae below (Wang et al., 2009).

$$AP = \sum\{[RR(s)-1]\times p(s)\} / \sum\{RR(s)\times p(s)] \qquad (4.1)$$

RR(s) is the relative risk for the health outcome difference that can be calculated using Equation 4.2; *p(s)* is the fraction of the population all in exposure class s, depending on the varying level of exposure within the field of study.

$$RR(s) = (C-T) / \{10\times(RR-1)+1) \qquad (4.2)$$

C is pollutant concentration in air, *T* is the WHO stipulated limit for detected pollutant; *RR* is the relative risk derived from the exposure-response function for selected health outcomes generated from local epidemiological studies.

To determine the rate and the estimated number of cases attributable to the pollution exposure, Equations 4.3 and 4.4 were utilized, taking into consideration that the theoretical baseline frequency of endpoint (incidence) and population size are known respectively (Miri et al., 2016). A baseline incidence is a theoretical threshold derived using mathematical procedures, to determine if an epidemic incidence is in excess (Procházka and Kynxcl, 2015).

$$IE = I \times AP \tag{4.3}$$

IE is the rate of the health outcome related to the exposure, *I* is the baseline frequency of the health endpoint in the population.

$$NE = IE \times N \tag{4.4}$$

NE is the number of cases attributed to the exposure, and *N* refers to the size of the investigated population.

4.2.3.3. Questionnaire survey data

As a predictive indicator to analyse on-the-spot respiratory well-being resulting from outdoor pollution exposure, a respiratory indicator-based questionnaire was utilized to investigate respiratory symptoms from respondents. The American Thoracic Society Division of Lung Disease questionnaire (ATS-DLD-78A) (Ferris, 1978) is a universally accepted process for detecting respiratory warning signs in a population. The design comprises of questions related to recurrent respiratory indicators such as cough, phlegm, wheeze and breathlessness. The questionnaire has been utilized by various studies (Albers et al., 2015; Goldberg et al., 2015; Schultz et al., 2016; Brown et al., 2017), to achieve their objectives. In our study, we applied a modified version of the questionnaire for adults, to trace the manifestation of respiratory symptoms. It comprises of questions pertaining to the occurrence of cough/phlegm for the most part of 3 consecutive months or more within a year; wheeze (noisy breath resulting in breathing difficulty on most days or only during the cold season); breathlessness Grade I, (rapid breathing as a result of hastening on a level or pacing up a slight hill) and Grade II (not being able to walk at the same pace with one's age class on a level or pausing for breath when strolling at own pace on a level). The account of past ailments (described as bronchitis, pneumonia, asthma, emphysema, hay fever confirmed by a doctor) and hereditary likelihoods (described as any of the biological parents who had any chronic lung condition such as chronic bronchitis, asthma or lung cancer, confirmed by a doctor). We restricted the questionnaire survey to participants that are stationed within a 30-meter radius of sample sites, for at least 6 hours a day, for the last 1 year (which will coincide with our pollution sampling duration). We ensured that their ages were ≥ 20 years. With this criterion, we could confirm that such participants were mature enough and have been exposed to the recorded concentration levels of pollutants, for a considerable amount of the sample time. The sample size of participants was determined based on the minimum population sample size for research activities (Krejcie and Morgan, 1970). The questionnaire was drafted in the English language and if necessary, translated to the Hausa language. The participants had paper-assisted interviews which were controlled for prolonged/already existing respiratory illnesses and likely hereditary symptoms. During the administration process, the investigator ensured that the respondents comfortably and accurately understood the value of all questions, most especially respiratory symptoms, such as phlegm and wheeze. Participants gave verbal and written informed consent. The participants were restricted to non-smoking individuals situated at the selected sample sites so that the results are not skewed as a result of their personal habits.

4.2.3.4. Socio-economic influence data

A remote sensing Landsat data was employed to ascertain if socio-economic factors contributed to reports of respiratory well-being within the study period. Landsat data was adopted because it is an independent data that can be freely accessed from the United States Geological Survey (USGS). For our study site, the Landsat 8 at Path/Row 189/52, was acquired from the USGS website (https://earthexplorer.usgs.gov/) for the study period (1 December 2015 – 30 November 2016). To improve accuracy, the image data was restricted to satellite image tiles with less than 10 per cent cloud cover. Only ten image files fulfilled the specified criteria for the entire study period. The socio-economic factor can be interpreted in the Landsat data as Land surface temperature (LST) and normalized difference vegetation index (NDVI). The derivation techniques for LST and NDVI are described in Sobrino et al. (2004) and Xu and Guo (2014).

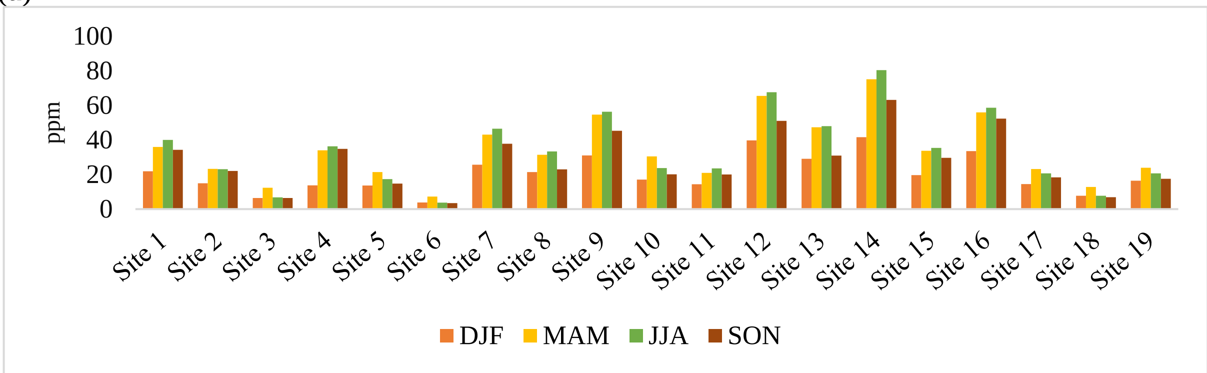
4.2.4. Data analysis

The day-time weighted average for observed criteria pollutants was computed for the 1-year running. The spatial data (easting, northings and elevation) of the sampling points and their individually observed pollution levels were analysed to determine for skewness of sampling position. The spatial distribution of reported respiratory symptoms was analysed for homogeneity of variance using the Levene’s test. The respiratory health data with variables (age group, gender and resulting mortality) were subjected to statistical logistics, to determine their association with outdoor pollution exposure through a likelihood ratio test. To determine population exposed response, the ATS questionnaire responses were coded and analysed for all responded respiratory outcomes. The empirical analysis did correct for possible priors and hereditary respiratory traits. A reliability test was also conducted on the ATS questionnaire. All statistical computations were executed using Microsoft Excel, SPSS 19 statistical software from IBM and Matlab R2014b from MathWorks, all for Windows.

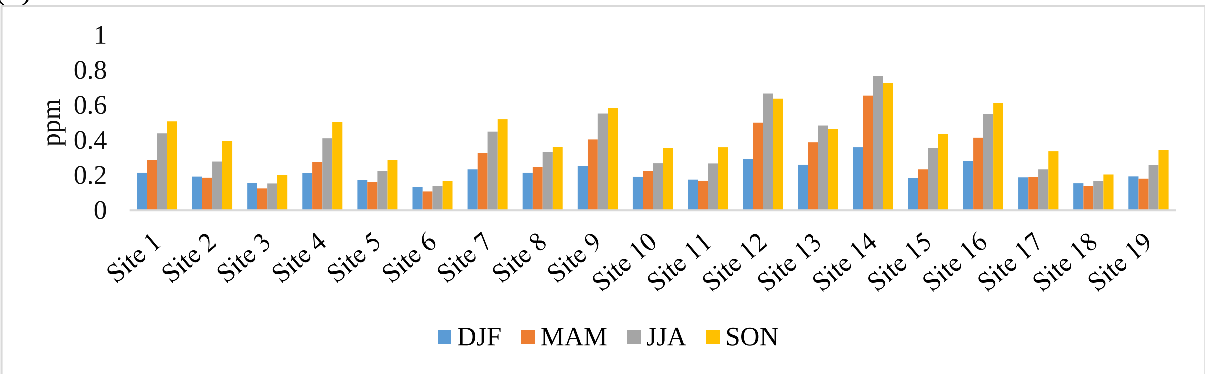
4.3. Results

The day-time seasonal statistics for CO (ppm), SO_2 (ppm), $PM_{2.5}$ (µgm^{-3}) and PM_{10} (µgm^{-3}) is averaged over the 19 sample stations in Zaria, Nigeria during the period December 2015 – November 2016 (Figure 4.3). The 1-year day-time weighted average concentration of criteria pollutants revealed values of 29.22 ppm for CO, 0.32 ppm for SO_2, 219.73 µgm^{-3} for $PM_{2.5}$ and 451.89 µgm^{-3} for PM_{10}.

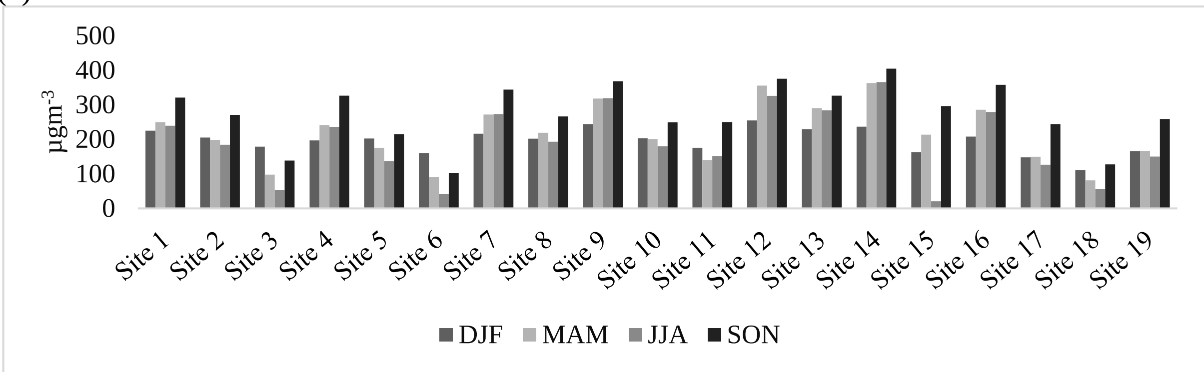
(a)



(b)



(c)



(d)

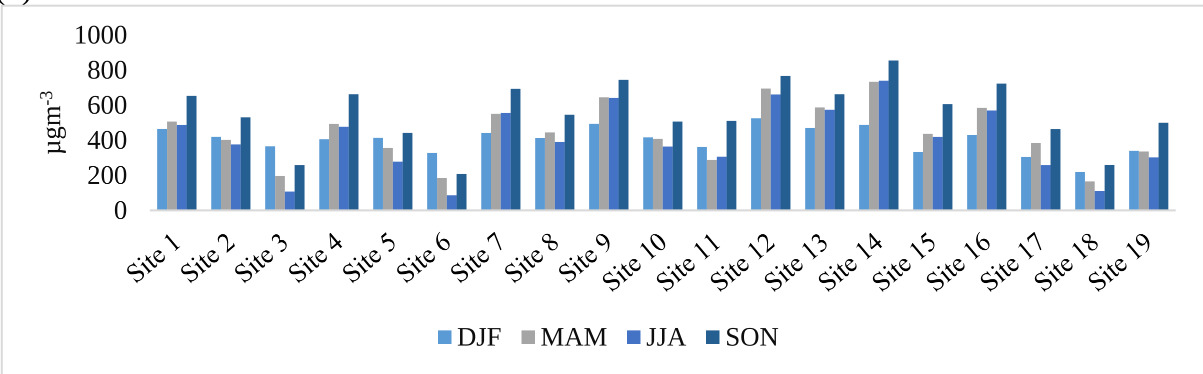


Figure 4.3. *Histogram of seasonal day-time pollutant concentrations across the 19 sampling sites (a) CO and (b)* SO_2 *(c)* $PM_{2.5}$ *(d)* PM_{10} *(Sites 3, 6 and 18 are control sites). DJF, December–January–February; MAM, March–April–May; JJA, June–July–August; SON, September–October–November*

From the health records obtained, an aggregate of 31, 042 respiratory-related illnesses were reported in the five major government-owned health facilities in Zaria from January 2011 – December 2016 (Table 4.1). A total of 461 respiratory-related casualties were recorded. All the years of interest (2011 – 2016) did record respiratory-related death, with the year 2013 having the peak (112 deaths). On average, the case fatality rate (CFR) was 1.67%, over the study period under investigation.

Table 4.1. *Recorded respiratory cases and related deaths in Zaria metropolis, 2011 – 2016*

			0-14 years	15-29 years	30-44 years	45 years above	Male	Female	Death	CFR
Year	Total cases	Case / 100, 000	Case (%)	Case (%)	Case (%)	Case (%)	Case (%)	Case (%)		
2011	4, 992	635	2, 065 (41.4)	1, 650 (33.0)	784 (15.7)	493 (9.9)	2, 746 (55.0)	2, 246 (45.0)	78	1.6
2012	5, 996	741	1, 498 (25.0)	2, 757 (46.0)	1, 126 (18.8)	615 (10.2)	3, 525 (58.8)	2, 471 (41.2	95	1.6
2013	3, 003	360	815 (27.1)	1, 361 (45.3)	482 (16.1)	345 (11.5)	1, 694 (56.4)	1, 309 (43.6)	45	1.5
2014	3, 297	383	1, 056 (32.0)	1, 302 (39.5)	554 (16.8)	385 (11.7)	1, 909 (57.9)	1, 388 (42.1)	112	3.4
2015	5, 428	614	1, 757 (32.4)	2, 392 (44.1)	826 (15.2)	453 (8.3)	3, 136 (57.8)	2, 292 (42.2)	66	1.2
2016	8, 326	914	2, 818 (33.8)	3, 522 (42.3)	1, 313 (15.8)	673 (8.1)	4, 993 (60.0)	3, 333 (40.0)	65	0.8

*derived from the yearly population estimates

To determine if the outdoor pollution level significantly did contribute to exposed population respiratory symptoms, a total of 396 responses were obtained. We ensured that each of the 19 sample stations had at least 20 responses, i.e. participants situated at the exposed station were tagged as exposed. While participants responding from control stations were tagged as the control. There were 352 (88.9%) males and 44 (11.1%) females as participants. The internal-consistency reliability (Cronbach's alpha) of the ATS interview was within acceptable limits ($\alpha > 0.70$). The predominant respiratory symptom was phlegm (97.2%), followed by chest cough (80.8%), dyspnoea (55.6%), chest cough plus phlegm (54.8%) and wheeze (49.8%). Pneumonia (14.1%) was the major medically-diagnosed past respiratory illness. This can be attributed to the annual natural windy 'harmattan' period that is characterized by dusty conditions and low temperatures. Table 4.2 shows the descriptive statistics of respiratory symptoms among interviewed respondents. The interviewed responses were coded for further analysis.

4.4. Discussions

4.4.1 Outdoor air quality

The skewness analysis ($P < 0.184$) revealed that the recorded criteria pollutant levels were normally distributed across the 19 study sites. The pollution level of the observed criteria-pollutants was lowest during the December-January-February (DJF) season; this can be attributed to the windy Harmattan (cold season) in the study area. The windy harmattan season has the tendency to quickly disperse pollution emissions. In addition, outdoor activities are limited due to low ambient temperature, especially during morning and evening periods. The weighted average concentration level of CO measured were above WHO/FEPA (Nigeria) stipulated limit (Table 4.3) in 15 of the 19 sample sites; SO_2 and PM_{10} levels were above WHO/FEPA limit in all the sites; $PM_{2.5}$ were above WHO limit in all the sample sites (Nigeria's Federal Environmental Protection Agency (FEPA) guidelines has no specified limit for $PM_{2.5}$); PM_{10} was above the WHO/FEPA limit in all the sites. Considering the global ambient air pollution update WHO 2016 results, the weighted average concentration level of recorded $PM_{2.5}$ and PM_{10} firmly puts Zaria among the top five polluted cities of the World.

Table 4.2. *Descriptive statistics of respiratory symptoms among interviewed respondents in the study area*

Case characteristics	Male (n)	Female (n)	Total (n, (%))
Study population (n, %)	352 (88.9)	44 (11.1)	N = 396
Age			
20 – 29 years	38	15	53 (13.4)
30 – 39 years	133	10	143 (36.1)
40 – 49 years	149	9	158 (39.9)
≥ 50 years	32	10	42 (10.6)
Education			
Primary	33	2	35 (8.9)
Secondary	169	16	185 (46.7)
Tertiary	150	26	176 (44.4)
Respiratory conditions			
Chest cough	289	31	320 (80.8)
Phlegm	344	41	385 (97.2)
Cough + phlegm	200	17	217 (54.8)
Wheeze	175	22	197 (49.8)
Breathlessness	192	28	220 (55.6)
Past Illnesses			
Lung trouble before 16 years	18	3	21 (8.3)
Bronchitis attack	14	3	17 (4.3)
Pneumonia attack	47	9	56 (14.1)
Asthma attack	15	4	19 (4.8)
Emphysema	31	1	32 (8.1)
Hay fever	2	-	2 (0.5)
Chest illness	5	1	6 (1.5)
Chest operation	3	-	3 (0.8)
Chest injury	12	2	14 (3.5)
Heart trouble	5	3	8 (2.0)
High blood pressure	23	5	28 (7.1)
Hereditary probability			
Father	36	3	39 (9.9)
Mother	60	10	70 (17.7)

Table 4.3*. The threshold of selected air pollutants, modified after (FEPA, 1999; WHO, 2017).*

Stipulated limits	Pollutants			
	CO	$PM_{2.5}$	PM_{10}	SO_2
FEPA	20 ppm	-	150 μgm^{-3}	0.1 ppm
WHO	9 ppm	25 μgm^{-3}	50 μgm^{-3}	0.01 ppm

4.4.2 Attributable health risk

A Levene's test revealed that the spatial distribution of reported respiratory symptoms in Zaria metropolis was heterogeneous (P = 0.050). From Table 4.2, the health records indicate the most respiratory cases were notified in Ahmadu Bello University Medical Centre (D) [3, 856.83; 95% confidence interval (CI): 2, 199.9 – 5, 513.8]. This is attributed to the fact that it is the only major health facility within a 4 km radius of Zaria's Samaru axis. The least notified cases were reported at the Ahmadu Bello University Teaching Hospital (E) [34.5; 95% confidence interval (CI): 4.2 – 64.9]. This may be attributed to its location, which is at the outskirts of the metropolis. Using the population estimates, the respiratory illness incidence rate was highest in 2016 (914 per 100 000). Table 4.2 above highlights the trend of reported respiratory-related complaints obtained from the major health facilities. Respiratory illnesses were reported for age ranging from infancy (< 1 year) to the elderly (76 years). The physically active group of 15–44 years, which accounts for 58.21 % (18, 069) of all notified cases, were most at risk over the study period. Their case was remarkably high in 2016 with 58.07 % (4, 835) of cases. The age group 0–14 ranked second, accounting for 32.24 % (10, 009) of all notified cases and 33.85 % (2, 818) in 2016. The age group of 45 and older were the least affected by respiratory illnesses, accounting for 9.55 % (2, 964) of total notified cases and a major report of 8.08 % (673) in 2016. From 2011 – 2016, respiratory-related illnesses afflicted more males 58.0 % (18, 003) compared to females 42.0 % (13, 039). This trend was harmonious all through the study period (R^2 = 0.994; P < 0.01). With available pollution data for the year 2016, the WHO AirQ+ software was utilized to compute the theoretical attributable risk proportion for the study area in 2016.

To determine the theoretical AP for 2016, the total of 8, 326 cases of respiratory diseases, the day-time weighted running average of $PM_{2.5}$ and PM_{10} are 219.73 µgm^{-3} and 451.89 µgm^{-3} and all other parameters were inserted into the AirQ+ software. The model report revealed that 32.62 % and 29.12 % of notified respiratory cases can be attributed to pollutants $PM_{2.5}$ and PM_{10} respectively, having exceeded the stipulated threshold. In Table 4.3, we can see that for every 10 µgm^{-3} increase in $PM_{2.5}$ pollutant concentration, the corresponding amount of RR for the hospital accessed respiratory illnesses was 1.484 % as well as 1.411 % for every 20 µgm^{-3} increase in PM_{10}. An average of 31.8 % (2, 648 cases) could have been avoided if the WHO guideline for $PM_{2.5}$ and PM_{10} had been respected in the year 2016. However, the theoretical baseline incidence per 100, 000 for short-term effects of the population exposed to

$PM_{2.5}$ and PM_{10} (298.10 μgm^{-3} and 271.27 μgm^{-3}) are minimal compared to the WHO guideline of 1, 260 for the land mass and total estimated population of Zaria.

The adopted relative risk (RR) value for concerned air pollutants (see Table 4.4) are based on multiple analysis of peer-reviewed findings conducted in Asia, North America and Western Europe (Nagpure et al., 2014; Miri et al., 2016; WHO, 2017). Even though our study understood that the adoption of the theoretical RR obtained from researches conducted outside our region may alter predictions of the model, we felt that there is the need to most importantly, drive the step in providing valuable evidence on the effects of air pollution for Nigeria's policy-makers. We were also optimistic that our findings will assist the WHO AirQ+ software developers to further moderate any prediction error. Based on the available datasets, we utilized the theoretical WHO AirQ+ software to assess the interim effects of $PM_{2.5}$ and PM_{10}.

Table 4.4. *WHO theoretical values of relative risks (RR) implemented in AirQ+ corresponding to hospital admission/access for respiratory diseases and estimated RR in percentage and excess of number cases in the year 2016 resulting from short-term exposure to $PM_{2.5}$/PM_{10} above the 10/20 μgm^{-3} limits respectively.*

	WHO default values		Theoretical outcome			
Pollutant	Annual Threshold (μgm^{-3})	RR (95% CI)	Annual mean concentration (μgm^{-3})	RR (95% CI)	Attributable respiratory cases	Baseline Incidence*
$PM_{2.5}$	10	1.019 (0.9982 – 1.0402)	219.73	1.4840 (0.9629 – 2.2856)	2, 798	298.10
PM_{10}	20	1.008 (1.0048 – 1.0112)	451.89	1.4108 (1.235 – 1.6177)	2, 498	271.27

*the $PM_{2.5}$ and PM_{10} threshold limit prescribed by the WHO for theoretical baseline incidence per 100 000 is 1, 260

4.4.3 Pollution exposure response

To determine if the outdoor air pollutants measured within the study area can contribute to the respiratory condition of the present population, we analysed the relationship between each measured criteria pollutant against the individual respiratory response interviewed. Table 4.5 shows the association between the presence of respiratory symptoms from interviewed respondents and observed criteria pollutant level.

Table 4.5. *The relationship between individual respiratory symptoms from respondents and each observed pollutant level*

	Cough		Phlegm		Cough + Phlegm		Wheeze		Breathlessness	
	R	RMSE	R	RMSE	R	RMSE	R	RMSE	R	RMSE
CO	0.90	29.61	0.86	33.63	0.79	10.68	0.80	15.72	0.82	13.71
SO_2	0.91	28.44	0.87	33.07	0.81	10.17	0.80	15.61	0.78	14.86
$PM_{2.5}$	0.89	31.17	0.87	32.95	0.90	7.60	0.80	15.71	0.76	15.36
PM_{10}	0.88	32.88	0.83	37.04	0.79	10.45	0.71	18.63	0.72	16.54

*Shaded cell highlights the possible association of pollution exposure and respiratory condition

Additionally, we determined the contribution of the measured pollution level to the general respiratory outcome of the interviewed population. The interviewed respondent outcomes were controlled for past illnesses and possible family hereditary influence using Equation 4.5 below.

$$PER = \left[\sum_{i=1}^{n} S_i - \left(\sum_{i=1}^{n} P_i + \sum H \right) \right] \quad (4.5)$$

PER is the pollution exposure-response; *Si* is responses from respondents for the varying symptoms (chest cough, phlegm, cough plus phlegm, wheeze and breathlessness); *Pi* is responses with regards past illnesses (lung disease before 16 years of age, bronchitis, asthma, chest injuries/operation, high blood pressure) and *H* is the responses with regards possible inheritance of symptoms from biological parents.

From Figure 4.4 below, we would see that the $PM_{2.5}$ is the predominant cause of interviewed respiratory symptoms (R = 0.93). This result is supported the WHO AirQ+ software findings (Table 4.3) and also literature (Halonen et al., 2009; Miri et al., 2016). In addition, SO_2 ranked second after $PM_{2.5}$, which is in agreement with Ren et al., (2017). Their study reported SO_2 as their major cause of respiratory-related illnesses, however, $PM_{2.5}$ was not investigated.

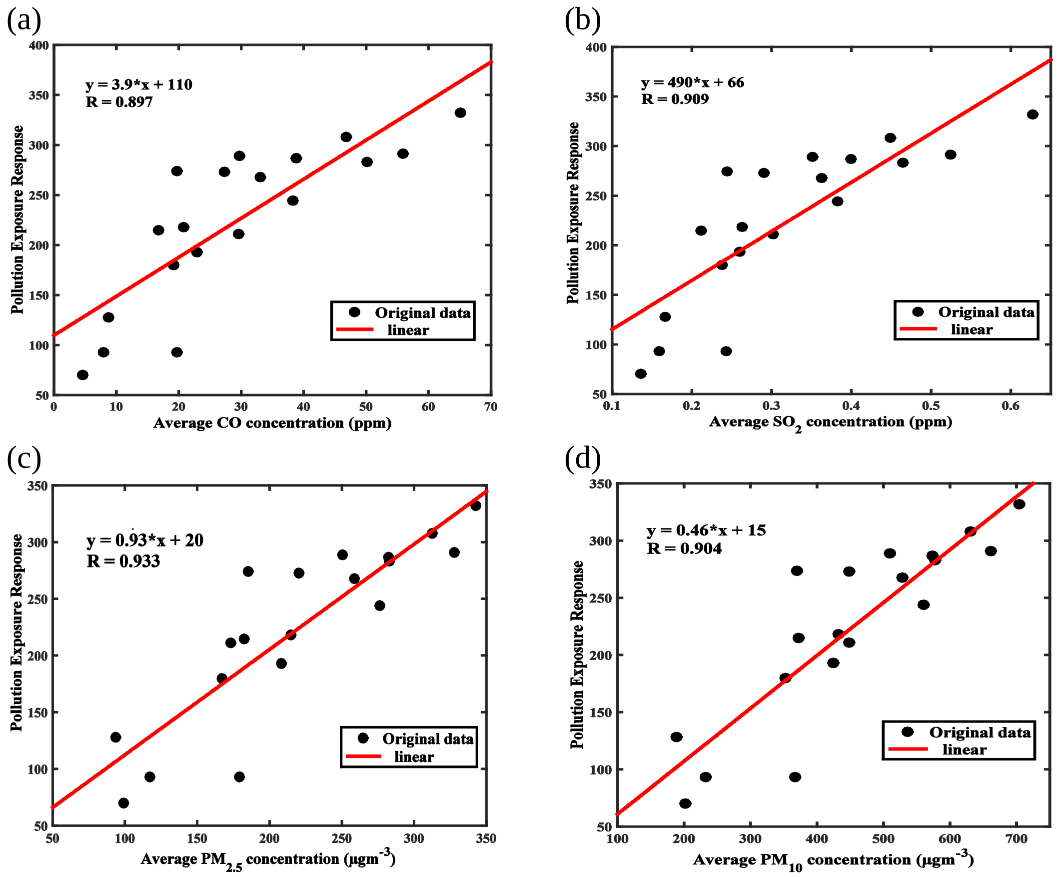


Figure 4.4. *Scatter plot showing a strong positive relationship between criteria pollutants (a) CO, (b) SO_2, (c) $PM_{2.5}$ and (d) PM_{10} respectively) against at-risk population respondents from the sample sites*

To certify that the exposure to outdoor air pollutants in this population was the major contributor to the measured respiratory symptoms, we analysed the level of significance of the socio-economic factor on respiratory well-being. Using an independent remote sensing approach, we derived the land surface temperature (LST) and the normalized difference vegetation index (NDVI) from Landsat 8 data, in the ArcGIS 10.2.1 software. The LST and NDVI values over the 19 sample points were extracted, collocated and correlated with ATS questionnaire responses across the sample sites. The analysis shows that socio-economic factors, LST (R = 0.76) and NDVI (R = 0.69). These results were not as significant as the measured pollutants level for the respondent respiratory outcome in Figure 4.4 ($R \geq 0.90$). Note that the Landsat data was validated (R = 0.94) using the extracted LST and collocating ground temperature data obtained from the Nigerian Meteorological Agency station within the study area.

4.5. Conclusions

The study utilized portable pollutant sensors, ATS-respiratory questionnaire and WHO AirQ+ software model to evaluate the contributory effects of outdoor air pollution to respiratory outcomes in a highly polluted area. The study provides an encyclopaedic picture of outdoor air pollution exposure and possible ramifications to human health in a Nigerian city-scale. The study confirmed that a substantial amount of outdoor air pollution contributed significantly to respiratory indicators (cough, phlegm, wheeze and breathlessness) from the interviewed respondents. This relationship advocates the use of AirQ+ software and ATS questionnaire for estimating the incidence of respiratory symptoms, as they are effective tools when assessing the liability of respiratory symptoms in any polluted cities. The results of this study indicate that there is a relationship between the observed criteria-pollutants, (CO, SO_2, $PM_{2.5}$ and PM_{10}) and respiratory well-being of study population in Zaria metropolis, Nigeria.

The study had five key strengths. (1) It revealed a metropolitan city air pollution level, high enough to be ranked amongst the WHO polluted cities. (2) The sources of respiratory-related data obtained from the five major health facilities within the study area ensured their authenticity and dependability. (3) Two certified respiratory epidemiological indicators (ATS–DLD-78A questionnaire and WHO AirQ+ software model) were adopted to examine the health effects of observed criteria pollutants. (4) The suspended particles ($PM_{2.5}$) had the most influence on the study population respiratory health, which is harmonious with other findings on this subject. (5) Our findings conclude that the respiratory symptoms investigated in this study are hypothetically associated with outdoor air pollutants measured using the MSA Altair 5x gas monitor and CW-HAT200 particulate counter.

We do recognize the following limitations in our study. First, since the only two population censuses conducted in Nigeria were in 1991 and 2006, this study was constrained to adopt population estimates. Second, the RR coefficients adopted might have under-estimated the extent of the attributable cases. However, we are confident that our results offer vital information on which Nigeria's policymakers can base its public health strategies and interventions. Finally, the unavoidable time variation in collecting outdoor pollutant samples may have introduced marginal errors, we, however, believe like similar studies in this field that these errors are not significant enough to alter the findings of this study.

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Conflicts of interest

The authors affirm that there is no conflict of interest.

References

1. Abbasi, I.N., Ahsan, A. & Nafees, A.A. 2012. Correlation of respiratory symptoms and spirometric lung patterns in a rural community setting, Sindh, Pakistan: a cross sectional survey. *BMC Pulmonary Medicine*, 12: 81-89. https://doi.org/10.1186/1471-2466-12-81
2. Adams, M.D. & Kanaroglou, P.S. 2016. Mapping real-time air pollution health risk for environmental management: Combining mobile and stationary air pollution monitoring with neural network models. *Journal of Environmental Management*, 168: 133-141. https://doi.org/10.1016/j.jenvman.2015.12.012
3. Albers, P.N., Wright, C.Y., Mathee, A. & Voyi, K.V. 2015. Household fuel use and child respiratory ill health in two towns in Mpumalanga, South Africa: research. *South African Medicine Journal*, 105(7): 573-577. https://doi.org/10.7196/SAMJnew.7934
4. Ana, G.R.E.E., Odeshi, T.A., Sridhar, M.K.C. & Ige, M.O. 2014. Outdoor respirable particulate matter and the lung function status of residents of selected communities in Ibadan, Nigeria. *Perspective in Public Health*, 134(3): 169-175. https://doi.org/10.1177/1757913913494152
5. Bell, M.L. & Davis, D.L. 2001. Reassessment of the lethal London fog of 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. *Environmental Health Perspectives*, 109 (Suppl 3): 389-394.
6. Brown, J., Roy, A., Harris, R., Filson, S., Johnson, M., Abubakar I. & Lipman, M. 2017. Respiratory symptoms in people living with HIV and the effect of antiretroviral therapy: a systematic review and meta-analysis. *Thorax*, 72: 355-366. http://doi.org/10.1136/thoraxjnl-2016-208657
7. Dash, I. 2016. *Space-time observations for city level air quality modelling and mapping*. MSc Thesis, University of Twente, The Netherlands, 80 pages.
8. Deary, M.E., Bainbridge, S.J., Kerr, A., McAllister, A. & Shrimpton, T. 2016. Practicalities of mapping PM10 and PM2.5 concentrations on city-wide scales using a portable particulate monitor. *Air Quality Atmosphere and Health*, 9(8): 923-930. https://doi.org/10.1007/s11869-016-0394-3
9. Efe, S.I. & Efe, A.T. 2008. Spatial distribution of particulate matter (PM10) in Warri metropolis, Nigeria. *The Environmentalist*, 28(4): 385-394. http://doi.org/10.1007/s10669-007-9154-0
10. Evans, J., van Donkelaar, A., Martin, R.V., Burnett, R., Rainham, D.G., Birkett, N.J. & Krewski, D. 2013. Estimates of global mortality attributable to particulate air pollution using satellite imagery. *Environmental Research*, 120: 33-42. https://doi.org/10.1016/j.envres.2012.08.005
11. Fattore, E., Paiano, V., Borgini, A., Tittarelli, A., Bertoldi, M., Crosignani, P. & Fanelli, R. 2011. Human health risk in relation to air quality in two municipalities in an industrialized area of Northern Italy. *Environmental Research*, 111(8): 1321-1327. https://doi.org/10.1016/j.envres.2011.06.012
12. FEPA (Federal Environmental Protection Agency), 1999. *Nationale Environmental (Effluent Limitation) Regulations*. http://www.placng.org/new/laws/F10.pdf. Last access: September 2016.

