Cape Peninsula
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ASSESSMENT OF ENVIRONMENTAL EXPOSURE TO AIR POLLUTION WITHIN FOUR NEIGHBOURHOODS OF THE WESTERN CAPE, SOUTH AFRICA

By

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DECLARATION

I, **Benett Siyabonga Madonsela**, declare that the contents of this dissertation/thesis represent my own unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

Background: A recent review on the effects of ambient air pollution on human health in sub-Saharan Africa, specifically calls for an urgent need for more epidemiological studies in developing countries due to a lack of data in these countries. Air pollution information on exposure is important for understanding and addressing its public health impact in developing countries. In many African countries, the spatial distribution of air pollutants has not been quantified even though air pollution is a global public health risk. The main goal of the study was to quantify and compare the seasonal spatial variation of household air pollution in the 4 Western Cape neighbourhoods.

Methods: Weekly indoor and outdoor measurements of Particulate Matter ($PM_{2.5}$), Sulphur dioxide (SO_2), Ozone (O_3), Carbon monoxide (CO) and Nitrogen dioxide (NO_2) were conducted at **127** households in four informal settlement areas (Khayelitsha, Marconi-Beam, Masiphumulele and Oudtshoorn) during one month each in summer and winter. $PM_{2.5}$ measurements were conducted using Mesa Labs GK2.05 (KTL) cyclone with the GilAir Plus Air Sampling Pump, Gases were measured using Passam passive samplers. Statistical analyses were performed using Stata V12. Simple linear regression was used to evaluate the relationship between continuous exposure levels and the respective predictor variables. These include distance to major roads, bus routes, open grills and waste burning sites.

Results: The highest average weekly outdoor $PM_{2.5}$ and NO_2 concentrations for summer were recorded in Milnerton (8.76 µg/m^3 and 16.32 µg/m^3 respectively). However, the highest average concentrations during winter for $PM_{2.5}$ were recorded in Oudtshoorn ($PM_{2.5}$: 16.07 µg/m^3), whilst the highest NO_2, was recorded in Khayelitsha (NO_2: 35.69 µg/m^3). SO_2 levels were consistently low during both seasons. Noordhoek generally recorded the lowest average levels for all pollutants. Winter average weekly concentrations were generally higher than the levels recorded in summer for all pollutants. In a sub-sample of indoor and outdoor measurements, the results were comparable for $PM_{2.5,}$ NO_2 and CO. However, the results of Ozone (O_3) showed relatively higher (~10 times) outdoor compared to indoor levels. Linear regression modelling results revealed that significant predictors of elevated exposure to $PM_{2.5}$ were proximity to construction activities and open grills. Analysis demonstrated a clear dose-response relationship with distance, with open grills within 1000m associated with a 0.33 µg/m^3 increase in $PM_{2.5}$ to 6.77 µg/m^3 at a distance of 25 meters. Results from the linear regression modelling revealed that significant predictors of exposure to NO_2 were proximity to rapid transport bus stops, bus routes, taxi routes and major routes. Distance to rapid transport bus stops demonstrated an increase in NO_2 between 0.09 µg/m^3 (at 1km) to 2.16 µg/m^3 (at 50m) during summer. A similar pattern was observed for taxi routes and bus routes

displaying an increase of 6.26 µg/m^3 and 6.82 µg/m^3 respectively within the proximity of 1000 meters.

Conclusion: In conclusion, ambient air concentrations demonstrate seasonal and spatial heterogeneity in exposure levels. Ambient exposure levels in winter were almost double the exposure concentration of summer, for all pollutants except for NO_2 in one neighbourhood. The study also found outdoor levels of all pollutants to be similar to indoor apart from ozone which was 10 times higher outdoor. Whilst there are no legislative guidelines to compare the current study weekly averages, the concentrations were still lower than the World Health Organisation (WHO) and South African Air Quality Standards values for all pollutants. This study was able to show relationships between various potential sources of air pollution within these neighbourhoods. The sources and spatial distribution of these pollutants can be very different in African countries, from European counterparts. Significant predictors of variability in exposure to $PM_{2.5}$ were the distance to open grills and construction, though the models performed poorly. Variability in NO_2 was significantly associated with rapid transport bus stops, bus routes, taxi routes and major routes, with models performing slightly better. The poor performance of regression models underscores the notion of possibly fundamental differences in the spatial determinants of particles in this African context and the challenges faced in terms of data availability and reference measurements from monitoring sites. Thus, applicability to health studies may be limited and further research is needed to better understand the spatial patterns and determinants of air pollution levels in these areas of South Africa.

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DEDICATION

I dedicate this thesis to Joshua Philani Madonsela

(Mtimande,

Kunene,

Bambolunye)

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ACRONYMS

CO	**Carbon Monoxide**
CTC	**City of Cape Town**
DEADP	**Department of Environmental Affairs and Development Planning**
H_2S	**Hydrogen sulphite**
NAAQS	**National Ambient Air Quality**
NEMAQA	**National Environmental Management Act**
NO_2	**Nitrogen Dioxide**
O_3	**Ozone**
PAH	**Polycyclic Aromatic Hydrocarbons**
PM_{10}	**Particulate Matter aerodynamic diameter equal to or less than 10µm**
$PM_{2.5}$	**Particulate Matter aerodynamic diameter equal to or less than 2.5µm**
Ppb	**Parts per billion**
SANAAQS	**South African National Ambient Air Quality Standards**
SO_2	**Sulphur Dioxide**
VOC	**Volatile Organic Compounds**
µg/m^3	**micrograms per cubic meter**

CHAPTER ONE
INTRODUCTION

1.1 Background

Although it has been more than a decade since the inception and promulgation of the National Environmental Management Air Quality Act 2004 (Act 39 of 2004), poor air quality exposure levels in some provinces of South Africa is still relatively high. According to Mannucci and Franchini (2017), poor air quality is responsible for almost seven million premature deaths in developing countries.

Available data indicate that sub-Saharan Africa experiences the greatest environmental air pollution exposure associated with morbidity (Coker & Kizito, 2018). Air pollution has proved to be a distinguished pollutant that exceeds all form of environmental pollution in Africa. Roy (2016) stated that in Africa air pollution is increasing at an alarming rate, thus, it is responsible for significant premature deaths than polluted water and childhood malnutrition.

WHO (2014) labelled air pollution as “the world’s largest single environmental health risk”. The International Federation of Environmental Health declared air pollution as a major public health issue facing our generation (IFEH, 2017). Excessive exposure to ambient air pollution exceeding recommended limits is a major environmental health problem affecting both developed and developing countries (WHO, 2016). Thus, 92% of the low-income and middle-income world population is exposed to air pollution exposure levels exceeding recommended guidelines (Das & Horton, 2018).

Furthermore, the 2016 air quality database by World Health Organization corroborated this information after ascertaining that 98% of cities in low and middle- income countries with more than 100 000 inhabitants fail to comply with the recommended WHO air quality guidelines. However, in all this conundrum high-income countries only recorded 56% non-compliance to recommended guidelines (WHO, 2016).

The urban environment is considered an epitome of air pollution due to anthropogenic activities that emit pollutants (Chattopadhyay et al., 2010). South Africa’s air pollution exposure levels within urban areas exceed international acceptable levels. WHO (2016) discoveries indicate that air quality is deteriorating. For instance, in South Africa, the total number of 14,356 mortality cases are associated with air pollution-related diseases every year (WHO, 2016). This finding is

in line with Szyszkowicz et al. (2008) who asserted that air pollution is significantly associated with high risks of morbidity and mortality. Muchapondwa (2010) conceded that air pollution is a great challenge particularly for poor South Africans living in the informal settlements. Overall, South Africa has an exposure level rate annual average of 27 µg/m3 of $PM_{2.5}$. Thus, the WHO air quality recommended safety level for $PM_{2.5}$ is exceeded almost three times (WHO, 2016).

The most polluted area in the Republic of South Africa is the Johannesburg city. Johannesburg has a scoring rate of 99th in the world attributable to air pollution. On the contrary, the City of Cape Town ranks number six against other cities in the country with exposure levels of 30 ug/m3 particulate matter (WHO, 2016). By definition air pollution is usually referred to as suspended particulate matter (PM), gaseous pollutants and odours (Gordon et al., 2004).

Suspended particulates matter are considered significant pollutants of concern owing to their ability to penetrate deep into the respiratory system, see Figure 1.1. However, penetration of the human respiratory system by particulates matter merely depends on the size of the particle. The atmosphere contains various types of suspended particulate matter ranging from diesel exhaust particles, coal fly ash, wood smoke and mineral dust (Kjellstrom et al., 2006).