13. Ferris, B.G. 1978. Epidemiology standardization project (American Thoracic Society), *American Review of Respiratory Disease*, 118(6): 1-120.
14. Goldberg, M.S., Wheeler, A.J., Burnett, R.T., Mayo, N.E., Valois, M.F., Brophy, J.M. & Giannetti, N. 2015. Physiological and perceived health effects from daily changes in air pollution and weather among persons with heart failure: A panel study. *Journal of Exposure Science and Environmental Epidemiology*, 25(2): 187-199. https://doi.org/10.1038/jes.2014.43
15. Gong, X., Zhan, F.B., Brender, J.D., Langlois, P.H. & Lin, Y. 2016. Validity of the emission weighted proximity model in estimating air pollution exposure intensities in large geographic areas. *Science of the Total Environment*, 563: 478-485. https://doi.org/10.1016/j.scitotenv.2016.04.088
16. Halonen, J.I., Lanki, T., Yli-Tuomi, T., Tiittanen, P., Kulmala, M. & Pekkanen, J. 2009. Particulate air pollution and acute cardiorespiratory hospital admissions and mortality among the elderly. *Epidemiology*, 20: 143-153. https://doi.org/10.1097/EDE.0b013e31818c7237
17. Khaniabadi, Y.O., Hopke, P.K., Goudarzi, G., Daryanoosh, S.M., Jourvand, M. & Basiri, H. 2017. Cardiopulmonary mortality and COPD attributed to ambient ozone. *Environmental Research*, 31(152): 336-341. https://doi.org/10.1016/j.envres.2016.10.008
18. Krejcie, R.V. & Morgan, D.W. 1970. Determining sample size for research activities. *Educational and Psychological Measurement*, 30: 607–610. https://doi.org/10.1177/001316447003000308
19. Krupnick, A.J. 2008. Challenges to managing air pollution. *Journal of Toxicology and Environmental Health*, A71: 13-23. https://doi.org/10.1080/15287390701557404
20. Maheswaran, R. 2016. Air pollution and stroke - an overview of the evidence base. *Spatial and Spatio-temporal Epidemiology*, 18: 74-81. https://doi.org/10.1016/j.sste.2016.04.004
21. Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K. & Sauvage, B. 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space. *Atmospheric Environment*, 99: 32-40. https://dx.doi.org/10.1016/j.atmosenv.2014.09.055
22. Mehta, S., Shin, H., Burnett, R., North, T. & Cohen, A.J. 2013. Ambient particulate air pollution and acute lower respiratory infections: a systematic review and implications for estimating the global burden of disease. *Air Quality Atmosphere and Health*, 6(1): 69-83. https://doi.org/10.1007/s11869-011-0146-3
23. Miranda, A.I., Ferreira, J., Silveira, C., Relvas, H., Duque, L., Roebeling, P., Lopes, M., Costa, S., Monteiro, A., Gama, C. & Sá, E. 2016. A cost-efficiency and health benefit approach to improve urban air quality. *Science of the Total Environment*, 569: 342-351. https://doi.org/10.1016/j.scitotenv.2016.06.102
24. Miri, M., Derakhshan, Z., Allahabadi, A., Ahmadi, E., Conti, G.O., Ferrante, M. & Aval, H.E. 2016. Mortality and morbidity due to exposure to outdoor air pollution in Mashhad metropolis, Iran. The AirQ model approach. *Environmental Research*, 151: 451-457. https://doi.org/10.1016/j.envres.2016.07.039

25. Moltchanov, S., Levy, I., Etzion, Y., Lerner, U., Broday, D.M. & Fishbain, B. 2015. On the feasibility of measuring urban air pollution by wireless distributed sensor networks. *Science of the Total Environment*, 502: 537–547. https://doi.org/10.1016/j.scitotenv.2014.09.059
26. Nagpure, A.S., Gurjar, B.R. & Martel, Jc. 2014. Human health risks in national capital territory of Delhi due to air Pollution. *Atmospheric Pollution Research*, 5: 371-380. https://doi.org/10.5094/APR.2014.043
27. NPC (National Population Commission), 2010. *Population distribution by sex, state, LGA, senatorial district, 2006 population and housing census*. Available from: http://www.population.gov.ng/images/NPCNEW/Pr%20Vol%203%20Pop%20by%20State%20&%20Senatorial%20District.zip. Last access: December 2016.
28. Obaseki, D.O., Adeniyi, B., Jumbo, J., Oyewo, A., Irabor, I. & Erhabor, G.E. 2014. Respiratory symptom, lung function and exhaled carbon monoxide among a sample of traffic workers in Lagos, Nigeria: A pilot survey. *Nigerian Medical Journal: Journal of the Nigeria Medical Association*, 55(4): 306-309. https://doi.org/10.4103/0300-1652.137190
29. Oltra, V. & Saint Jean, M. 2009. Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis. *Journal of Cleaner Production*, 17: 201-213. https://doi.org/10.1016/j.jclepro.2008.04.023
30. Oluwole, O., Arinola, G.O., Huo, D. & Olopade, C.O. 2017. Household biomass fuel use, asthma symptoms severity, and asthma underdiagnosis in rural schoolchildren in Nigeria: a cross-sectional observational study. *BMC Pulmonary Medicine*, 17(1): 3. https://doi.org/10.1186/s12890-016-0352-8
31. Patton, A.P., Laumbach, R., Ohman-Strickland, P., Black, K., Alimokhtari, S., Lioy, P.J. & Kipen, H.M. 2016. Scripted drives: A robust protocol for generating exposures to traffic-related air pollution. *Atmospheric Environment*, 143: 290-299. https://doi.org/10.1016/j.atmosenv.2016.08.038
32. Peters, A., von Klot, S., Mittleman, M.A., Meisinger, C., Hormann, A., Kuch, B. & Wichmann, H.E. 2013. Triggering of acute myocardial infarction by different means of transportation. *European Journal of Preventive Cardiology*, 20: 750-758. https://doi.org/10.1177/2047487312446672
33. Plaia, A. & Ruggieri, M. 2010. Air quality indices: a review. *Reviews in Environmental Science and Bio-Technology*, 10: 165-179. https://doi.org/10.1007/s11157-010-9227-2
34. Procházka, B. & Kynxcl, J. 2015. Estimating the baseline and threshold for the incidence of diseases with seasonal and long-term trends. *Central European Journal of Public Health*, 23(4): 352-359. https://doi.org/10.21101/cejph.a4392
35. Ren, M., Li, N., Wang, Z., Liu, Y., Chen, X., Chu, Y., Li, X., Zhu, Z., Tian, L. & Xiang, H. 2017. The short-term effects of air pollutants on respiratory disease mortality in Wuhan, China: comparison of time-series and case-crossover analyses. *Scientific Reports*, 7: 40482. https://doi.org/10.1038/srep40482

36. Sarnat, J.A., Golan, R., Greenwald, R., Raysoni, A.U., Kewada, P., Winquist, A., Sarnat, S.E., Flanders, W.D., Mirabelli, M.C., Zora, J.E. & Bergin, M.H. 2014. Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. *Environmental Research*, 133: 66-76. https://doi.org/10.1016/j.envres.2014.05.004
37. Schultz, E.S., Hallberg, J., Bellander, T., Bergström, A., Bottai, M., Chiesa, F., Gustafsson, P.M., Gruzieva, O., Thunqvist, P., Pershagen, G. & Melén, E. 2016. Early-life exposure to traffic-related air pollution and lung function in adolescence. *American Journal of Respiratory and Critical Care Medicine*, 193(2): 171-177. https://doi.org/10.1164/rccm.201505-0928OC
38. Sobrino, J.A., Jiménez-Muñoz, J.C. & Paolini, L. 2004. Land surface temperature retrieval from LANDSAT TM 5. *Remote Sensing of the Environment*, 90(4): 434-440. https://doi.org/10.1016/j.rse.2004.02.003
39. Svendsen, E.R., Gonzales, M., Mukerjee, S., Smith, L., Ross, M., Walsh, D., Rhoney, S., Andrews, G., Ozkaynak, H. & Neas, L.M. 2012. GIS-modeled indicators of traffic-related air pollutants and adverse pulmonary health among children in El Paso, Texas. *American Journal of Epidemiology*, 176(suppl. 7): S131-141. https://doi.org/10.1093/aje/kws274
40. Thiering, E. & Heinrich, J. 2015. Epidemiology of air pollution and diabetes. *Trends in Endocrinology and Metabolism*, 26(7): 384-394. https://doi.org/10.1016/j.tem.2015.05.002
41. Thompson, J.E. 2016. Crowd-sourced air quality studies: A review of the literature & portable sensors. *Trends in Environmental Analytical Chemistry*, 11: 23-34. https://doi.org/10.1016/j.teac.2016.06.001
42. Vizcaíno, M.A., González-Comadran, M. & Jacquemin B. 2016. Outdoor air pollution and human infertility: a systematic review. *Fertility and Sterility*, 106(4): 897-904. https://doi.org/10.1016/j.fertnstert.2016.07.1110
43. Wang, S., Feng, X., Zeng, X., Ma, Y. & Shang, K. 2009. A study on variations of concentrations of particulate matter with different sizes in Lanzhou. China. *Atmospheric Environment*, 43: 2823–2828. https://doi.org/10.1016/j.atmosenv.2009.02.021
44. WHO (World Health Organization), 2017. *AirQ+: software tool for health risk assessment of air pollution*. Available from: http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution. Last access: February 2017.
45. WHO (World Health Organization), 2016. *Global urban ambient air pollution database update*. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/WHO_AAP_database_May2016_v3web.xlsx?ua=1. Last access: September 2016.
46. Wolff, H. 2014. Keep your clunker in the suburb: low-emission zones and adoption of green vehicles. *The Economic Journal*, 124: F481-F512. https://doi.org/10.1111/ecoj.12091/
47. Xu, D. & Guo, X. 2014. Compare NDVI extracted from Landsat 8 imagery with that from Landsat 7 imagery. *American Journal of Remote Sensing*, 2(2): 10-14. https://doi.org/10.11648/j.ajrs.20140202.11

48. Yazdi, M.N., Delavarrafiee, M. & Arhami, M. 2015. Evaluating near highway air pollutant levels and estimating emission factors: Case study of Tehran, Iran. *Science of the Total Environment*, 538: 375-384. https://doi.org/10.1016/j.scitotenv.2015.07.141

Chapter 5

Appraising city-scale pollution monitoring capabilities of multi-satellite datasets using portable pollutant monitors‡‡

Abstract

The retrieval characteristics for a city-scale satellite experiment was explored over a Nigerian city. The study evaluated carbon monoxide and aerosol contents in the city atmosphere. We utilized the MSA Altair 5x gas detector and CW-HAT200 particulate counter to investigate the city-scale monitoring capabilities of satellite pollution observing instruments; atmospheric infrared sounder (AIRS), measurement of pollution in the troposphere (MOPITT), moderate resolution imaging spectroradiometer (MODIS), multi-angle imaging spectroradiometer (MISR) and ozone monitoring instrument (OMI). To achieve this, we employed the Kriging interpolation technique to collocate the satellite pollutant estimations over 19 ground sample sites for the period of 2015 - 2016. The portable pollutant devices were validated using the WHO air filter sampling model. To determine the city-scale performance of the satellite datasets, performance indicators: correlation coefficient, model efficiency, reliability index and root mean square error, were adopted as measures. The comparative analysis revealed that MOPITT carbon monoxide (CO) and MODIS aerosol optical depth (AOD) estimates are the appropriate satellite measurements for ground equivalents in Zaria, Nigeria. Our findings were within the acceptable limits of similar studies that utilized reference stations. In conclusion, this study offers direction to Nigeria's air quality policy organizers about available alternative air pollution measurements for mitigating air quality effects within its limited resource environment.

Keywords: *Nigeria; Air pollution; Portable monitors; Satellite pollution estimates*

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5.1. Introduction

Air quality is undoubtedly a key subject of public concern (Gozzi et al., 2016). Petroleum derivatives and biomass consumption are the major sources of air pollution in developing cities and have been linked to unfriendly respiratory impacts (Marais et al., 2014). Exposure to air pollutants is increasing respiratory and cardiovascular morbidity and mortality (2.8 million deaths), with developing countries still experiencing the worst air pollution (WHO, 2016). With over a decade of global awareness on air pollution, studies are still reporting the effects of criteria pollutants on the human cardiovascular and respiratory systems (Ghozikali et al., 2015; Miri et al., 2016; Ren et al., 2017).

Rapid economic development coupled with scarce administrative policies within the African continent is leading to an increased level of air pollution, thus putting the wellbeing of its major population at risk (Marais and Chance, 2015). In Africa, studies on surface air pollution monitoring are insufficient, with only a few nations have established environmental procedures. South Africa is the only African country that appears to have established well-defined standards and a comprehensive monitoring network (Kgabi, 2014; Hersey et al., 2015).

Nigeria is Africa's most populated country (182 million people as at 2015) and also the largest economy, recently surpassing South Africa (The Economist, 2017; UN, 2017). Nigeria's rapid growth stimulates a variety of environmental worries, most especially air quality. Outdoor air pollution is majorly worsened by inept automobiles, unsystematic road structure leading to traffic obstruction, dependence on power generating sets by commercial outlets due to poor electricity infrastructure and congested roadside activities (Adewunmi et al., 2015; Orogade et al., 2016). The measurements of outdoor pollutants are essential for human exposure awareness (Duvall et al., 2012; Bereznicki and Kamal, 2013).

Since urban air pollution undergoes several processes which generate its spatial variable concentrations, a network of pollution station units can be employed to predict concentrations at unmeasured locations and also effectively monitor urban air pollution (Kanaroglou et al., 2005; Adams et al., 2012; Dash, 2016). The density of an urban environment combined with natural variability and unpredictable anthropogenic emission sources compels for the constant appraisal of pollution models by means of up-to-date datasets (Neophytou et al., 2011).

Low-cost pollutant monitors are getting extra attention in the area of air pollution monitoring when compared with established reference devices (Kumar et al., 2015). The majority of the lower cost sensors is robustly designed using micro-electro-mechanical techniques and energy efficient sensor circuits. This makes them cost-effective, light-weight and compact, thus consuming minimum power for detecting selected toxic gases and particulates in any industrialized environment (Mead et al., 2013). Their user-friendliness enables efficient near real-time resolution data acquisition, thus allowing for larger spatial coverage especially in remote/developing areas (Snyder et al., 2013). The availability of portable pollution monitoring detectors has considerably increased the possibility of identifying pollution hot spots, enriching air pollution maps, evaluating air quality policies and safeguarding public health (Engel-Cox et al., 2013; Gozzi et al., 2016). Cities across the globe are embracing the concept of portable test sites for gathering air quality variability and statistics for mitigation planning. Validated portable pollutant monitors can be adopted as ground-based retrieval stations, as they provide fast and transparent dissemination of observed dataset (Kumar et al., 2015; Gozzi et al., 2016). However, the challenges regarding the deployment of portable sensors for air pollution monitoring are their operational maintenance which in most cases eventually exceeds the actual cost of the sensor. The operation maintenance comprises of device stability (such as sensor re-calibration, sensor/battery replacement), data management costs and operational longevity before replacement (Kumar et al., 2015).

Considerable achievements are still being realised in the area of space-based atmospheric pollution monitoring. Satellite pollution sensors have continued to show the increased capability of observing chemical species at high 4-D resolutions that can be utilized for a wide range of environmental-friendly atmospheric related applications (Duncan et al., 2014; Zhang et al., 2016). While the particle satellite instruments measure the extinction of light to retrieve the chemical aerosols, the trace gas instruments measure the number density of the trace gas, all in a vertical column of air. This approach is also used to further estimate the chemical particles precisely under that column of air, as long as their movement and chemical conversion is minimally interfered with or compensated for (Streets et al., 2013). The advantage of satellite pollution data is its spatial and temporal coverage. This coverage serves as a surrogate for long-term regional air quality monitoring, as well as the development of emission inventories (Engel-Cox et al., 2004; Schaap et al., 2009). The space-based pollution measurements are also being embraced as a distinctive resource for detecting air quality in regions with scarce ground-based information (Marais et al., 2014). The main challenge of satellite pollution instrument is its resolution at low-altitude. The measurements at low altitudes are perceived to be influenced by all kinds of atmospheric attenuations thus generating errors.

For this reason, the satellite brochures continue to encourage researches to utilize the retrieved satellite datasets for surface test/validation procedures. Another familiar challenge of the satellite pollution instrument with limited resources establishments is the technical know-how to access, process and accurately interpret the satellite pollution observational datasets (Duncan et al., 2014).

The dependence on portable monitors for air pollution monitoring is on the rise. There is also no record of Nigeria's air quality planners acknowledging the use of satellite pollution data resources. These are the motivation for the study. Thus, we attempt to determine, the level of pollution measurements these satellite pollution estimates represent in a developing Nigerian city. It is on this basis, that this study pilots an approach for appraising city-scale monitoring capabilities of multi-satellite pollution datasets using ground-positioned, portable pollutant monitors.

5.2. Methods

5.2.1. Study area

Zaria metropolis is the centre for educational advancement for the Northern part of Nigeria. The city is experiencing a rapid population increase and urban sprawl thus deteriorating the air quality within the city. It covers an area of 296.036 square kilometres, with an estimated population of 938, 521. The topography is mainly flat at 670 m above mean sea level (Figure 5.1). The climate is categorized into dry (October – May) and wet (June – September) seasons. The seasons are distinguished by low temperature (14.1°C) during the harmattan in January and peak temperature (35.2°C) in April. The population is majorly Hausa speaking and dominant land use outside the built-up area is sparse vegetation except during the rainy season. The area is drained by the Kubanni River and its many tributaries.

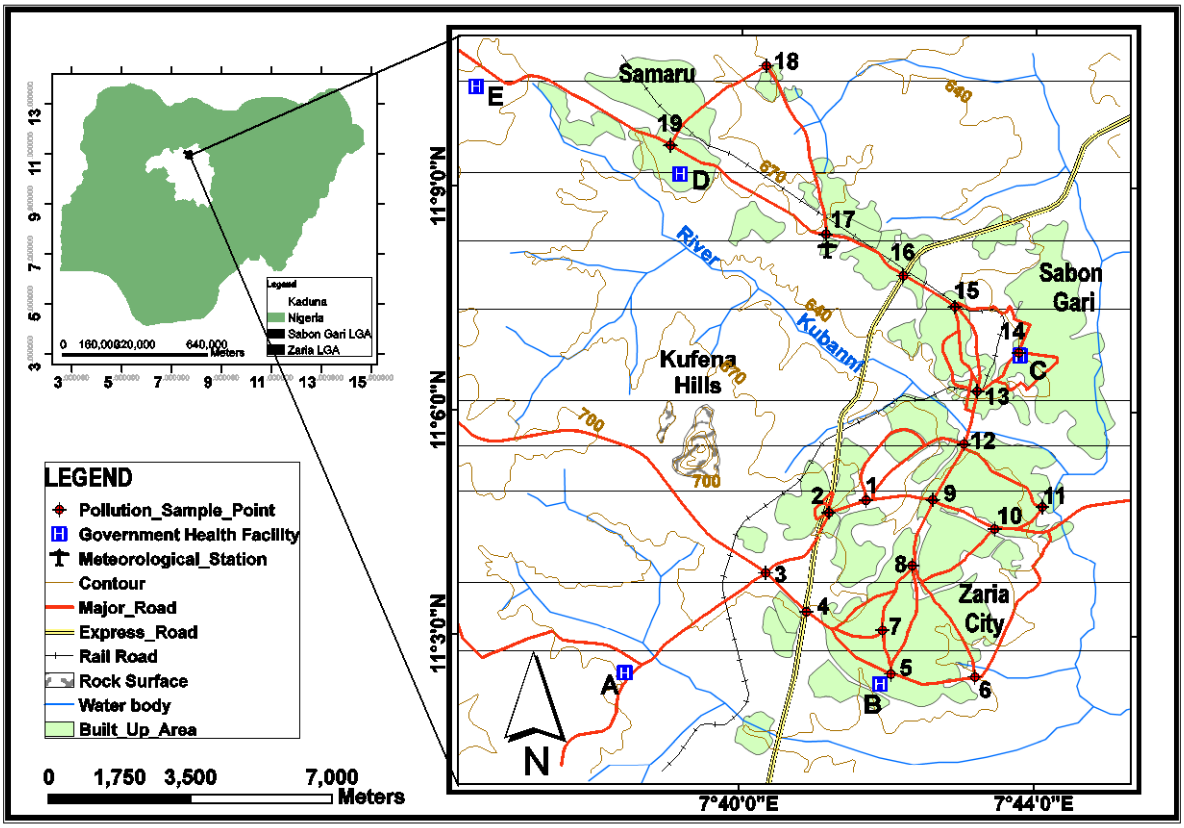


Figure 5.1. Study area displaying the Kufena hill, meteorological station and distribution of the 19 sample sites (Sites 3, 6 and 18 are control sites)

5.2.2. Ground CO and PM datasets

Figure 5.1 shows the distribution of the 19 sampling sites across the study area. The sample sites were distributed to represent the majority of outdoor activities contributing to air pollution in the study area. 16 sites are located along major road intersections with dense population activity across residential and commercial settlements, while the remaining 3 control sites are positioned strategically at the outskirts of the city with minimal population activity. The control sites were adopted to serve as checks for results comparison. The portable monitoring devices are the MSA Altair 5x which measures carbon monoxide (CO) in parts per million (ppm) and the CW-HAT200 which measures particulate matter (PM_{10}) in microgram per meter cube (μgm^{-3}). The use of these devices has been assessed by Liu et al., (2014): Mishra et al., (2015); Shibata et al., (2015). The devices were procured solely to collect ground-level pollution concentrations of selected criteria pollutants across the study period (1 December 2015 – 30 November 2016).

Prior to the commencement of the ground sample collection using the portable monitors, the devices were validated using filter sampling papers to obtain total suspended particulates (TSP) at 2 sample test sites. This is based on the WHO air sampling model (Equation 5.1) described in Efe and Efe (2008).

$$TSP\ (\mu gm^{-3}) = \frac{M_S - M_O}{V} \tag{5.1}$$

Where TSP is the particulate matter, *Mo* is mass of filter paper prior to sampling, *Ms* is the mass filter paper after sampling, *V* is the TSP volume. To determine the concentration (μgm^{-3}), model equation 5.1 was divided by the sample time in hours.

102 filter samples were utilized to collect totally suspended particles (TSP) concurrently with the portable devices' measurements. Validation samples were obtained on Mondays, Wednesdays, Fridays and Sundays in the month of November 2015. One of the sample sites had dense outdoor population activity and the other had minimal population activity (control site). Samples were collecting for morning, afternoon and evening periods. The portable devices and sample filters were positioned at the same 1.5m above ground elevation. The obtained measurements at each site were weighted in order to obtain the 8-hr day-time average for outdoor activities over the 17 sampling days. Since our study is interested in air pollution resulting from outdoor population activities, we believed all pollutant emissions resulting from the population activities would strongly correlate against one another (Guo et al., 2017). It is for this reason that we utilized the filter samples from the two selected sample sites for validation of CW-HAT200 particulate counter and MSA Altair 5x multi-gas detector using PM_{10} and CO values respectively. The validation statistics showed that the correlation coefficient between the TSP concentrations from filter sampling and PM_{10}/CO for the CW-HAT200/MSA Altair 5x were highly significant. The correlation value (R) of TSP/PM_{10} and TSP/CO was very strong across the two sites. The WHO procedure validated the reliability of the portable devices (Figure 5.2).

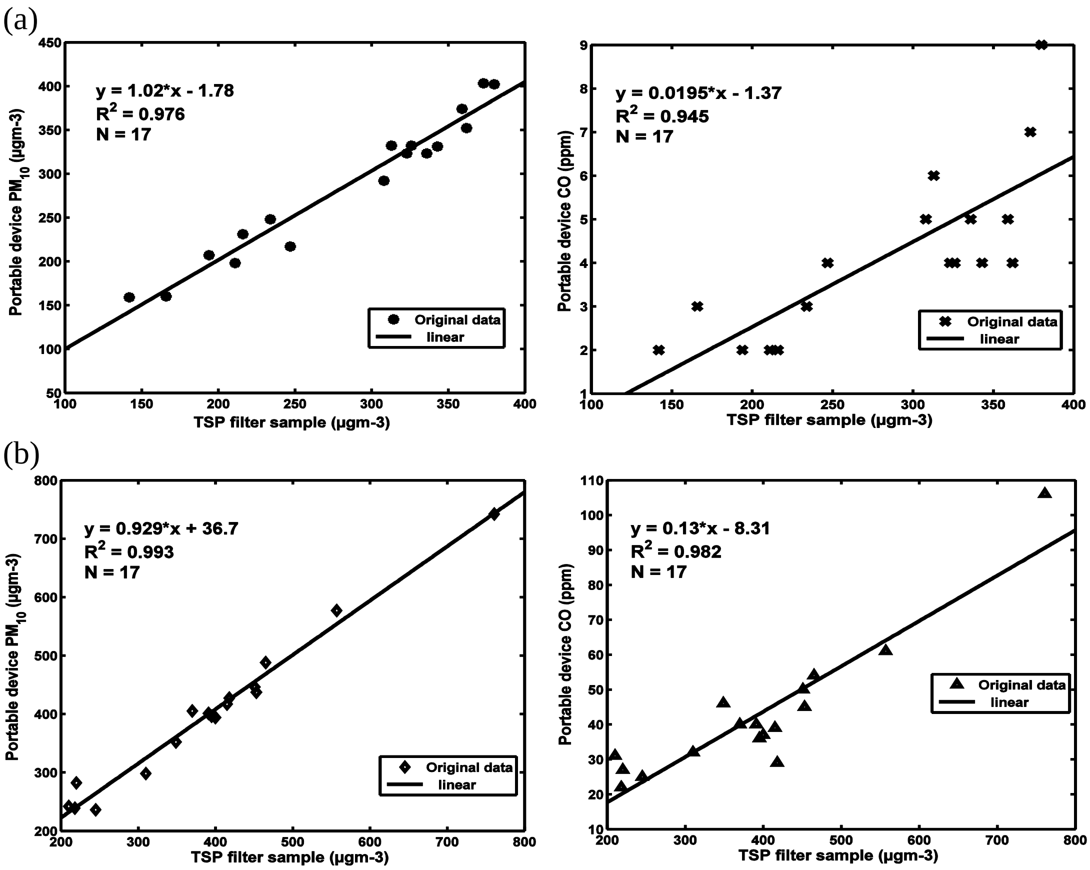
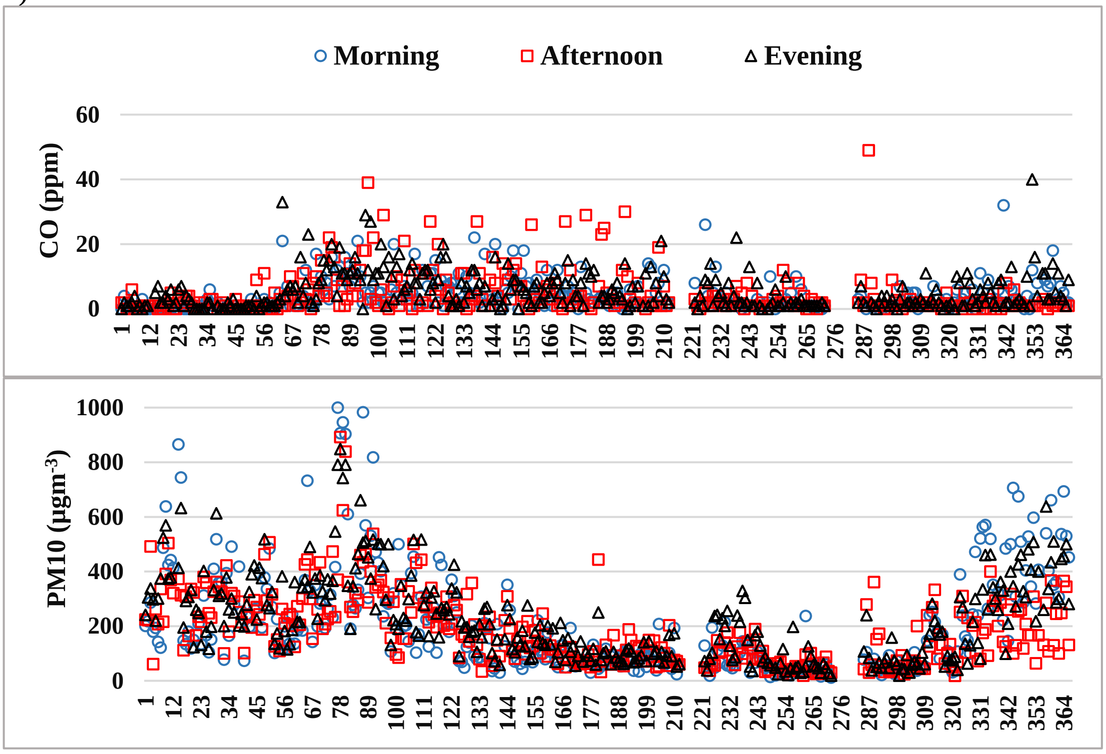


***Figure 5.2.** Linear regression showing validation of portable pollutant monitors and TSP samples using the WHO air sampling model. (a) Control site, (b) dense activity site*

The criteria pollutants measured across the study site are ground-level carbon monoxide (GCO) and particulate matter with a diameter less than 10 microns (GPM). The accuracy obtained was similar to those stated in the instrument configuration. To determine day-time averages, ground in-situ samples were collected daily across three epochs. The epochs are peak morning (0730 – 0845 hrs), moderate afternoon (1300 – 1415 hrs) and peak evening (1700 – 1815 hrs) (Bell and Davis, 2001; Yazdi et al., 2015). A sample resolution time of 3 minutes was adopted per site. For each sampling, the highest perceived CO and PM_{10} concentrations were recorded based on instrument configuration. The values were weighted for the morning, afternoon and evening epochs respectively (Llanes, 2016). The samples were collected with devices positioned at 1.5 metres above ground level. Ground pollution samples (N) for GCO and GPM were collected for 339 out of the 366 days. A time-series plot for a control site (Site 6) and a seeming polluted site (Site 16) is displayed in Figure 5.3. The characteristics of the portable devices employed are highlighted in Table 5.1 and the descriptive statistics of recorded concentrations are shown in Table 5.2.

a)



(b)

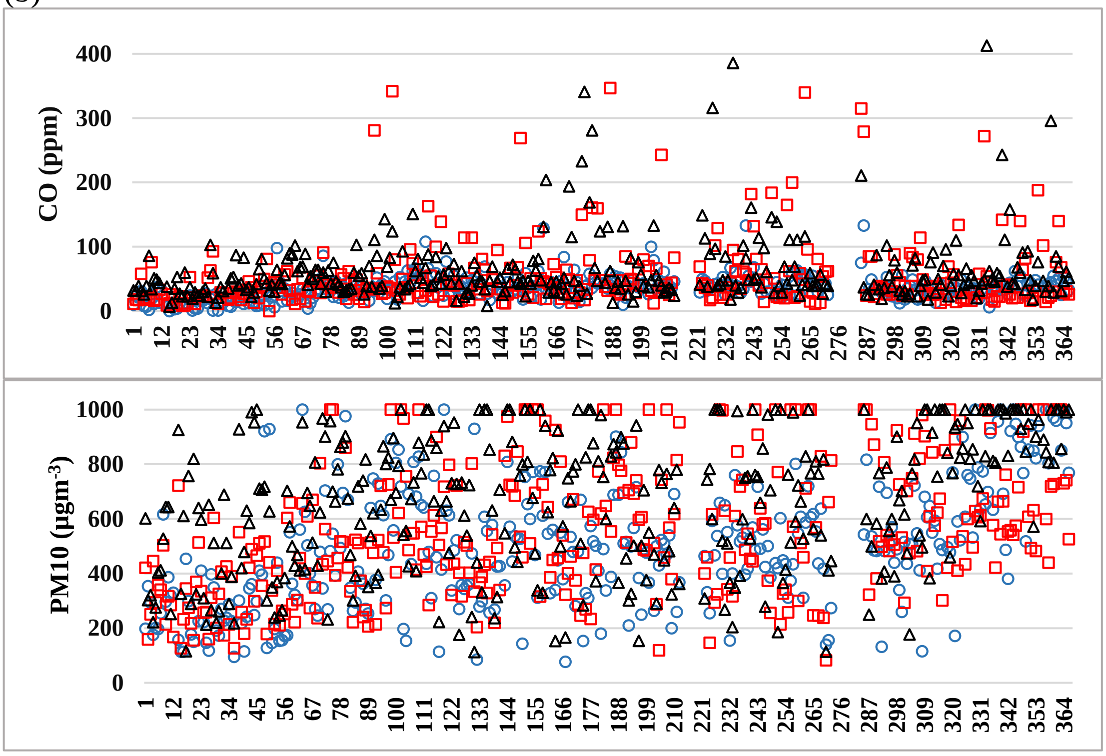


Figure 5.3. *Times-series of the GCO and GPM concentrations (a) control site 6 (b) populated site 16, for the study period (1 December 2015 – 30 November 2016). Note that the blue, red and black scatter plots represent the morning, afternoon and evening sampling periods respectively.*

Table 5.1. *Specifications of the portable pollutant monitors utilized for ground measurements*

Specifications	MSA Altair 5x Gas Detector[a]	Chinaway CW-HAT200 Particulate Counter
Dimension (cm)	17 (H) x 8.94 (W) x 4.88 (D)	18 (H) x 9.3 (W) x 4.8 (D)
Weight (kg)	0.45	0.60
Measuring method	Internal pump; Catalytic/electrochemical sensor	Internal pump; laser light scattering
Pollutant measured	CO; SO_2; H_2S; LEL (Combustible)	$PM_{2.5}$, PM_{10}
Concentration Range	CO (0 - 500 ppm) SO_2 (0 - 25 ppm) H_2S (0 - 100 ppm) LEL (0 - 100 %)	$PM_{2.5}$ (0 - 500 µgm^{-3}) PM_{10} (0 - 1000 µgm^{-3})
Sample/Response Time	CO (15 secs) SO_2 (20 secs) H_2S (15 secs)	$PM_{2.5}$ (60 secs) PM_{10} (60 secs)
Accuracy	±10% of reading	±5% of reading
Operating temperature	-10 °C to 40 °C	5 °C to 45 °C
Operating humidity	15 - 90% RH	<90% RH
Calibration Due	6 months	1 year
Battery	Rechargeable lithium-ion	Rechargeable lithium-ion polymer
Display	Monochrome	LCD
Certification	CE, UL, CSA, IEC, IP	CE

.[a]Instrument was re-calibrated during the data collection stage (January 2016 and June 2016). The calibration mixed gas specifications are CO – 50 ppm; SO_2 – 5 ppm; H_2S – 15 ppm; LEL – 58 %.