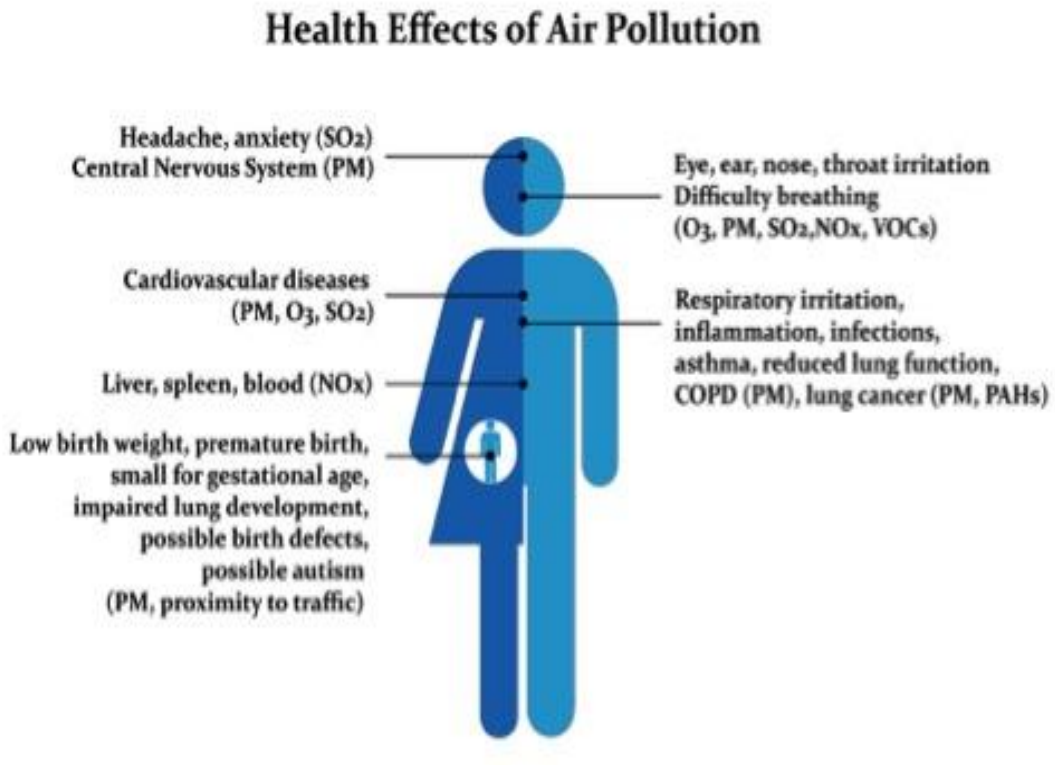


Figure 1.1: Anon. Health effects associated with air pollution exposure

The most predominant gaseous pollutants are carbon monoxide, nitrogen dioxide, sulphur dioxide and ground ozone. These gaseous pollutants are usually associated with the incidence of causing breathing difficulties, respiratory problems and exacerbating asthma attacks. Most of these gaseous pollutants are primary pollutants, with the exception of ozone which is formed when primary pollutants interact in the atmosphere.

For many developing countries, ambient air pollution has been reported to be a major health problem as well. Gordon et al. (2004) described the quality of air for many cities in developing countries as polluted. This is because a significant proportion of people in developing countries are exposed to unsafe ambient air concentrations that exceed the World Health Organization guidelines.

In South Africa, unsafe ambient air concentrations are likely to be experienced at informal settlements. The problem affecting South African informal settlements and townships is aggravated by the need for energy use for various reasons. Muchapondwa (2010) corroborated

that localised pollution sources are caused by informal settlers burning wood for fuel cooking and space heating motives.

Furthermore, Verbaan (2015) reported that Durban and Cape Town are faced with great air quality problems. An exposure assessment and health risk assessment study conducted in Durban South Africa in 2006 discovered that residential areas in the Durban south industrial residences face environmental health risks due to exposure to significant exposure levels of ambient air pollution (Naidoo et al., 2006).

In the City of Cape Town, high exposure concentrations of particulate matter were discovered in Khayelitsha Township. The quality of air in Cape Town diminishes due to domestic burning of fuels, vehicular traffic, burning of waste and meat braai's in informal trading. Similarly, during winter seasons Cape Town experiences brown haze as a result of poor air quality (Keen, and Altier, 2016). Regardless of these frequent scientific findings in recent times, a systematic approach for air quality monitoring programs has either been reported flawed or discontinued in sub-Saharan Africa (Petkova et al., 2013).

1.2 Statement of the research problem

In many developing countries there is a lack of air pollution exposure data (Kirenga et al., 2015) despite the fact that air pollution is the global public health risk responsible for premature deaths in the Sub Saharan Africa (Schwela, 2012). A recent review on the effects of ambient air pollution on human health in Sub-Saharan Africa, specifically calls for an urgent need for more epidemiological studies and exposure levels in developing countries due to a lack of data in these countries (Amegah & Agyei-Mensah, 2017; Coker & Kizito, 2018). Additionally, whatever data is available has not been published (Lourens et al., 2011).

South Africa faces a range of persistent air pollution problems (Scorgie, 2012). Significantly high exposure levels of gases and fine particulate matter continue to be a concern in the informal settlements and peri-urban areas of South Africa. This is problematic considering that air pollution is associated with health impacts (Kelly & Fussell, 2015). Impacts of exposure to air pollution have been confirmed to be prevalent even in low exposure levels (Brunekreef & Holgate, 2002). Thus, air pollution exposure poses a threat to the health and well-being of the people living in the informal and peri-urban areas of South Africa (Friedl et al., 2008).

In South Africa, exposure assessment of air pollution is frequently performed by municipalities and private industry. Therefore, there is limited assessment and information on seasonal and spatial variability exposure of pollutants levels in the informal areas. Dionisio et al. (2010) and Egondi et al. (2016) corroborates that in Sub-Saharan Africa only a few studies have conducted exposure assessment of air pollution within the informal areas. Therefore, there is a need to quantify the levels of pollutants which people within the informal settlements are exposed to in order to determine risk exposure to health and well-being.

This study, therefore, aimed to provide a more detailed characterisation of spatial and seasonal variation of air pollution exposure levels within the informal settlement neighbourhoods of Western Cape, South Africa. Through conducting environmental exposure assessment in different seasons over a 24 months period. Furthermore, to determine factors contributing to environmental air pollution exposure levels within the four neighbourhoods.

1.3 Research questions

- What are the exposure levels of ambient air pollution in the 4 neighbourhoods?
- What are the exposure levels of indoor and outdoor in the 4 neighbourhoods, do the exposure levels vary?
- Are there any seasonal variations in air pollution?
- Do neighbourhoods demonstrate significant variability of air quality levels?
- What are the possible predictor variables that influence ambient air pollution levels?

1.4 Objectives

The objectives are:

- To assess and compare ambient exposure levels of $PM_{2.5}$, SO_2 and NO_2 in the four neighbourhoods
- To assess and compare indoor and outdoor exposure concentrations of $PM_{2.5}$, SO_2, NO_2, CO and O_3 in a small sample of households within the 4 neighbourhoods
- To determine exposure variation of air pollutants between and within the study areas, and across summer and winter season.
- To investigate which determinants (sources) of air pollution explain exposure variability in $PM_{2.5}$, NO_2 across neighbourhoods

1.5 Significance of the study

Air pollution information on exposure provides a fundamental platform for understanding and addressing the burden of air pollution in developing countries. Most of air pollution studies only focus on exposure assessment monitoring through the use of secondary data from fixed air quality monitoring stations. Such methods have proven to be limited in terms of data collected and its reliability. Furthermore, such methods do not consider air pollution exposure variability within the neighbourhoods. But it only assigns a certain quantified exposure for a, particularly large area. The significance of this study is to characterise the spatial and seasonal variation of air pollution exposure levels within neighbourhoods, through the use of passive monitoring equipment in children school attending households in order to determine their exposure.

Subsequently, such passive equipment will determine exposure assessment of air pollution within residential addresses and such an approach will maximize the contrast of exposure. The residential exposure to $PM_{2.5}$ will be quantified of which exposure to $PM_{2.5}$ is not constantly monitored in Western Cape. Therefore as a result, sufficient exposure assessment information is not available in general concerning the measurement of $PM_{2.5}$ in the Western Cape.

The air quality exposure levels will be used in the development of land use regression model and asthma exposure-response for epidemiology study. Since this study is a substudy of a bigger health outcome project, the expected outcomes of this study are the spatial and seasonal exposure variation levels of air pollutants in the 4 neighbourhoods. This research study is expected to analyse, characterise, determine and evaluate determinants of exposure variability. Additionally, this study will provide contemporary exposure levels of pollutants monitored within the 4 neighbourhoods.

CHAPTER TWO:
LITERATURE REVIEW

2.1 Introduction

Air pollution is defined as the state in which the atmospheric condition contains certain concentration of substances that may produce harmful effects on man and the environment (Chattopadhyay, 2014). The following chapter presents the literature review which discusses the most common ambient air pollutants affecting public health in the African continent and globally. The exposure levels of the air pollutants measured locally and globally together with their sources are discussed in this chapter.

Furthermore, this literature review focused on ambient air pollutants which are the main contributors to the global burden of disease comprising of particulate matter ($PM_{2.5}$), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO). Sources associated with these ambient air pollutants include but not limited to industrial waste emitted into the air, motor vehicle exhaust, agriculture, wood combustion and coal. Wood combustion and coal are used as a source of fuel for both cooking and space heating (Dhillon, 2007).

There are numerous ways used to measure exposure levels of ambient air quality. However, for the purpose of this research, the amount of pollution is measured in terms of mass/volume concentration usually expressed as micrograms of pollutant per cubic metre of air ($\mu g/m^3$) with the exception of carbon monoxide measured and expressed in mg/m^3 (Chattopadhyay, 2014). According to statistical reports, more than 80% of people living in urban areas are exposed to air quality exposure levels exceeding the World Health Organisation's recommended limit (WHO, 2016). Ambient air pollution is considered a great environmental health challenge in both developing and developed countries. It contributes significantly to the global burden of disease and is associated with various chronic non-communicable diseases such as respiratory and cardiovascular diseases (WHO, 2013).

Exposure to unsafe pollution levels was associated with 3.7 million premature deaths globally in 2012, with 88% of the reported number of premature deaths in middle and low-income countries. In South Africa, it is estimated by the WHO that 80% premature deaths were caused by ischaemic heart disease, strokes and 14% of the deaths were caused by chronic obstructive pulmonary disease or acute lower respiratory infections and 6% is associated with lung cancer (Eze et al., 2015).