Table 5.2. *Descriptive statistics of the GCO and GPM for the study area in 2015 – 2016 (N = 19, 104)*

Ground Measurements	Period	Mean	Median	SD
GCO (ppm)	Whole Year	29.2	23.0	28.3
	December-January-February	20.3	16.0	20.1
	March-April-May	34.3	28.0	30.2
	June-July-August	34.2	27.0	32.2
	September-October-November	28.0	23.0	27.1
GPM (µgm^{-3})	Whole Year	451.9	403.0	251.4
	December-January-February	401.8	350.0	213.5
	March-April-May	442.5	405.0	248.1
	June-July-August	405.7	363.0	251.0
	September-October-November	557.6	529.0	265.9

5.2.3. Satellite CO and AOD datasets

The National Aeronautics and Space Administration (NASA) has a catalogue of datasets generated from several nadir-viewing earth observing system (EOS) instruments which include: atmospheric infrared sounder (AIRS); multi-angle imaging spectroradiometer (MISR); moderate resolution imaging spectroradiometer (MODIS); measurements of pollution in the troposphere (MOPITT) and ozone monitoring instrument (OMI) (Streets et al., 2013). The NASA-funded exploration aims to enable researches trace, link and cite these data to the scientific literature (NASA, 2017).

Carbon monoxide is a gaseous pollutant that usually results from incomplete combustion of anthropogenic sources, or oxidation of hydrocarbons (Rinsland et al., 2006). CO retrievals are exceptional for detecting anthropogenic activities, assessing emissions, and resolving wind effect on emission sources (Fisher et al., 2010). NASA's EOS instrument records nadir measurements of CO at 4.6 µm from low Earth orbit using varying retrieval algorithms: AIRS (McMillan et al., 2005) and MOPITT (Deeter et al., 2003). For the city-scale evaluation, the vertical mixing ratio for satellite CO estimates was utilized based on data source recommendation. The reason is that the AIRS CO total column is the integral over the entire atmospheric column (AskAirs, personal communication, 16 February 2016). The lowest altitude/pressure level for AIRS and MOPITT CO mixing ratios are 925 hPa and 900 hPa respectively. These pressure levels are a weighted average of a good portion of the lower and middle troposphere. Normally, the same altitude/pressure level should be adopted for consistency. However, the lowest collocating CO mixing ratio altitude between the AIRS and MOPITT sensor is 700 hPa. This pressure level is not good enough for comparison with ground-level data (Marey et al. 2015).

Particulate matter is reported to adversely affect the respiratory health of varying age-groups (Yoshizaki et al., 2017). The primary satellite parameter for PM is aerosol optical depth (AOD). AOD is the total extinction effects on the incident radiation after its atmospheric interaction with particulates of different dimensions (Liou, 2002). To evaluate AOD and PM, available literatures have indicated that, there is a linear relationship between these two quantities. This empirical approach is the most recognised for distinguishing PM concentration from satellite data, whereby the degree of prediction can be determined using the level of correlation between the in-situ PM measurement and corresponding satellite AOD, of equal variables (Schäfer et al., 2008; Yap and Hashim, 2013). A detailed data processing method for distinguishing AOD from PM is described in Filip and Stefan (2011). For the satellite AOD estimates used in this study, the MODIS (1 km resolution) and OMI (13*24 km resolution) instruments provide daily global AOD coverage via recording of the Earth's spectral radiance. The MISR as well delivers AOD information at 17.6 km resolution approximately twice a month.

5.2.4. Satellite data parameter

Level 3 data was adopted for the various satellite instruments. This is due to their geophysical parameters which have been averaged into longitude/latitude grid cells. The map coordinates are gridded from -180.0° to +180.0° across longitude and -90.0° to +90.0° across latitude (Tian *et al*., 2014). The NASA satellite data provide global coverage of atmospheric pollution in Hierarchical Data Format-Earth Observing System (HDF-EOS) and Network Common Data Form (NetCDF) formats, which can be accessed using software such as Panoply (Vollmer, 2010). Users are encouraged to embrace the level 3 processing as every essential filters and rectification have been affected (Streets et al., 2013). The NASA data acquisition portal also made provision for sub-setting locations and variables of interest.

A subset covering the study area was adopted using spatial boundary box of (7.0, 11.0, 12.0, 8.0) degrees for West, South, North and East respectively. The satellite data estimates were synchronized with the ground measurements using Kriging interpolation technique (Araki *et al*., 2015). The AIRS standard product and MOPITT (near and thermal infrared radiance) were utilized. The data variables used for this study are available on the NASA retrieval platform (https://reverb.echo.nasa.gov). Table 5.3 shows the retrieval characteristics of the satellite instrument datasets adopted for the study.

Table 5.3. *Retrieval characteristics of the selected NASA satellite instruments*

Instrument	Species	Version	Sample size	URL	Variable
AIRS	CO	6	251	http://disc.sci.gsfc.nasa.gov/SSW/#keywords=AIRX3STD 006	ascending_TqJoint:CO_VMR_TqJ_A
MOPITT	CO	6	79	https://eosweb.larc.nasa.gov/project/mopitt/mop03j_table	RetrievedCOMixingRatioProfileDay
MODIS	AOD	5.1	210	http://disc.sci.gsfc.nasa.gov/SSW/#keywords=MYD08_D3 5.1	Deep_Blue_Aerosol_Optical_Depth_Land_Mean
MISR	AOD	4	47	https://eosweb.larc.nasa.gov/project/misr/misr_table	Optical_depth_average
OMI	AOD	3	143	http://disc.sci.gsfc.nasa.gov/SSW/#keywords=OMAEROe 003	AerosolOpticalThicknessMW: Best Fit Spectral Aerosol Optical Thickness derived with the Multi-Wavelength method, scaled by a factor 1000

To determine the city-scale performance of these satellite pollution datasets, four performance indicators; reliability index, correlation coefficient, root mean square error and model efficiency, were utilized. The indicators are described as follows:

The Cronbach's alpha (α) is an index of reliability (RI) which reveals the internal consistency associated with the variation accounted for a test or scale. The internal consistency defines the extent to which all the items in an investigation are inter-related. The reliability should be determined before an investigation can be employed for research to ensure validity (Le Boennec and Salladarré, 2017). It is expressed as a number between 0 and 1, with ≥ 0.7 regarded as an acceptable reliability coefficient. It is expressed in Equation 5.2 below.

$$\alpha = \frac{N \cdot \overline{C}}{\overline{\upsilon} + (N-1) \cdot \overline{C}} \qquad (5.2)$$

N is the sample size; c average covariance between the observed ground-level pollutants O_i (i.e., GCO and GPM) and the predicting P_i (i.e., AIRS, MOPITT, MODIS, OMI and MISR) retrievals; $\overline{\upsilon}$ is the average variance

The Correlation Coefficient R is the measure of how intimate the statistical data are to the fitted line of regression. As expressed in Equation 5.3 below, it is the correlation coefficient or anomaly correlation coefficient (ACC) (Jolliffe and Stephenson, 2012).

$$R = \left[\frac{\sum_{i=1}^{n} \left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)}{\left[\sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2 \times \sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2\right]^{\frac{1}{2}}} \right] \quad (5.3)$$

The Root Mean Square Error (RMSE) is the square root of the variance of the residuals which describes how close the observed pollution data points are, to modelled predicted values (Chai and Draxler, 2014). It is expressed in Equation 5.4 below.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (O_i - P_i)^2} \quad (5.4)$$

The Nash-Sutcliffe model efficient coefficient (NSE) is a statistic of fitness that evaluates how one model forecasts the other relative to the average of the observation between both, with values varying between 0 and 1 (McCuen et al., 2006). It is expressed by Equation 5.5.

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Bias_i\right)^2}{\sum_{i=1}^{n} \left(\left|(P_i - \overline{O}\right|) - \left(\left|(O_i - \overline{O}\right|\right)^2} \quad (5.5)$$

Oi and *Pi* are respectively the time series of the observed ground-level pollutants (i.e., CO and PM) and the predicting (i.e., AIRS, MOPITT, MODIS, OMI and MISR) retrievals. The average of the observed and predicted retrieval values is indicated by *O* and *P*, respectively, and the number of observations is indicated by *N*.

The *NSE* and *R*, are unit-less prediction measures that are indicative of model fit. The model prediction performance is acceptable if the NSE and R, are respectively greater than 0.4 and 0.5 (Engel et al., 2007).

5.3. Results

This section discusses the results of the various satellite retrievals evaluation at diurnal and seasonal scales, with relation to the respective validated ground measurements (GCO and

GPM). Table 5.4 highlights the number of collocating samples size between the satellite retrievals and ground measurements as well as collocating samples size between co-satellite retrievals for the study period.

Table 5.4. *Collocating sample size of the satellite retrieved estimates with ground measurements*

Indicators	Pollutants	Collocating Instruments	Seasons			
			DJF	MAM	JJA	SON
Sample size, N	CO	GCO-AIRS CO	78	75	64	11
		GCO- MOPITT CO	26	21	6	20
		AIRS CO-MOPITT CO	26	21	8	2
	PM (AOD)	GPM-OMI AOD	40	40	8	19
		GPM-MODIS AOD	82	70	23	12
		GPM-MISR AOD	17	13	5	11
		OMI-MODIS AOD	41	31	2	3
		OMI AOD-MISR AOD	1	2	-	1
		MODIS AOD-MISR AOD	11	13	5	1

5.3.1. Diurnal distribution of the satellite retrievals and ground measurements

The collocated diurnal averages of satellite retrievals (AIRS-MOPITT CO and MODIS-MISR-OMI AOD) were plotted respectively against GCO and GPM as shown in Figure 5.4. Our findings showed that the day-time 8-hour averaged samples from ground measurements were above the stipulated threshold (WHO, 2017) of 9 ppm and 50 µgm^{-3} for CO and PM_{10} respectively. For the GPM measurements, there was a sudden increase in GPM concentrations in late 2016. This is attributed to the commencement of intense construction works (drainage and road rehabilitation) by the Kaduna state government across the study area. For satellite retrieved pollutants, AIRS CO mixing ratio (ppb) and MOPITT CO vertical mixing ratio (ppbv) recorded CO peak values of 229.876 and 247.338 respectively (Figures 5.4a and b), while MODIS AOD, MISR AOD and OMI AOD recorded 3.146, 1.135 and 5.817 (no units) respectively (Figure 5.4c). This study notes that there was data breach from the NASA download portal for the satellite instruments AIRS CO data from 25 September 2016 and MODIS AOD data from 7 October 2016 to the end of study period (30 November 2016).

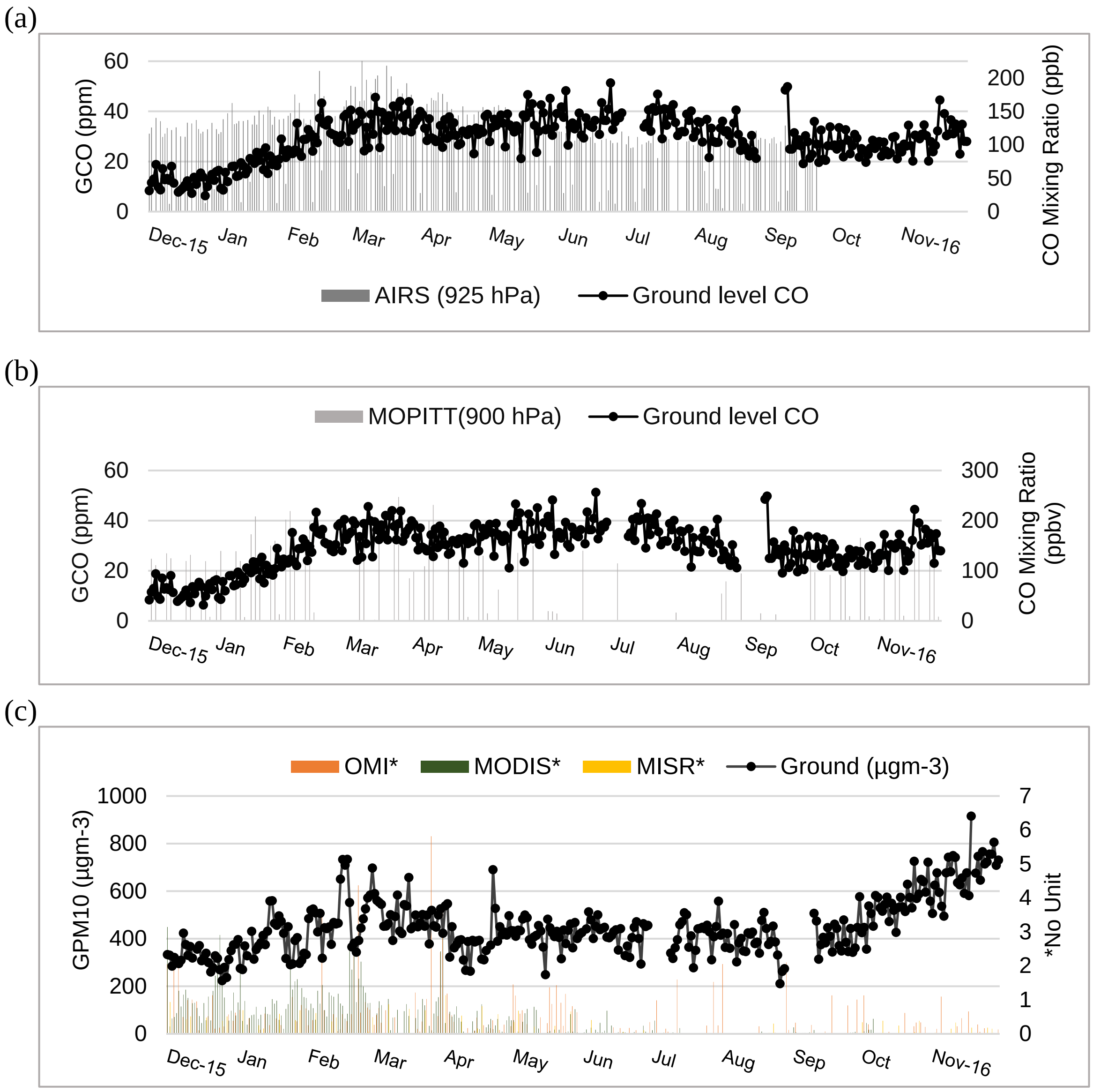
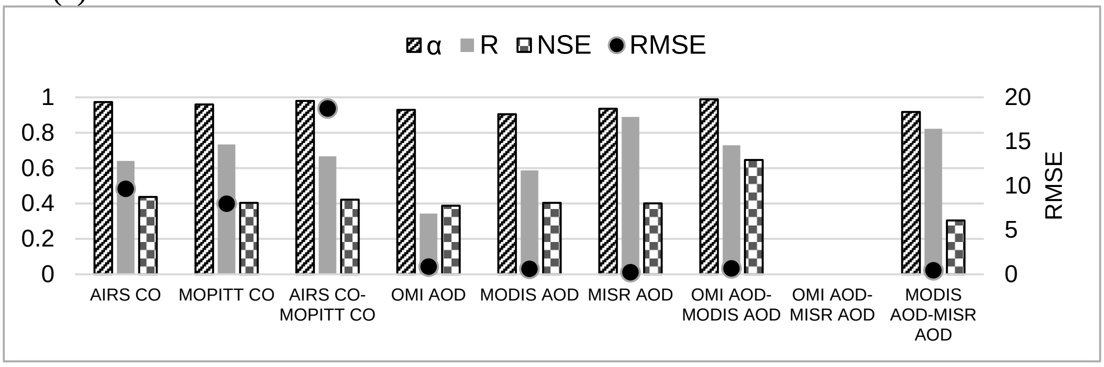


Figure 5.4. *Collocating time series plots (a) GCO-AIRS CO (b) GCO-MOPITT CO (c) GPM – MODIS-MISR-OMI AODs.*

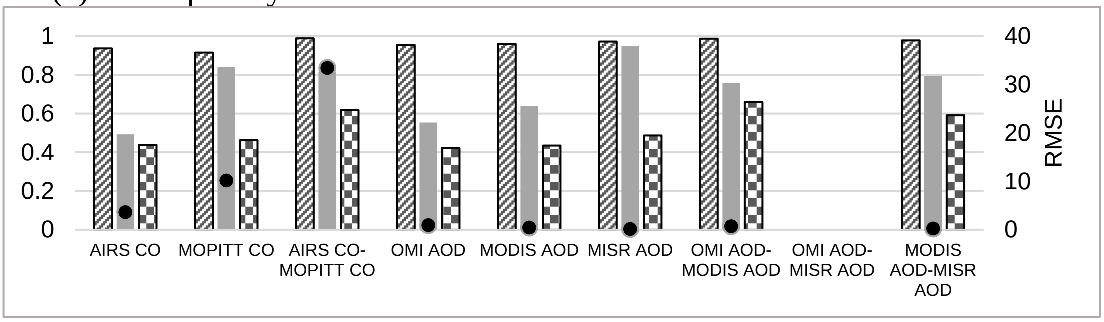
5.3.2. Seasonal relationship of the satellite retrievals with ground measurements

For analysis suitability, the seasonal pollution estimates of AIRS CO, MOPITT CO, MODIS AOD, MISR AOD and OMI AOD were harmonized (i.e. pairing of common days in 2015 and 2016) with the respective validated GCO and GPM measurements. The study period was also categorized into December-January-February (DJF); March-April-May (MAM); June-July-August (JJA); September-October-November (SON). Satellite retrievals were also harmonized against one another, to serve as a check. Their statistical performance is displayed in Figure 5.5.

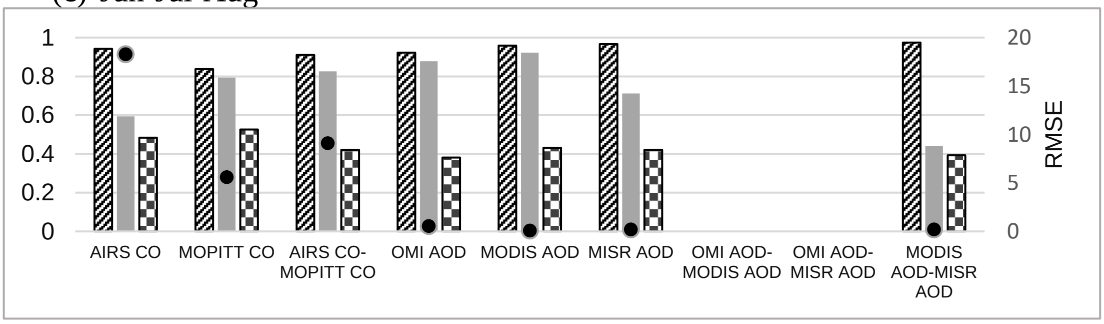
(a) Dec-Jan-Feb



(b) Mar-Apr-May



(c) Jun-Jul-Aug



(d) Sep-Oct-Nov

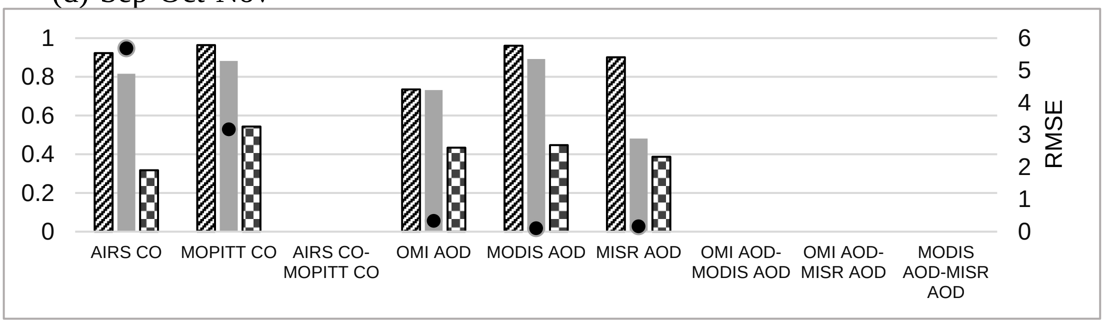


Figure 5.5. *Seasonal performance of satellite retrieved estimates with collocating ground measurements. The α, R and NSE value ranges from 0 – 1 (Left axis). Note that the collocating instruments that did not display any information, is due to their collocating sample size data being less than 5 (See Table 5.4).*

5.3.2.1. CO analysis

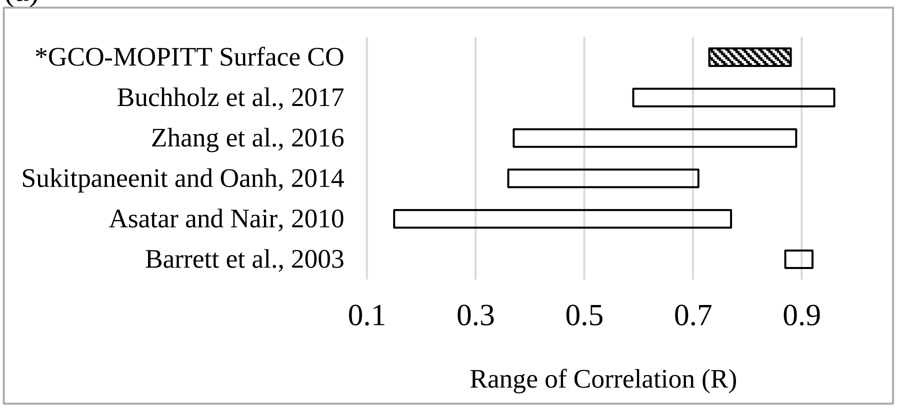
The seasonal coefficients of reliability amongst synchronized retrieval instruments varied between (0.923 – 0.973) and (0.838 – 0.964) for AIRS CO and MOPITT CO respectively. AIRS CO showed a higher RI which can be attributed to its higher paired measurement samples of 228 with GCO, compared to MOPITT CO's 73. Both models' reliability coefficients were within acceptable limits. Accuracy measures for the satellite retrievals showed acceptable results of RMSE for AIRS CO (3.629 – 18.289) and MOPITT CO (3.171 – 10.171). The MOPITT CO showed a better correlation compared to the AIRS CO. The efficiency of the models as indicated by the NSE in Figure 5.5, displayed that both AIRS CO and MOPITT CO had acceptable values (> 0.40) for all the season except for season SON where AIRS CO recorded 0.317. The correlation of paired data over the 2015 – 2016 period yielded coefficient value for AIRS CO and MOPITT CO in the range of (0.493 – 0.814) and (0.734 – 0.841) respectively. The reference AIRS CO - MOPITT CO model showed acceptable values for the four performance indicators except for the SON season, where paired common days was less than 5 (Table 5.4). The analysis revealed that the MOPITT CO product displayed the better performance and therefore, is deemed the better-suited satellite CO measurement instrument for users in the Zaria. To further improve our findings on the MOPITT CO analysis, we compared the MOPITT CO surface variable (RetrievedCOSurfaceMixingRatioDay) with the GCO. Using the above-listed performance measures, the results (Table 5.5) confirmed the performance of the MOPITT CO surface, as still, the well-matched satellite CO instrument for Zaria users.

Table 5.5. *Seasonal performance of MOPITT CO surface estimates against validated GCO*

Pollutant	Collocating Instrument	Indicators	Seasons			
			DJF	MAM	JJA	SON
CO	GCO/ MOPITT CO Surface Mixing Ratio	*Sample size, n*	26	21	6	20
		A	0.972	0.970	0.914	0.975
		RMSE	7.997	9.113	6.162	3.005
		NSE	0.417	0.450	0.462	0.520
		R	0.732	0.875	0.910	0.895

Our evaluation of the MOPITT CO estimates for city-scale monitoring are similar to documented studies on comparison using validated ground measurements (Barret et al., 2003; Asatar and Nair, 2010; Zhang et al., 2016; Buchholz et al., 2017) and better than Sukitpaneenit and Oanh (2014) (Figure 5.6a).

(a)



(b)

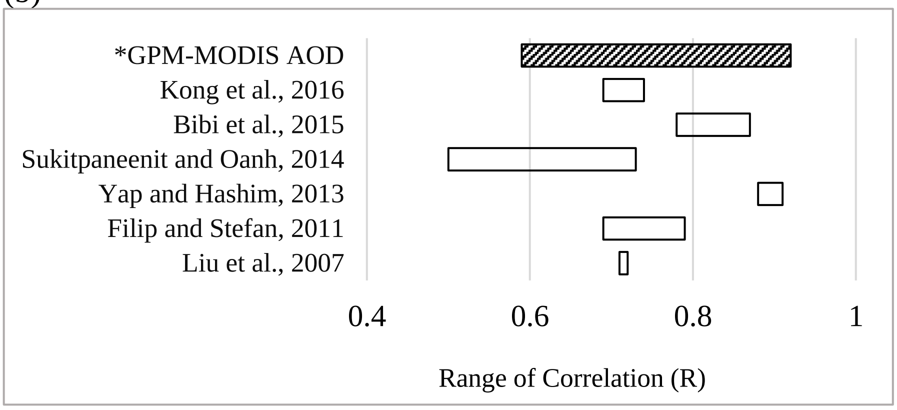


Figure 5.6. *The range of correlation coefficient obtained in comparison with similar literature (a) ground CO-MOPITT CO, (b) ground PM-MODIS AOD; (*) shaded bars – authors' findings*

5.3.2.2. AOD analysis

In Figure 5.5, the reliability of the collocating satellite datasets across the seasons averaged 0.885, 0.946 and 0.944 for OMI AOD, MODIS AOD and MISR AOD respectively. These values were within acceptable limits. RMSE ranged from 0.094 – 0.937, with MISR AOD recording the most precise of the three models. For model efficiency, the MODIS AOD averaged highest with 0.430, followed by MISR AOD with 0.424 and finally OMI AOD with 0.406. They were all within acceptable limits (NSE > 0.40). Correlating satellite retrievals with respective GPM, the model estimations (R) varied from (0.343 – 0.878), (0.587 – 0.922) and

(0.481 – 0.950) for OMI AOD, MODIS AOD and MISR AOD respectively. On average, the MISR AOD outpaced other comparatives in the DJF and MAM seasons. The performance reduced in the latter part of 2016. This can be attributed to its reduced sample size during the JJA and SON seasons (N = 16). Analysis between AOD satellite-satellite retrievals revealed that none of their comparisons had collocating paired data (common days greater than 5) for all the seasons of the study period. While MODIS AOD - MISR AOD was affected in SON and OMI AOD - MODIS AOD in JJA and SON, OMI AOD - MISR AOD was affected for the entire study period. The MODIS AOD valuation using validated ground PM measurements are similar to results drawn from other comparative in-situ PM and MODIS AOD studies (Liu et al., 2007; Filip and Stefan, 2011; Yap and Hashim, 2013; Sukitpaneenit and Oanh, 2014; Bibi et al., 2015; Kong et al., 2016). Our findings are within the acceptable range established by similar literature (Figure 5.6b). This reveals that MODIS is the most suited satellite PM measurement instrument for users in the Zaria metropolis, Nigeria.

5.4. Conclusion

Studies have established that satellite datasets from remote sensing of surface air quality contain a wealth of knowledge that is still being exploited, thus, the need to evaluate satellite-based pollution monitoring to specific areas or regions of the world. In a limited resource environment like Nigeria, portable pollutant monitors are being embraced for air pollution monitoring. This study utilized validated MSA Altair 5x gas sensor and the CW-HAT200 particulate counter to evaluate the city-scale monitoring capability of selected NASA pollution monitoring instruments. The findings revealed that the MOPITT CO and MODIS AOD are the better-suited satellite pollution estimates for representing ground-level CO and PM_{10} measurement within Zaria metropolis, Nigeria. Our city-scale evaluation of satellite pollution estimates using portable monitors was within acceptable boundary limits when compared to other similar studies that utilized the reference pollution monitoring stations. These findings pilot a fundamental issue in air pollution monitoring within the Nigerian frontier, where none has been previously carried out. We are optimistic that our findings offer Nigeria's air quality planners with the framework of portable cost-effective pollutant monitors and satellite air pollution measurements, to mitigate the adverse impacts of air quality within its rapidly growing population and scarce air quality information.