2.1.1 Particulate Matter (PM)

Particulate matter is the most common air pollutant comprising of a mixture of particles from natural and anthropogenic sources (WHO, 2003). These particulates contain both liquid and solid constituents. The size of the particle is important in determining the impact of particulate matter on health. Thus, particulate matter is categorised into two types: coarse particulates (2.5-10) and fine particles (<2.5). Coarse particles are PM_{10} particles with an aerodynamic diameter of 10 µm or less and fine particles are $PM_{2.5}$ particles with an aerodynamic diameter of 2.5 µm or less.

Fine particles ($PM_{2.5}$) are considered to have a greater risk of causing human health effects compared to coarse particles (PM_{10}) (Wang et al., 2015). Sources of particulate matter emission include power plants industries and diesel trucks. Particulates are emitted by either natural or anthropogenic sources and could be emitted directly into the atmosphere as primary particles or formed by secondary processes.

The most significant natural sources of particulate matter are sea salt aerosols, bushfires, and crustal dust, vegetation made up of pollen and fungal spores, volatile organic compounds (VOCs) and animal remains. Anthropogenic sources include combustion of engines, power stations, mining, other industrial processes, agriculture and domestic heating appliances (Hime et al., 2015).

Furthermore, PM_{10} is emitted from biological particles, particles generated mechanically from agriculture, mining construction, road traffic and other related sources. $PM_{2.5}$ include particles from motor vehicle combustion, burning coal, wood, fuel and dust from the road and soil (Laden et al., 2000). However, combustion sources of $PM_{2.5}$ are considered more harmful and risky to health compared to other sources (Jansenn et al., 2011).

The effect of PM on human health includes breathing problems through penetration of the alveolus and oxidative stress leading to cardiovascular and neurological problems (Amaral, 2015). Mortality rates and health risks are considered to be greater for $PM_{2.5}$ than for PM_{10} (Fierro, 2000) because $PM_{2.5}$ has the ability to penetrate the alveoli which are the gas exchange region deeper in the lungs, subsequently causing lung diseases (Xing et al., 2016).

The WHO Air Quality Guideline recommends a maximum annual mean concentration of 10µg/m^3 and 20µg/m^3 for $PM_{2.5}$ and PM_{10} respectively and a maximum daily 24-hour mean concentration for $PM_{2.5}$ and PM_{10} at 25µg/m^3 and 50µg/m^3 respectively (IFC, 2007). However, here in South Africa, the maximum annual mean concentration of PM_{10} is 40µg/m^3 and the maximum daily 24-hour mean concentration of PM_{10} is 75µg/m^3 (RSA, 2009).

Prior to January 2015, the annual and daily maximum concentrations of PM_{10} in South Africa were 50µg/m^3 and 120µg/m^3 respectively. South Africa just like other developing countries has air quality standard guidelines for PM higher than the WHO requirements. The WHO estimates a 15% reduction of air pollution-related deaths if the annual average of PM_{10} is reduced to the 20µg/m^3 guideline levels from 40µg/m^3 (IFC, 2007).

2.1.2 Ozone (O_3)

It has been decades since exposure to a high concentration of ground-level ozone has been identified as a harmful pollutant on both the environment and human health (Khiem et al., 2010). Exposure to ozone has increased in recent years due to the increase in motor traffic and agricultural activities (Sicard et al., 2009). Ozone is a reactive oxidant and respiratory irritant colourless gas that significantly contributes to atmospheric smog associated with adverse health events (World Bank Group, 1999; Chen et al., 2008).

Ground level ozone, unlike most other primary pollutants, is not emitted directly into the ambient air. It is a secondary pollutant formed in the presence of chemical reactions of NOx family in the ambient air and Volatile Organic Compounds. Ground level ozone is associated with impaired lung function and breathing health effects on humans (Lin, 2012).

Environmental exposure to high levels of O_3 is a concern due to effects on human health and ecological system (Lai, 2010). Local meteorological conditions have a direct bearing and significant impact on ground-level ozone formation (Ebi & McGregor, 2009). A chemical reaction between Volatile Organic Compounds (VOCs) and nitrogen oxides (NOx) in the presence of sunlight (photochemical) yield ozone formation (Geddes & Murphy, 2012).

Meteorological conditions influence the formation of physical and chemical processes involved in the formation of secondary pollutants such as ozone. Thus, O_3 is regarded as a secondary pollutant because of its formation reliance on sunlight as a precursor. Vibenholt (2013) argued

that high levels of O_3 are normally observed in densely populated areas with high exposure to sunshine.

Because of O_3 formation dependence on sunlight. It is imperative to note that changes in local meteorological conditions, such as wind direction, wind speed, relative humidity, and temperature can greatly affect variations in ozone concentrations (Elminir, 2005). Seventy percent of ozone variability on daily basis is reportedly caused by changes in temperature, relative humidity, and wind speed (Tarasova & Karpetchko, 2003).

Several studies have corroborated that there is an increase in Ozone concentrations during summer periods because of high temperatures (Khiem et al., 2010; Atkinson et al., 2012). The atmospheric ozone exposure concentrations are usually assessed as 1-hour maximum or a maximum of 8-hour average concentrations because they are closely associated with sunlight (EPA, 2013). The abundant presence of ozone in the atmosphere can have significant health effects ranging from asthma, impaired lung function, and the development of lung diseases (EPA, 2013).

2.1.3 Nitrogen dioxide (NO_2)

Nitric oxide and nitrogen oxide are well known composite gases of NOx family abundant in the atmosphere. Nitrogen oxides form part of the highly reactive gases of nitrogen oxides (NOx) family and also contributes to the atmospheric reaction in the formation of the ozone pollution. The well-known pollutants from this group are nitric oxides and nitrogen dioxide. Nitrogen gas is described as reddish brown and very reactive in the atmosphere with a pungent suffocating smell. Han and Naeher (2006) assert that nitrogen gas exposure is pervasive in developing countries in comparison to countries that are developed. While nitric oxide is described as a colourless and odourless gas (Han & Naeher, 2006; Yaseen et al., 2014).

Sources of NO_2 are thought to be of primary or secondary pollutants. Primary pollutant comes directly from emission sources, while secondary pollutant is formed during chemical reactions in the atmosphere (Han & Naeher, 2006). Primary NOx gases are the product of combusting fuel at high temperatures which lead to emissions from, for example, metallurgical furnace, blast furnace emissions and also emissions from vehicles (Chen & Kan, 2008). Ali and Haruna (2015) further associate NO_2 with point source combustion site, vehicle traffic, domestic fuel combustion and industrial activities.

Similarly, Chaney et al. (2011) maintain that high atmospheric concentrations of nitrogen oxides family emanate from vehicle traffic and that high exposure levels are on major urban roadways proximity. Significant exposure levels of nitrogen dioxide are associated with health effects. There is evidence in the literature from numerous studies that exposure to environmental nitrogen dioxide is associated with health impact (Ali & Haruna, 2015). A review study in Europe of the acute and long term impacts of exposure to nitrogen dioxide investigating air pollution and health established associations between nitrogen oxide and increased daily mortality, cardiovascular mortality, hospital admissions and exacerbation of asthma in children (Searl, 2004).

NOx are strong oxidizing agents and capable of reacting with water in the atmosphere to form nitric acid that significantly contributes towards acid rain. High NO_2 personal exposure of 21 $\mu g/m^3$ was reported to result in asthma exacerbation (Bernstein et al., 2004). The WHO AQG and the SA-NAAQS values for short-term NO_2 exposures for an average 1-hour are 200$\mu g/m^3$ and 40$\mu g/m^3$ for the annual average (Tiwari et al., 2015; Bai et al., 2017).

2.1.4 Sulphur dioxide (SO_2)

Sulphur dioxide is a colourless gas with a sharp odour existing in both aerosol and gaseous form on the surface of the earth (WHO, 2014). SO_2 emissions in the developing countries have been relatively increasing compared to developed countries which have recorded a decrease in the last decade (Cofala et al., 2004).

Fossil fuel containing sulphur compounds is the prominent source of environmental sulphur dioxide exposure levels. This is a result of burning fossil fuels like coal, heavy oils and smelting of sulphur-containing ores (Ali & Haruna, 2015). Yaseen (2014) reported that 93% of the SO_2 emissions are from the northern hemisphere, while the southern hemisphere is only responsible for 7% emissions. Sources of sulphur just like many other gases include both natural and anthropogenic sources. However, sulphur is predominantly present in the atmosphere in a gaseous state as SO_2 (Stevenson et al., 2003).

Additionally, SO_2 discharged into the atmosphere can transform through oxidation reaction processes and be converted into fine particulate sulphate (De, 2012). Fine particulate sulphate contributes towards harmful fine components of both PM_{10} and $PM_{2.5}$ (Chaney et al., 2011).

Furthermore, it is well known that SO_2 through complex oxidation reactions forms part of the acid rain precipitation that has a potential effect on sensitive ecosystems.

Oxidation of SO_2 in the atmosphere form sulphate aerosols that contribute to acid rain deposition and high concentration of sulphate ions (SO_{4-2}) found in rainwater is the result of intense SO_2 emissions (Skinder et al., 2014). In South Africa, burning of fuel containing sulphur content is comprehensively used for domestic heating, motor vehicles and power stations. The Major Sources of SO_2 in the country include power stations. They have been reported to be major sources of SO_2 exposure levels. SO_2 affect human health in the respiratory systems, further cause's inflammation of the respiratory tract that results in mucus secretion, coughing, exacerbating asthma condition and chronic bronchitis (WHO, 2014).

The WHO Air Quality Guidelines recommends that SO_2 concentration of 500µg/m^3 must not be exceeded over a 10-minutes mean duration and the long-term average exposure in 24-hours should not exceed 20µg/m^3 (IFC, 2007). The South African National Ambient Air Quality Standards (SA-NAAQS) for SO_2 mean concentration at 10-minutes and 24-hours is 500µg/m^3 and 125µg/m^3 (RSA, 2004).

2.1.5 Carbon monoxide (CO)

Carbon monoxide is a colourless and odourless poisonous gas produced by incomplete combustion of fossil fuels such as natural gas, petrol and oil. In South Africa, major sources of carbon monoxide include motor vehicles and industrial processes. Other sources include cigarette smoke, wood stoves and fires from the forest.

Carbon monoxide exposure is reportedly higher in the urban area and displays a habit to increase with traffic density. The high greatest exposure to carbon monoxide concentrations tends to be recorded weekdays during commuter's hours (NRC, 2002). Najjar (2011) asserts that the incomplete combustion of carbon in vehicles is responsible for more than 90% of carbon monoxide emissions resulting in air pollution.

In the cities, motor vehicles are considered the greatest exposure sources of carbon monoxide. Studies have indicated that where concentration levels of carbon monoxide reach an average of 3-4 parts per million (ppm) along the roadways, the concentration inside the motor vehicles

tends to be 5 ppm (NRC, 2002). Exposure to such ambient levels is a risk that may affect both vehicle drivers and a group of individuals working along the streets.

Exposure to carbon monoxide is associated with human health effects. Carbon monoxide inhibits the inherent ability of blood to carry oxygen into the tissues. CO has a high affinity for haemoglobin. When carbon monoxide is inhaled, it quickly reaches oxygen and binds with haemoglobin to form carboxyhaemoglobin (COHb) (Fierro et al., 2001). The Environmental Protection Agency NAAQS for CO is 9ppm and 35ppm for an 8-hour average and 1-hour averages respectively, while the SA-NAAQS for CO concentrations are relatively lower at 10 mg/m3 and 30 mg/m3 for a mean 8-hour and 1-hour averages respectively.

2.1.6 Air quality standards

The air quality standards are significant for effective air quality management. These air quality standards are used to determine the maximum concentration levels of a substance in the atmosphere. The air quality standards provide a guideline which assists to determine and indicate a difference between polluted and non-polluted atmosphere. Furthermore, these standards indicate what is considered to be a safe exposure level for public health and for general welfare purposes. Higher concentrations measured against air quality standards are likely to affect public health and cause environmental pollution. These air quality standards and their resultant effects are based on scientific findings (Araújo et al., 2014).

The WHO is responsible for providing countries with scientific findings that serve as reference and guidance for developing air quality standards cognitive of health effects. However, the challenge with WHO scientific guidelines is that they are generic in approach and they do not consider individual economic status per country (Table 2.1).

The South African National Air Quality Standards are given in Schedule 2 of the National Environmental Management: Air Quality Act (AQA) (Act No. 39 of 2004). The Act covers the following substances and their concentrations together with their average periods, sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), particulate matter less than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) and Nitrogen dioxide (NO_2) as shown in (Table 2.2):

Table 2.1: World Health Organisation air quality guidelines (WHO, 2018).

Air quality standards for Sulphur Dioxide		
Average period	**Concentration**	**Reference**
10 minutes	500 µg/m^3	WHO (2018)
24 hours	20 µg/m^3	WHO (2018)
Air quality standards for Nitrogen Dioxide		
1 hour	200 µg/m^3	WHO (2018)
1 year	40 µg/m^3	WHO (2018)
Air quality standards for particulate matter		
24 hours	25 µg/m^3	WHO (2018)
1 year	10 µg/m^3	WHO (2018)
Air quality standards for Ozone		
8 hours (running)	100 µg/m^3	WHO (2018)
Air quality standards for carbon monoxide		
1 hour	30 mg/ m^3 (26 ppm)	WHO (2006)
8 hour (calculated on 1 hourly average)	10 mg/ m^3 (8.7 ppm)	WHO (2006)

Table 2.2: South African Air Quality Standards (DEA, 2009).

Air quality standards for Sulphur Dioxide		
Average period	**Concentration**	**Reference**
10 minutes	500 µg/m^3 (191 ppb)	DEA (2009)
1hour	350 µg/m^3 (191 ppb)	DEA (2009)
24 hours	125 µg/m^3 (191 ppb)	DEA (2009)
1 year	50 (191 ppb)	DEA (2009)
Air quality standards for Nitrogen Dioxide		
1 hour	200 µg/m^3 (106 ppb)	DEA (2009)
1 year	400 µg/m^3 (21 ppb)	DEA (2009)
Air quality standards for particulate matter		
24 hours	75 µg/m^3	DEA (2009)
1 year	40 µg/m^3	DEA (2009)
Air quality standards for Ozone		
8 hours (running)	120 µg/m^3 (61ppb)	DEA (2009)
Air quality standards for carbon monoxide		
1 hour	30 mg/ m^3 (26 ppm)	DEA (2009)
8 hour (calculated on 1 hourly average)	10 mg/ m^3 (8.7 ppm)	DEA (2009)

2.2 The sources of criteria ambient air pollutants in Western Cape neighbourhoods

The World Health Organisation (2013) identified industries, households, cars and trucks as the main contributing factors of ambient air pollution. The Western Cape neighbourhoods' sources of air pollution originating from a variety of both combustion and non–combustion sources (Walton, 2015). However, transportation, mining activities, agriculture, domestic fuel burn, fires and industrialisation are considered significant sources of the air pollutants in the province (Singh et al., 2013).

According to DEADP (2013), 42% of industrial emission contributes 58% of the particulate matter followed by domestic emissions on 42%. Sulphur dioxide emissions industry emits 96% of the concern gas and households only contribute 4%. Lastly, the industrial sector in the Cape Town metropolitan area contributes 82% of NOx emissions and 18% is produced by domestic emissions.

Sources of combustion generally include pollution from a point source such as burning of tyres, industrial emissions, households fuel burning, transportation, wildfires and fuel burning appliances. Sources of non-combustion generally include pollution from non-point sources such as fugitive emissions from wind erosion, agriculture, evaporative losses, landfill operations and wastewater treatment (Scorgie, 2003).

Furthermore, the local climate contributes to the dispersion of the aforementioned criteria ambient air pollutants. The Western Cape Province weather is influenced by cold fronts during winter periods. These cold fronts are from the southern Atlantic Ocean. Summer periods are associated with a high-pressure system pushing wet systems towards the south and east.

2.2.1 Household fuel burning

About three billion poor people in the world rely on the use of solid fuel and gas as a means of energy source (Pilishvili et al., 2016). Solid fuel includes wood, animal dung, charcoal, crop wastes and coal (Bonjour et al., 2013). Most population in sub-Saharan Africa relies on solid fuel for cooking (WHO, 2014). The use of solid fuel is predominant in both rural and urban areas of South Africa.

In South Africa, high electricity tariffs and personal preference is cited as reasons for the combustion of solid fuel in electrified households (Singh et al., 2013). Furthermore, Chafe et al. (2015) allude that this practice is most common in urban households to accommodate both cooking and space heating. This is caused by prioritising and limiting electricity usage for households illumination purposes (IARC, 2010).

Burning fuel releases toxic pollutants of PM and gases such as polycyclic aromatic hydrocarbons, CO, SO_2 and NO_2 (Clark et al., 2013; Abbott et al., 2016). Furthermore, Smith et al (2004) associate fuel combustion with respirable particles, carbon monoxide, oxides of nitrogen and sulphur. Agrawal and Yamamoto (2015) corroborated that the combustion of fossil fuel and biomass produce toxic pollutants such as $PM_{2.5}$, CO, NOx, and SOx.

However, during summer season preferred fuels are paraffin, candles, electricity and gas. The combustion of gas is associated with the release of atmospheric nitrogen oxides and $PM_{2.5}$. Several studies have indicated an association between gas combustion and NO_2 concentration emissions (García Algar et al., 2004).

A study recently conducted in Irish established and corroborated that gas stoves in the households produce high concentration values of NO_2 compared to other combustions (Semple et al., 2012). Furthermore, gas is considered a clean fuel and preferred for cooking purposes compared to solid fuel; however, it is expensive compared to paraffin.

Additionally, the use of paraffin possesses certain risks including emissions of atmospheric particulates pollutants but it is still a common fuel in informal settlements without electricity for cooking purposes (Naidoo et al., 2014). A study conducted in Cape Town of spatial and temporal disaggregation of anthropogenic carbon dioxide emissions measured domestic emissions. The study established an estimate of 27.7 Mg of Carbon dioxide emission per hour during winter periods (Nickless et al., 2015).

During winter periods pollutants are significantly prevalent due to human needs for space heating. Accumulation of pollutants is noted in the early hours of the winter mornings in the urban areas (townships) due to temperature inversions (CoCT, 2002). In 2002, the City of Cape Town (CoCT) reported that because of inadequate service delivery, many households within the informal settlements and urban areas (township) use solid fuel in the form of coal, paraffin, and wood as the sources for cooking and space heating (CoCT, 2002).

According to the WHO (2014) report, air pollution from household fuel combustion is the greatest environmental health risk faced globally. This practice is common in both developed and developing countries. Combustion of fuel in households is considered a reliable source of energy that is used by almost three billion people in the world. This is due to inaccessibility to modern fuel such as liquefied petroleum gas, kerosene and electricity for purposes of cooking and space heating and the majority of these people are from developing countries (Clark et al., 2013).