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References

1. Adams, M.D., De Luca, P.F., Corr, D. & Kanaroglou, P.S. 2012. Mobile air monitoring: measuring change in air quality in the city of Hamilton, 2005-2010. *Social Indicators Research*, 108: 351-364. https://doi.org/10.1007/s11205-012-0061-5
2. Adewunmi, R., Adewunmi, R., Obi, P. & Odumosu, A. 2015. P15 assessment of cumulative exposures of traffic wardens to vehicular emissions in Zaria, Nigeria. *Journal of Transport and Health*, 2(2): S71. https://doi.org/10.1016/j.jth.2015.04.474
3. Araki, S., Yamamoto, K. & Kondo, A. 2015. Application of regression kriging to air pollutant concentrations in Japan with high spatial resolution. *Aerosol and Air Quality Research*, 15: 234-241. https://doi.org/10.4209/aaqr.2014.01.0011
4. Asatar, G.I. & Nair, P.R. 2010. Spatial distribution of near-surface CO over Bay of Bengal during winter: role of transport. *Journal of Atmospheric and Solar-Terrestrial Physics*, 72(17): 1241-1250. https://doi.org/10.1016/j.jastp.2010.07.025
5. Barret, B., Mazière, M.D. & Mahieu, E. 2003. Ground-based FTIR measurements of CO from the Jungfraujoch: characterisation and comparison with in situ surface and MOPITT data. *Atmospheric Chemistry and Physics*, *3*(6): 2217-2223. https://doi.org/10.5194/acp-3-2217-2003
6. Bell, M.L. & Davis, D.L. 2001. Reassessment of the lethal London fog of 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. *Environmental Health Perspectives*, 109 (3): 389-394.
7. Bereznicki, S.D. & Kamal, A. 2013. Observations of interference between portable particle counters and NOx monitors. *Atmospheric Environment*, 75: 303-307. https://doi.org/10.1016/j.atmosenv.2013.04.064
8. Bibi, H., Alam, K., Chishtie, F., Bibi, S., Shahid, I. & Blaschke, T. 2015. Intercomparison of MODIS, MISR, OMI, and CALIPSO aerosol optical depth retrievals for four locations on the Indo-Gangetic plains and validation against AERONET data. *Atmospheric Environment*, 111: 113-126. https://doi.org/10.1016/j.atmosenv.2015.04.013
9. Buchholz, R.R., Deeter, M.N., Worden, H.M., Gille, J., Edwards, D.P., Hannigan, J.W., Jones, N.B., Paton-Walsh, C., Griffith, D.W., Smale, D. & Robinson, J. 2017. Validation of MOPITT carbon monoxide using ground-based Fourier transform infrared spectrometer data from NDACC. *Atmospheric Measurement Techniques*, 10(5): 1927-1956. https://doi.org/10.5194/amt-10-1927-2017
10. Chai, T. & Draxler, R.R. 2014. Root mean square error (RMSE) or mean absolute error (MAE)?–Arguments against avoiding RMSE in the literature. *Geoscience Model Development*, 7(3): 1247-1250. https://doi.org/10.5194/gmd-7-1247-2014
11. Dash, I. 2016. *Space-time observations for city level air quality modelling and mapping*. MSc Thesis, University of Twente, The Netherlands, 80 pages.
12. Deeter, M.N., Emmons, L.K., Francis, G.L., Edwards, D.P., Gille, J.C., Warner, J.X., Khattatov, B., Ziskin, D., Lamarque, J.-F., Ho, S.-P., Yudin, V., Attié, J.L., Packman, D., Chen, J., Mao, D. & Drummond, J.R. 2003. Operational carbon monoxide retrieval algorithm and selected results for the MOPITT instrument. *Journal of Geophysical Research*, 108: 4399. https://doi.org/10.1029/2002JD003186

13. Duncan, B.N., Prados, A.I., Lamsal, L.N., Liu, Y., Streets, D.G., Gupta, P., Hilsenrath, E., Kahn, R.A., Nielsen, E., Beyersdorf, A.J., Burton, S.P., Fiore, A.M., Fisherman, J., Henze, D.K., Hosteltler, C.A., Krotkov, N.A., Lee, P., Lin, M., Pawson, S., Pfister, S., Pickering, K.E., Bradley Pierce, R., Yoshida, Y. & Ziemba, L.D. 2014. Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. *Atmospheric Environment*, 94: 647-662. https://doi.org/10.1016/j.atmosenv.2014.05.061
14. Duvall, R., Norris, G., Burke, J., Olson, D., Vedantham, R. & Williams, R. 2012. Determining spatial variability in $PM_{2.5}$ source impacts across Detroit, MI. *Atmospheric Environment*, 47: 491-498. https://doi.org/10.1016/j.atmosenv.2011.09.071
15. Efe, S.I. & Efe, A.T. 2008. Spatial distribution of particulate matter (PM10) in Warri metropolis, Nigeria. *The Environmentalist*, 28(4): 385-394. http://doi.org/10.1007/s10669-007-9154-0
16. Engel, B., Storm, D., White, M., Arnold, J. & Arabi, M. 2007. A hydrologic/water quality model application protocol. *Journal of the American Water Resources Association*, 43(5): 1223-1236. https://doi.org/10.1111/j.1752-1688.2007.00105.x
17. Engel-Cox, J.A., Holloman, C.H., Coutant, B.W. & Hoff, R.M. 2004. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmospheric Environment*, 38: 2495–2509. https://doi.org/10.1016/j.atmosenv.2004.01.039
18. Engel-Cox, J., Oanh, N.T.K., van Donkelaar, A., Martin, R.V. & Zell, E. 2013. Toward the next generation of air quality monitoring: particulate matter. *Atmospheric Environment*, 80: 584-590. https://doi.org/10.1016/j.atmosenv.2013.08.016
19. Filip, L. & Stefan, S. 2011. Study of the correlation between the near-ground PM10 mass concentration and the aerosol optical depth. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(13): 1883-1889. https://doi.org/10.1016/j.jastp.2011.04.027
20. Fisher, J.A., Jacob, D.J., Purdy, M.T., Kopacz, M., Le Sager, P., Carouge, C., Holmes, C.D., Yantosca, R.M., Batchelor, R.L., Strong, K., Diskin, G.S., Fuelberg, H.E., Holloway, J.S., Hyer, E.J., McMillan, W.W., Warner, J., Streets, D.G., Zhang, Q., Wang, Y. & Wu, S. 2010. Source attribution and interannual variability of Arctic pollution in spring constrained by aircraft (ARCTAS, ARCPAC) and satellite (AIRS) observations of carbon monoxide. *Atmospheric Chemistry and Physics*, 10: 977-996. https://doi.org/10.5194/acp-10-977-2010
21. Ghozikali, M.G., Mosaferi, M., Safari, G.H. & Jaafari, J. 2015. Effect of exposure to O3, NO2, and SO2 on chronic obstructive pulmonary disease hospitalizations in Tabriz, Iran. *Environment Science and Pollution Research*, 22(4): 2817-2823. https://doi.org/10.1007/s11356-014-3512-5
22. Gozzi, F., Della Ventura, G. & Marcelli, A. 2016. Mobile monitoring of particulate matter: State of art and perspectives. *Atmospheric Pollution Research*, 7(2): 228-234. https://doi.org/10.1016/j.apr.2015.09.007

23. Guo, H., Wang, Y. & Zhang, H. 2017. Characterization of criteria air pollutants in Beijing during 2014–2015. *Environmental Research*, 154: 334-344. https://doi.org/10.1016/j.envres.2017.01.029
24. Hersey, S.P., Garland, R.M., Crosbie, E., Shingler, T., Sorooshian, A., Piketh, S. & Burger, R. 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. *Atmospheric Chemistry and Physics*, 15(8): 4259-4278. https://doi.org/10.5194/acp-15-4259-2015
25. Jolliffe, I.T. & Stephenson, D.B., (Eds.) 2012. *Forecast verification: A practitioner's guide in atmospheric science*. John Wiley and Sons, Chichester, pp. 240
26. Kanaroglou, P., Jerrett, M., Morrison, J., Beckerman, B., Arain, M.A., Gilbert, N.L. & Brook, J.R. 2005. Establishing an air pollution monitoring network for intraurban population exposure assessment: a location-allocation approach. *Atmospheric Environment*, 39: 2399-2409. https://doi.org/10.1016/j.atmosenv.2004.06.049
27. Kgabi, N. A. 2014. *Air quality policy and scientific research in Southern Africa*. In: Longhurst, J.W.S. & Brebbia, C.A. ed. Air Pollution XX. WIT Press, Southampton, UK, pp. 151-163.
28. Kong, L., Xin, J., Zhang, W. & Wang, Y. 2016. The empirical correlations between PM 2.5, PM 10 and AOD in the Beijing metropolitan region and the PM 2.5, PM 10 distributions retrieved by MODIS. *Environmental Pollution*, 216: 350-360. https://doi.org/10.1016/j.envpol.2016.05.085
29. Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L. & Britter, R. 2015. The rise of low-cost sensing for managing air pollution in cities. *Environment International*, 75: 199-205. https://doi.org/10.1016/j.envint.2014.11.019
30. Le Boennec, R. & Salladarré, F. 2017. The impact of air pollution and noise on the real estate market. The case of the 2013 European Green Capital: Nantes, France. *Ecological Economics*, 138: 82-89. https://doi.org/10.1016/j.ecolecon.2017.03.030
31. Liou, K.N. 2002. *An introduction to atmospheric radiation*. 2nd ed. Academic Press, New York, pp. 350–353.
32. Liu, J., Man, Y. & Liu, Y. 2014. Temporal variability of PM_{10} and $PM_{2.5}$ inside and outside a residential home during 2014 Chinese spring festival in Zhengzhou, China. *Natural Hazards*, 73(3): 2149-2154. https://doi.org/10.1007/s11069-014-1157-9
33. Liu, Y., Franklin, M., Kahn, R. & Koutrakis, P. 2007. Using aerosol optical thickness to predict ground-level PM 2.5 concentrations in the St. Louis area: a comparison between MISR and MODIS. *Remote Sensing of the Environment*, 107(1): 33-44. https://doi.org/10.1016/j.rse.2006.05.022
34. Llanes, S., 2016. How to calculate time-weighted average (TWA). 26th Annual California Industrial Hygiene Council (CIHC) Conference, San Diego. Available from: http://www.thecohengroup.com/article/calculate-time-weighted-average-twa/. Last access: October 2017.
35. Marais, E.A. & Chance, K. 2015. A geostationary air quality monitoring platform for Africa. *Clean Air Journal*, 25(1): 40-45. https://doi.org/10.17159/2410-972X/2015/v25n1a3

36. Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K. & Sauvage, B. 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space. *Atmospheric Environment*, 99: 32-40. https://doi.org/10.1016/j.atmosenv.2014.09.055
37. Marey, H.S., Hashisho, Z., Fu, L. & Gille, J. 2015. Spatial and temporal variation in CO over Alberta using measurements from satellites, aircraft, and ground stations. *Atmospheric Chemistry and Physics*, 15(7): 3893-3908. https://doi.org/10.5194/acp-15-3893-2015
38. McCuen, R.H., Knight, Z. & Cutter, A.G. 2006. Evaluation of the Nash–Sutcliffe efficiency index. *Journal of Hydrologic Engineering*, 11(6): 597-602.
39. McMillan, W.W., Barnet, C., Strow, L., Chahine, M.T., McCourt, M.L., Warner, J.X., Novelli, P.C., Korontzi, S., Maddy, E.S. & Datta, S. 2005. Daily global maps of carbon monoxide from NASA’s Atmospheric Infrared Sounder. *Geophysical Research Letters*, 32: L11801. https://doi.org/10.1029/2004GL021821
40. Mead, M.I., Popoola, O.A.M., Stewart, G.B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J.J., McLeod, M.W., Hodgson, T.F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J.R. & Jones, R.L. 2013. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, 70: 186-203. http://doi.org/10.1016/j.atmosenv.2012.11.060
41. Miri, M., Derakhshan, Z., Allahabadi, A., Ahmadi, E., Conti, G.O., Ferrante, M. & Aval, H.E. 2016. Mortality and morbidity due to exposure to outdoor air pollution in Mashhad metropolis, Iran. The AirQ model approach. *Environmental Research*, 151: 451-457. https://doi.org/10.1016/j.envres.2016.07.039
42. Mishra, R.K., Joshi, T., Goel, N., Gupta, H. & Kumar, A. 2015. Monitoring and analysis of PM10 concentration at Delhi Metro construction sites. *International Journal of Environment and Pollution*, 57(1-2): 27-37. https://doi.org/10.1504/IJEP.2015.072111
43. NASA (National Aeronautics and Space Administration), 2017. https://www.nasa.gov/open/researchaccess/nasa-data-portal. Last access: March 2017.
44. Neophytou, M., Gowardan, A. & Brown, M.J. 2011. An inter-comparison of three urban wind models using Oklahoma City Joint Urban 2003 wind field measurements. *Journal of Wind Energy and Industrial Aerodynamics*, 99: 357–368. https://doi.org/10.1016/j.jweia.2011.01.010
45. Orogade, S.A., Owoade, K.O., Hopke, P.K., Adie, D.B., Ismail A. & Okuofu, C.A. 2016. Source apportionment for fine and coarse particulate matter in industrial areas of Kaduna, northern Nigeria. *Aerosol and Air Quality Research*, 16: 1179-1190. https://doi.org/10.4209/aaqr.2015.11.0636
46. Ren, M., Li, N., Wang, Z., Liu, Y., Chen, X., Chu, Y., Li, X., Zhu, Z., Tian, L. & Xiang, H. 2017. The short-term effects of air pollutants on respiratory disease mortality in Wuhan, China: comparison of time-series and case-crossover analyses. *Scientific Reports*, 7: 40482. https://doi.org/10.1038/srep40482

47. Rinsland, C.P., Luo, M., Logan, J.A., Beer, R., Worden, H., Kulawik, S.S., Rider, D., Osterman, G., Gunson, M., Eldering, A., Goldman, A., Shephard, M., Clough, S.A., Rodgers, C., Lampel, M. & Chiou, L. 2006. Nadir measurements of carbon monoxide distributions by the Tropospheric Emission Spectrometer instrument onboard the Aura Spacecraft: overview of analysis approach and examples of initial results. *Geophysical Research Letters*, 33: L22806. https://doi.org/10.1029/2006GL027000
48. Schaap, M., Apituley, A., Timmermans, R.M.A., Koelemeijer, R.B.A. & de Leeuw, G. 2009. Exploring the relation between aerosol optical depth and PM2.5 at Cabauw, the Netherlands. *Atmospheric Chemistry and Physics*, 9: 909–925. https://doi.org/10.5194/acp-9-909-2009
49. Schäfer, K., Harbusch, A., Emeis, S., Koepke, P. & Wiegner, M. 2008. Correlation of aerosol mass near the ground with aerosol optical depth during two seasons in Munich. *Atmospheric Environment*, 42(18): 4036-4046. https://doi.org/10.1016/j.atmosenv.2008.01.060
50. Shibata, T., Wilson, J.L., Watson, L.M., Nikitin, I.V., La Ane, R. & Maidin, A. 2015. Life in a landfill slum, children's health, and the millennium development goals. *Science of the Total Environment*, 536: 408-418. https://doi.org/10.1016/j.scitotenv.2015.05.137
51. Snyder, E.G., Watkins, T., Solomon, P., Thoma, E., Williams, R., Hagler, G., Shelow, D., Hindin, D., Kilaru, V. & Preuss, P. 2013. The changing paradigm of air pollution monitoring. *Environmental Science and Technology*, 47: 11369–11377. https://doi.org/10.1021/es4022602
52. Streets, D.G., Canty, T., Carmichael, G.R., de Foy, B., Dickerson, R.R., Duncan, B.N., Edwards, D.P., Haynes, J.A., Heinze, D.K., Houyoux, M.R., Jacob, D.J., Krotkov, N.A., Lamsal, L.N., Liu, Y., Lu, Z., Martin, R.V., Pfister, G.G. Pinder, R.W., Salawitch, R.J. & Wecht, K.J., 2013. Emissions Estimation from Satellite Retrievals: A Review of Current Capability. *Atmospheric Environment*, 77: 1011-1042. https://doi.org/10.1016/j.atmosenv.2013.05.051
53. Sukitpaneenit, M. & Oanh, N.T. 2014. Satellite monitoring for carbon monoxide and particulate matter during forest fire episodes in Northern Thailand. *Environmental Monitoring and Assessment*, 186(4): 2495-2504. https://doi.org/10.1007/s10661-013-3556-x
54. The Economist, 2017. *Nigeria: Africa's new number one*, 2014. Available from: http://www.economist.com/news/leaders/21600685-nigerias-suddenly-supersized-economy-indeed-wonder-so-are-its-still-huge. Last access: February 2017.
55. Tian, B., Manning, E., Fetzer, E., Olsen, E., Wong, S., Susskind, J. & Iredel, L. 2014. *AIRS/AMSU/HSB version 6 level 3 product user guide*. Available from: http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v6_docs/v6releasedocs1/V6_L3_User_Guide.pdf. Last access: June 2016.
56. UN (United Nations) Economic and Social Affairs, 2017. *World population prospects: the 2015 revision*. New York. Available from: http://esa.un.org/unpd/wpp/. Last access: September 2017.

57. Vollmer, B. 2010. *AIRS Data and Services at the GSFC Earth Sciences Data and Information Services Centre (GES DISC).* Available from: http://airs.jpl.nasa.gov/documents/science_team_meeting_archive/2010_11/slides/Vollmer.pdf. Last access: June 2016.
58. WHO (World Health Organization), 2016. *Global urban ambient air pollution database update*, 2016. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/WHO_AAP_database_May2016_v3web.xlsx?ua=1. Last access: September 2016.
59. WHO (World Health Organization), 2017. *Evolution of WHO air quality guidelines. Past, present and future*. Available from: http://www.euro.who.int/__data/assets/pdf_file/0019/331660/Evolution-air-quality.pdf. Last access: September 2017.
60. Yap, X.Q. & Hashim, M. 2013. A robust calibration approach for PM10 prediction from MODIS aerosol optical depth. *Atmospheric Chemistry and Physics*, 13(6): 3517-3526. https://dx.doi.org/10.5194/acpd-12-31483-2012
61. Yazdi, M.N., Delavarrafiee, M. & Arhami, M. 2015. Evaluating near highway air pollutant levels and estimating emission factors: Case study of Tehran, Iran. *Science of the Total Environment*, 538: 375-384. https://dx.doi.org/10.1016/j.scitotenv.2015.07.141
62. Yoshizaki, K., Brito, J.M., Silva, L.F., Lino-dos-Santos-Franco, A., Frias, D.P., Silva, R.C., Amato-Lourenço, L.F., Saldiva, P.H., Tibério, I.D., Mauad, T. & Macchione, M. 2017. The effects of particulate matter on inflammation of respiratory system: Differences between male and female. *Science of the Total Environment*, 586: 284-295. https://dx.doi.org/10.1016/j.scitotenv.2017.01.221
63. Zhang, L., Jiang, H., Lu, X. & Jin, J. 2016. Comparison analysis of global carbon monoxide concentration derived from SCIAMACHY, AIRS, and MOPITT. *International Journal of Remote Sensing*, 37(21): 5155-5175. https://dx.doi.org/10.1080/01431161.2016.1230282

Chapter 6

Appraising the effects of atmospheric aerosols and ground particulates concentrations on GPS-derived PWV estimates[§§]

Abstract

In 2016, three Nigerian cities were listed amongst the World's most polluted in terms of particulate matter (PM). Acknowledging Nigeria's limited resources for outdoor air pollution monitoring, this study attempts to investigate the effects on atmospheric aerosol optical depth and ground PM on GPS derived-precipitable water vapour estimates. The study utilized available GPS-derived precipitable water vapour (GPS_{PWV}), the moderate resolution imaging spectroradiometer aerosol optical depth ($MODIS_{AOD}$) and the ground-level particulate matter of less than 10 microns (GPM) datasets for December 2015 – November 2016. All the datasets were tested for normality. To evaluate the atmospheric aerosol properties, the $MODIS_{PWV}$ estimates were pre-validated using the GPS_{PWV} measurements. The results revealed GPS_{PWV}-$MODIS_{PWV}$ agreement ($R = 0.964$; $RMSE = 3.810$ mm). The GPS_{PWV}-$MODIS_{AOD}$ analysis showed the relationship ($R \leq -0.636$; $RMSE \leq 0.563$) for the atmospheric aerosol experiment, while the collocating GPS_{PWV}-GPM seasonal analysis also revealed a significant correlation ($R < -0.660$). The correlation of combined seasonal datasets for the GPS_{PWV}-$MODIS_{AOD}$ and GPS_{PWV}-GPM relationships showed high negative correlation values of 0.79 and 0.68 respectively. The findings of this study are in agreement with similar related studies, as well as serve as position accuracy for future related studies.

Keywords: *GPS PWV; MODIS AOD; Particulate Matter PM_{10}; Nigeria*

[§§]*This chapter is a formatted text of a peer-reviewed journal article described as follows:*

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6.1. Introduction

Atmospheric water vapour plays a crucial role in the Earth's climate system as well as the monitoring of aerosols/particulate properties (Solomon et al., 2010; Zhang et al., 2017). Despite its importance to a wide range of spatial and temporal atmospheric processes, it is one of the poorly understood components of the Earth's atmosphere (Boutiouta and Lahcene, 2013). Observational studies have reported that the intensity of aerosol particles contributes to climatic variables such as precipitation of liquid water and electrification of thunderstorms (Middey and Chaudhuri, 2013; Zhao et al., 2016). The significance of atmospheric studies for aerosol/water vapour projections has attracted earth observation satellites and global positioning system (GPS) approaches (Nordio et al., 2013; Ortiz de Galisteo et al., 2014).

Scientists have since embraced the concept of GPS meteorology as it provides the ability to measure atmospheric water vapour content for application in diverse topics such as atmospheric chemistry and global climate change (Bevis et al., 1992). GPS offers consistent and precise atmospheric information for precise-point positioning (PPP), ionospheric/tropospheric studies and general environmental assessments that can be used for sensing atmospheric water vapour contents (Zumberge et al., 1997). The GPS signals recorded using ground-level continuous operating reference station (CORS), are usually subjected to various attenuations such as multipath, ionosphere/troposphere delay and signal strength fluctuations. Some of these signal attenuations are presently being assimilated into models for aerosol evaluation.

Since the introduction of the space-based pollution monitoring instruments in the mid-90s, the instruments have continued to display increased user-friendly proficiency for atmospheric processes estimations in 4-dimensional resolution (Duncan et al., 2014; Tsay et al., 2016). Aerosols (particulates) are a composite combination of suspended solid and liquid elements (excluding cloud units) that are being monitored using satellite-based instruments (Gupta et al., 2006). They are an essential component of the climate system and a major concern of the earth's existing anthropogenic radiative force. To minimize these concerns, precise and regular appraisal of these aerosols' distributions are necessary so as to regulate its negative impact on man's environment. Accurate monitoring of atmospheric processes such as aerosols and trace gases are also vital for developing efficient local, regional or global climate models (Madrigano et al., 2013; Chew et al., 2016).

Air pollution remains a serious environmental challenge in many developing countries (Lau and He, 2017). Nigeria accommodates Africa's largest sophisticated population, many of whom continue to migrate to the high-density settlements that surround the urban cities. Three of its developing cities (Onitsha, Kaduna and Aba) were listed amongst the World's top ten most polluted cities (Figure 6.1), in terms of the particulate matter of less than 10 microns (WHO, 2016). Nigeria is reported to have five air monitoring stations established by the Nigerian Meteorological Agency (NiMET) (UNEP, 2015), their operational status remains sceptical as the review of the literature showed that there is no record of their data being utilized.

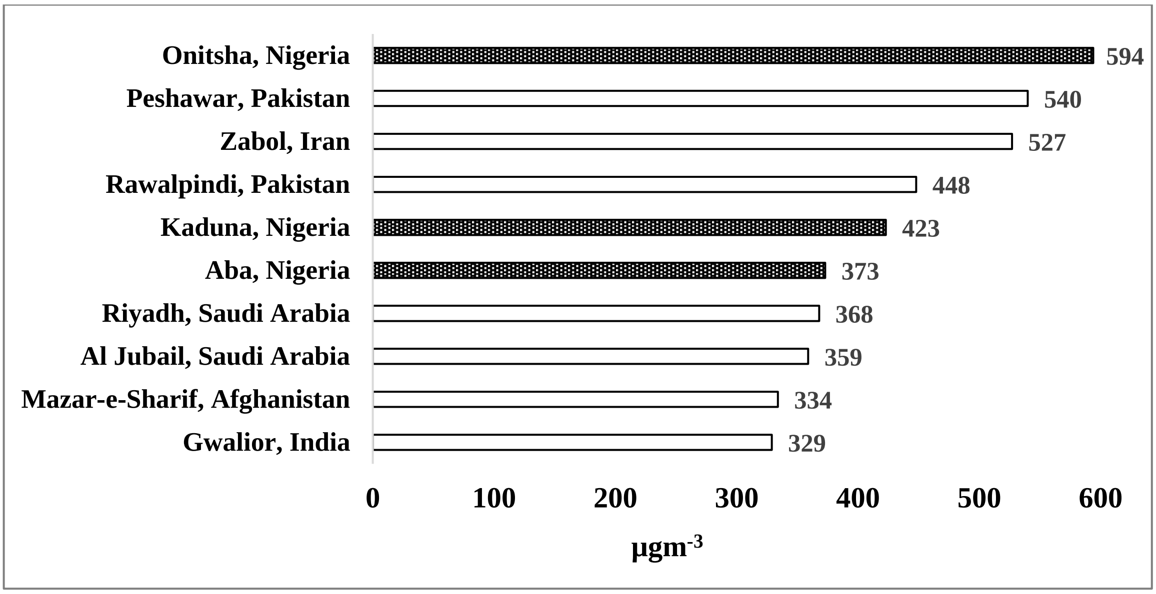

Figure 6.1. *The World's 10 most polluted cities in terms of particulates less than 10 microns, modified after the (WHO, 2016). The shaded column highlights the Nigerian cities.*

Satellite-based observations provide a comprehensive view of the earth's atmosphere (Streets et al., 2013) and serve as a practical means for the retrieval of both water vapour and aerosol estimates in a limited resources environment like Nigeria. If the precision and legitimacy of satellite-based estimates are to be verified, the availability of ground-based pollution network/dataset is crucial. Ground-based GNSS operates a meteorological technique whereby its signal delays can be used to derive PWV estimates (Boutiouta and Lahcene, 2013). GNSS remote sensing is becoming necessary due to the technical improvements applied to their inexpensive processing and easy-access of weather insensitive signals (Bonafoni and Biondi, 2016).

It is important for a country like Nigeria to exploit available resources for mitigating particulate air pollution. It is on this basis that this study utilizes the seasonal variability of input parameters; GPS-derived precipitable water vapour, MODIS AOD estimates and ground PM measurements, to appraise the effect of atmospheric aerosols and ground particulates concentrations on GPS derived PWV estimates. This study plans to direct a latent position for Nigeria, on the practicability of its existing Nigerian global navigational satellite system reference network (NIGNET) for ground particulates and atmospheric aerosols monitoring. The data processing techniques are described as follows.

6.2. Methodology

6.2.1. Study area

Nigeria established a GNSS Reference Network (NIGNET) through a joint collaboration between Nigeria's Office of the Surveyor General of the Federation (OSGOF) and the Africa Reference Frame (AFREF) programme (Ayorinde et al., 2016). The ABUZ station was utilized for the extraction of the GPS PWV estimates (Figure 6.2). The ABUZ station is hosted in the main campus of the Ahmadu Bello University Zaria, northern Nigeria. The ABUZ station is hosted in the main campus of the Ahmadu Bello University Zaria, northern Nigeria. The climate within the study area is categorized into dry (October–May) and wet (June–September) seasons. It is further characterized by the peak low temperature (14.1 °C) during the harmattan in January and the peak high temperature (35.2 °C) in April. The ABUZ Continuous Operating Reference Station (CORS) is a Trimble NETR8 receiver type with antenna TRM59800.00. The system(s) of observations are GPS and GLONASS. The vertical antenna height specification is 0.17m. The ABUZ station utilized in this study was adopted for two reasons. First, it is the only study location with collocating time-series atmospheric and ground particulates (aerosols) measurements, to achieve the study objectives. Secondly, Abbasy et al. (2017) have endorsed the practicability of utilizing a single GPS station for meteorological studies. The meteorological parameters (surface temperature and pressure) required for the ABUZ GPS derived PWV estimates were synchronized with existing automatic weather observing station (AWOS). The derived PWV were extracted from GPS data obtained in Receiver Independent Exchange (RINEX) format. The ABUZ RINEX observation sampling frequency is 30 secs and was accessed via NIGNET portal (http://www.nignet.net/data/RINEX).

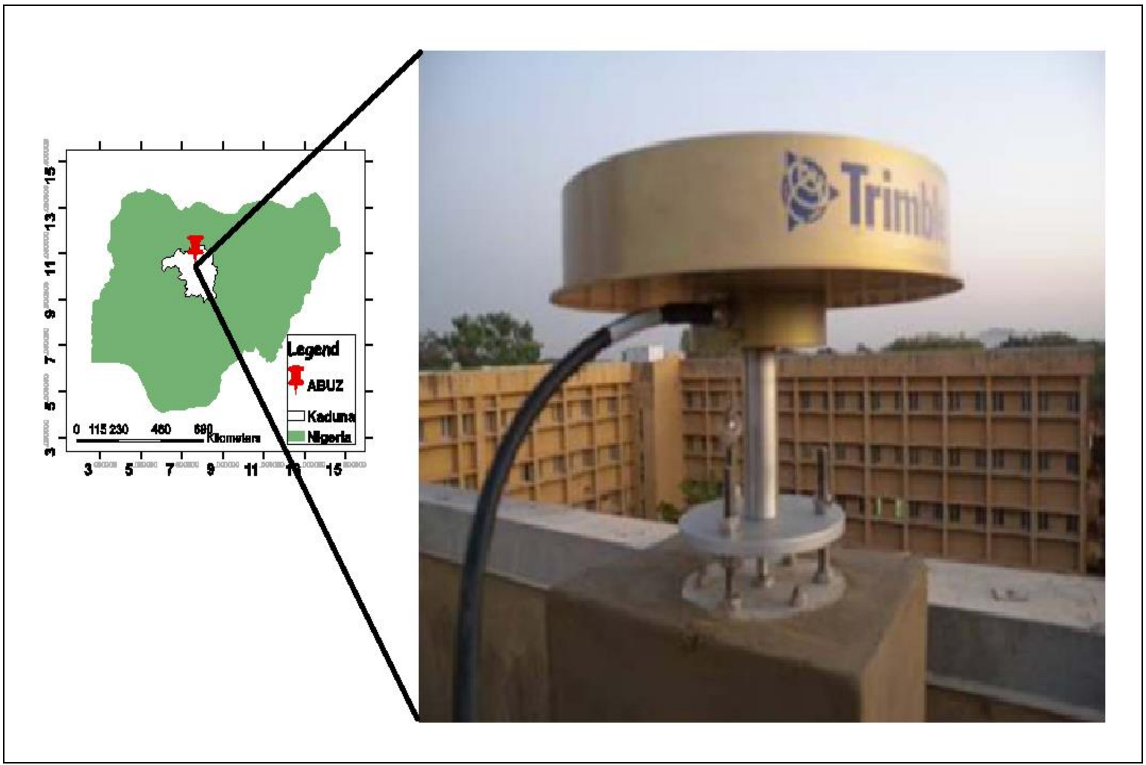

Figure 6.2. *The ABUZ NIGNET station situated within the Ahmadu Bello University Main Campus, Zaria – Nigeria from which precipitable water vapour (PWV) estimates were extracted for this study*

6.2.2. GPS PWV estimates

To extract the PWV estimates for precise-point positioning (PPP), the GPS RINEX observation data was processed using WaSoft GNSS software designed by Wanninger (2000) and validated by Schröder et al. (2017). We utilized International GNSS service (IGS) final paths and earth revolution parameters for tropospheric delay derivation and antenna phase centre offsets. Satellite elevation mask of 10 degrees was adopted (Kouba, 2009). The Saastamoinen model (1972) plus random-walk mechanism from meteorologically sourced global pressure and temperature (GPT) model was employed as a priori tropospheric model while the zenith delay was processed via the Vienna mapping function (VMF) (Boehm et al., 2006). The WaSoft software is capable of determining the three-dimensional data as well as tropospheric factors, which incorporates the Zenith Tropospheric Delay (ZTD).

We transferred atmospheric temperature and pressure to the ABUZ station from the nearby meteorological (AWOS) station using Equation (6.1) (Bai and Feng, 2003; Musa et al., 2011). We took into consideration the horizontal distance and observation height between the GPS and AWOS station (Table 6.1).

$$\left.\begin{aligned} T_{GNSS} &= T_{MSL} - 0.0065 \times H_{GNSS} \\ P_{GNSS} &= P_{MSL}\left(1 - 0.0000226 \times H_{GNSS}\right)^{5.225} \end{aligned}\right\} \tag{6.1}$$

Where T_{GNSS}; P_{GNSS} are the respective reduced temperature and pressure at the ABUZ station of interest, T_{MSL}; P_{MSL} are the respective temperature and pressure values at the automatic weather observing station (AWOS) mean sea level. The Equation (6.1) takes into consideration, possible variability in the sensitivity of temperature and pressure at the GNSS antenna height, H_{GNSS}.

Table 6.1. *Properties of the ABUZ station and the matching AWOS station from which meteorological parameters were interpolated to the actual station level (modified after Isioye et al., 2017)*

GNSS Station	GNSS station coordinate		AWOS station	AWOS station coordinate		Horizontal distance (m)	Station height (m)	
	Longitude (deg.)	Latitude (deg.)		Longitude (deg.)	Latitude (deg.)		GNSS	AWOS
ABUZ	7.65	11.15	Zaria	7.68	11.10	6855.03	705.05	655.00

To apply GNSS for meteorological purposes, it is necessary to scale down the Zenith Tropospheric Delay (ZTD) into its constituent fractions; the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The ZHD is majorly accountable for the ZTD (~ 90% using experimental models with given surface temperature and pressure). The ZWD is of meteorological importance, due to its significant relationship with humidity changes both spatially and temporally. The PWV can be derived from ZWD as described by Bevis et al. (1994) in Equation (6.2).

$$PWV = \frac{10^6}{R_W \rho_W \left(K_2^{'} + K_3 / T_m\right)} \times (ZTD - ZHD) \tag{6.2}$$

ρ_w - water density; R_w - water vapour specific gas constant {461.525 ± 0.003 [J kg^{-1} K^{-1}]}; k'_2 and k_3 - [refraction constants in K mb^{-1} (22.1 ± 2.2 K mb^{-1} and 373900 ± 0.012)]; T_m - weighted mean temperature in troposphere gauged in Kelvin; *PWV* - precipitable water vapour

The mean temperature (T_m) utilized for the extraction of the PWV estimate is described in Equation (6.3) below.

$$T_m = (T_0 - \beta H)\left[1 - \frac{\beta R}{g_m \lambda'}\right] \quad (6.3)$$

T_o, β *and* λ are meteorological parameters; H – orthometric height in metres; $\lambda' = \lambda + 1$ (unitless); R is the gas constant for dry air (287.054Jkg^{-1}K^{-1}); g_m – gravity acceleration at the atmospheric column centroid in ms^{-2}.

Applying Saastamoinen (1972) model for the ZHD constituent and meteorologically sourced global pressure-temperature (GPT) model, a simplified PWV (mm) relationship to ZWD is described in Equation (6.4) as follows:

$$PWV = ZWD \times \left[9.80392 - \frac{16917.64}{0.053499 T_s + 1739.07624}\right] \quad (6.4)$$

ZWD = zenith wet delay; T_s - surface temperature measured in Kelvin

6.2.3. Atmospheric aerosol estimates

MODIS is the most appropriate atmospheric satellite information for investigating aerosols with proficiency for local, regional and global scale air pollution monitoring (Ali *et al*., 2017). It comprises of 36 spectral bands for precise observation of atmospheric heat and humidity, as well as its constituents which include aerosols and trace gases (Misra *et al*., 2015). The algorithm for the MODIS aerosol optical depth (AOD) retrieval is centred on the theory of recording aerosol reflectance from reflectance at the atmospheric top using Rayleigh path radiance and surface reflectance. This is expressed by Wong *et al*. (2008) using Equation (6.5).

$$\rho_{TOA}(\theta_o, \theta_s, \phi) = \rho_{ATM}(\theta_o, \theta_s, \phi, \tau_{Aer}, \tau_{Ray}, p(\theta), \omega_o) + \frac{T_{Tot}(\theta_o) \times T_{Tot}(\theta_s) \times \rho_{Surf}(\theta_o, \theta_s)}{1 - \rho_{Surf}(\theta_o, \theta_s) \times r_{Hem}(\tau_{Tot}, g)} \quad (6.5)$$

θ_o - peak slant of sun; θ_s - peak slant of satellite; ϕ – clockwise horizontal slant from meridian; $\rho(\theta)$ - phase function (angular dispersal of scattered light); ρ_{ATM} - atmospheric path reflectance; g - asymmetry parameter; τ_{Hem} (τ_{Tot}, g) - hemispheric reflectance; ω_o – single scattering albedo; τ_{Tot} (m_o) - total transmittance; $\rho_{Surf}(\theta_o, \theta_s)$ - surface reflectance; τ_{Aer}, τ_{Ray} and τ_{Tot} - aerosol optical thickness, Rayleigh optical thickness, and overall optical thickness respectively.

The Rayleigh path radiance is obtained from Equation (6.6) by computing its spectral requirements and phase function, as described by Bucholtz (1995).

$$\tau_{Ray}(\lambda) = P \times \lambda^{-(Q + R\lambda + S/\lambda)} \times \frac{p(z)}{p_o} \quad (6.6)$$

where *P*, *Q*, *R*, *S* are the standard atmospheric aggregate of Rayleigh scattering cross-section plus volume scattering coefficients while *p(h)*, the appropriate height pressure is defined in Equation (6.7).

$$p(h) = p_o \times \exp\left[\frac{-29.87 \times g \times 0.75 \times h}{8.315 \times (T_S - g \times 0.75 \times h)}\right] \tag{6.7}$$

Where *h* – altitude from digital elevation model; *g* – acceleration due to gravity and T_s – surface temperature

For the MODIS aerosol estimates, the deep blue level 3 version 5.1 aerosol products (http://disc.sci.gsfc.nasa.gov/SSW/#keywords=MYD08_D3 5.1) was adopted for its geophysical parameter, averaged into (-90.0° to +90.0°) latitude and (-180.0° to +180.0°) longitude grid cells (Tian *et al.*, 2014). The variable [Deep_Blue_Aerosol_Optical_Depth_Land_Mean] takes the convenience of the dark-exterior attributes at 0.47 µm blue wavelengths and frail dust penetration at 0.65 µm red wavelength (Shi *et al.*, 2013; Misra *et al.*, 2015). The downloaded MODIS precipitable water vapour variable (IR retrieval) datasets were accessed using Panoply software (Vollmer, 2010). The subset $MODIS_{AOD}$ and $MODIS_{PWV}$ estimates were then collocated over the ABUZ station using the Kriging interpolation mechanism (Araki *et al.*, 2015; Li *et al.*, 2016).

6.2.4. Ground particulate measurements

The use of efficient portable sensors for particulate matter (PM_{10}) measurements is getting major attention across the globe (Liu *et al.*, 2014; Li and Biswas, 2017). The study utilized the validated Chinaway CW-HAT200 particulate counter, to obtain ground samples measurements for PM_{10} in (microgram per meter cube, µg m^{-3}) using the laser diode principle. The sample measurements were collected for the duration of 1 year (1 December 2015 – 30 November 2016) and collocated with the available daytime averaged ABUZ GPS_{PWV} and $MODIS_{AOD}$ estimates. Instrument background and pump flow were also examined prior to conducting each measurement session. The portable PM_{10} instrument was validated using the WHO air filter sampling technique, described in Efe and Efe (2008). The validation results are displayed in Figure 6.3.

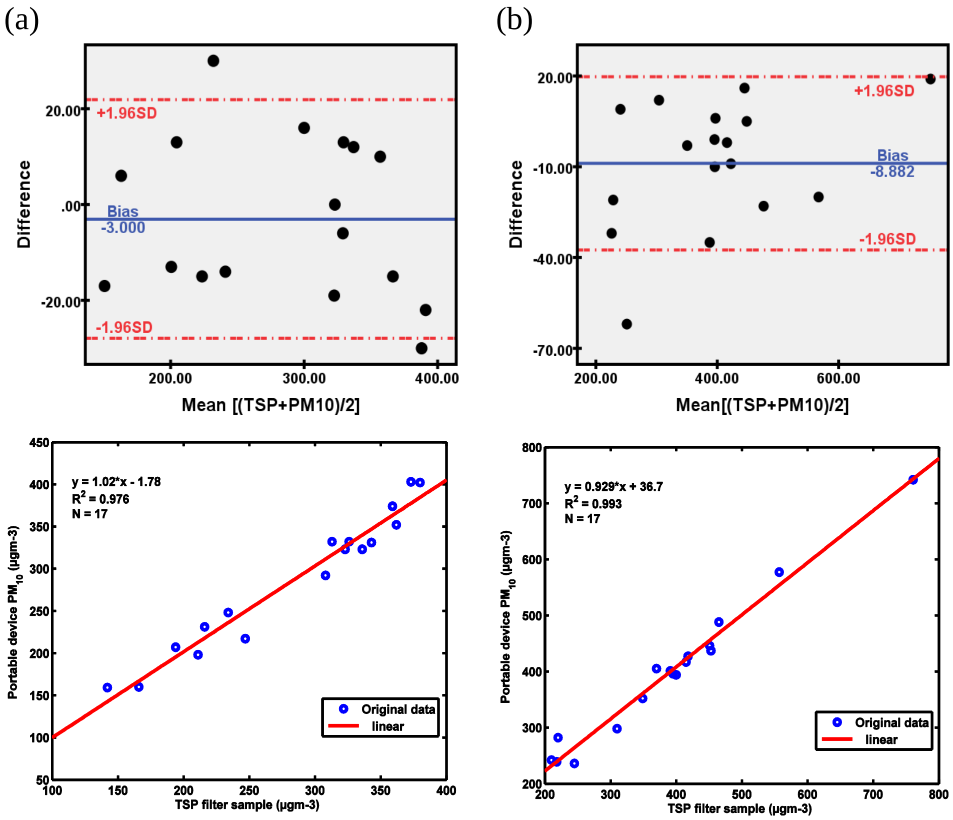

Figure 6.3. *Agreement and linear regression plots showing the bias and coefficient of determination between the TSP and the CW-HAT200 particulate monitor samples at two sample sites (a) control site, (b) dense activity site (modified after Aliyu and Botai, 2018)*

6.2.5. Data analysis approach

The study is interested in evaluating the effects of atmospheric aerosols and ground particulates concentrations on GPS_{PWV} estimates. Figure 6.4 highlights the flowchart which describes the steps taken to achieve this study. The datasets utilized in this study covered the duration of 1-year (December 2015 – November 2016).

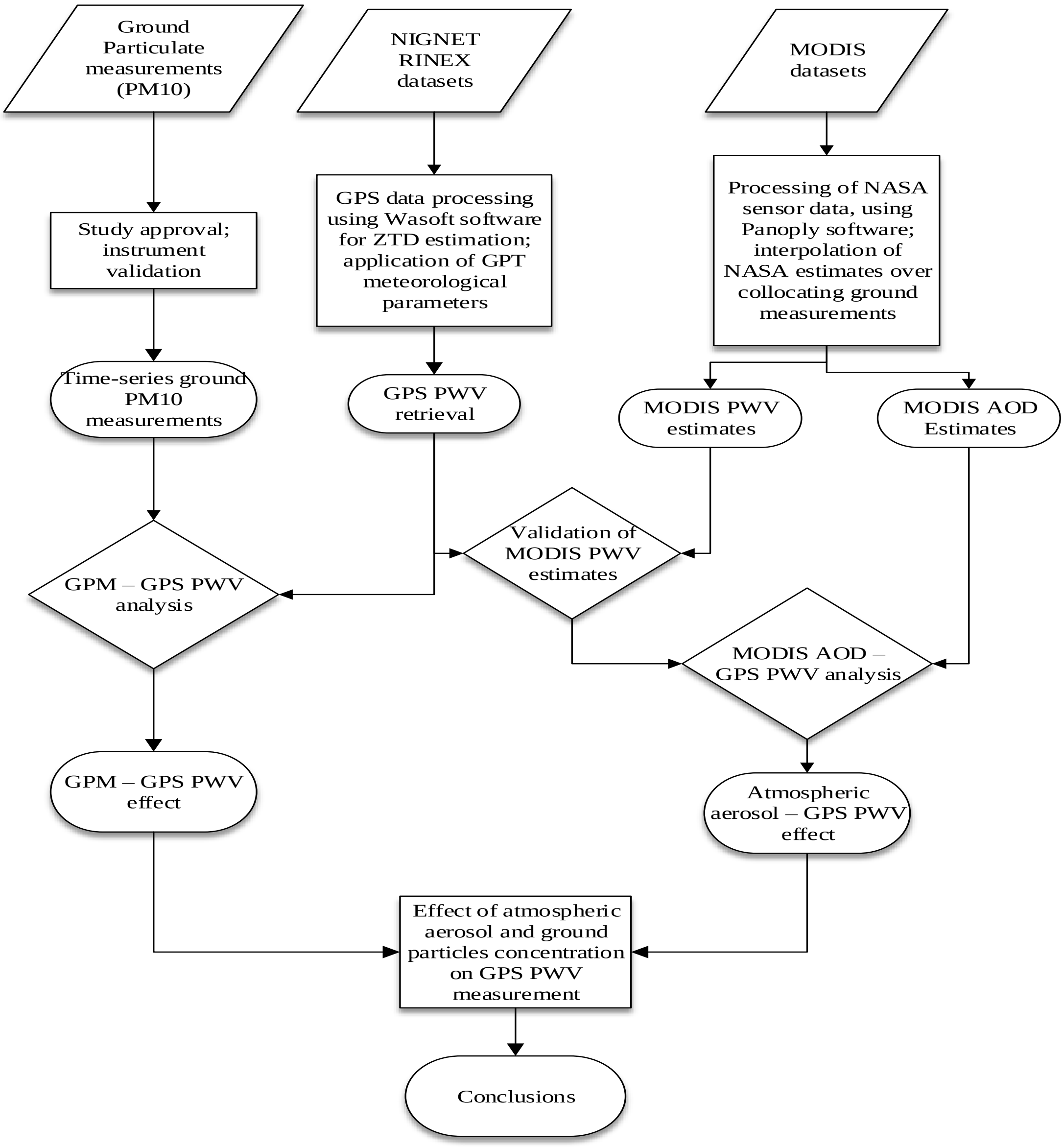

Figure 6.4. *Flowchart of the data analysis steps*

The assimilation process for aerosol estimation using GPS-derived PWV estimates involves three empirical steps (Equations 6.1 – 6.3). First, we determined the ZTD. It is the GNSS signal attenuation primarily responsible for indicating precipitable water vapour contents (Bevis *et al*., 1994; Rohm *et al*., 2014). Second, we utilized the GPS meteorology concept. This extracts the precipitable water vapour (PWV) from the GPS–ZTD estimates given that the atmospheric temperature and pressure at the ABUZ station is known (Isioye *et al*., 2017). Finally, we utilized literature which indicated that water vapour takes out aerosol from the atmosphere that usually occurs as a result of particulate matter (PM) floating in the air/gas or dissolved in water. PM is a major contributor of aerosol constituents in the troposphere from which the PWV is derived using the GPS ZTD signal (Lau and He, 2017). It has been established that PWV and particulates (aerosols) have a significant inverse relationship (Gui *et al*., 2017a). Furthermore, the degree of relationship between the PM and AOD quantities have established by literature. Their relationship can be determined using their level of correlation (Schäfer et al., 2008; Yap and Hashim, 2013). This practical approach is acknowledged for examining PM concentration from satellite remote sensing AOD data. A full data processing technique for relating PM with AOD is discussed in Filip and Stefan (2011).

To ensure the reliability of our results, we adopted four performance indicators to evaluate the GPS-derived PWV estimates for aerosol monitoring. The indicators include: alpha data reliability (Le Boennec and Salladarré, 2017), correlation coefficient (R) (Murphy, 1988) and root mean square error (RMSE) (Chai and Draxler, 2014). They are represented mathematically in Equations (6.8 – 6.10). The alpha data reliability index computes the average factor by which observed measurements of interest differ from one another. The correlation (R) weighs the level of variability in the actual values that is explained by the model. RMSE expresses the difference between observations predicted by a model.

$$\alpha = \frac{N \cdot \overline{C}}{\overline{\upsilon} + (N-1) \cdot \overline{C}} \tag{6.8}$$

$$R = \frac{\sum_{i=1}^{n} \left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)}{\left[\sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2 \times \sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2\right]^{\frac{1}{2}}} \tag{6.9}$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2\right]^{\frac{1}{2}} \tag{6.10}$$

where N is the sample size, c is average covariance between the GPS$_{PWV}$ estimates (O_i) and the predicting MODIS$_{PWV}$ and MODIS$_{AOD}$ estimates (P_i), ϑ is the average variance, O_i is the time series of reference GPS$_{PWV}$ estimates, P_i, is the time series of predicted MODIS$_{PWV}$ and MODIS$_{AOD}$ models, $\overline{O}$ and $\overline{P}$ denote the averages of the reference and predicted model values; N indicates the number of observation samples.

The statistical analyses were performed using Microsoft Excel 2013, Sigma Plot and SPSS software. MATLAB was also exploited to generate some of the plots which were presented.

6.3. Results and discussion

The distribution of the GPS-derived PWV (GPS$_{PWV}$) estimates over the ABUZ station was analysed for skewness and kurtosis. The GPS$_{PWV}$ data revealed a skewness value (- 0.256) and kurtosis value (-1.509). The standard error across the GPS$_{PWV}$ variables is 1.240 mm. This indicated that the GPS-derived PWV estimates were normally distributed with the 95% confidence interval. To further certify the assumption of normality, the Shapiro-Wilk's test based on an empirical standardization of the GPS$_{PWV}$ observation residuals was conducted. The test displayed a value of 0.890. For the MODIS$_{PWV}$, the value for skewness and kurtosis is -0.312 and -1.426 respectively. The Shapiro-Wilks test of the MODIS$_{PWV}$ observation residuals is 0.882. These results did conclude that the GPS$_{PWV}$ observations are normally distributed. Figure 6.5 illustrates the time-series data of the collocating average PWV estimates from the ABUZ and MODIS instruments for the time interval (1300 – 1415 hours). The time series data revealed varying data breaches for the collocating observations. While the data gap for the ABUZ station is restricted to hardware issues, he MODIS breaches is as a result of the Lance-MODIS latency plus hardware issues.

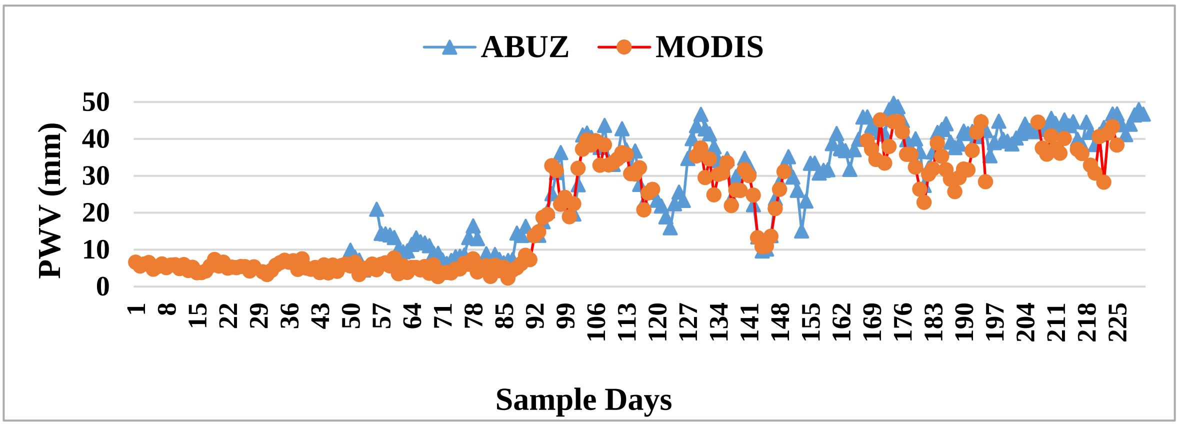

Figure 6.5. *Time series of collocating averaged PWV from the ABUZ station and MODIS instrument for the study period (available sample days' equals 232)*

6.3.1. Effects of MODIS$_{AOD}$ concentrations on GPS$_{PWV}$

Prior to the GPS$_{PWV}$-MODIS$_{AOD}$ investigation, we conducted a pre-validation of the MODIS instrument (MODIS$_{PWV}$) using the GPS$_{PWV}$ measurements. The MODIS$_{PWV}$ estimates were extracted from the MODIS MYD08_D3 5.1 IR retrieval variable. We utilized available GPS$_{PWV}$ data for the study period. The available datasets were categorized across seasons;

December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). The time-analysis in Figure 6.5 showed that MODIS$_{PWV}$ recorded good correlating estimates when compared to the GPS$_{PWV}$ estimates over the ABUZ station. Figure 6.6 displays the Bland-Altman agreement plot, linear regression and boxplots of the compared PWV residuals. The daily average PWV (mm) recorded across the collocated stations ranged from (4.60 – 49.66) and (2.25 – 45.09) for GPS and MODIS instrument respectively (Figure 6.6b).

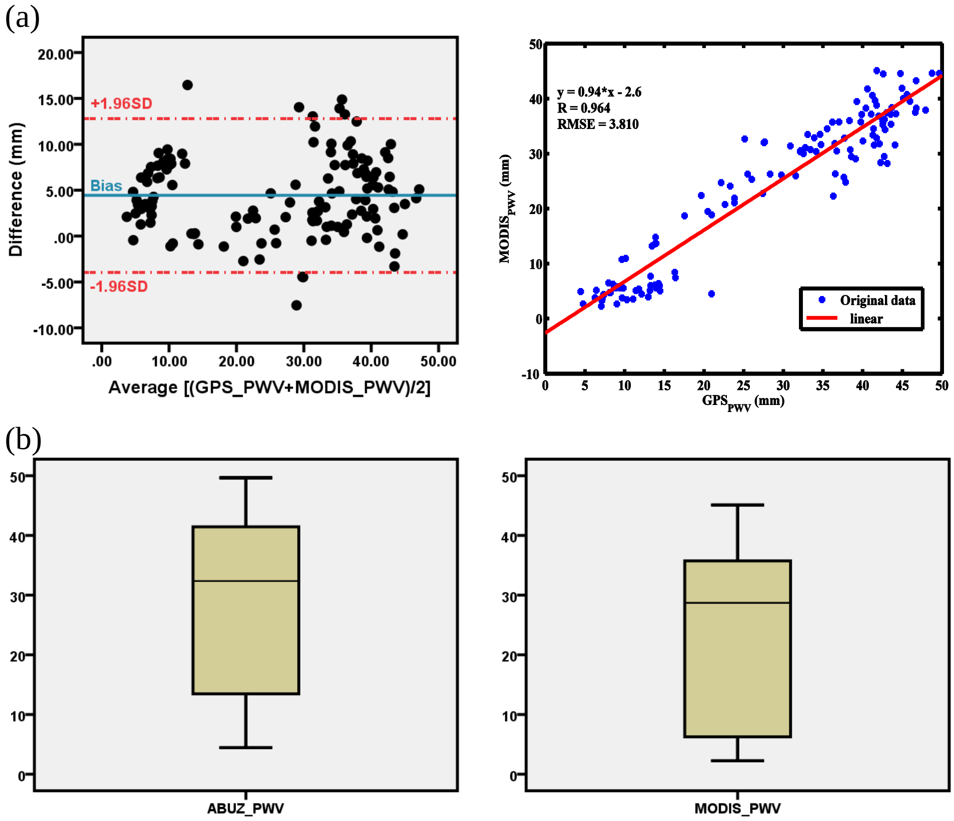

Figure 6.6. *(a) Difference - linear regression plot of the GPS$_{PWV}$ and MODIS$_{PWV}$ estimates (b) Boxplots showing the range of PWV values*

The GPS data acquisition process revealed that there were no available datasets for SON season. From Figures 6.5 and 6.6, it can see that the MODIS$_{PWV}$ estimates showed a good linear agreement with GPS$_{PWV}$ estimates. Table 6.2 illustrates the GPS$_{PWV}$-MODIS$_{PWV}$ validation results. The descriptive revealed good GPS$_{PWV}$-MODIS$_{PWV}$ agreement at surface level (R = 0.96; RMSE = 3.81). This MODIS$_{PWV}$ validation is within the range of acceptable results, when compared to similar research findings on PWV validation (Tsidu *et al.*, 2015; Gui et al., 2017b) but slightly lower than Ningombam *et al.*, (2016). From Table 6.2, we can also conclude that the computed alpha reliability, correlation coefficient, root mean square error and bias, were within the range of PWV estimation with GPS positioning.

Table 6.2. *Performance statistics between GPS_{PWV} and $MODIS_{PWV}$ retrievals estimates*

GPS station	Season	α	R	RMSE (mm)	Bias (mm)
ABUZ	DJF	0.98	0.77	1.03	5.46
	MAM	0.99	0.93	3.42	2.94
	JJA	0.98	0.79	3.95	6.49
	Combined	0.97	0.96	3.81	4.41

To determine the effect of $MODIS_{AOD}$ concentrations on GPS_{PWV} estimates, $MODIS_{AOD}$ estimates were collected over the ABUZ station collocating with the GPS_{PWV} estimates for the study period. The $MODIS_{AOD}$ measurement over the ABUZ station was obtained after the initial spatial boundary box sub-setting and subsequent Kriging interpolation described in Aliyu and Botai (2018). The descriptive statistics of the $MODIS_{AOD}$ estimates over the ABUZ station showed that the standard error of mean ranged from 0.04. The standard error of skewness and kurtosis were computed as 0.17 and 0.34 respectively. The Shapiro-Wilks test of normality (0.83) also indicated that the estimates are normally distributed over the ABUZ station. All the collocating data observations (GPS_{PWV} and $MODIS_{AOD}$) indicated strong reliability ($\alpha > 0.90$) over the ABUZ station. Figure 6.7 displays the time-series of the $MODIS_{AOD}$ measurements against the GPS_{PWV} estimates.

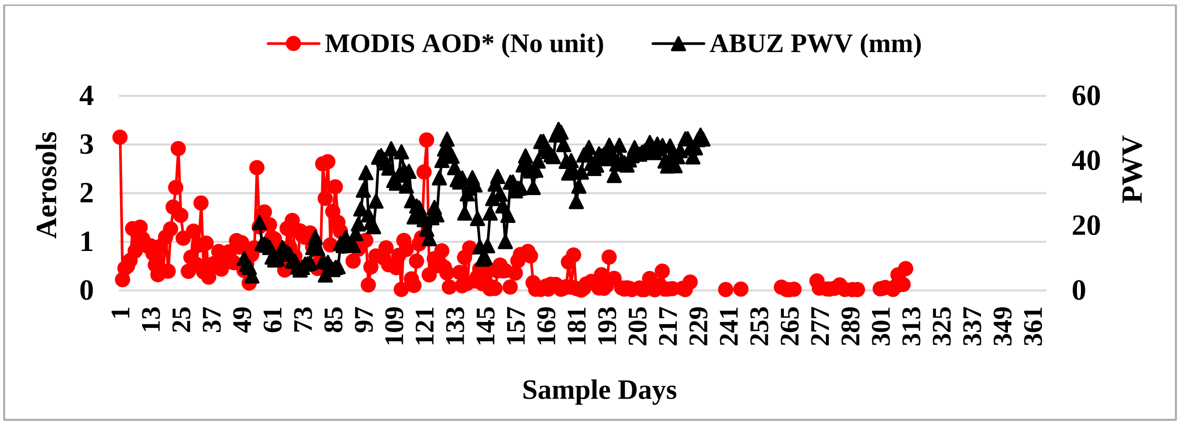

Figure 6.7. *Time-series of the collocating averaged GPS_{PWV} estimates and $MODIS_{AOD}$ measurements*

The GPS_{PWV} and $MODIS_{AOD}$ measurements were significant ($p < 0.05$). The GPS_{PWV} and $MODIS_{AOD}$ analysis showed good correlation performance ($R \leq -0.64$) with the JJA season recorded the better performance ($R = -0.79$; $\alpha = 0.999$; RMSE = 0.46). Our finding for the GPS_{PWV} - $MODIS_{AOD}$ analysis does agree with Gui et al. (2017a) that evaluated atmospheric aerosols with PWV estimates from radiosondes and weather stations.

6.3.2. Effects of GPM concentrations on GPS_{PWV}

Secondly, we evaluated the applicability of the GPS_{PWV} estimates derived from the ABUZ station for monitoring ground particulate matter (GPM) measurements. We utilized the available collocating GPM time-series data. The linear relationship between the GPS_{PWV} and GPM measurement is illustrated in Figure 6.8. Table 6.3 also displays the descriptive statistics of the collocating GPM measurements.

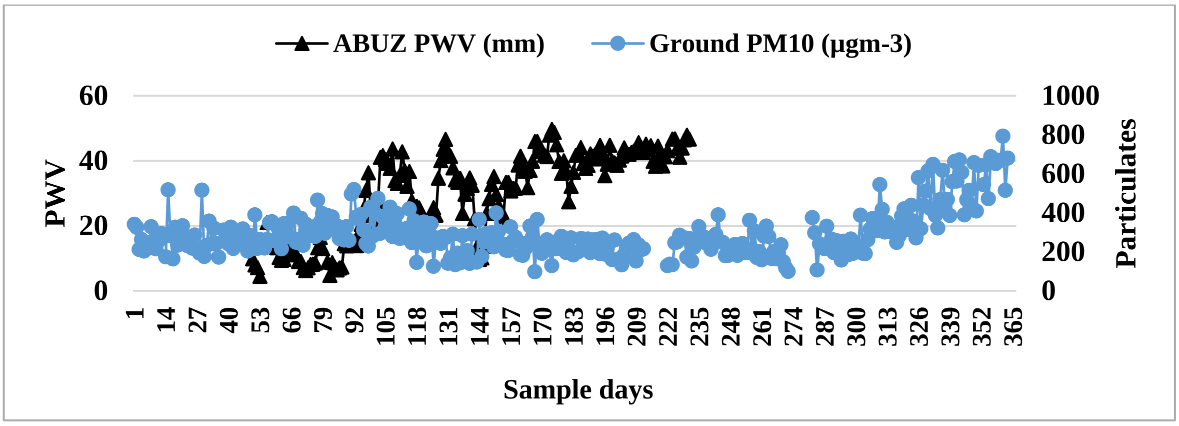

Figure 6.8. *Time-series of the collocating averaged GPS_{PWV} estimates and GPM measurements*

In Table 6.3, we can see that the probabilities of datasets normality are greater than 0.05, thus the null hypothesis (H_0) is accepted. This indicates that the datasets are normally distributed as well as within satisfactory skewness and kurtosis. Also, the MAM and JJA season recorded higher GPM concentrations. This could be attributed to the massive construction activities that commenced within the study area.

Table 6.3. *Descriptive statistics of collocating GPM measurements*

Season	DJF	MAM	JJA
Mean (µg m^{-3})	309.08	300.94	224.01
SE of mean	12.24	10.99	9.71
SD	127.25	114.30	100.90
Skewness	1.12	0.49	0.167
Kurtosis	1.28	-0.12	-1.01
Shapiro-Wilk's Test	0.92	0.97	0.97

For the comparative results of the GPM concentrations against the GPS_{PWV} estimates. The GPS_{PWV} and GPM measurements were significant ($p < 0.05$). Similarly, the GPS_{PWV} and GPM analysis showed good correlation (R) range of values (-0.66, -0.67 and -0.79) for the DJF, MAM and JJA seasons. The GPS_{PWV}-GPM recorded the better relationship (R = -0.79; α = 0.99; RMSE = 2.39) in the JJA season. This is also similar to the GPS_{PWV}-$MODIS_{AOD}$ comparison. This indicated that the presence of ground-level particulates resulting from anthropogenic activities contributes significantly, to the atmospheric aerosol concentration within the study area. There are very limited studies that have performed the GPS_{PWV}-GPM analysis. However, this correlation coefficient was satisfactory, if compared to AOD – PM_{10} study (R = -0.70) reported by Filip and Stefan (2011). Furthermore, the GPS_{PWV}-GPM investigation can contribute to the position accuracy for similar related studies in the future.

From the above-described results, we can conclude that the prediction of MODIS AOD and particulate matter, PM_{10} from GPS_{PWV} estimations, does provide a convincing argument for the study location. The better performance of the GPS_{PWV}-GPM to the GPS_{PWV}-$MODIS_{AOD}$ can also be attributed to the alternating humidity and cloud across the study seasons, as it may impact negatively on the MODIS retrievals thus responsible for observation variations.

6.4. Conclusions

With the World Health Organization reporting alarming particulate pollution level across Nigerian cities, this paper presents seasonal variability of the input parameters; GPS-derived precipitable water vapour, MODIS AOD estimates and ground PM measurements over Zaria, Nigeria for December 2015 - November 2016. We examined the effect of atmospheric aerosols and ground particulate matter concentrations on GPS derived precipitable water estimates. The collocating datasets utilized for this study revealed satisfactory results for skewness and normality. The MODIS-GPS pre-validation procedure results showed good agreement for GPS_{PWV}-$MODIS_{PWV}$ across the instruments. The analysis of the GPS_{PWV}-$MODIS_{AOD}$ and the GPM_{PWV}-GPM measurements revealed promising relationships which were similar to related studies. The spatial variability of particulates/aerosols concentration within the Nigerian territory cannot be ignored, thus the need to explore alternative operational techniques for effective atmospheric pollution monitoring. Our study introduced a novel physical mechanism of the PWV-PM relationship that can be utilized for future position accuracy. The incorporation of our findings will provide a basis for the improved analysis of the aerosol/particulates processes. These findings present applicability of the Nigerian GNSS Reference Network (NIGNET) for monitoring ground particulates and satellite aerosol measurements. Thus, the Nigerian air pollution planners can begin to consider its NIGNET stations as an alternative for aerosol monitoring, taking into consideration its limited air pollution monitoring capabilities.

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References

1. Abbasy, S., Abbasi, M., Asgari, J. & Ghods, A. 2017. Precipitable water vapour estimation using the permanent single GPS station in Zanjan, Iran. *Meteorological Applications,* 24(3): 415-422. https://doi.org/10.1002/met.1639
2. Ali, M.A., Assiri, M. & Dambul, R. 2017. Seasonal aerosol optical depth (AOD) variability using satellite data and its comparison over Saudi Arabia for the period 2002–2013. *Aerosol and Air Quality Research,* 17(5): 1267-1280. https://doi.org/10.4209/aaqr.2016.11.0492
3. Aliyu, Y.A. & Botai, J.O. 2018. Appraising city-scale pollution monitoring capabilities of multi-satellite datasets using portable pollutant monitor. *Atmospheric Environment,* 179: 239-249. https://doi.org/10.1016/j.atmosenv.2018.02.034
4. Araki, S., Yamamoto, K. & Kondo, A. 2015. Application of regression kriging to air pollutant concentrations in Japan with high spatial resolution. *Aerosol and Air Quality Research,* 15: 234-241. https://doi.org/10.4209/aaqr.2014.01.0011
5. Ayorinde, T.T., Rabiu, A.B. & Amory-Mazaudier, C. 2016. Inter-hourly variability of total electron content during the quiet condition over Nigeria, within the equatorial ionization anomaly region. *Journal of Atmospheric and Solar-Terrestrial Physics,* 145: 21-33. https://doi.org/10.1016/j.jastp.2016.04.005
6. Bai, Z. & Feng, Y. 2003. GPS water vapour estimation using interpolated surface meteorological data from Australian automatic weather stations. *Journal of Global Positioning Systems,* 2(2): 83-89.
7. Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, R.A. & Ware, R.H. 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *Journal of Geophysical Research*, 97: 15787–15801. https://doi.org/10.1029/92JD01517
8. Bevis, M., Businger, S., Chiswell, S., Herring, T.A., Anthes, R.A., Rocken, C. & Ware, R.H. 1994. GPS meteorology: mapping zenith wet delays onto precipitable water. *Journal of Applied Meteorology*, 33(3): 379-386. https://doi.org/10.1175/1520-0450(1994)033<0379:GMMZWD>2.0.CO;2
9. Bonafoni, S. & Biondi, R. 2016. The usefulness of the Global Navigation Satellite Systems (GNSS) in the analysis of precipitation events. *Atmospheric Research*, 167: 15-23. https://doi.org/10.1016/j.atmosres.2015.07.011
10. Bucholtz, A. 1995. Rayleigh-scattering calculations for the terrestrial atmosphere. *Applied Optics,* 34(15): 2765-2773. https://doi.org/10.1364/AO.34.002765
11. Boehm, J., Werl, B. & Schuh, H. 2006. Troposphere mapping functions for GPS and very long baseline interferometry from European centre for medium-range weather forecasts operational analysis data. *Journal of Geophysical.Research. B: Solid Earth,* 111(2): B02406. https://doi.org/10.1029/2005JB003629
12. Boutiouta, S. & Lahcene, A. 2013. Preliminary study of GNSS meteorology techniques in Algeria. *International Journal of Remote Sensing,* 34(14): 5105-5118. https://doi.org/10.1080/01431161.2013.786850

13. Chai, T. & Draxler, R.R. 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – arguments against avoiding RMSE in the literature. *Geoscience Model Development*, 7(3): 1247-1250. https://doi.org/10.5194/gmd-7-1247-2014
14. Chew, B.N., Campbell, J.R., Hyer, E.J., Salinas, S.V., Reid, J.S., Welton, E.J., Holben, B.N. & Liew, S.C. 2016. Relationship between aerosol optical depth and particulate matter over Singapore: effects of aerosol vertical distributions. *Aerosol and Air Quality Research*, 16: 2818-2830. https://doi.org/10.4209/aaqr.2015.07.0457
15. Duncan, B.N., Prados, A.I., Lamsal, L.N., Liu, Y., Streets, D.G., Gupta, P., Hilsenrath, E., Kahn, R.A., Nielsen, E., Beyersdorf, A.J., Burton, S.P., Fiore, A.M., Fisherman, J., Henze, D.K., Hosteltler, C.A., Krotkov, N.A., Lee, P., Lin, M., Pawson, S., Pfister, S., Pickering, K.E., Bradley Pierce, R., Yoshida, Y. & Ziemba, L.D. 2014. Satellite data of atmospheric pollution for US air quality applications: examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. *Atmospheric Environment*, 94: 647-662. https://doi.org/10.1016/j.atmosenv.2014.05.061
16. Efe, S.I. & Efe, A.T. 2008. Spatial distribution of particulate matter (PM10) in Warri metropolis, Nigeria. *The Environmentalist*, 28(4): 385-394. http://doi.org/10.1007/s10669-007-9154-0
17. Filip, L. & Stefan, S. 2011. Study of the correlation between the near-ground PM10 mass concentration and the aerosol optical depth. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(13): 1883-1889. https://doi.org/10.1016/j.jastp.2011.04.027
18. Gui, K., Che, H., Chen, Q., Zeng, Z., Zheng, Y., Long, Q., Sun, T., Liu, X., Wang, Y., Liao, T. & Yu, J. 2017a. Water vapour variation and the effect of aerosols in China. *Atmospheric Environment,* 165: 322-335. https://doi.org/10.1016/j.atmosenv.2017.07.005
19. Gui, K., Che, H., Chen, Q., Zeng, Z., Liu, H., Wang, Y., Zheng, Y., Sun, T., Liao, T., Wang, H. & Zhang, X. 2017b. Evaluation of radiosonde, MODIS-NIR-Clear, and AERONET precipitable water vapor using IGS ground-based GPS measurements over China. *Atmospheric Research*, 197: 461-473. https://doi.org/10.1016/j.atmosres.2017.07.021
20. Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y.C. & Kumar, N. 2006. Satellite remote sensing of particulate matter and air quality over global cities. *Atmospheric Environment*, 40(30): 5880–5892. https://doi.org/10.1016/j.atmosenv.2006.03.016
21. Isioye, O.A., Combrinck, L. & Botai, J.O. 2017. Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria. *International Journal of Remote Sensing,* 38(20): 5710-5735. https://doi.org/10.1080/01431161.2017.1346401
22. Kouba, J. 2009. *A Guide to Using International GNSS Service (IGS) Products.* Available from: http://acc.igs.org/UsingIGSProductsVer21.pdf. Last access: August 2017.
23. Lau, L. & He, J. 2017. Investigation into the effect of atmospheric particulate matter (PM2. 5 and PM10) concentrations on GPS signals. *Sensors*, 17(3): 508. https://doi.org/10.3390/s17030508