Developing countries are reportedly accounting for 70% of solid fuel usage through combustion of wood, dung and crop residues for cooking (IARC, 2010). Air pollution from burning solid fuel is caused by incomplete combustion of energy resources (Makonese et al., 2015). Smith et al (2009) argued that the main cause of health-damaging gases and particles are from the combustion of solid fuel in inefficient cookstoves. These stoves are incapable of executing complete combustion of energy resources.

2.2.2 Industrial emissions

Industrialisation is associated with emissions of particulate matter and gases (Walton, 2005). In the Western Cape Province and specifically in the city of Cape Town metropolitan area, fuel combustion within industrial, road transport, residential and other sectors, accounts for the major sources of air pollution. A study conducted in Cape Town of spatial and temporal disaggregation of anthropogenic CO emissions established that the largest per pixel emission of CO under listed industrial activities was 57 Mg per hour.

Industrial listed activities included ceramic processes, hydrocarbon refining processes, iron and steel processes, road processes for asphalt production, and waste incineration processes and electricity generation at gas turbine power plants (Nickless et al., 2015). Particulates and gases emissions such as SO_2, NOx and CO are linked to industrial emissions (Thomas et al., 2011). The metal sector and other industries in the Western Cape generate significant exposure pollutants of gases and PM.

Combustion of fuels in the industrial sector, such as paraffin, coal diesel and heavy oil used in the production processes is associated with emissions of volatile organic compounds and aforementioned pollutants of concern. Furthermore, there are multiple brickfields industries identified within the neighbourhoods of Western Cape. These industries emit fugitive dust during manufacturing activities. Manufacturing processes that include combustion release SOx, NOx, CO_2 and CO pollutants (Singh et al., 2013). The location of industrial sectors is a concern in many cities. Most industries are reported to be situated within residential areas, exposing residents to environmental health risks (Chipindu, 2009). Industrial air emissions consist of several environmental harmful pollutants discharged into the atmosphere through primary and secondary processes (Etim, 2012).

Following traffic emissions, industrial emission is regarded as the second largest pollutant of the atmosphere (Gull et al., 2013). Industrial emission is one of the global challenges responsible for the majority of pollution. Walton (2006) cited that melting industry is responsible for the release of 99% total emissions of particles and gases. Industrial pollution consists of particles especially waste gases like carbon monoxide, sulphur oxides, and nitrogen oxides (Jerumeh et al., 2015).

These gases are classified as the waste products of industry which ultimately end up in the air (Jerumeh et al., 2015). Carbon dioxide is a predominant pollutant in the manufacturing industrial

sector (Lu & Price, 2012). However, pollution generated by the industry is influenced by what product is manufactured in the process.

Industries that manufacture glass and metals generate emissions such as CO, NOx, SO_2 and PM. Furthermore, the combustion of various fuels used for production contributes to the level of VOCs produced and the release of heavy metals into the environment (NHDES, 2015). Majority of the industrial emissions are reported to emanate from metallurgical plants and smelters, chemical plants and petroleum refineries, cement production, fertilizers and synthetic rubber manufacturing, pulp and paper milling (Chipindu, 2009).

2.2.3 Traffic emissions

Traffic contributes to significant emissions from vehicles in the developing countries urban areas (Gaita et al., 2014). This is exacerbated by the need for economic development activities that rely on transportation and personal excessive use of private transport. The engine model of contemporary vehicles is capable of emitting pollutants such as NOx and SO_2 amongst other pollutants. A review study conducted in South Africa revealed that traffic emission is at the centre of anthropogenic sources contributing to air pollution (Norman et al., 2007).

In Cape Town, traffic emissions significantly contribute as one of the sources to the infamous brown haze (Piketh & Walton, 2004). Traffic emissions are high in urban areas and assumed to contribute to significant carbon dioxide and nitrogen dioxide concentration exposure levels particularly in areas susceptible to traffic congestion such as the central business district (CBD) (Schwela, 2012). Singh et al. (2013) corroborated that in the City of Cape Town, traffic volume is considered to be too high in Cape Town's metropolitan area because that is where the majority of the population in the province reside. Moreover, Cape Town's airport and harbour are considered the source of localised pollution because of the high volume of vessels and aircraft that enters the ports. Furthermore, the port welcomes 10 vessels a day and serves as a hub for marine fuel, gas and oil storage.

On average, recorded emissions of CO_2 from aircraft a month are 10 890 Mg. The hourly average concentration was recorded to be 15.1 Mg of CO_2. This data does not factor in emissions from vehicles on the airport premises. High emissions are said to be recorded from November to January periods. Data from vessels entering the port at berth and during manoeuvring procedure are on average of 4171.6 Mg of CO_2 per month (Nickless et al., 2015).

Vehicle emissions are the major contributor to ambient pollution in urban areas. Kim Oanh et al. (2008) maintain that developing countries are at risk of vehicle emissions pollution due to growth in the number of people owning vehicles. Growth in the number of vehicle ownership increase chances for high traffic density. High traffic density is associated and considered a significant contributor to high levels of pollution concentration along the roadside (Kim Oanh et al., 2008).

There seems to be an established relationship between exposure to transport-related pollution and public health concern (Gupta et al., 2010). Vehicles produce pollutants which have the ability to compromise human health and cause ecological damage (Litman, 2013). Transport emission is considered to be contributing to long-lived greenhouse gases; thus, it has a great impact on both atmosphere and climate change (Elmar Uherek et al., 2010). In urban areas, transport emission is a major source of air pollution exposure to particulate matter (Janssen et al., 2011).

Exposure to traffic-related air pollution is associated with the risk of respiratory symptoms increase (Kim Oanh et al., 2008). Traffic pollution is generally associated with high levels emission of nitrogen oxides; however, research indicates that it depends on the nature of the fuel being used (Lu, 2011). Vehicles that use petrol are considered to produce significant, CO, HC and PAHs emissions in high levels, while diesel vehicles produce a significant amount of particulate matter and nitrogen oxides in high levels (Nelson et al., 2008). Lu (2011) concluded that each fuel type possesses both flaws and benefits.

Furthermore, exposure to diesel emission is associated with certain adverse public health effects such as premature death, respiratory symptoms, impaired lung function and cardiovascular diseases. Atmospheric pollutants contributed by the vehicles include SO_2, Particulates, NO_x and hydrocarbons. Hydrocarbons are the product of incomplete combustion of fuel in the engine, similarly, carbon monoxide is the result of incomplete combustion when the carbon in the fuel is partially oxidised to carbon dioxide (Tiwary & Colls, 2010).

2.2.4 Wildfires

Africa experiences a number of fire incidents, thus it has always been known as the ‘the fire continent’ (Archibald et al., 2010). High-frequency episodes of fires are recorded to occur in the Western Cape, Mpumalanga Province and KwaZulu-Natal (Strydom & Savage, 2016). During

biomass, combustion fire emits pollutants such as carbon monoxide, carbon dioxide and ozone. Wildfires are generally recognised as the results of human activities.

The major pollutants attributed to wildfires are particulate matter, carbon monoxide and volatile organic compounds (EPA, 2008). In the Western Cape wildfires naturally, occur during the summer seasons due to the prevalence of dry seasons. During this season the Fynbos vegetation is dry and temperatures are high (DEADP, 2013). In the past 20 years, wildfires have claimed 34851 hectares of vegetation land in the Cape Peninsula (Rowles, 2012.)

2.2.5 Agricultural emissions

Agricultural activities are responsible for being significant contributors to particulate emissions. Dryland and wetland agricultural activities impact on air quality by activating dust particles and releasing gases such as CO during cultivating and harvesting processes and other relevant activities associated with field preparation (DEADP, 2013).

2.3 Emission sources in African developing countries including the City of Cape Town

In the Western Cape Province and specifically in the City of Cape Town metropolitan area, fuel combustion within industries, road transport, residential and other sectors, accounts for the major sources of air pollution. Harbour and airport emissions are the additional transport sources within the City of Cape Town.

In addition to the transport and industrial sources, biomass burning (mostly periodic wildfires and agricultural burning), and waste burning accounts for further significant sources of emissions in the province. Table 2.3 below summarises data from an emission inventory for the criteria air pollutant compiled sources from the only recent existing summary emission and new data from various sectors which include all emissions for the criteria air pollutants within the Western Cape. Additionally, metropolitan areas in other cities such as Johannesburg have similar anthropogenic emission sources. The City of Johannesburg's prominent emission sources includes transportation, energy production, industrialisation and domestic fuel emissions (Lourens, 2012). Similarly, cities outside the country such as Nairobi in Kenya, Kampala in Uganda and Maputo in Mozambique also have these emission sources (Robinsoon & Hammitt, 2009).

The data in Table 2.3 indicates that highest air pollution emissions in the City of Cape Town are for CO emissions (69559 tons per annum), followed by NOx (17580 tons per annum). Surprisingly, the emission of PM_{10} was the second lowest (9030 tons per annum). Sources that emitted the highest of CO were domestic emissions and industrial activities (DEADP, 2013). In Johannesburg, the highest emissions were associated with NOx (1033122 metric tons per year), followed by SOx on 401487 metric tons per year. PM_{10} emissions were the lowest (192271 metric tons per annum). Of course, the majority of the aforementioned pollutants come from industrial activities, domestic emissions and vehicle sources.

In Kampala, Uganda the highest recorded emissions were for PM_{10} (30901 tons per year) followed by $PM_{2.5}$ (16220 tons). SOx emissions were lowest on 2540 metric tons per annum. Fifty per cent (50%) of pollutant sources in Kampala emanate from domestic sources. The rest are from vehicles and fugitive dust road (Robinson & Hammitt, 2009). A qualitative study in Nairobi found high carbon dioxide emissions of 350078 tons per annum. Followed by PM_{10} (98056 t/y) and SO_2 (32025 tons/year). In Nairobi, industries do not contribute much to emissions of concern. Significant emissions emanate from vehicles that are not well maintained and domestic emissions from wood combustion and charcoal (Schwela, 2012).