24. Le Boennec, R. & Salladarré, F. 2017. The impact of air pollution and noise on the real estate market. The case of the 2013 European green capital: Nantes, France. *Ecological Economic*, 138: 82-89. https://doi.org/10.1016/j.ecolecon.2017.03.030
25. Li, J. & Biswas, P. 2017. Optical characterization studies of a low-cost particle sensor. *Aerosol and Air Quality Research*, 17(7): 1691-1704. https://doi.org/10.4209/aaqr.2017.02.0085
26. Li, S., Ma, Z., Xiong, X., Christiani, D.C., Wang, Z. & Liu, Y. 2016. Satellite and ground observations of severe air pollution episodes in the winter of 2013 in Beijing, China. *Aerosol and Air Quality Research*, 16(4): 977-989. https://doi.org/10.4209/aaqr.2015.01.0057
27. Liu, J., Man, Y. & Liu, Y. 2014. Temporal variability of PM_{10} and $PM_{2.5}$ inside and outside a residential home during 2014 Chinese spring festival in Zhengzhou, China. *National Hazards*, 73(3): 2149-2154. https://doi.org/10.1007/s11069-014-1157-9
28. Madrigano, J., Kloog, I., Goldberg, R., Coull, B.A., Mittleman, M.A. & Schwartz, J. 2013. Long-term exposure to PM2.5 and incidence of acute myocardial infarction. *Environmental Health Perspective*, 121(2): 192–196. https://doi.org/10.1289/ehp.1205284
29. Middey, A. & Chaudhuri, S. 2013. The reciprocal relation between lightning and pollution and their impact over Kolkata, India. *Environmental Science and Pollution Research*, 20: 3133–3139. https://doi.org/10.1007/s11356-012-1219-z
30. Misra, A., Jayaraman, A. & Ganguly, D. 2015. Validation of version 5.1 MODIS aerosol optical depth (deep blue algorithm and dark target approach) over a semi-arid location in Western India. *Aerosol and Air Quality Research*, 15(1): 252-262. https://doi.org/10.4209/aaqr.2014.01.0004
31. Murphy, A.H. 1988. Skill scores based on the mean square error and their relationships to the correlation coefficient. *Monthly Weather Reviews*, 116(12): 2417-2424. https://doi.org/10.1175/1520-0493(1988)116<2417:SSBOTM>2.0.CO;2
32. Musa, T.A., Amir, S., Othman, R., Ses, S., Omar, K., Abdullah, K., Samsung, L. & Rizos, C. 2011. GPS meteorology in a low latitude region: remote sensing of atmospheric water vapour over Malaysian peninsula. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73: 2410-2422. https://doi.org/10.1016/j.jastp.2011.08.014
33. Ningombam, S.S., Jade, S., Shrungeshwara, T.S. & Song, H.J. 2016. Validation of water vapour retrieval from moderate resolution imaging spectro-radiometer (MODIS) in near infrared channels using GPS data over IAO-Hanle, in the Trans-Himalayan Region. *Journal of Atmospheric and Solar-Terrestrial Physics*, 137: 76-85. https://doi.org/10.1016/j.jastp.2015.11.019
34. Nordio, F., Kloog, I., Coull, B.A., Chudnovsky, A., Grillo, P., Bertazzi, P.A., Baccarelli, A.A. & Schwartz, J. 2013. Estimating spatio-temporal resolved PM10 aerosol mass concentrations using MODIS satellite data and land use regression over Lombardy, Italy. *Journal of Atmospheric and Solar-Terrestrial Physics*, 74: 227-236. https://doi.org/10.1016/j.atmosenv.2013.03.043

35. Ortiz de Galisteo, J.P., Bennouna, Y., Toledano, C., Cachorro, V., Romero, P., Andrés, M.I. & Torres, B. 2014. Analysis of the annual cycle of the precipitable water vapour over Spain from 10-year homogenized series of GPS data. *Quarterly Journal of the Royal Meteorological Society,* 140: 397–406. https://doi.org/10.1002/qj.2146
36. Rohm, W., Yuan, Y., Biadeglgne, B., Zhang, K. & Le Marshall, J. 2014. Ground-based GNSS ZTD/IWV estimation system for numerical weather prediction in challenging weather conditions. *Atmospheric Research,* 138: 414-426. https://doi.org/10.1016/j.atmosres.2013.11.026
37. Saastamoinen, J. 1972. Atmospheric correction for troposphere and stratosphere in radio ranging of satellites', In the use of artificial satellites for geodesy, Henriksen, S.W., Mancini, A. & Chovitz, B.H. (Eds.), vol. 15 of Geophysics Monograph Series, pp. 247–252, American Geophysical Union (AGU), AIAA, NOAA, U.S. ATC, Washington, D.C.
38. Schäfer, K., Harbusch, A., Emeis, S., Koepke, P. & Wiegner, M. 2008. Correlation of aerosol mass near the ground with aerosol optical depth during two seasons in Munich. *Atmospheric Environment*, 42(18): 4036-4046. https://doi.org/10.1016/j.atmosenv.2008.01.060
39. Schröder, L., Richter, A., Fedorov, D.V., Eberlein, L., Brovkov, E.V., Popov, S.V., Knöfel, C., Horwath, M., Dietrich, R., Matveev, A.Y. & Scheinert, M. 2017. Validation of satellite altimetry by kinematic GNSS in central east Antarctica. *The Cryosphere*, 11(3): 1111-1130. https://doi.org/10.5194/tc-11-1111-2017
40. Shi, Y., Zhang, J., Reid, J.S., Hyer, E.J. & Hsu, N.C. 2013. Critical evaluation of the MODIS deep blue aerosol optical depth product for data assimilation over North Africa. *Atmospheric Measuring Techniques*, 6(4): 949-969. https://doi.org/10.5194/amt-6-949-2013
41. Solomon, S., Rosenlof, K.H., Portmann, R.W., Daniel, J.S., Davis, S.M., Sanford, T.J. & Plattner, G.K. 2010. Contributions of stratospheric water vapour to decadal changes in the rate of global warming. *Science*, 327: 1219–1223. https://doi.org/10.1126/science.1182488
42. Streets, D.G., Canty, T., Carmichael, G.R., de Foy, B., Dickerson, R.R., Duncan, B.N., Edwards, D.P., Haynes, J.A., Henze, D.K., Houyoux, M.R. & Jacob, D.J. 2013. Emissions estimation from satellite retrievals: a review of current capability. *Atmospheric Environment*, 77: 1011-1042. https://doi.org/10.1016/j.atmosenv.2013.05.051
43. Tian, B., Manning, E., Fetzer, E., Olsen, E., Wong, S., Susskind, J. & Iredel, L. 2014. *AIRS/AMSU/HSB version 6 level 3 product user guide*. Available from: http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v6_docs/v6releasedocs1/V6_L3_User_Guide.pdf. Last access: June 2016.
44. Tsay, S.C., Maring, H.B., Lin, N.H., Buntoung, S., Chantara, S., Chuang, H.C., Gabriel, P.M., Goodloe, C.S., Holben, B.N., Hsiao, T.C. & Hsu, N.C. 2016. Satellite-surface perspectives of air quality and aerosol-cloud effects on the environment: an overview of 7-SEAS/BASELInE. *Aerosol and Air Quality Research*, 16: 2581-2602. https://doi.org/10.4209/aaqr.2016.08.0350

45. Tsidu, G.M., Blumenstock, T. & Hase, F. 2015. Observations of precipitable water vapour over complex topography of Ethiopia from ground-based GPS, FTIR, radiosonde and ERA-Interim reanalysis. *Atmospheric Measurement Techniques*, 8(8): 3277-3295. https://doi.org/10.5194/amt-8-3277-2015
46. UNEP (United Nations Environment Programme) 2015. *Fuel quality progress in Nigeria for Nigeria national air quality management program. Report presented by the Federal Ministry of Environment on 18 May 2015.* Available from: http://www.unep.org/Transport/new/PCFV/pdf/2015_Ecowas_FuelQualityProgress_Emmanuel.pdf. Last access: October 2017.
47. Vollmer, B. 2010. *AIRS data and services at the GSFC Earth Sciences Data and Information Services Centre (GES DISC).* Available from: http://airs.jpl.nasa.gov/documents/science_team_meeting_archive/2010_11/slides/Vollmer.pdf. Last access: June 2016.
48. Wanninger, L. 2000. Interpolation von GPS-Beobachtungen. *Allg. Vermnachr*. 107: 360–363.
49. WHO, (World Health Organization) 2016. *Global urban ambient air pollution database update*. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/WHO_AAP_database_May2016_v3web.xlsx?ua=1. Last access: September 2016.
50. Wong, M.S., Nichol, J., Lee, K.H. & Li, Z. 2008. *Retrieval of aerosol optical thickness using MODIS 500 x 500m^2, a study in Hong Kong and Pearl River Delta region.* 2008 International Workshop on Earth Observation and Remote Sensing Applications.
51. Yap, X.Q. & Hashim, M. 2013. A robust calibration approach for PM10 prediction from MODIS aerosol optical depth. *Atmospheric Chemistry and Physics*, 13(6): 3517-3526. https://dx.doi.org/10.5194/acpd-12-31483-2012
52. Zhang, H., Yuan, Y., Li, W., Ou, J., Li, Y. & Zhang, B. 2017. GPS PPP-derived precipitable water vapour retrieval based on Tm/Ps from multiple sources of meteorological data sets in China. *Journal of Geophysical Research: Atmospheres*, 122(8): 4165-4183. https://doi.org/10.1002/2016JD026000
53. Zhao, P., Yin, Y., Xiao, H., Zhou, Y. & Liu, J. 2016. Role of water vapour content in the effects of aerosol on the electrification of thunderstorms: A numerical study. *Atmosphere*, 7(10): 137. https://doi.org/10.3390/atmos7100137
54. Zumberge, J. F., Heflin, M.B., Jefferson, D.C., Watkins, M. M. & Webb, F. H. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research*, 102: 5005–5017. https://doi.org/10.1029/96JB03860

Chapter 7

Overview, conclusions and recommendations

7.1. Overview of study motivation

Air pollution is an endemic that should be of serious concern in a limited pollution monitoring resource environment like Nigeria. Nigeria is experiencing a rapid increase in anthropogenic activities, that continues to be compounded by the unchanging effort to monitor air pollution exposure within its population. Despite efforts by individual researches within Nigeria to evaluate atmospheric pollution effects, the Nigerian population upsurge and struggle reveal that the efforts are still inadequate. Portable pollutant monitors have proven to be a viable alternative to the present reference monitoring methods, thus providing acceptable quality observations at local and regional scales. It is for this reason that this study attempted to tackle important issues that confront Nigeria's air pollution status.

The PhD syllabus presented in this thesis is the result of a four-year multidisciplinary effort on improving air pollution innovation for Nigeria using one of its cities. The wider context investigated in the course of this study was formulated from an aim towards city-scale atmospheric pollution monitoring in a limited resource environment utilizing portable remote pollutant sensors. This was achieved with the introduction of an empirical multi-technique approach for air pollution assessment.

This thesis is self-initiated with bursary support from the University of Pretoria, South Africa; Ahmadu Bello University, Zaria, Nigeria, the Surveyors Council of Nigeria among others. With the global concerns on the rising air pollution level, especially in developing cities, this study sought to address this by proposing a network of lower cost remote pollutant sensors that can electronically detect airborne pollutants by exploiting the science of atmospheric interaction.

This approach offered significant improvements to the currently available experimental methods that have been utilized. The multi-technique air pollution monitoring approach enabled the adoption of advanced data analysis tools within a limited resource environment. This created a robust air pollution monitoring, simplify atmospheric pollution measures and made population exposure forecasting more efficient.

It is within this context that this PhD study focused on adopting a multi-technique approach to address its four specific objectives that are fundamental to the success of the study: first, determine the seasonal distribution of city-scale outdoor criteria pollutants in comparison to locally and globally stipulated air quality indices; second, evaluate the effects of outdoor pollution on the respiratory well-being of the exposed city population; third, appraise multi-satellite datasets pollution monitoring capabilities using city-scale ground datasets as a city-scale bottom-top analysis and finally investigate the effects of atmospheric aerosols and ground particulates on the existing Nigerian GNSS signals, thus serve as a ground-surface aerosol monitoring system.

7.1.1. Summary of principal findings

This thesis is a study that adopts a multi-technique approach to appraise city-scale atmospheric pollution in Nigeria. This section summarises the scientific contributions of this thesis, as follows:

- A review of the literature revealed that the mitigation of air pollution remains a challenge in many Nigerian cities. Generally, the rationale for this type of study is usually as a result of historical data availability. This, however, is not always possible within the Nigerian context, since no prior data is available or has been collected. This may perhaps be partly due to non-existent reference air monitoring facilities as well as minimal collaborative efforts among environmental policy makers, academic and research institutes leading to low research output on the collective use of modern pollution monitoring technologies.

- Prior air pollution studies across Nigeria adopted portable pollutant monitoring devices due to the non-availability of real-time pollution reference monitors across its population. None of these studies has collected time-series ground-level criteria pollutant measurements within the Nigerian territory. For this reason, a pilot phase of city-scale air pollution monitoring becomes necessary. With the World Health Organization (WHO) 2016 report introducing Nigerian cities amongst the World's most polluted, this thesis presents the first time-series spatial and temporal analysis of ground-level pollutant measurements in a Nigerian city. This was achieved using validated portable pollutant sensors. The 1-year variation and trend of the ground pollutant measurements provide vital analysis of a Nigerian candidate for World Health Organization's list of polluted cities, thus signifying a pilot step towards the urgency of air pollution application in Nigeria.

- The thesis integrates time-series outdoor pollutant measurements and certified population exposure health markers, to ascertain the degree of relationship between measured outdoor pollution level and the exposed population. It presents the exposure appraisal of outdoor air pollution on the respiratory well-being of a Nigerian city population.

- For the first time, the study utilized the National Aeronautics and Space Administration (NASA) satellite pollution measurements and portable pollutant sensor datasets for ground-surface city-scale atmospheric pollution monitoring in Nigeria. It identifies available alternative satellite air pollution measurements for mitigating air quality effects within its limited resource environment

- The study synergizes observational datasets from the outdoor pollution measurements, satellite pollution sensing instruments, Global Navigation Satellite Systems Continuous Operating Reference Station (GNSS CORS) and Automatic Weather Observing Stations (AWOS) within Nigeria. The satellite pollution retrieval instruments are operated by NASA while the GNSS CORS is operated by Office of the Surveyor General of the Federation (OSGOF) in collaboration with African Reference Frame (AFREF). This provides an insight into the viability for Nigeria to monitor atmospheric aerosol/ground particulate effects using PWV estimates from the existing GNSS stations.

7.2. Conclusions

The specific objectives of this thesis were addressed in the respective chapters. The conclusion is hereby presented as reflected in the chapters.

- ***Reviewing the local and global implications of air pollution trends in Zaria, northern Nigeria***

This chapter addressed the first objective of this thesis. It highlights the background information on city-scale outdoor air pollution by providing operational prerequisites and standards in comparison with the existing facilities available for an African city-scale air pollution monitoring. A detailed review revealed that portable pollutant devices can be utilized as a point of reference for city-scale air pollution studies. The study adopted portable pollutant monitors that were validated with the World Health Organization (WHO) air filter technique. Outdoor pollution measurements were collected over 19 ground sample sites for the period of December 2015 – November 2016. The study revealed particulate matter ($PM_{2.5}$ and PM_{10}) measurements that were high enough to place Zaria amongst the World Health Organization's most polluted cities. This thesis offers direction to Nigeria's air quality policy organizers on available alternative air pollution measurements for mitigating air quality effects within its limited resource environment.

- ***An exposure appraisal of outdoor air pollution on the respiratory well-being of a developing city population***

This chapter addressed the second objective of this thesis. It utilized the outdoor pollutant measurements to appraise its influence on the respiratory well-being of the exposed population. The incorporation of pollution measurements, health records and questionnaire field survey datasets provided a unique approach to evaluate the exposure appraisal to the study population. The study findings showed that 2, 648 reported cases could have been avoided if the WHO limit for $PM_{2.5/10}$ had been adhered to. Regression analysis identified the $PM_{2.5}$ as the most predominant cause of respiratory symptoms among interviewed respondents. It concludes that outdoor air pollution did significantly contribute to the respiratory health status of the study population.

- ***Appraising city-scale pollution monitoring capabilities of multi-satellite datasets using portable pollutant monitors***

This chapter addressed the third objective of this thesis. It evaluated carbon monoxide and aerosol contents in the city atmosphere by employing the MSA Altair 5x gas detector and CW-HAT200 particulate counter to investigate the city-scale monitoring capabilities of satellite pollution observing instruments; atmospheric infrared sounder (AIRS), measurement of pollution in the troposphere (MOPITT), moderate resolution imaging spectroradiometer (MODIS), multi-angle imaging spectroradiometer (MISR) and ozone monitoring instrument (OMI). comparative analysis revealed that MOPITT carbon monoxide (CO) and MODIS aerosol optical depth (AOD) estimates are the appropriate satellite measurements for ground equivalents in Zaria, Nigeria. The results were within the acceptable limits of similar studies that utilized reference stations.

- ***Appraising the effects of atmospheric aerosols and ground particulates concentrations on GPS-derived PWV estimates***

This chapter addressed the fourth objective of this study. It utilized available GPS-derived precipitable water vapour (GPS_{PWV}), moderate resolution imaging spectroradiometer aerosol optical depth ($MODIS_{AOD}$) and ground-level particulate matter of fewer than 10 microns (GPM) datasets, to appraise the effect on atmospheric aerosol optical depth (AOD) and ground PM on GPS derived-precipitable water vapour (PWV) estimate. All the datasets were tested and were adjudged as normally distributed. The study conducted a pre-validation for the $MODIS_{PWV}$ estimates using the GPS_{PWV} measurements. The correlation of combined seasonal datasets for the GPS_{PWV}-$MODIS_{AOD}$ and GPS_{PWV}-GPM relationships showed significant correlation values of -0.79 and -0.68 respectively. This chapter provided valuable particulates - GPS_{PWV} estimates assessment, which would serve as future position accuracy for similar related studies.

7.2.1. The significant contribution of the study

In line with the goal of this study which was to conduct a city-scale appraisal of atmospheric pollution in Nigeria using a multi-technique approach, the strategies adopted to achieve the set objectives, the achieved findings and the resulting contributions are provided as follows:

- The study conducted a field experiment from which it generated novel time-series outdoor pollutant measurements using validated portable pollutant monitors, to determine the spatial variability of outdoor air pollution in a Nigeria city.
- The study established that day-time outdoor air pollution levels have exceeded the air quality threshold stipulated by the World Health Organization (WHO) for

measured pollutants. That is, outdoor pollutant measurements in the study area were high enough to place it amongst the WHO list of polluted cities.

- The study determined the spatial/statistical dependence of the measured outdoor air pollutants and their effects on the exposed study population within the study area. This can be adopted for control measures, diligent resource management and public awareness by the Nigerian environmental policy planners.

- The study established city-scale accuracies between the measurements from the portable pollutant devices and selected remotely-sensed pollution retrieval datasets operated by the National Aeronautics and Space Administration (NASA).

- The study established that GPS-derived precipitable water vapour (PWV) estimates can be utilized for appraising atmospheric aerosols and ground-level particulate concentrations. It also presents a future position accuracy for similar related studies.

7.2.2. Limitations of the study

Amidst significant findings of this study, it cannot be said to be free of limitations. There may be concerns about the possible effect of meteorological factors and non-climatic factors such as population growth/economic status, not considered in this study. Additionally, there might be concerns about the sampling datasets being limited to 1 year. The portable pollutant monitors utilized for the study were procured solely for the purpose of the PhD study. Thus, the reason why the observation datasets were limited to December 2015 and November 2016. Another drawback of the ground-based pollutant datasets is that they do not provide atmospheric profile information. The missing night-time air pollution measurements can also be seen as a challenge to the real-world applications of atmospheric pollution monitoring. This data gap is attributed to a number of reasons ranging from the security of the life of the researcher to likely possibilities of theft and vandalism. Thus, the reason why the study data/analysis was restricted to day-time sampling site locations.

7.3. Recommendations

The experience achieved during the course of this study has without any doubt shed light on the possibilities of continued research on atmospheric pollution monitoring, especially within a limited resource environment. A number of future research perspectives are highlighted below:

- Future studies should be conducted in Nigeria to improve the procedure and applicability of the portable pollutant measurements. It should also consider the above highlighted climatic/non-climatic factors so as to provide a robust prediction monitoring of the spatial and temporal pattern of atmospheric pollution across Nigerian cities.

- In this study, the MSA Altair 5x multi-gas detector and the Chinaway CW-HAT200 particulate counter were utilized to provide ground pollution measurements. Another promising area is in the field of portable pollutant monitor design. Future research should make use of a different brand(s) of portable pollutant monitors. This would provide a performance gateway for future research using portable pollutant estimates pending the densification of reference pollutant monitors in Nigerian cities.

- As a step towards a more efficient population exposure assessment due to air pollution, there is a need for clear policies on health data sharing among the various health/environmental organizations. This synergy will assist in real-time logging of health risk data that will provide a more efficient exposed population incidence/baseline rate.

- Future research should evaluate city-scale accuracies between ground measurements and other non-NASA satellite pollution estimates within other African cities. This will develop/improve on the top-bottom atmospheric pollution experiments at the local scale. Also, since satellite pollution instruments do obtain atmospheric pollution measurements across the vertical profile, it is recommended that future study should adopt atmospheric profile techniques and dispersion factors, to attain effective atmospheric operational status.

List of references

1. Abam, F.I. & Unachukwu, G.O. 2009. Vehicular emissions and air quality standards in Nigeria. *European Journal of Science and Research*, 34(4): 550-560.
2. Abbasi, I.N., Ahsan, A. & Nafees, A.A. 2012. Correlation of respiratory symptoms and spirometric lung patterns in a rural community setting, Sindh, Pakistan: a cross sectional survey. *BMC Pulmonary Medicine*, 12: 81-89. https://doi.org/10.1186/1471-2466-12-81
3. Abbasy, S., Abbasi, M., Asgari, J. & Ghods, A. 2017. Precipitable water vapour estimation using the permanent single GPS station in Zanjan, Iran. *Meteorological Applications*, 24(3): 415-422. https://doi.org/10.1002/met.1639
4. Adams, M.D. & Kanaroglou, P.S. 2016. Mapping real-time air pollution health risk for environmental management: Combining mobile and stationary air pollution monitoring with neural network models. *Journal of Environmental Management*, 168: 133-141. https://doi.org/10.1016/j.jenvman.2015.12.012
5. Adams, M.D., De Luca, P.F., Corr, D. & Kanaroglou, P.S. 2012. Mobile air monitoring: measuring change in air quality in the city of Hamilton, 2005-2010. *Social Indicators Research*, 108: 351-364. https://doi.org/10.1007/s11205-012-0061-5
6. Adewunmi, R., Adewunmi, R., Obi, P. & Odumosu, A. 2015. P15 assessment of cumulative exposures of traffic wardens to vehicular emissions in Zaria, Nigeria. *Journal of Transport and Health*, 2(2): S71. https://doi.org/10.1016/j.jth.2015.04.474
7. Agarwal, P., Sharma, S., Sharma, M., Takshak, A. & Sharma, V. 2017. Isolation and characterization of Tyrosinase (a carbon trapping enzyme) producing microorganisms, in the agricultural soil of western Uttar Pradesh and the study of enzymatic activity of Tyrosinase produced. *Biochemistry and Molecular Biology Letters*, 3(1): 105.
8. Akande, J.M., Ajaka, E.O., Omosogbe, F.M. & Lawal, A.I. 2013. Environmental effects of processing marine clay in Olotu, Ondo State, Nigeria. *Civil and Environmental Research*, 3(2): 82-86.
9. Akinlo, A.E. 2009. Electricity consumption and economic growth in Nigeria: evidence from cointegration and co-feature analysis. *Journal of Policy Modelling*, 31: 681-693. https://doi.org/10.1016/j.jpolmod.2009.03.004
10. Al-Awadi, L.T., Popov, V. & Khan, A.R. 2015. Seasonal effects of major primary pollutants in Ali Sabah Al-Salem residential area in Kuwait. *International Journal of Environmental Technology and Management*, 18(1): 54-82. https://doi.org/10.1504/IJETM.2015.068417
11. Albers, P.N., Wright, C.Y., Mathee, A. & Voyi, K.V. 2015. Household fuel use and child respiratory ill health in two towns in Mpumalanga, South Africa: research. *South African Medicine Journal*, 105(7): 573-577. https://doi.org/10.7196/SAMJnew.7934
12. Al-Haseen, S.I., Al-Qarroni, E.H., Qassim, M.H., Al-Saad, H.T. & Al-Hello, A.Z. 2015. An experimental study on the determination of air pollutant concentrations released from selected outdoor gaseous emission sources in Basra city, Southern Iraq. *Journal of International Academic Research for Multidisciplinary*, 3(1): 88-98.

13. Ali, M.A., Assiri, M. & Dambul, R. 2017. Seasonal aerosol optical depth (AOD) variability using satellite data and its comparison over Saudi Arabia for the period 2002–2013. *Aerosol and Air Quality Research*, 17(5): 1267-1280. https://doi.org/10.4209/aaqr.2016.11.0492
14. Aliyu, Y.A. & Botai, J.O. 2018. Appraising city-scale pollution monitoring capabilities of multi-satellite datasets using portable pollutant monitor. *Atmospheric Environment*, 179: 239-249. https://doi.org/10.1016/j.atmosenv.2018.02.034
15. Aliyu, Y.A., Musa, I.J. & Jeb, D.N. 2014. Geostatistics of pollutant gases along high traffic points in urban Zaria, Nigeria. *International Journal of Geomatics Geosciences*, 5(1): 19-31.
16. Ana, G., Adeniji, B., Ige, O., Oluwole, O. & Olopade, C. 2013. Exposure to emissions from firewood cooking stove and the pulmonary health of women in Olorunda community, Ibadan, Nigeria. *Air Quality Atmosphere and Health*, 6(2): 465-471. https://doi.org/10.1007/s11869-012-0183-6
17. Ana, G.R.E.E., Odeshi, T.A., Sridhar, M.K.C. & Ige, M.O. 2014. Outdoor respirable particulate matter and the lung function status of residents of selected communities in Ibadan, Nigeria. *Perspective in Public Health*, 134(3): 169-175. https://doi.org/10.1177/1757913913494152
18. Araki, S., Yamamoto, K. & Kondo, A. 2015. Application of regression kriging to air pollutant concentrations in Japan with high spatial resolution. *Aerosol and Air Quality Research*, 15: 234-241. https://doi.org/10.4209/aaqr.2014.01.0011
19. Arbex, M.A., Santos, U.D.P., Martins, L.C., Saldiva, P.H.N., Pereira, L.A.A. & Braga, A.L.F. 2012. Air pollution and the respiratory system. *Jornal Brasileiro de Pneumologia*, 38(5): 643-655. https://doi.org/10.1590/S1806-37132012000500015
20. Asatar, G.I. & Nair, P.R. 2010. Spatial distribution of near-surface CO over Bay of Bengal during winter: role of transport. *Journal of Atmospheric and Solar-Terrestrial Physics*, 72(17): 1241-1250. https://doi.org/10.1016/j.jastp.2010.07.025
21. Assamoi, E.M. & Liousse, C. 2010. A new inventory for two-wheel vehicle emissions in West Africa for 2002. *Atmospheric Environment*, 44(32): 3985-3996. https://doi.org/10.1016/j.atmosenv.2010.06.048
22. Ayorinde, T.T., Rabiu, A.B. & Amory-Mazaudier, C. 2016. Inter-hourly variability of total electron content during the quiet condition over Nigeria, within the equatorial ionization anomaly region. *Journal of Atmospheric and Solar-Terrestrial Physics*, 145: 21-33. https://doi.org/10.1016/j.jastp.2016.04.005
23. Bai, Z. & Feng, Y. 2003. GPS water vapour estimation using interpolated surface meteorological data from Australian automatic weather stations. *Journal of Global Positioning Systems*, 2(2): 83-89.
24. Bailey, T.C. & Gatrell, A.C. 1996. Interactive spatial data analysis in medical geography. *Social Science and Medicine*, 42(6): 843-855. https://doi.org/10.1016/0277-9536(95)00183-2

25. Barret, B., Mazière, M.D. & Mahieu, E. 2003. Ground-based FTIR measurements of CO from the Jungfraujoch: characterisation and comparison with in situ surface and MOPITT data. *Atmospheric Chemistry and Physics*, *3*(6): 2217-2223. https://doi.org/10.5194/acp-3-2217-2003

26. Bell, M.L. & Davis, D.L. 2001. Reassessment of the lethal London fog of 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. *Environmental Health Perspectives*, 109 (3): 389-394.