Maputo as a city recorded the lowest emissions relative to the other three cities in Mozambique with the PM_{10} emissions estimates at 900 tons/year, followed by $PM_{2.5}$ (910 metric tons per year). Moreover, NO_x recorded estimates levels of 281 t/y, with SO_2 reaching a low value of zero. In the precinct of Maputo, domestic and industrial emissions significantly contribute to significant air pollution exposure levels (Robinson & Hammitt, 2009).

Table 2.3: Total emissions for Cape Town, 2012 (tons/annum)

Group	PM_{10}	NO_x	NO_2	SO_2	CO
Airport	3	616	62	31	1132
Roads	917	11412	1435	102	32228
Shipping	92	1644	164	667	8
Rail	0	7	1	0	5572
Domestic	3906	1360	136	585	22290
Listed Activities	1895	2225	223	7365	8312
Solid waste sites	1931	0	0	0	0
Fuel Burning	288	321	32	3074	0
Total	9030	17580	2052	11820	69550

Adapted from the Western Cape Government Environmental Affairs and Development Planning, 2013.

2.4 Meteorological effects and temperature inversions on ambient air pollution

Meteorology plays a key role in the formation, transport, and dispersion of air pollutants. The state of the atmosphere in an area has a direct impact on the accumulation and dispersion of pollutants in the atmosphere (Verma & Desai, 2008). Meteorological conditions such as atmospheric wind speed, wind direction, relative humidity, rain cloud cover and temperature influence the concentration of air pollutants in ambient air.

Thus, the concentration of ambient air pollution discharged into the atmosphere from various sources is also influenced either by the stability or instability of the atmosphere to absorb or disperse pollutants (Jayamurugan et al., 2013). The city of Cape Town in the two study neighbourhoods during winter periods experiences the north-westerly winds that come as the results of cold fronts.

Rain cleanses the atmosphere. The anti-cyclones that ridge eastward over the southern Cape coast follows after the rainy days. Then the table mountain's shielding properties and the climatic factors in winter and Table Mountain's shielding properties circumstances influence the accumulation of pollution (Jury et al., 1990).

2.5 Overview of exposure assessment models

There are many difficulties in measuring air pollution that compromises exposure assessment results (Han & Naeher, 2006). Sellier et al. (2014) suggest that measurement methods for estimating exposure to air pollution may have an influence on the outcome of results. Air pollution measurements usually include quantitative estimations such as direct-reading from devices, continuous monitoring analysers, sampling and analytical methods including either pumped or passive sampling methods. In order for epidemiological studies to present valid, accurate and representative information, data from a large number of individuals should be obtained (Monn, 2001).

Investigating large sample size becomes convenient when sampling is conducted in a large area that allows for quantification of air pollution within the area. Failure to quantify large areas in air pollution assessment poses a potential for exposure misclassification considering that the distribution of air pollutants is not constant throughout the environmental atmosphere. In most studies of air pollution and health outcomes, modelling of exposures have been the main method of assigning exposures, and such methods have different strengths and limitations.

2.5.1 The Proximity model

The Proximity model is considered to be the simplest approach to assessing air pollutants exposure within a geographical area (Kanaroglou et al., 2005). Proximity modelling measures the proximity of the exposed subject in relation to the source of exposure. Proximity model studies make use of a restricted number of covariates that could be capable of confounding the relationship between air pollution and health. Proximity modelling is the most applicable approach in distinguishing air pollution exposure within a city because it measures how close the subject to a pollution source is. This method is good in discovering an existing association between health effects consequences and air pollution exposure on assumption that the closer the subject to the emission sources proxies for exposure in human populations. However, it has its limitations because it uses a restricted number of covariates that could possibly confound the relationship between air pollution and health. For instance studies of this nature has a potential to result to misclassification and biased risk estimation due to the fact that they do not take into consideration exposure from outside the place of residence, work or school (Zartarian et al., 1997).

2.5.2 Land use regression model (LUR)

Land use regression model predicts the concentrations of pollution in a specific place based on surrounding land use and traffic pollution (Isakov et al., 2011). LUR has the ability to provide exposition for small scale variability in pollutant concentrations within the city (Jerrett et al., 2005). The limitation of LUR is associated with monitoring data from an extensive number of sites to present reliable information which is considered to be a challenge (Jerrett et al., 2001). However, having contrasted these models this research study adopted the LUR model because of its practicability and applicability in the research study.

2.5.3 Interpolation model

The levels of the air pollutants are acquired from specified monitoring stations scattered all over the study area (Gaines Wilson & Zawar-Reza, 2006). Interpolation model techniques have an advantage over the proximity models due to their use of real pollution measurements in the computation of exposure estimates (Wichmann & Voyi, 2012). Multiple interpolation methods face challenges in obtaining available monitoring data, due to their requirement of a reasonably dense network of sampling sites.

2.6 Assessment of air pollution exposure in epidemiological studies

Modern epidemiological studies take place at the population level and use ambient air pollution levels as the exposure of interest (Mandel et al., 2015). When conducting long term epidemiological studies involving personal exposure estimation for large populations, it is imperative to consider population density together with geographic information systems (Han & Naeher, 2006). In numerous studies, air pollution measurement is achieved by using stationary monitors within an area of interest. However, these stationary monitors in most cases are not accurate enough. Furthermore, stationary monitors are not optimised to detect spatial variability of pollutants within large areas. Thus, this study conducts exposure assessment in households.

2.7 Air pollution levels in African countries

Previous studies conducted by WHO (2009) realised air pollution as an important contributor to the burden of disease in South Africa. Table 2.4 demonstrates exposure levels of air pollutants in South Africa and other African countries that have conducted an exposure assessment of air pollution within their respective regions. The table indicates the disparities in exposure levels and assessment methods for different air pollution gases and particulates. Exposure assessment of air pollution is important for determining health risks, health conscious, urban

planning and developing strategies to reduce costs associated with air pollution and enforcing air quality standards (Petkova et al., 2013). Regardless of air monitoring significance and associated benefits thereof, the majority of African cities do not monitor exposure to air pollution.

Where there is exposure monitoring to air pollution, the monitoring system is usually regarded either flawed or working intermittently (Schwela, 2006). Moreover, monitored data is not readily available in scientific journals for evaluations which makes it difficult to determine the levels of exposure (Lourens et al., 2011). Similarly, where air monitored data is available, it is either not easily accessible to the public or not communicated clearly, this challenge affects policy making and limits public knowledge (Petkova et al., 2013).

Most of the African countries experience similar exposures to air pollution and reports suggest that Africa as a continent is faced with multiple air pollution challenges but are not well equipped to confront and address them. As a result, the Sub-Saharan Africa region lacks sufficient air pollution data, enforced regulation and air quality laws (Wichmann, 2017). However, South Africa is recognised as the only country in the continent with air quality standards authorised by air quality laws and regulations. Wichmann (2017) further asserts that many countries in the African continent either have air quality standards, regulations or air quality laws. It is seldom for African countries to possess all these three elements.

2.7.1 Studies on particulate matter levels

Table 2.4 shows exposure levels for particulate matter in South Africa and other African countries. Venter et al. (2012) conducted a study in the Marikana Village 35 kilometre east of Rustenburg in the North West Province of South Africa. The study entailed exposure assessment of particulate matter air pollution conducted for a period of two years and three months. Exposure assessment results revealed that 24-h average PM concentration of 222 $\mu g/m^3$ was recorded with the maximum annual concentration being 46 $\mu g/m^3$.

These results indicate that both National Ambient Air Quality Standards (NAAQS) and international standards were exceeded for both 24-h average concentration and mean annual PM concentration. Significant exposure levels were attributed to combustion from informal and semi-formal households. Similarly, a Ghanaian study of spatial and temporal variability of air

pollution conducted in areas of different socioeconomic status in West Africa region established significant exposure levels of 96 µg/m^3 in the informal settlement.

However, on the contrary, urban neighbourhoods recorded low particulate matter exposure levels of 45 µg/m^3 (Dionisio et al., 2010). The authors suggest that particulate matter concentrations exceeded recommended WHO ambient air quality standards in the region. Exposure sources of air pollution include combustion of biomass and vehicular traffic.

2.7.2 Studies on nitrogen dioxide and sulphur dioxide levels

Exposure levels of SO_2 and NO_2 differ greatly in different study areas. A spatial and temporal assessment of gaseous pollutants study conducted by Lourens et al. (2011) in Gauteng and Mpumalanga, South Africa discovered significant spatial and temporal variation of NO_2 and SO_2 exposure levels. Furthermore, measured study areas ranged from industrialised area to remote rural areas. The study revealed high significant spatial and temporal variations for values of NO_2 and SO_2 concentrations monitored in sites located in high industrial areas.

In contrary, Sandow (2016) recorded low exposure levels of nitrogen dioxide in Ghana, Accra but high significant concentrations for sulphur dioxide. High significant concentrations for sulphur dioxide were attributed to vehicular traffic. Similarly, a study conducted by Adoki (2012) in Nigeria recorded nitrogen exposure levels of 81.0µg/m^3 and 150µg/m^3 and high significant concentrations of sulphur dioxide (92.0µg/m^3 and 430µg/m^3). Air pollution high exposure values are associated with anthropogenic and natural activities. Additionally, a Ugandan study determining spatial variability demonstrated high exposure variation of nitrogen dioxide between study areas of Jinja and Kampala.

Kampala city recorded a mean concentration of 26.69 µg/m^3 compared to the city of Jinja with a mean concentration of 17.49 µg/m^3. Additionally, there was a high spatial variation of sulphur dioxide exposure levels between the areas. The City of Jinja had a high concentration value of SO_2 (7.3 µg/m^3) 10 times higher compared to Kampala industrial area (<0.69 µg/m3). High values of SO_2 concentrations were evident in industrial areas in contrast to commercial land use area. Both concentrations of SO_2 and NO_2 never exceeded World Health Organisation guidelines (Kirenga et al., 2015).

2.7.3 Studies on carbon monoxide levels

A study in Pretoria using data from a fixed monitoring station indicated that emissions of CO did not exceed the NAAQS minimum exposure recommendations of 29770 µg/m^3 for 1-hour and 10305 µg/m^3 for 8-hour exposure. CO concentration value for 1-hour average reached 1442.6 µg/m^3, whereas the 8-hour average reached a value of 618.30 µg/m^3 (Morakinyo et al., 2017). Similarly, CO pollutant concentrations recorded in Mpumalanga by Venter et al. (2012) (2200 µg/m^3) did not exceed a 1-hour average of (30 000 µg/m^3) recommended by NAAQS. Similarly, the South Durban Basin study in KwaZulu-Natal South Africa that sought to determine the exposure from vehicular transportation and other industrial activities in the vicinity of Umlazi Township discovered relatively low exposure levels of CO concentrations (2.03 mg/m^3). CO values were relatively low compared to other measured gases (Buthelezi & Davies, 2015).

2.7.4 Studies on ozone levels

The spatial and temporal variation of ozone is studied in South Africa (Lourens et al., 2011). Laban et al. (2015) remarked that monitoring of ozone is done by government and industry ambient air quality monitoring stations. The previous measurement of O_3 revealed that high values of O_3 occurred in Mpumalanga province and Botswana. The average day concentrations of ozone in Botswana reach 40 ppb in the early hours of the morning. This average day concentration has been reported to remain above these levels for 10 hours.

Furthermore, Laban et al. (2015) cite that measurement exposure of ozone in these areas can reach exposure level values between 40 and 55 ppb during the spring season. Moreover, high-value concentrations of 90 ppb have been recorded during the season of spring in Southern Africa. Measurements of O_3 are conducted in Cape Point under Cape Point Global Atmosphere Watch and South African Weather Service (Zunckel et al., 2004).

Results showed that concentration of O_3 representative of maritime air reach values of 15 ppb in summer and double the figure to 30 ppb in winter, with recorded average annual concentrations of 15 ppb (Laban et al., 2015). Additionally, a study of seasonal variation of trace gases and aerosol optical properties conducted in Johannesburg Highveld area observed O_3 concentrations being higher during the dry winter periods reaching values as high as 80 ppb (Laakso et al., 2012).

In contrast, a study conducted in Egypt at Cairo measured diurnal, seasonal and weekdays–weekends variations of ground-level ozone concentrations, refer to table 7. During the period of the summer season, highest O_3 levels in the area were recorded due to the local photochemical production. The daily mean exposure values of O_3 were 43.89, 65.30, 91.30 during and 58.10 ppb and 29.69, 47.80, 64.00 and 42.70 ppb during winter, spring, summer and autumn seasons. The mean day concentration of O_3 during spring, summer, autumn were recorded to be 75%, 100%, 34.78% and 52.63% respectively. These mean day concentrations exceeded the Egyptian and European Union air quality standards (60 ppb) for daytime (8-hours) (Khoder, 2009).

Table 2.4: Summary of studies measuring air pollutants in African Countries

REFERENCE	POLLUTANT	COUNTRIES	AIM OF STUDY	SAMPLING PERIOD	SAMPLING DURATION	MONITORED SITES	EXPOSURE ASSESSMENT EQUIPMENT	SOURCES OF POLLUTANT	EXPOSURE ASSESSMENT RESULTS	AIR QUALITY STANDARDS
Venter et al., (2012)	Particulate matter	South Africa (Rustenburg, North West)	Air quality assessment in the industrialised western Bushveld Igneous Complex	All Seasons	27 months	1	Particulate monitor (Model 5030, (Thermo Fisher Scientific Inc.)	Wood & coal	Maximum annual concentration of 46 µg/m^3	Both South African & WHO guidelines exceeded
Dionisio et al., (2010)	Particulate matter	Ghana (Accra)	Assessment of air pollution in Accra neighbourhoods of different socioeconomic status	All Seasons	22 months	4	DustTrak model 8520 monitors(Inc., Shoreview, MN, USA)	Biomass fuel use	Maximum concentration ranged from 80 to 108 µg/m^3at roadside sites and 57 to 106 µg/m^3	WHO guideline exceeded
Lourens et al., (2011)	Nitrogen & sulphur dioxide	South Africa (Vanderbijlpark, Delmas, Witbank, Ermelo, Carolina, Amersfoort, Standerton and Balfour)	To determine spatial and temporal distributions of nitrogen dioxide (NO_2), sulphur dioxide (SO_2)	All Seasons	12 months	8	Passive Samplers	Natural & anthropogenic activities	levels at all sites were below the annual standards	Both South African & WHO guidelines were not exceeded

REFERENCE	POLLUTANT	COUNTRIES	AIM OF STUDY	SAMPLING PERIOD	SAMPLING DURATION	MONITORED SITES	EXPOSURE ASSESSMENT EQUIPMENT	SOURCES OF POLLUTANT	EXPOSURE ASSESSMENT RESULTS	AIR QUALITY STANDARDS
Sandow (2016).	Nitrogen & sulphur dioxide	Ghana (Accra)	To assess the diurnal rhythms of ambient air pollution due to vehicle traffic	Winter	8 days	4	Aeroqual series 500 (Aeroqual Limited., Auckland, New Zealand)	Vehicular traffic	Annual SO_2 concentration 0.12 ppm. NO_2 0.10 ppm	SO_2 WHO guidelines exceeded, NO_2 guidelines not exceeded
Buthelezi & Davies, 2015 (2015)	Carbon monoxide	KwaZulu-Natal (Umlazi)	CO, O_3 and NO_2 exposure from vehicular transportation and other industrial activities in the vicinity of Umlazi Township, South of Durban, KwaZulu-Natal Province, South Africa	Summer & Spring	582 days	1	Extract Transform and Load Environmental (ETL) gas analyser	Vehicle emissions	CO mean concentration 2.03 mg/m^3.	South African guidelines not exceeded
Morakinyo et al., (2017)	Carbon monoxide	South Africa (Pretoria West)	To assess the health risks associated with exposure to pollutants	All Seasons	12 months	1	ambient air quality monitoring station	Industrial activities	CO concentrations of 1442.6 $\mu g/m^3$ (1-hour average) and 618.30 $\mu g/m^3$ (8-hour average)	Both South African & WHO guidelines exceeded

REFERENCE	POLLUTANT	COUNTRIES	AIM OF STUDY	SAMPLING PERIOD	SAMPLING DURATION	MONITORED SITES	EXPOSURE ASSESSMENT EQUIPMENT	SOURCES OF POLLUTANT	EXPOSURE ASSESSMENT RESULTS	AIR QUALITY STANDARDS
Khoder (2008)	Ozone	Egypt (Cairo)	To diurnal, seasonal and weekdays–weekends variations of ground-level ozone concentrations in an urban area	All Seasons	11 months	1	Dasibi ozone monitor (Dasibi, Model 1003-AH, Environmental Corp. Glendale, Calif. 91205)	Anthropogenic activities	O3 concentrations were significantly high during summer	Both Egyptian & WHO guidelines exceeded
Josipovic et al., (2010)	Ozone	South Africa (industrial Highveld areas)	To assess concentrations, distributions and critical level exceedance of pollutants in South Africa	All Seasons	24 months	37	Passive sampling	Industrial activities	In the case of ozone, no exceedance of the measured annual mean was found for either 40 or 30 ppb	Both South African & WHO guidelines exceeded

2.8 Air pollution levels in global countries

In most cases, air pollution is the result of localised and regional activities; however, air pollution exceeds national boundaries. Zhang (2017) contends that it is global knowledge that both regional and local air quality can be affected by pollution from atmospheric transport of pollutants from other continents. This then renders air pollution a trans-boundary pollutant and global risk factor. Air pollution is recognised as one of the important global risk factors that cannot be ignored anymore. Table 2.5 provides global studies that have conducted an exposure assessment of pollutants outside the African context.

Akimoto (2003) states that measurements of air pollutants in 1981 revealed high levels of concentration over Africa, Asia and South America through measurement of air pollution from the satellite. Furthermore, the satellites images revealed that pollution generated from industrial activities is not the only one with the potential to impact both local and global air but there are numerous sources that possess the same potential to cause global pollution. These sources range from burning biomass, agricultural waste and vegetation. This then indicated that indeed air pollution is a global risk issue.

2.8.1 Studies on particulate matter levels

In Table 2.5, Modaihsh and Mahjoub (2013) conducted a study of particulate matter exposure assessment in Saudi Arabia. Results revealed exposure levels of 563.37 µg/m^3 and 141.66 µg/m^3. Sources of PM were associated with dust particles. In contrary, a study measuring for long term exposure to particulate matter in Europe's neighbourhoods (Spain, Italy, Austria, Switzerland, Germany, Finland, Sweden, Norway and Portugal) discovered a degeneration of particulate matter exposure levels (Cusack et al., 2012). Results discovered that highest exposure levels of 12.6 µg/m^3 were recorded in Montseny neighbourhood in Spain. This means the concentration value of particulate matter is regarded as the highest exposure level in comparison to other monitoring stations in the regional background of Spain.