27. Bereznicki, S.D. & Kamal, A. 2013. Observations of interference between portable particle counters and NOx monitors. *Atmospheric Environment*, 75: 303-307. https://doi.org/10.1016/j.atmosenv.2013.04.064

28. Bernstein, J.A., Alexis, N., Bacchus, H., Bernstein, I.L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., Oullette, J. & Reijula, K. 2008. The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*, 121(3): 585-591. https://doi.org/10.1016/j.jaci.2007.10.045

29. Bevis, M., Businger, S., Chiswell, S., Herring, T.A., Anthes, R.A., Rocken, C. & Ware, R.H. 1994. GPS meteorology: mapping zenith wet delays onto precipitable water. *Journal of Applied Meteorology*, 33(3): 379-386. https://doi.org/10.1175/1520-0450(1994)033<0379:GMMZWD>2.0.CO;2

30. Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, R.A. & Ware, R.H. 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *Journal of Geophysical Research*, 97: 15787–15801. https://doi.org/10.1029/92JD01517

31. Beychok, M.R. 2005. *Fundamentals of Stack Gas Dispersion* (4th Edition). Author-published. ISBN: 0-9644588-0-2

32. Bibi, H., Alam, K., Chishtie, F., Bibi, S., Shahid, I. & Blaschke, T. 2015. Intercomparison of MODIS, MISR, OMI, and CALIPSO aerosol optical depth retrievals for four locations on the Indo-Gangetic plains and validation against AERONET data. *Atmospheric Environment*, 111: 113-126. https://doi.org/10.1016/j.atmosenv.2015.04.013

33. Boehm, J., Werl, B. & Schuh, H. 2006. Troposphere mapping functions for GPS and very long baseline interferometry from European centre for medium-range weather forecasts operational analysis data. *Journal of Geophysical.Research. B: Solid Earth*, 111(2): B02406. https://doi.org/10.1029/2005JB003629

34. Bonafoni, S. & Biondi, R. 2016. The usefulness of the Global Navigation Satellite Systems (GNSS) in the analysis of precipitation events. *Atmospheric Research*, 167: 15-23. https://doi.org/10.1016/j.atmosres.2015.07.011

35. Boutiouta, S. & Lahcene, A. 2013. Preliminary study of GNSS meteorology techniques in Algeria. *International Journal of Remote Sensing*, 34(14): 5105-5118. https://doi.org/10.1080/01431161.2013.786850

36. Brook, J.R., Dann, T.F. & Burnett, R.T. 1997. The relationship among TSP, PM10, PM2. 5, and inorganic constituents of atmospheric participate matter at multiple Canadian locations. *Journal of the Air and Waste Management Association*, 47(1): 2-19. https://doi.org/10.1080/10473289.1997.10464407

37. Brown, J., Roy, A., Harris, R., Filson, S., Johnson, M., Abubakar I. & Lipman, M. 2017. Respiratory symptoms in people living with HIV and the effect of antiretroviral therapy: a systematic review and meta-analysis. *Thorax*, 72: 355-366. http://doi.org/10.1136/thoraxjnl-2016-208657
38. Buchholz, R.R., Deeter, M.N., Worden, H.M., Gille, J., Edwards, D.P., Hannigan, J.W., Jones, N.B., Paton-Walsh, C., Griffith, D.W., Smale, D. & Robinson, J. 2017. Validation of MOPITT carbon monoxide using ground-based Fourier transform infrared spectrometer data from NDACC. *Atmospheric Measurement Techniques*, 10(5): 1927-1956. https://doi.org/10.5194/amt-10-1927-2017
39. Bucholtz, A. 1995. Rayleigh-scattering calculations for the terrestrial atmosphere. *Applied Optics*, 34(15): 2765-2773. https://doi.org/10.1364/AO.34.002765
40. Budde, M., El Masri, R., Riedel, T. & Beigl, M. 2013. Enabling low-cost particulate matter measurement for participatory sensing scenarios. In: *Proceedings of the 12th International Conference on Mobile and Uxi Quitous Multimedia*, ACM, p. 19. https://doi.org/10.1145/2541831.2541859
41. Cairncross, E.K., John, J. & Zunckel, M. 2007. A novel air pollution index based on the relative risk of daily mortality associated with short-term exposure to common air pollutants. *Atmospheric Environment*, 41: 8442–8454. https://doi.org/10.1016/j.atmosenv.2007.07.003
42. Chai, T. & Draxler, R.R. 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscience Model Development*, 7(3): 1247-1250. https://doi.org/10.5194/gmd-7-1247-2014
43. Chew, B.N., Campbell, J.R., Hyer, E.J., Salinas, S.V., Reid, J.S., Welton, E.J., Holben, B.N. & Liew, S.C. 2016. Relationship between aerosol optical depth and particulate matter over Singapore: effects of aerosol vertical distributions. *Aerosol and Air Quality Research*, 16: 2818-2830. https://doi.org/10.4209/aaqr.2015.07.0457
44. Contreras, L. & Ferri, C. 2016. Wind-sensitive interpolation of urban air pollution forecasts. *Procedia Computer Science*, 80: 313-323. https://doi.org/10.1016/j.procs.2016.05.343
45. Dash, I. 2016. *Space-time observations for city level air quality modelling and mapping*. MSc Thesis, University of Twente, The Netherlands, 80 pages.
46. Deary, M.E., Bainbridge, S.J., Kerr, A., McAllister, A. & Shrimpton, T. 2016. Practicalities of mapping PM10 and PM2.5 concentrations on city-wide scales using a portable particulate monitor. *Air Quality Atmosphere and Health*, 9(8): 923-930. https://doi.org/10.1007/s11869-016-0394-3
47. Deeter, M.N., Emmons, L.K., Francis, G.L., Edwards, D.P., Gille, J.C., Warner, J.X., Khattatov, B., Ziskin, D., Lamarque, J.-F., Ho, S.-P., Yudin, V., Attié, J.L., Packman, D., Chen, J., Mao, D. & Drummond, J.R. 2003. Operational carbon monoxide retrieval algorithm and selected results for the MOPITT instrument. *Journal of Geophysical Research*, 108: 4399. https://doi.org/10.1029/2002JD003186
48. DeMott, P.J., Sassen, K., Poellot, M.R., Baumgardner, D., Rogers, D.C., Brooks, S.D., Prenni, A.J. & Kreidenweis, S.M. 2003. African dust aerosols as atmospheric ice nuclei. *Geophysical Research Letters*, 30(14). https://doi.org/10.1029/2003GL017410

49. Diem, J.E. & Comrie, A.C. 2002. Predictive mapping of air pollution involving sparse spatial observations. *Environmental Pollution*, 119: 99-117. https://doi.org/10.1016/S0269-7491(01)00308-6
50. Dimari, G.A., Hati, S.S., Waziri, M. & Maitera, O.N. 2008. Pollution synergy from Particulate Matter Sources: the harmattan, fugitive dust and combustion emissions in Maiduguri metropolis, Nigeria. *European Journal of Scientific Research*, 23: 465–473. https://doi.org/10.13140/2.1.3407.6160
51. Duan, K., Sun, G., Zhang, Y., Yahya, K., Wang, K., Madden, J.M., Caldwell, P.V., Cohen, E.C. & McNulty, S.G. 2017. Impact of air pollution induced climate change on water availability and ecosystem productivity in the conterminous United States. *Climatic Change*, 140(2): 259-272. https://doi.org/10.1007/s10584-016-1850-7
52. Duncan, B.N., Prados, A.I., Lamsal, L.N., Liu, Y., Streets, D.G., Gupta, P., Hilsenrath, E., Kahn, R.A., Nielsen, E., Beyersdorf, A.J., Burton, S.P., Fiore, A.M., Fisherman, J., Henze, D.K., Hosteltler, C.A., Krotkov, N.A., Lee, P., Lin, M., Pawson, S., Pfister, S., Pickering, K.E., Bradley Pierce, R., Yoshida, Y. & Ziemba, L.D. 2014. Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. *Atmospheric Environment*, 94: 647-662. https://doi.org/10.1016/j.atmosenv.2014.05.061
53. Duvall, R., Norris, G., Burke, J., Olson, D., Vedantham, R. & Williams, R. 2012. Determining spatial variability in $PM_{2.5}$ source impacts across Detroit, MI. *Atmospheric Environment*, 47: 491-498. https://doi.org/10.1016/j.atmosenv.2011.09.071
54. Ediagbonya, T.F. & Tobin, A.E. 2013. Air pollution and respiratory morbidity in an urban area of Nigeria. *Greener Journal of Environmental Management and Public Safety*, 2(1): 10-15.
55. Efe, S.I. & Efe, A.T. 2008. Spatial distribution of particulate matter (PM10) in Warri metropolis, Nigeria. *The Environmentalist*, 28(4): 385-394. http://doi.org/10.1007/s10669-007-9154-0
56. Elliott, D.A., Pagano, T.S., Aumann, H.H. & Broberg, S.E. 2015. Performance status of the AIRS instrument thirteen years after launch. In *SPIE Optical Engineering+ Applications* (pp. 961109-961109). International Society for Optics and Photonics.
57. Engel, B., Storm, D., White, M., Arnold, J. & Arabi, M. 2007. A hydrologic/water quality model application protocol. *Journal of the American Water Resources Association*, 43(5): 1223-1236. https://doi.org/10.1111/j.1752-1688.2007.00105.x
58. Engel-Cox, J., Oanh, N.T.K., van Donkelaar, A., Martin, R.V. & Zell, E. 2013. Toward the next generation of air quality monitoring: particulate matter. *Atmospheric Environment*, 80: 584-590. https://doi.org/10.1016/j.atmosenv.2013.08.016
59. Engel-Cox, J.A., Holloman, C.H., Coutant, B.W. & Hoff, R.M. 2004. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmospheric Environment*, 38: 2495–2509. https://doi.org/10.1016/j.atmosenv.2004.01.039
60. EPA, 2000. *NSW State of the Environment 2000*, NSW Environment Protection Authority, Sydney.

61. ESRI (Environmental Systems Research Institute), 2007. GIS for Air Quality. Available from: https://www.esri.com/library/bestpractices/air-quality.pdf. Last access: November 2017.
62. Evans, J., van Donkelaar, A., Martin, R.V., Burnett, R., Rainham, D.G., Birkett, N.J. & Krewski, D. 2013. Estimates of global mortality attributable to particulate air pollution using satellite imagery. *Environmental Research*, 120: 33-42. https://doi.org/10.1016/j.envres.2012.08.005
63. Fadeyibi, I.O., Jewo, P.I., Opoola, P., Babalola, O.S., Ugburo, A. & Ademiluyi, S.A. 2011. Burns and fire disasters from leaking petroleum pipes in Lagos, Nigeria: an 8-year experience. *Burns*, 37: 145-152. https://doi.org/10.1016/j.burns.2010.06.012
64. Fattore, E., Paiano, V., Borgini, A., Tittarelli, A., Bertoldi, M., Crosignani, P. & Fanelli, R. 2011. Human health risk in relation to air quality in two municipalities in an industrialized area of Northern Italy. *Environmental Research*, 111(8): 1321-1327. https://doi.org/10.1016/j.envres.2011.06.012
65. FEPA (Federal Environmental Protection Agency), 1999. *Nationale Environmental (Effluent Limitation) Regulations*. http://www.placng.org/new/laws/F10.pdf. Last access: September 2016.
66. Ferris, B.G. 1978. Epidemiology standardization project (American Thoracic Society), *American Review of Respiratory Disease*, 118(6): 1-120.
67. Filip, L. & Stefan, S. 2011. Study of the correlation between the near-ground PM10 mass concentration and the aerosol optical depth. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(13): 1883-1889. https://doi.org/10.1016/j.jastp.2011.04.027
68. Fisher, J.A., Jacob, D.J., Purdy, M.T., Kopacz, M., Le Sager, P., Carouge, C., Holmes, C.D., Yantosca, R.M., Batchelor, R.L., Strong, K., Diskin, G.S., Fuelberg, H.E., Holloway, J.S., Hyer, E.J., McMillan, W.W., Warner, J., Streets, D.G., Zhang, Q., Wang, Y. & Wu, S. 2010. Source attribution and interannual variability of Arctic pollution in spring constrained by aircraft (ARCTAS, ARCPAC) and satellite (AIRS) observations of carbon monoxide. *Atmospheric Chemistry and Physics*, 10: 977-996. https://doi.org/10.5194/acp-10-977-2010
69. Francesco, N., Tubiello, R.D., Cóndor-Golec, M., Salvatore, A.P., Sandro, F., Alessandro, F., Simone, R., Alessandro, F., Paola, C., Riccardo, B., Heather, J., Paulina, P. & Paolo, P. 2014. *Estimating Greenhouse Gas Emissions in Agriculture. A Food and Agriculture Organization (FAO) of the United Nations manual to Address Data Requirements for Developing Countries* http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Glossary_Acronyms_BasicInfo/Glossary.pdf. Last access: March 2015.
70. Gerengi, H., Bereket, G. & Kurtay, M. 2016. A morphological and electrochemical comparison of the corrosion process of aluminum alloys under simulated acid rain conditions. *Journal of the Taiwan Institute of Chemical Engineers*, 58: 509-516. https://doi.org/10.1016/j.jtice.2015.05.023

71. Ghozikali, M.G., Mosaferi, M., Safari, G.H. & Jaafari, J. 2015. Effect of exposure to O3, NO2, and SO2 on chronic obstructive pulmonary disease hospitalizations in Tabriz, Iran. *Environment Science and Pollution Research*, 22(4): 2817-2823. https://doi.org/10.1007/s11356-014-3512-5
72. Goldberg, M.S., Wheeler, A.J., Burnett, R.T., Mayo, N.E., Valois, M.F., Brophy, J.M. & Giannetti, N. 2015. Physiological and perceived health effects from daily changes in air pollution and weather among persons with heart failure: A panel study. *Journal of Exposure Science and Environmental Epidemiology*, 25(2): 187-199. https://doi.org/10.1038/jes.2014.43
73. Gong, X., Zhan, F.B., Brender, J.D., Langlois, P.H. & Lin, Y. 2016. Validity of the emission weighted proximity model in estimating air pollution exposure intensities in large geographic areas. *Science of the Total Environment*, 563: 478-485. https://doi.org/10.1016/j.scitotenv.2016.04.088
74. Gorai, A.K., Tchounwou, P.B. & Mitra, G. 2017. Spatial variation of ground-level ozone concentrations and its health impacts in an urban area in India. *Aerosol and Air Quality Research*, 17(4): 951-964. https://doi.org/10.4209/aaqr.2016.08.0374
75. Gozzi, F., Della Ventura, G. & Marcelli, A. 2016. Mobile monitoring of particulate matter: state of art and perspectives. *Atmospheric Pollution. Research*, 7(2): 228-234. https://doi.org/10.1016/j.apr.2015.09.007
76. Grace, U.M., Sawa, B.A. & Jaiyeoba, I.A. 2015. Multi-temporal remote sensing of landuse dynamics in Zaria, Nigeria. *Journal of Environment and Earth Science*, 5(9): 121-138.
77. Gray, D.L., Wallace, L.A., Brinkman, M.C., Buehler, S.S. & La Londe, C. 2015. Respiratory and cardiovascular effects of metals in ambient particulate matter: a critical review. In *Reviews of Environmental Contamination and Toxicology* (pp. 135-203). Springer International Publishing. https://doi.org/10.1007%2F978-3-319-10638-0_3
78. Gui, K., Che, H., Chen, Q., Zeng, Z., Zheng, Y., Long, Q., Sun, T., Liu, X., Wang, Y., Liao, T. & Yu, J. 2017a. Water vapour variation and the effect of aerosols in China. *Atmospheric Environment*, 165: 322-335. https://doi.org/10.1016/j.atmosenv.2017.07.005
79. Gui, K., Che, H., Chen, Q., Zeng, Z., Liu, H., Wang, Y., Zheng, Y., Sun, T., Liao, T., Wang, H. & Zhang, X. 2017b. Evaluation of radiosonde, MODIS-NIR-Clear, and AERONET precipitable water vapor using IGS ground-based GPS measurements over China. *Atmospheric Research*, 197: 461-473. https://doi.org/10.1016/j.atmosres.2017.07.021
80. Guo, H., Wang, Y. & Zhang, H. 2017. Characterization of criteria air pollutants in Beijing during 2014–2015. *Environmental Research*, 154: 334-344. https://doi.org/10.1016/j.envres.2017.01.029
81. Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y.C. & Kumar, N. 2006. Satellite remote sensing of particulate matter and air quality over global cities. *Atmospheric Environment*, 40(30): 5880–5892. https://doi.org/10.1016/j.atmosenv.2006.03.016

82. Halonen, J.I., Lanki, T., Yli-Tuomi, T., Tiittanen, P., Kulmala, M. & Pekkanen, J. 2009. Particulate air pollution and acute cardiorespiratory hospital admissions and mortality among the elderly. *Epidemiology*, 20: 143-153. https://doi.org/10.1097/EDE.0b013e31818c7237
83. Hanna, R. & Oliva, P. 2016. Implications of climate change for children in developing countries. *The Future of Children*, 26(1): 115-132. https://doi.org/10.1353/foc.2016.0006
84. Hansen, J., Sato, M., Ruedy, R., Lacis, A. & Oinas, V. 2000. Global warming in the twenty-first century: An alternative scenario. *Proceedings of the National Academy of Sciences*, 97(18): 9875-9880. https://doi.org/10.1073/pnas.170278997
85. Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., Arn, T., Beutel, J. & Thiele, L. 2015. Deriving high-resolution urban air pollution maps using mobile sensor nodes. *Pervasive and Mobile Computing*, 16: 268-285. https://doi.org/10.1016/j.pmcj.2014.11.008
86. Heck, W.W., Taylor, O.C. & Tingey, D.T. 1988. *Assessment of crop loss from air pollutants*. London: Elsevier Applied Science.
87. Hersey, S.P., Garland, R.M., Crosbie, E., Shingler, T., Sorooshian, A., Piketh, S. & Burger, R. 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. *Atmospheric Chemistry and Physics*, 15(8): 4259-4278. https://doi.org/10.5194/acp-15-4259-2015
88. Hopkins, J.R., Evans, M.J., Lee, J.D., Lewis, A.C., Marsham, J.H., McQuaid, J.B., Parker, D.J., Stewart, D.J., Reeves, C.E. & Purvis, R.M. 2009. Direct estimates of emissions from the megacity of Lagos. *Atmospheric Chemistry and Physics*, 9: 8471-8477. https://doi.org/10.5194/acp-9-8471-2009
89. Ichoku, C., Ellison, L.T., Willmot, K.E., Matsui, T., Dezfuli, A.K., Gatebe, C.K., Wang, J., Wilcox, E.M., Lee, J., Adegoke, J. & Okonkwo, C. 2016. Biomass burning, land-cover change, and the hydrological cycle in Northern sub-Saharan Africa. *Environmental Research Letters*, 11(9): 095005. https://doi.org/10.1088/1748-9326/11/9/095005/meta
90. Isioye, O.A., Combrinck, L. & Botai, J.O. 2017. Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria. *International Journal of Remote Sensing*, 38(20): 5710-5735. https://doi.org/10.1080/01431161.2017.1346401
91. Ite, A.E., Ogunkunle, C.O., Obadimu, C.O., Asuaiko, E.R. & Ibok, U.J. 2017. Particulate matter and staff exposure in an air-conditioned office in Akwa Ibom State University–Nigeria. *Journal of Atmospheric Pollution*, 5(1): 24-32.
92. Jacob, D.J. & Winner, D.A. 2009. Effect of climate change on air quality. *Atmospheric Environment*, 43(1): 51-63. https://doi.org/10.1016/j.atmosenv.2008.09.051
93. Jain, K.K. 2017. Carbon monoxide and other tissue poisons. In *Textbook of hyperbaric medicine* (pp. 131-154). Springer International Publishing. https://doi.org/10.1007/978-3-319-47140-2_13

94. Jang, D.H., Kelly, M., Hardy, K., Lambert, D.S., Shofer, F.S. & Eckmann, D.M. 2017. A preliminary study in the alterations of mitochondrial respiration in patients with carbon monoxide poisoning measured in blood cells. *Clinical Toxicology*, 55(6): 579-584. https://doi.org/10.1080/15563650.2017.1288912
95. Jerome, A. (2000). *Use of economic instruments for environmental management in Nigeria*. Paper presented at workshop on Environmental Management in Nigeria and Administration (NCEMA), 2000.
96. Jimmy, E.O., Solomon, M.S., Peter, A.I. & Asuquo, C. 2014. Environmental health implications of motorcycles emitted gases in a metropolitan Nigeria. *American Journal of Environmental Protection*, 2(1): 7-10. https://doi.org/10.12691/env-2-1-2
97. Jolliffe, I.T. & Stephenson, D.B., (Eds.) 2012. *Forecast verification: A practitioner's guide in atmospheric science*. John Wiley and Sons, Chichester, pp. 240
98. Kampa, M. & Castanas, E. 2008. Human health effects of air pollution. *Environmental Pollution*, 151(2): 362-367. https://doi.org/10.1016/j.envpol.2007.06.012
99. Kanaroglou, P., Jerrett, M., Morrison, J., Beckerman, B., Arain, M.A., Gilbert, N.L. & Brook, J.R. 2005. Establishing an air pollution monitoring network for intraurban population exposure assessment: a location-allocation approach. *Atmospheric Environment*, 39: 2399-2409. https://doi.org/10.1016/j.atmosenv.2004.06.049
100. Kgabi, N. A. 2014. *Air quality policy and scientific research in Southern Africa*. In: Longhurst, J.W.S. & Brebbia, C.A. ed. Air Pollution XX. WIT Press, Southampton, UK, pp. 151-163.
101. Khaniabadi, Y.O., Hopke, P.K., Goudarzi, G., Daryanoosh, S.M., Jourvand, M. & Basiri, H. 2017. Cardiopulmonary mortality and COPD attributed to ambient ozone. *Environmental Research*, 31(152): 336-341. https://doi.org/10.1016/j.envres.2016.10.008
102. Knippertz, P., Evans, M.J., Field, P.R., Fink, A.H., Liousse, C. & Marsham, J.H. 2015. The possible role of local air pollution in climate change in West Africa. *Nature Climate Change*, 5(9): 815-822. https://doi.org/10.1038/nclimate2727
103. Koku, C.A. & Osuntogun, B.A. 2007. Environmental-impacts of road transportation in southwestern states of Nigeria. *Journal of Applied Sciences*, 7(16): 2536-2560.
104. Kong, L., Xin, J., Zhang, W. & Wang, Y. 2016. The empirical correlations between PM 2.5, PM 10 and AOD in the Beijing metropolitan region and the PM 2.5, PM 10 distributions retrieved by MODIS. *Environmental Pollution*, 216: 350-360. https://doi.org/10.1016/j.envpol.2016.05.085
105. Kouba, J. 2009. *A Guide to Using International GNSS Service (IGS) Products.* Available from: http://acc.igs.org/UsingIGSProductsVer21.pdf. Last access: August 2017.
106. Krejcie, R.V. & Morgan, D.W. 1970. Determining sample size for research activities. *Educational and Psychological Measurement*, 30: 607–610. https://doi.org/10.1177/001316447003000308
107. Krupnick, A.J. 2008. Challenges to managing air pollution. *Journal of Toxicology and Environmental Health*, A71: 13-23. https://doi.org/10.1080/15287390701557404

108. Kumar, K.R., Yin, Y., Sivakumar, V., Kang, N., Yu, X., Diao, Y., Adesina, A.J. & Reddy, R.R. 2015. Aerosol climatology and discrimination of aerosol types retrieved from MODIS, MISR and OMI over Durban (29.88 S, 31.02 E), South Africa. *Atmospheric Environment*, 117: 9-18. https://doi.org/10.1016/j.atmosenv.2015.06.058
109. Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L. & Britter, R. 2015. The rise of low-cost sensing for managing air pollution in cities. *Environment International*, 75: 199-205. https://doi.org/10.1016/j.envint.2014.11.019
110. Künzli, N., Perez, L. & Rapp, R. 2010. *Air quality and health.* Lausanne: European Respiratory Society. ISBN: 978-1-84984-008-8
111. Lau, L. & He, J. 2017. Investigation into the effect of atmospheric particulate matter (PM2. 5 and PM10) concentrations on GPS signals. *Sensors*, 17(3): 508. https://doi.org/10.3390/s17030508
112. Le Boennec, R. & Salladarré, F. 2017. The impact of air pollution and noise on the real estate market. The case of the 2013 European Green Capital: Nantes, France. *Ecological Economics*, 138: 82-89. https://doi.org/10.1016/j.ecolecon.2017.03.030
113. Leiva, V., Vilca, F., Balakrishnan, N. & Sanhueza, A. 2010. A skewed sinh-normal distribution and its properties and application to air pollution. *Communications in Statistics—Theory and Methods*, 39(3): 426-443. https://doi.org/10.1080/03610920903140171
114. Levelt, P., Veefkind, J.P., Bhartia, P.K., Joiner, J. & Tamminen, J. 2014. Ten Years of OMI Observations: A Unique Contribution to Air Quality, Ozone Layer and Climate Research from Space. In *AGU Fall Meeting Abstracts*.
115. Li, J. & Biswas, P. 2017. Optical characterization studies of a low-cost particle sensor. *Aerosol and Air Quality Research*, 17(7): 1691-1704. https://doi.org/10.4209/aaqr.2017.02.0085
116. Li, S., Ma, Z., Xiong, X., Christiani, D.C., Wang, Z. & Liu, Y. 2016. Satellite and ground observations of severe air pollution episodes in the winter of 2013 in Beijing, China. *Aerosol and Air Quality Research*, 16(4): 977-989. https://doi.org/10.4209/aaqr.2015.01.0057
117. Lin, C., Gillespie, J., Schuder, M.D., Duberstein, W., Beverland, I.J. & Heal, M.R. 2015. Evaluation and calibration of Aeroqual series 500 portable gas sensors for accurate measurement of ambient ozone and nitrogen dioxide. *Atmospheric Environment*, 100: 111-116. https://doi.org/10.1016/j.atmosenv.2014.11.002
118. Lindley, S.J., Gill, S.E., Cavan, G., Yeshitela, K., Nebebe, A., Woldegerima, T., Kibassa, D., Shemdoe, R., Renner, F., Buchta, K. & Abo-El-Wafa, H. 2015. Green infrastructure for climate adaptation in African cities. In *Urban Vulnerability and Climate Change in Africa* (pp. 107-152). Springer International Publishing. https://doi.org/10.1007%2F978-3-319-03982-4_4
119. Liou, K.N. 2002. *An introduction to atmospheric radiation*. 2nd ed. Academic Press, New York, pp. 350–353.

120. Liu, J., Man, Y. & Liu, Y. 2014. Temporal variability of PM_{10} and $PM_{2.5}$ inside and outside a residential home during 2014 Chinese spring festival in Zhengzhou, China. *Natural Hazards*, 73(3): 2149-2154. https://doi.org/10.1007/s11069-014-1157-9
121. Liu, Y., Franklin, M., Kahn, R. & Koutrakis, P. 2007. Using aerosol optical thickness to predict ground-level PM 2.5 concentrations in the St. Louis area: a comparison between MISR and MODIS. *Remote Sensing of the Environment*, 107(1): 33-44. https://doi.org/10.1016/j.rse.2006.05.022
122. Llanes, S. 2016. How to calculate time-weighted average (TWA). 26th Annual California Industrial Hygiene Council (CIHC) Conference, San Diego, http://www.thecohengroup.com/article/calculate-time-weighted-average-twa/. Last access: October 2017.
123. Luo, M., Shephard, M.W., Cady-Pereira, K.E., Henze, D.K., Zhu, L., Bash, J.O., Pinder, R.W., Capps, S.L., Walker, J.T. & Jones, M.R. 2015. Satellite observations of tropospheric ammonia and carbon monoxide: Global distributions, regional correlations and comparisons to model simulations. *Atmospheric Environment*, 106: 262-277. https://doi.org/10.1016/j.atmosenv.2015.02.007
124. Madrigano, J., Kloog, I., Goldberg, R., Coull, B.A., Mittleman, M.A. & Schwartz, J. 2013. Long-term exposure to PM2.5 and incidence of acute myocardial infarction. *Environmental Health Perspective*, 121(2): 192–196. https://doi.org/10.1289/ehp.1205284
125. Maheswaran, R. 2016. Air pollution and stroke - an overview of the evidence base. *Spatial and Spatio-temporal Epidemiology*, 18: 74-81. https://doi.org/10.1016/j.sste.2016.04.004
126. Maione, M., Fowler, D., Monks, P.S., Reis, S., Rudich, Y., Williams, M.L. & Fuzzi, S. 2016. Air quality and climate change: Designing new win-win policies for Europe. *Environmental Science and Policy*, 65: 48-57. https://doi.org/10.1016/j.envsci.2016.03.011
127. Marais, E.A. & Chance, K. 2015. A geostationary air quality monitoring platform for Africa. *Clean Air Journal*, 25(1): 40-45. http://dx.doi.org/10.17159/2410-972X/2015/v25n1a3
128. Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T.P., Chance, K. & Sauvage, B. 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space. *Atmospheric Environment*, 99: 32-40. https://doi.org/10.1016/j.atmosenv.2014.09.055
129. Marey, H.S., Hashisho, Z., Fu, L. & Gille, J. 2015. Spatial and temporal variation in CO over Alberta using measurements from satellites, aircraft, and ground stations. *Atmospheric Chemistry and Physics*, 15(7): 3893-3908. https://doi.org/10.5194/acp-15-3893-2015
130. Martin, R.V. 2008. Satellite remote sensing of surface air quality. *Atmospheric Environment* 42: 7823-7843. https://doi.org/10.1016/j.atmosenv.2008.07.018
131. McCuen, R.H., Knight, Z. & Cutter, A.G. 2006. Evaluation of the Nash–Sutcliffe efficiency index. *Journal of Hydrologic Engineering*, 11(6): 597-602.

132. McMillan, W.W., Barnet, C., Strow, L., Chahine, M.T., McCourt, M.L., Warner, J.X., Novelli, P.C., Korontzi, S., Maddy, E.S. & Datta, S. 2005. Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder. *Geophysical Research Letters*, 32: L11801. https://doi.org/10.1029/2004GL021821
133. Mead, M.I., Popoola, O.A.M., Stewart, G.B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J.J., McLeod, M.W., Hodgson, T.F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J.R. & Jones, R.L. 2013. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, 70: 186-203. http://doi.org/10.1016/j.atmosenv.2012.11.060
134. Mehta, S., Shin, H., Burnett, R., North, T. & Cohen, A.J. 2013. Ambient particulate air pollution and acute lower respiratory infections: a systematic review and implications for estimating the global burden of disease. *Air Quality Atmosphere and Health*, 6(1): 69-83. https://doi.org/10.1007/s11869-011-0146-3
135. Middey, A. & Chaudhuri, S. 2013. The reciprocal relation between lightning and pollution and their impact over Kolkata, India. *Environmental Science and Pollution Research*, 20: 3133–3139. https://doi.org/10.1007/s11356-012-1219-z
136. Miranda, A.I., Ferreira, J., Silveira, C., Relvas, H., Duque, L., Roebeling, P., Lopes, M., Costa, S., Monteiro, A., Gama, C. & Sá, E. 2016. A cost-efficiency and health benefit approach to improve urban air quality. *Science of the Total Environment*, 569: 342-351. https://doi.org/10.1016/j.scitotenv.2016.06.102
137. Miri, M., Derakhshan, Z., Allahabadi, A., Ahmadi, E., Conti, G.O., Ferrante, M. & Aval, H.E. 2016. Mortality and morbidity due to exposure to outdoor air pollution in Mashhad metropolis, Iran. The AirQ model approach. *Environmental Research*, 151: 451-457. https://doi.org/10.1016/j.envres.2016.07.039
138. Mishra, R.K., Joshi, T., Goel, N., Gupta, H. & Kumar, A. 2015. Monitoring and analysis of PM10 concentration at Delhi Metro construction sites. *International Journal of Environment and Pollution*, 57(1-2): 27-37. https://doi.org/10.1504/IJEP.2015.072111
139. Misra, A., Jayaraman, A. & Ganguly, D. 2015. Validation of version 5.1 MODIS aerosol optical depth (deep blue algorithm and dark target approach) over a semi-arid location in Western India. *Aerosol and Air Quality Research*, 15(1): 252-262. https://doi.org/10.4209/aaqr.2014.01.0004
140. Moen, E. 2008. *Vehicle emissions and health impacts in Abuja, Nigeria*, [B.Sc. Dissertation] Rhodes Island, Browns University, Rhodes Island. Available from: http://envstudies.brown.edu/theses/archive20072008/ericamoenthesis.pdf. Last access: January 2012.
141. Mohammed, Y., Uzairu, A. & Ujoh, J.O. 2013. Determination of sulphur dioxide concentrations in ambient air of some selected traffic areas in Kaduna metropolis. *Research Journal of Applied Science Engineering Technology*, 6(16): 2923-2930.
142. Moltchanov, S., Levy, I., Etzion, Y., Lerner, U., Broday, D.M. & Fishbain, B. 2015. On the feasibility of measuring urban air pollution by wireless distributed sensor networks. *Science of the Total Environment*, 502: 537–547. https://doi.org/10.1016/j.scitotenv.2014.09.059

143. Moral, F.J., Ivarez, P.A. & Canito, J.L. 2006. Mapping and hazard assessment of atmospheric pollution in a medium sized urban area using the Rasch model and geostatistics techniques, *Atmospheric Environment,* 40: 1408–1418. https://doi.org/10.1016/j.atmosenv.2005.10.054
144. Murphy, A.H. 1988. Skill scores based on the mean square error and their relationships to the correlation coefficient. *Monthly Weather Reviews*, 116(12): 2417-2424. https://doi.org/10.1175/1520-0493(1988)116<2417:SSBOTM>2.0.CO;2
145. Musa, T.A., Amir, S., Othman, R., Ses, S., Omar, K., Abdullah, K., Samsung, L. & Rizos, C. 2011. GPS meteorology in a low latitude region: remote sensing of atmospheric water vapour over Malaysian peninsula. *Journal of Atmospheric and Solar-Terrestrial Physics,* 73: 2410-2422. https://doi.org/10.1016/j.jastp.2011.08.014
146. Nagpure, A.S., Gurjar, B.R. & Martel, Jc. 2014. Human health risks in national capital territory of Delhi due to air Pollution. *Atmospheric Pollution Research*, 5: 371-380. https://doi.org/10.5094/APR.2014.043
147. NASA (National Aeronautics and Space Administration), 2017. https://www.nasa.gov/open/researchaccess/nasa-data-portal. Last access: March 2017.
148. Nazaroff, W.W. & Weschler, C.J. 2004. Cleaning products and air fresheners: exposure to primary and secondary air pollutants. *Atmospheric Environment*, 38(18): 2841-2865. https://doi.org/10.1016/j.atmosenv.2004.02.040
149. Ndoke, P.N., Akpan, U.G. & Kato, M.E. 2006. Contribution of vehicular traffic to carbon dioxide emission in Kaduna and Abuja, northern Nigeria. *Leonardo Electronic Journal of Practices and Technologies*, 5: 81–90.
150. Neophytou, M., Gowardan, A. & Brown, M.J. 2011. An inter-comparison of three urban wind models using Oklahoma City Joint Urban 2003 wind field measurements. *Journal of Wind Energy and Industrial Aerodynamics*, 99: 357–368. https://doi.org/10.1016/j.jweia.2011.01.010
151. NESREA (National *Environmental* Standards and Regulations Enforcement Agency), 2013. *Air quality control monitoring in the FCT*. Available from: http://www.nesrea.gov.ng/news/air-quality.php. Last access: November 2015.
152. Ningombam, S.S., Jade, S., Shrungeshwara, T.S. & Song, H.J. 2016. Validation of water vapour retrieval from moderate resolution imaging spectro-radiometer (MODIS) in near infrared channels using GPS data over IAO-Hanle, in the Trans-Himalayan Region. *Journal of Atmospheric and Solar-Terrestrial Physics,* 137: 76-85. https://doi.org/10.1016/j.jastp.2015.11.019
153. Njoku, K.L., Rumide, T.J., Akinola, M.O., Adesuyi, A.A. & Jolaoso, A.O. 2016. Ambient air quality monitoring in metropolitan city of Lagos, Nigeria. *Journal of Applied Sciences and Environmental Management*, 20(1): 178-185. http://doi.org/10.4314/jasem.v20i1.21
154. Nordio, F., Kloog, I., Coull, B.A., Chudnovsky, A., Grillo, P., Bertazzi, P.A., Baccarelli, A.A. & Schwartz, J. 2013. Estimating spatio-temporal resolved PM10 aerosol mass concentrations using MODIS satellite data and land use regression over Lombardy, Italy. *Journal of Atmospheric and Solar-Terrestrial Physics,* 74: 227-236. https://doi.org/10.1016/j.atmosenv.2013.03.043

155. NPC (National Population Commission), 2010. *Population distribution by sex, state, LGA, senatorial district, 2006 population and housing census*. http://www.population.gov.ng/images/NPCNEW/Pr%20Vol%203%20Pop%20by%20State%20&%20Senatorial%20District.zip. Last access: December 2016.
156. Nriagu, J.O. & Pacyna, J.M. 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. *Nature*, 333(6169): 134-139. https://doi.org/10.1038/333134a0
157. Nsubuga, F.N.W., Olwoch, J.M. & Rautenbach, H. 2013. Variability procedures for daily and monthly observed near-surface temperatures in Uganda. *International Journal of Climatology*, 34(2): 303-314. https://doi.org/10.1002/joc.3686
158. Nwaichi, E.O. & Uzazabona, M.A. 2011. Estimation of the CO_2 level due to gas flaring in the Niger Delta. *Research Journal of Environmental Sciences*, 5: 565–572. https://doi.org/10.3923/rjes.2011.565.572
159. Obaseki, D.O., Adeniyi, B., Jumbo, J., Oyewo, A., Irabor, I. & Erhabor, G.E. 2014. Respiratory symptom, lung function and exhaled carbon monoxide among a sample of traffic workers in Lagos, Nigeria: A pilot survey. *Nigerian Medical Journal: Journal of the Nigeria Medical Association*, 55(4): 306-309. https://doi.org/10.4103/0300-1652.137190
160. Ocak, T., Tekin, E., Basturk, M., Duran, A., Serinken, M. & Emet, M. 2016. Treatment in carbon monoxide poisoning patients with headache: a prospective, multicenter, double-blind, controlled clinical trial. *The American Journal of Emergency Medicine*, 34(11): 2140-2145. https://doi.org/10.1016/j.ajem.2016.08.002
161. Ogundipe, S. 2018. *Air pollution: Nigeria ranks 4th deadliest globally*. Available from: https://www.vanguardngr.com/2018/09/air-pollution-nigeria-ranks-4th-deadliest-globally/ Last access: February 2019.
162. Okunola, O.J., Uzairu, A., Gimba, C.E. & Ndukwe, G.I. 2012**.** Assessment of gaseous pollutants along high traffic roads in Kano, Nigeria. *International. Journal of Environmental Sustainability*, 1(1): 1-15.
163. Olowoporoku, D. 2011. *How clean is the air Nigerians breathe?* A case for national air quality management framework. Nigeria World Feature Article 201. Available from: http://nigeriaworld.com/articles/2011/feb/012.html. Last access: October 2017.
164. Oltra, V. & Saint Jean, M. 2009. Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis. *Journal of Cleaner Production*, 17: 201-213. https://doi.org/10.1016/j.jclepro.2008.04.023
165. Olumayede, E.G. & Okuo, J.M. 2013. Ambient air pollution and assessment of ozone creation potential for reactive volatile organic compounds in urban atmosphere of southwestern, Nigeria. *African Journal of Environmental Science and Technology*, 7(8) 815-823. https://doi.org/10.5897/AJEST11.167
166. Oluwande, P.A. 1977. Automobile traffic and air pollution in a developing country: an example of affluence-caused environmental problems. *International Journal of Environmental Studies*, 11(3): 197-203. https://doi.org/10.1080/00207237708737353

167. Oluwole, O., Arinola, G.O., Huo, D. & Olopade, C.O. 2017. Household biomass fuel use, asthma symptoms severity, and asthma under diagnosis in rural schoolchildren in Nigeria: a cross-sectional observational study. *BMC Pulmonary Medicine*, 17(1): 3. http://doi.org/10.1186/s12890-016-0352-8
168. Orogade, S.A., Owoade, K.O., Hopke, P.K., Adie, D.B., Ismail A. & Okuofu, C.A. 2016. Source apportionment for fine and coarse particulate matter in industrial areas of Kaduna, northern Nigeria. *Aerosol and Air Quality Research*, 16: 1179-1190. https://doi.org/10.4209/aaqr.2015.11.0636
169. Ortiz de Galisteo, J.P., Bennouna, Y., Toledano, C., Cachorro, V., Romero, P., Andrés, M.I. & Torres, B. 2014. Analysis of the annual cycle of the precipitable water vapour over Spain from 10-year homogenized series of GPS data. *Quarterly Journal of the Royal Meteorological Society*, 140: 397–406. https://doi.org/10.1002/qj.2146
170. Osuji, L.C. & Avwiri, G.O. 2005. Flared gases and other pollutants associated with air quality in industrial areas of Nigeria: an overview. *Chemistry and Biodiversity*, 2: 1277-1289. https://doi.org/10.1002/cbdv.200590099
171. Owoade, O.K., Fawole, O.G., Olise, F.S., Ogundele, L.T., Olaniyi, H.B., Almeida, M.S., Ho M.D. & Hopke, P.K. 2013. Characterization and source identification of airborne particulate loadings at receptor site-classes of Lagos Mega-City, Nigeria. *Journal of Air and Waste Management Association*, 63: 1026–1035. https://doi.org/10.1080/10962247.2013.793627
172. Palliyaguru, N.P.L. & Jayaweera, P.M. 2017. Investigation of photochemical smog formation after removal of water soluble organic and inorganic fractions in the diesel exhaust fume. In *Proceedings of International Forestry and Environment Symposium* (Vol. 21).
173. Pattinson, W., Longley, I. & Kingham, S. 2014. Using mobile monitoring to visualise diurnal variation of traffic pollutants across two near-highway neighbourhoods. *Atmospheric Environment*, 94: 782-792. https://doi.org/10.1016/j.atmosenv.2014.06.007
174. Patton, A.P., Laumbach, R., Ohman-Strickland, P., Black, K., Alimokhtari, S., Lioy, P.J. & Kipen, H.M. 2016. Scripted drives: A robust protocol for generating exposures to traffic-related air pollution. *Atmospheric Environment*, 143: 290-299. https://doi.org/10.1016/j.atmosenv.2016.08.038
175. Patton, A.P., Perkins, J., Zamore, W., Levy, J.I., Brugge, D. & Durant, J.L. 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighbourhoods near an interstate highway. *Atmospheric Environment*, 99: 309-321. https://doi.org/10.1016/j.atmosenv.2014.09.072
176. Peters, A., von Klot, S., Mittleman, M.A., Meisinger, C., Hormann, A., Kuch, B. & Wichmann, H.E. 2013. Triggering of acute myocardial infarction by different means of transportation. *European Journal of Preventive Cardiology*, 20: 750-758. https://doi.org/10.1177/2047487312446672
177. Plaia, A. & Ruggieri, M. 2010. Air quality indices: a review. *Reviews in Environmental Science and Bio-Technology*, 10: 165-179. https://doi.org/10.1007/s11157-010-9227-2

178. Powell, H.L. 2012. *Estimating air pollution and its relationship with human health* (Doctoral dissertation, University of Glasgow).
179. Procházka, B. & Kynxcl, J. 2015. Estimating the baseline and threshold for the incidence of diseases with seasonal and long-term trends. *Central European Journal of Public Health*, 23(4): 352-359. https://doi.org/10.21101/cejph.a4392
180. Rai, R., Rajput, M., Agrawal, M. & Agrawal, S.B. 2011. Gaseous air pollutants: a review on current and future trends of emissions and impact on agriculture. *Journal of Scientific Research*, *55*(771): 1.
181. Ramanathan, V. & Feng, Y. 2009. Air pollution, greenhouse gases and climate change: Global and regional perspectives. *Atmospheric Environment*, *43*(1): 37-50. https://doi.org/10.1016/j.atmosenv.2008.09.063
182. Ren, M., Li, N., Wang, Z., Liu, Y., Chen, X., Chu, Y., Li, X., Zhu, Z., Tian, L. & Xiang, H. 2017. The short-term effects of air pollutants on respiratory disease mortality in Wuhan, China: comparison of time-series and case-crossover analyses. *Scientific Reports*, 7: 40482. https://doi.org/10.1038/srep40482
183. Rinsland, C.P., Luo, M., Logan, J.A., Beer, R., Worden, H., Kulawik, S.S., Rider, D., Osterman, G., Gunson, M., Eldering, A., Goldman, A., Shephard, M., Clough, S.A., Rodgers, C., Lampel, M. & Chiou, L. 2006. Nadir measurements of carbon monoxide distributions by the Tropospheric Emission Spectrometer instrument onboard the Aura Spacecraft: overview of analysis approach and examples of initial results. *Geophysical Research Letters*, 33: L22806. https://doi.org/10.1029/2006GL027000
184. Robinson, T.P. & Metternicht, G. 2006. Testing the performance of spatial interpolation techniques for mapping soil properties. *Computer and Electronics in Agriculture*, 50: 97-108. https://doi.org/10.1016/j.compag.2005.07.003
185. Rohm, W., Yuan, Y., Biadeglgne, B., Zhang, K. & Le Marshall, J. 2014. Ground-based GNSS ZTD/IWV estimation system for numerical weather prediction in challenging weather conditions. *Atmospheric Research*, 138: 414-426. https://doi.org/10.1016/j.atmosres.2013.11.026
186. Roy, R., 2016. The cost of air pollution in Africa. https://doi.org/10.1787/5jlqzq77x6f8-en
187. Saastamoinen, J. 1972. Atmospheric correction for troposphere and stratosphere in radio ranging of satellites', In the use of artificial satellites for geodesy, Henriksen, S.W., Mancini, A. & Chovitz, B.H. (Eds.), vol. 15 of Geophysics Monograph Series, pp. 247–252, American Geophysical Union (AGU), AIAA, NOAA, U.S. ATC, Washington, D.C.
188. Samek, L., Furman, L., Mikrut, M., Regiel-Futyra, A., Macyk, W., Stochel, G. & van Eldik, R. 2017. Chemical composition of submicron and fine particulate matter collected in Krakow, Poland. Consequences for the APARIC project. *Chemosphere*, 187: 430-439. https://doi.org/10.1016/j.chemosphere.2017.08.090

189. SANS (South African National Standards), 2011. *Ambient air quality — limits for common pollutants*, https://archive.org/download/za.sans.1929.2011/za.sans.1929.2011.pdf. Last access: February 2019.
190. Sarnat, J.A., Golan, R., Greenwald, R., Raysoni, A.U., Kewada, P., Winquist, A., Sarnat, S.E., Flanders, W.D., Mirabelli, M.C., Zora, J.E. & Bergin, M.H. 2014. Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. *Environmental Research*, 133: 66-76. https://doi.org/10.1016/j.envres.2014.05.004
191. Saxena, N. and Bhargava, R. 2017. A review on air pollution, polluting agents and its possible effects in 21st century. *Advances in Bioresearch*, 8(2): 42-50.
192. Schaap, M., Apituley, A., Timmermans, R.M.A., Koelemeijer, R.B.A. & de Leeuw, G. 2009. Exploring the relation between aerosol optical depth and PM2.5 at Cabauw, the Netherlands. *Atmospheric Chemistry and Physics*, 9: 909–925. https://doi.org/10.5194/acp-9-909-2009
193. Schäfer, K., Harbusch, A., Emeis, S., Koepke, P. & Wiegner, M. 2008. Correlation of aerosol mass near the ground with aerosol optical depth during two seasons in Munich. *Atmospheric Environment*, 42(18): 4036-4046. https://doi.org/10.1016/j.atmosenv.2008.01.060
194. Schröder, L., Richter, A., Fedorov, D.V., Eberlein, L., Brovkov, E.V., Popov, S.V., Knöfel, C., Horwath, M., Dietrich, R., Matveev, A.Y. & Scheinert, M. 2017. Validation of satellite altimetry by kinematic GNSS in central east Antarctica. *The Cryosphere*, 11(3): 1111-1130. https://doi.org/10.5194/tc-11-1111-2017
195. Schultz, E.S., Hallberg, J., Bellander, T., Bergström, A., Bottai, M., Chiesa, F., Gustafsson, P.M., Gruzieva, O., Thunqvist, P., Pershagen, G. & Melén, E. 2016. Early-life exposure to traffic-related air pollution and lung function in adolescence. *American Journal of Respiratory and Critical Care Medicine*, 193(2): 171-177. https://doi.org/10.1164/rccm.201505-0928OC
196. Schwela, D. (2010). *Global atmospheric pollution forum air pollution monitoring manual*, [online] Stockholm Environment Institute (SEI). Available from: http://www.sei-international.org/rapidc/gapforum/html/technical/monitoring/GAP_Forum_Monitoring_Manual_2010.pdf. Last access: November 2015.
197. Seinfeld, J.H. & Pandis, S.N. 2016. *Atmospheric chemistry and physics: from air pollution to climate change*. John Wiley and Sons. ISBN 0-471-17815-2
198. Shad, R., Mesgari, M.S. & Shad, A. 2009. Predicting air pollution using fuzzy genetic linear membership kriging in GIS. *Computer Environment and Urban Systems*, 33(6): 472-481. https://doi.org/10.1016/j.compenvurbsys.2009.10.004
199. Shi, Y., Zhang, J., Reid, J.S., Hyer, E.J. & Hsu, N.C. 2013. Critical evaluation of the MODIS deep blue aerosol optical depth product for data assimilation over North Africa. *Atmospheric Measuring Techniques*, 6(4): 949-969. https://doi.org/10.5194/amt-6-949-2013

200. Shibata, T., Wilson, J.L., Watson, L.M., Nikitin, I.V., La Ane, R. & Maidin, A. 2015. Life in a landfill slum, children's health, and the millennium development goals. *Science of the Total Environment*, 536: 408-418. https://doi.org/10.1016/j.scitotenv.2015.05.137
201. Shumway, R.H. & Stoffer, D.S. 2000. *Time series analysis and its applications*. Springer Verlag.
202. Simos, J., Naissem, F.B., Naissem, J., Sokona, F.M., de Dieu Konongo, J., Sani, A., Corburn, J., Karanja, I., Makau, J., Aikins, A.D.G. & Haroun, A. 2017. Healthy cities in Africa: a continent of difference. In *Healthy Cities* (pp. 89-132). Springer New York. https://doi.org/10.1007%2F978-1-4939-6694-3_6
203. Snyder, E.G., Watkins, T., Solomon, P., Thoma, E., Williams, R., Hagler, G., Shelow, D., Hindin, D., Kilaru, V. & Preuss, P. 2013. The changing paradigm of air pollution monitoring. *Environmental Science and Technology*, 47: 11369–11377. https://doi.org/10.1021/es4022602
204. Sobrino, J.A., Jiménez-Muñoz, J.C. & Paolini, L. 2004. Land surface temperature retrieval from LANDSAT TM 5. *Remote Sensing of the Environment*, 90(4): 434-440. https://doi.org/10.1016/j.rse.2004.02.003
205. Solomon, S., Rosenlof, K.H., Portmann, R.W., Daniel, J.S., Davis, S.M., Sanford, T.J. & Plattner, G.K. 2010. Contributions of stratospheric water vapour to decadal changes in the rate of global warming. *Science*, 327: 1219–1223. https://doi.org/10.1126/science.1182488
206. Statheropoulos, M., Vassiliadis, N. & Pappa, A. 1998. Principal component and canonical correlation analysis for examining air pollution and meteorological data. *Atmospheric Environment*, 32(6): 1087-1095. https://doi.org/10.1016/S1352-2310(97)00377-4
207. Steinle, S., Reis, S. & Sabel, C.E. 2013. Quantifying human exposure to air pollution—moving from static monitoring to spatio-temporally resolved personal exposure assessment. *Science of the Total Environment*, 443: 184-193. https://doi.org/10.1016/j.scitotenv.2012.10.098
208. Streets, D.G., Canty, T., Carmichael, G.R., de Foy, B., Dickerson, R.R., Duncan, B.N., Edwards, D.P., Haynes, J.A., Henze, D.K., Houyoux, M.R. & Jacob, D.J. 2013. Emissions estimation from satellite retrievals: A review of current capability. *Atmospheric Environment*, 77: 1011-1042. https://doi.org/10.1016/j.atmosenv.2013.05.051
209. Sukitpaneenit, M. & Oanh, N.T. 2014. Satellite monitoring for carbon monoxide and particulate matter during forest fire episodes in Northern Thailand. *Environmental Monitoring and Assessment*, 186(4): 2495-2504. https://doi.org/10.1007/s10661-013-3556-x
210. Svendsen, E.R., Gonzales, M., Mukerjee, S., Smith, L., Ross, M., Walsh, D., Rhoney, S., Andrews, G., Ozkaynak, H. & Neas, L.M. 2012. GIS-modeled indicators of traffic-related air pollutants and adverse pulmonary health among children in El Paso, Texas. *American Journal of Epidemiology*, 176(suppl. 7): S131-141. https://doi.org/10.1093/aje/kws274

211. Syafei, A.D., Fujiwara, A. & Zhang, J. 2013. A comparative study on NO concentration interpolation in Surabaya city. *Proceedings of the Eastern Asia Society for Transportation Studies,* 9: 1-13.
212. Tecer, L.H., Alagha, O., Karaca, F., Tuncel, G. & Eldes, N. 2008. Particulate matter (PM2. 5, PM10-2.5, and PM10) and children's hospital admissions for asthma and respiratory diseases: A bidirectional case-crossover study. *Journal of Toxicology and Environmental Health, Part A*, 71(8): 512-520. https://doi.org/10.1080/15287390801907459
213. The Economist, 2017. *Nigeria: Africa's new number one*, 2014. Available from: http://www.economist.com/news/leaders/21600685-nigerias-suddenly-supersized-economy-indeed-wonder-so-are-its-still-huge. Last access: February 2017.
214. Thiering, E. & Heinrich, J. 2015. Epidemiology of air pollution and diabetes. *Trends in Endocrinology and Metabolism,* 26(7): 384-394. https://doi.org/10.1016/j.tem.2015.05.002
215. Thompson, J.E. 2016. Crowd-sourced air quality studies: A review of the literature & portable sensors. *Trends in Environmental Analytical Chemistry*, 11: 23-34. https://doi.org/10.1016/j.teac.2016.06.001
216. Tian, B., Manning, E., Fetzer, E., Olsen, E., Wong, S., Susskind, J. & Iredel, L. 2014. *AIRS/AMSU/HSB version 6 level 3 product user guide*. Available from: http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v6_docs/v6releasedocs1/V6_L3_User_Guide.pdf. Last access: June 2016.
217. Tsay, S.C., Maring, H.B., Lin, N.H., Buntoung, S., Chantara, S., Chuang, H.C., Gabriel, P.M., Goodloe, C.S., Holben, B.N., Hsiao, T.C. & Hsu, N.C. 2016. Satellite-surface perspectives of air quality and aerosol-cloud effects on the environment: an overview of 7-SEAS/BASELInE. *Aerosol and Air Quality Research*, 16: 2581-2602. https://doi.org/10.4209/aaqr.2016.08.0350
218. Tsidu, G.M., Blumenstock, T. & Hase, F. 2015. Observations of precipitable water vapour over complex topography of Ethiopia from ground-based GPS, FTIR, radiosonde and ERA-Interim reanalysis. *Atmospheric Measurement Techniques,* 8(8): 3277-3295. https://doi.org/10.5194/amt-8-3277-2015
219. UN (United Nations) Economic and Social Affairs, 2017. *World population prospects: the 2015 revision*. New York. Available from: http://esa.un.org/unpd/wpp/. Last access: September 2017.
220. UNEP (United Nations Environment Programme) 2015. *Fuel quality progress in Nigeria for Nigeria national air quality management program. Report presented by the Federal Ministry of Environment on 18 May 2015.* Available from: http://www.unep.org/Transport/new/PCFV/pdf/2015_Ecowas_FuelQualityProgress_Emmanuel.pdf. Last access: October 2017.
221. UNFPA (United Nations Population Fund), 2008. Annual report. ISBN 9780897149532, p. 20.

222. UNWPP (United Nations World Population Prospects), 2015. *World population prospects: the 2015 revision, highlights and advance tables*. Department of Economic and Social Affairs, Population Division. Working Paper No. ESA/P/WP.241. Available from: https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf. Last access: October 2017.
223. Upadhyay, S., Ganguly, K. & Stoeger, T. 2014. Inhaled ambient particulate matter and lung health burden. *European Medical Journal on Respiration*, 2: 88-95.
224. USEIA (US Energy Information Administration), 2016. Nigeria. Available from: https://www.eia.gov/beta/international/analysis_includes/countries_long/Nigeria/nigeria.pdf. Last access: September 2017.
225. USEPA (United States Environmental Protection Agency), 2017. Sulphur dioxide (SO_2) pollution: Sulphur dioxide basics. Available from: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects. Last access: October 2017.
226. Vakkari, V., Kerminen, V.M., Beukes, J.P., Tiitta, P., Zyl, P.G., Josipovic, M., Venter, A.D., Jaars, K., Worsnop, D.R., Kulmala, M. & Laakso, L. 2014. Rapid changes in biomass burning aerosols by atmospheric oxidation. *Geophysical Research Letters*, 41(7): 2644-2651. https://doi.org/10.1002/2014GL059396
227. Van den Bossche, J., Peters, J., Verwaeren, J., Botteldooren, D., Theunis, J. & De Baets, B. 2015. Mobile monitoring for mapping spatial variation in urban air quality: development and validation of a methodology based on an extensive dataset. *Atmospheric Environment*, 105: 148-161. https://doi.org/10.1016/j.atmosenv.2015.01.017
228. Vanos, J.K., Hebbern, C. & Cakmak, S. 2014. Risk assessment for cardiovascular and respiratory mortality due to air pollution and synoptic meteorology in 10 Canadian cities. *Environmental Pollution*, 185: 322-332. https://doi.org/10.1016/j.envpol.2013.11.007
229. Vizcaíno, M.A., González-Comadran, M. & Jacquemin B. 2016. Outdoor air pollution and human infertility: a systematic review. *Fertility and Sterility*, 106(4): 897-904. https://doi.org/10.1016/j.fertnstert.2016.07.1110
230. Vollmer, B. 2010. *AIRS Data and Services at the GSFC Earth Sciences Data and Information Services Centre (GES DISC).* Available from: http://airs.jpl.nasa.gov/documents/science_team_meeting_archive/2010_11/slides/Vollmer.pdf. Last access: June 2016.
231. Walker, S. 2012. Keeping Mineworkers Safe. *Engineering and Mining Journal*, 213(2): 42.
232. Wang, S., Feng, X., Zeng, X., Ma, Y. & Shang, K. 2009. A study on variations of concentrations of particulate matter with different sizes in Lanzhou. China. *Atmospheric Environment*, 43: 2823–2828. https://doi.org/10.1016/j.atmosenv.2009.02.021
233. Wang, Y., Li, J., Cheng, X., Lun, X., Sun, D. & Wang, X. 2014. Estimation of PM10 in the traffic-related atmosphere for three road types in Beijing and Guangzhou, China. *Journal of Environmental Science*, 26(1): 197-204. https://doi.org/10.1016/S1001-0742(13)60398-8

234. Wanninger, L. 2000. Interpolation von GPS-Beobachtungen. *Allg. Vermnachr*. 107: 360–363.
235. WHO (World Health Organization), 2005. *Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulphur dioxide.* Copenhagen: Druckpartner Moser. Available from: http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf. Last access: August 2016.
236. WHO (World Health Organization), 2014. 7 million premature deaths annually linked to air pollution. World Health Organization News Release. Available from: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/. Last access: September 2017.
237. WHO (World Health Organization), 2016. *Global urban ambient air pollution database update*, 2016. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/WHO_AAP_database_May2016_v3web.xlsx?ua=1. Last access: September 2016.
238. WHO (World Health Organization), 2016. WHO's urban ambient air pollution database–update. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/AAP_database_summary_results_2016_v02.pdf. Last access: November 2017.
239. WHO (World Health Organization), 2017. *AirQ+: software tool for health risk assessment of air pollution*. Available from: http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution. Last access: February 2017.
240. WHO (World Health Organization), 2017. *Evolution of WHO air quality guidelines. Past, present and future*. Available from: http://www.euro.who.int/__data/assets/pdf_file/0019/331660/Evolution-air-quality.pdf. Last access: September 2017.
241. Wolff, H. 2014. Keep your clunker in the suburb: low-emission zones and adoption of green vehicles. *The Economic Journal*, 124: F481-F512. https://doi.org/10.1111/ecoj.12091/
242. Wong, M.S., Nichol, J., Lee, K.H. & Li, Z. 2008. *Retrieval of aerosol optical thickness using MODIS 500 x 500m^2, a study in Hong Kong and Pearl River Delta region.* 2008 International Workshop on Earth Observation and Remote Sensing Applications.
243. Xiong, X., Angal, A., Madhavan, S., Link, D., Geng, X., Wenny, B., Wu, A., Chen, H. & Salomonson, V. 2014. MODIS instrument operation and calibration improvements. In *Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International* (pp. 1385-1388). IEEE.
244. Xu, D. & Guo, X. 2014. Compare NDVI extracted from Landsat 8 imagery with that from Landsat 7 imagery. *American Journal of Remote Sensing*, 2(2): 10-14. https://doi.org/10.11648/j.ajrs.20140202.11
245. Yap, X.Q. & Hashim, M. 2013. A robust calibration approach for PM10 prediction from MODIS aerosol optical depth. *Atmospheric Chemistry and Physics*, 13(6): 3517-3526. https://dx.doi.org/10.5194/acpd-12-31483-2012

246. Yazdi, M.N., Delavarrafiee, M. & Arhami, M. 2015. Evaluating near highway air pollutant levels and estimating emission factors: Case study of Tehran, Iran. *Science of the Total Environment*, 538: 375-384. https://doi.org/10.1016/j.scitotenv.2015.07.141
247. Yoshizaki, K., Brito, J.M., Silva, L.F., Lino-dos-Santos-Franco, A., Frias, D.P., Silva, R.C., Amato-Lourenço, L.F., Saldiva, P.H., Tibério, I.D., Mauad, T. & Macchione, M. 2017. The effects of particulate matter on inflammation of respiratory system: Differences between male and female. *Science of the Total Environment*, 586: 284-295. https://dx.doi.org/10.1016/j.scitotenv.2017.01.221
248. Youn, J.S., Csavina, J., Rine, K.P., Shingler, T., Taylor, M.P., Sáez, A.E., Betterton, E.A. & Sorooshian, A. 2016. Hygroscopic properties and respiratory system deposition behaviour of particulate matter emitted by mining and smelting operations. *Environmental Science and Technology*, 50(21): 11706-11713. https://doi.org/10.1021/acs.est.6b03621
249. Yusuf, K.A., Oluwole, S., Abdulsalam, I.O. & Adewusi, G.R. 2013. Spatial patterns of urban air pollution in an Industrial estate, Lagos, Nigeria. *International Journal of Engineering Inventory*, 4: 1-9.
250. Zeger, S.L., Thomas, D., Dominici, F., Samet, J.M., Schwartz, J., Dockery, D. & Cohen, A. 2000. Exposure measurement error in time-series studies of air pollution: concepts and consequences. *Environmental Health Perspectives*, 108(5): 419. https://doi.org/10.1289/ehp.00108419
251. Zhang, H., Yuan, Y., Li, W., Ou, J., Li, Y. & Zhang, B. 2017. GPS PPP-derived precipitable water vapour retrieval based on Tm/Ps from multiple sources of meteorological data sets in China. *Journal of Geophysical Research: Atmospheres*, 122(8): 4165-4183. https://doi.org/10.1002/2016JD026000
252. Zhang, L., Jiang, H., Lu, X. & Jin, J. 2016. Comparison analysis of global carbon monoxide concentration derived from SCIAMACHY, AIRS, and MOPITT. *International Journal of Remote Sensing*, 37(21): 5155-5175. https://dx.doi.org/10.1080/01431161.2016.1230282
253. Zhao, P., Yin, Y., Xiao, H., Zhou, Y. & Liu, J. 2016. Role of water vapour content in the effects of aerosol on the electrification of thunderstorms: A numerical study. *Atmosphere*, 7(10): 137. https://doi.org/10.3390/atmos7100137
254. Zumberge, J. F., Heflin, M.B., Jefferson, D.C., Watkins, M. M. & Webb, F. H. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research*, 102: 5005–5017. https://doi.org/10.1029/96JB03860

Appendices

***Appendix A**. Ethics approval - Ahmadu Bello University Teaching Hospital (ABUTH), Zaria, Nigeria (ABUTH/HREC/CL/05)*

HEALTH RESEARCH ETHICS COMMITTEE
AHMADU BELLO UNIVERSITY TEACHING HOSPITAL
SHIKA - ZARIA, NIGERIA.

E-mail: abuthshika@yahoo.com *website: www.abuth.org*

Chairman of Board: **Chief. Shuaib Oyedokun Afolabi** *Fnil*
Chief Medical Director: **Prof. Lawal Khalid,** *MBBS, FMCS, FWACS, FRCS(ED) mnl*
Chairman, Medical Advisory Committee: **Prof. Abdullahi Mohammed,** *MBBS, FWACP, FICS*
Director of Administration: **Barr. Ishak Bello,** *LL.B, BL., LL.M, PGDM, AHAN, FCAI*

Our Ref: ABUTH/HREC/CL/05 Date: 18th July, 2016

Your Ref:

ABUTH HREC FULL ETHICAL CLEARANCE CERTIFICATE

Ground and Satellite based retrievals of air Pollution concentrations and trends over Zaria Metropolis, Nigeria.

ABUTH Ethics Committee assigned number:	-	ABUTHZ/HREC/V08 / 2016.
Name of the principal Investigator:	-	Mr. Yahaya Abbas Aliyu
Address of the Principal Investigator:	-	Dept. of Geomatics, ABU Zaria
Date of receipt of valid application:	-	6Th May, 2016
Date of meeting when final determination On Ethical approval was made:	-	7Th June, 2016

This is to inform you that the research described in the submitted protocol, the consent forms and other participant information materials have been reviewed and given **full approval by the Health Research Ethics Committee.**

Please note: this approval dates from **18Th July, 2016 – 18Th July, 2017**

No participant recruitment into this research may be conducted outside these dates.

All informed consent forms in this study must carry the ABUTH HREC number assigned to this research and the duration of ABUTH HREC approval of the study.

This HREC expects that you submit your application as well as an annual report for ethical clearance renewal 3 months prior to expiration of study dates. This is to enable you obtain renewal of your approval and avoid interruption of your research.

If there is delay in starting the research, please inform the ABUTH HREC so that starting dates can be adjusted accordingly.

No changes are permitted in the research without prior approval by ABUTH HREC, except in circumstances outlined in national code for Health Research Ethics: **http://www.nhrec.net.**

ABUTH HREC reserves the right to conduct compliance assessment visits to your research site without prior notification.

Prof. Aisha.I. Mamman MBBS, FMCPath
Chairman, ABUTH HREC

***Appendix B**. Ethics approval – Kaduna State Ministry of Health, Kaduna, Nigeria (MOH/ADM/744/VOL.1/448)*

MINISTRY OF HEALTH AND HUMAN SERVICES
KADUNA STATE, NIGERIA

MOH/ADM/744/VOL.1/448 **29TH AUGUST,2016**

NOTICE OF APPROVAL AFTER FULL COMMITTEE REVIEW
GROUND AND SATELITE BASED RETRIEVALS OF AIR POLLUTION CONCENTRATIONS AND TRENDS OVER ZARIA METROPOLIS,NIGERIA.

Name of Principal Investigator:	**ALIYU YAHAYA ABBAS**
Address of Principal Investigator:	Dept.of Geomatics,Faculty of **Environment A.B.U-Zaria**
Date of receipt of Application	**5th August,2016**
Date of Ethical Approval	**17th August, 2016**

This is to inform you that the Research described in the submitted Protocol, the Consent forms, advertisements and other participant information materials have been reviewed and given full approval by the Health Research Ethics Committee (HREC).

If there is delay in starting the research or any change, inform the HREC so that the dates of approval can be adjusted accordingly.

However, Researcher is kindly requested to submit a copy of his/her findings to the State Ministry of Health, please.

DR. B. M. JATAU
CHAIRMAN

KADUNA STATE MINISTRY OF HEALTH
OPEN REGISTRY
DESPATCHED
SIGN ... DATE 31/8/16

Independence Way, P.M.B 2014, Kaduna, Kaduna State-Nigeria
Tel: +234 (0) 818 407 8693 | Website: www.kdsg.gov.ng | Email: health@kdsg.gov.ng

***Appendix C1**. Ethics approval (use of datasets) - Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa (EC170124-092)*

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

Date: 10 March 2017

ETHICS SUBMISSION: LETTER OF APPROVAL

Name of Applicant	Dr J Botai
Department	Geography, Geoinformatics and Meteorology
Reference number	EC170124-092
Title	Ground and Satellite Based Retrieval of Air Pollution and Trends over Zaria, Nigeria

Dear Dr Botai

The submission conforms to the requirements of the NAS EC. Any amendments must be submitted to the NAS EC on a relevant application form as used for the original application quoting the reference number and detailing the required amendment. An amendment would be for example differentiating within the research target population.

You are required to submit a progress report no later than two months after the anniversary of this application as indicated by the reference number. The progress report document is accessible of the NAS faculty's website: Research/Ethics Committee.

You are required to notify the NAS EC upon the completion or ending of the project using the form Project Completed. Completion will be when the data has been analysed and documented in a postgraduate student's thesis or dissertation, or in a paper or a report for publication.

The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

The NAS EC wishes you well with your research project.

Yours sincerely,

Chairperson
NAS Ethics Committee

***Appendix C2**. Ethics approval (engaging human participants) - Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa (EC170124-093)*

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

Date: 12/5/2017

ETHICS SUBMISSION: LETTER OF APPROVAL

Mr YA Aliyu
Department of Geography, Geoinformatics and Metereology
Faculty of Natural and Agricultural Sciences
University of Pretoria

Reference number: EC170124-093
Project title: Ground and satellite based retrievals of air pollution concentration and trends over Zaria, Nigeria.

Dear Mr Aliyu

We are pleased to inform you that your submission conforms to the requirements of the Faculty of Natural and Agricultural Sciences Ethics committee.

Please note you are required to submit annual progress reports (no later than two months after the anniversary of this approval) until the project is completed. Completion will be when the data has been analysed and documented in a postgraduate student's thesis or dissertation, or in a paper or a report for publication. The progress report document is accessible of the NAS faculty's website: Research/Ethics Committee.

If you wish to submit an amendment to the application, you can also obtain the amendment form on the NAS faculty's website: Research/Ethics Committee.

The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

Yours sincerely,

Chairperson: NAS Ethics Committee