2.8.2 Studies on nitrogen dioxide and sulphur dioxide levels

A study conducted by Naddafi et al. (2012) measured for nitrogen dioxide and sulphur dioxide exposure levels in the capital city of Iran. The study results indicate that significant levels of NO_2 were predominantly high during the autumn season and SO_2 exposure levels were reportedly high during the summer season and dropped significantly during the winter season. Both Iran's and WHO exposure levels of air quality were exceeded for both pollutants.

However, in contrast, a study in Bangladesh measured for sulphur dioxide and nitrogen dioxide. The study measured for these pollutants of concern in six selected study areas within the close proximity of the garment industry. The study discovered that monthly exposure levels of assessed SO_2 reached on average 25.74 mg/m^3. However, NO_2 studies revealed slightly a significant monthly average concentration of 28.18 mg/m^3. Results established that the highest exposure levels in all measured sites were within close proximity of industrial zone (Rabbi, 2018).

2.8.3 Studies on carbon monoxide levels

A Chinese study measured carbon monoxide concentrations in the megacity. The study used air quality monitoring stations for assessment purposes. It was conducted over a period of two years the study revealed that carbon monoxide annual mean concentration reached a level of 1.2 mg/m^3 (Song et al., 2017). Furthermore, a study conducted in seven different neighbourhoods of India megacity measured for spatial variability concentrations of gaseous pollutants. The study revealed that levels of carbon monoxide were significantly lower than the National Ambient Air Quality Standards and the US EPA standard. The study recorded daily mean concentration of CO at 2.3 ± 0.6 ppm (Tyagi et al., 2016)

2.8.4 Studies on ozone levels

A study conducted in Ireland measured for the annual concentration of ozone over a period of 15 years. The study established that average zone levels reached a maximum of 40 ppb. These average results of ozone are below the average concentration levels prescribed in central Europe (Tripathi et al., 2012). Furthermore, a study conducted in Western Asia measured ambient air quality in two cities in the state of Kuwait. The study measured ozone concentration factoring in the seasonal variability of ozone pollutant. Results indicated that ozone concentration was high during summer periods compared to winter periods. Summer levels reached maximum hourly concentrations of 42 ppb ozone concentration, while winter ozone maximum concentration reached the lowest hourly concentration of 30 ppb.

Table 2.5: Summary of studies measuring air pollutants in global Countries

REFERENCE	POLLUTANT	COUNTRIES	AIM OF STUDY	SAMPLING PERIOD	SAMPLING DURATION	MONITORED SITES	EXPOSURE ASSESSMENT EQUIPMENT	SOURCES OF POLLUTANT	EXPOSURE ASSESSMENT RESULTS	AIR QUALITY STANDARDS
Modaihsh and Mahjoub (2013)	Particulate matter	Saudi Arabia (Riyadh city)	To characterise particulate matter	Winter	88 days	1	Grimm model EDM 365 aerosol spectrometer (Grimm Aerosol Technik GmbH, Ainring, Germany)	Dust	PM_{10} 563.37 µg/$m^3$and $PM_{2.5}$ 141.66 µg/m^3.	WHO standards exceeded
Cusack et al. (2012)	Particulate matter	Spain (Montsey)	To assess trends of particulate matter	All Seasons	8 years	28	Quartz fibre filters	Anthropogenic sources	$PM_{2.5}$ 12.6 µg/m^3	WHO standards exceeded
Neddafi et al. (2012)	Nitrogen dioxide & Sulphur dioxide	Iran (Tehran)	Assessment of air pollution	All Seasons	12 months	5	Ambient air quality monitoring station	Vehicular traffic and industrial pollution	80 µg/m3 annual mean for NO2 & 400 µg/m3 as 24-hr mean	Both WHO and Iran's air quality levels were exceeded
Rabbi (2018)	Nitrogen dioxide & Sulphur dioxide	Bangladesh (Gazipur, Savar and Narayanganj)	To assess Nitrogen Oxides and Sulphur Dioxide in industries	Autumn	1 month	6	Respirable dust sampler	Industrial pollution	25.74 mg/m^3 for SO_2 & 28.18 mg/m^3 for NO_2	WHO 24hr mean exceeded for SO_2 & NO_2 1hr average not exceeded

REFERENCE	POLLUTANT	COUNTRIES	AIM OF STUDY	SAMPLING PERIOD	SAMPLING DURATION	MONITORED SITES	EXPOSURE ASSESSMENT EQUIPMENT	SOURCES OF POLLUTANT	EXPOSURE ASSESSMENT RESULTS	AIR QUALITY STANDARDS
Song et al. (2017)	Carbon monoxide	China (northern and southern China)	Status and spatiotemporal variations	All Seasons	3 years	31	Air quality monitoring stations	Industrial pollution	1.2 mg/m^3 for mean annual	CO annual standards for China not exceeded
Tyagi et al. (2016)	Carbon monoxide	India (Delhi)	Assessment spatial variability of gaseous pollutants	All Seasons	12 months	7	Air quality monitoring device (Thermo Electron model 48i)	Vehicular traffic & industrial pollution	The daily mean concentration of 2.3 ± 0.6 ppm	WHO standards not exceeded
Tripathi et al. (2012)	Ozone	Ireland	To conduct an assessment of the surface ozone trend in Ireland relevant to air pollution	All Seasons	15 years	8	UV photometry	?	Annual average concentration levels 40 ppb to 60 ppb	Compliant- Where 60 ppb levels were reached it never exceeded the limit of 25 exceedances in one year
Alenezi and Al-Anezi (2015)	Ozone	Asia (Kuwait)	To conduct an assessment of ambient air quality in two major cities	Summer & Winter	?	2	Fixed air quality monitoring station	Vehicular pollution	42 ppb for summer & 30 ppb for winter (hourly concentrations)	WHO hourly concentration for O_3 not exceeded.

2.9 Evaluation summary of studies that provided pollutants levels

The above-summarised studies of African and global countries with monitored air pollution data of exposure levels in the table form displayed both strength and shortcomings. For instance, a study in the North West Province of South Africa measured for particulate matter concentrations for a period of two years. In as much as air pollution monitoring was conducted for a long period, the monitoring of the air pollutants was only limited to one study area.

Therefore, the spatial variability of the air pollutants concentration within the study area was not monitored. Therefore, the measured ambient air data concentration may possibly be assigned to be the representative of exposure on Marikana, which is incorrect. Brauer (2010) corroborated that air pollution data monitored within a particular study area are usually averaged and the entire community is assigned the same exposure level.

In contrast, a study conducted by Dionisio et al. (2010) of spatial and temporal variability of air pollution within the neighbourhoods of the capital city of Ghana covered most of the factors that qualify it as a good study. This included covering the aspect of the meteorological factors and sources of air pollutants within the neighbourhoods. Dias and Tchepel (2018) assert that spatial and temporal variation of air pollution provides comprehensive information, which leads to better understanding of pollutant concentrations.

These factors and monitoring strategy provide noble spatial variability of air pollution. However, the identified shortcoming for such a nature of the study is the lack of dense network used as monitoring equipment. Additionally, this study does not consider seasonal variability exposure levels although it has been reported that in different seasons sources of air pollution changes giving effect to seasonal variability (Peng et al., 2005).

Furthermore, a study conducted in the Northern part of Gauteng assessed the health risks associated with exposure to airborne pollutants. The challenge associated with this study was to use secondary data from a fixed monitoring station which might significantly influence exposure misclassification. Data from government monitoring station has limitations such as being faulty and not recording exposure levels on daily basis and thus leads to a lack of consistency in data monitoring. Jenner (2013) in a study of sulphur pollution had to discard and disregard SO_2 ambient concentrations data monitored from the City of Cape Town fixed air quality monitoring

station; stating that data from the monitoring station was not appropriate for a study of ambient air quality due to exposure misclassification.

Lastly, one of the limitations associated with these African studies is the lack of comprehensive exposure assessment of airborne criteria pollutants. Olaniyan et al. (2015) corroborated in a review of ambient air pollution studies and childhood asthma that limitations in the results of many South African studies are associated with methodological issues. Thus, in order for Africa to reduce the health burden of air pollution and develop strategies that will enable transportation policy and urban planning favourable to health and air quality comprehensive systematic air quality monitoring is of significance (Petkova et al., 2013).

While on the contrary, in Europe, the Spain study is a good case study for long term exposure assessment studies that can be linked to health risks outcome. The study was conducted over a long period of time. The study compares its findings to Europe at large and provides comprehensive utility data capable to inform air quality management policies. Amongst others, numerous studies failed to document sources of pollutant exposure in their particular study areas where significant exposure levels were discovered.

Lastly, studies that made use of secondary data to analyse exposure to pollutants of concern could not discuss variability of the pollutants. This may be due to the limitations associated with using government air quality monitors, such as missing periodical data. Baxter et al (2013) affirmed that fixed monitors for air pollution may lack the ability to capture spatial variability of air pollutants. Thus, the monitoring method for this study ensured that samplers are not concentrated within one area of the neighbourhood but cover a wide area of the neighbourhood in order to increase exposure variability assessment.

CHAPTER THREE:
METHODOLOGY

3.1 Study population and design

This is a sub-study of the two-year cohort study investigating the effects of ambient air pollution on asthma among primary school children in the Western Cape (Olaniyan et al., 2017). Primary school attending children were from Ikhusi and Sosebenza primary school within the neighbourhoods of Khayelitsha, Bongolethu and Saturnus primary school situated in Oudtshoorn, Marconi Beam primary school found within Milnerton and Ukhanyo Primary school within Masiphumelele's neighbourhood in Noordhoek. Figure 3.1 below shows the 4 neighbourhoods considered for exposure assessment monitoring.

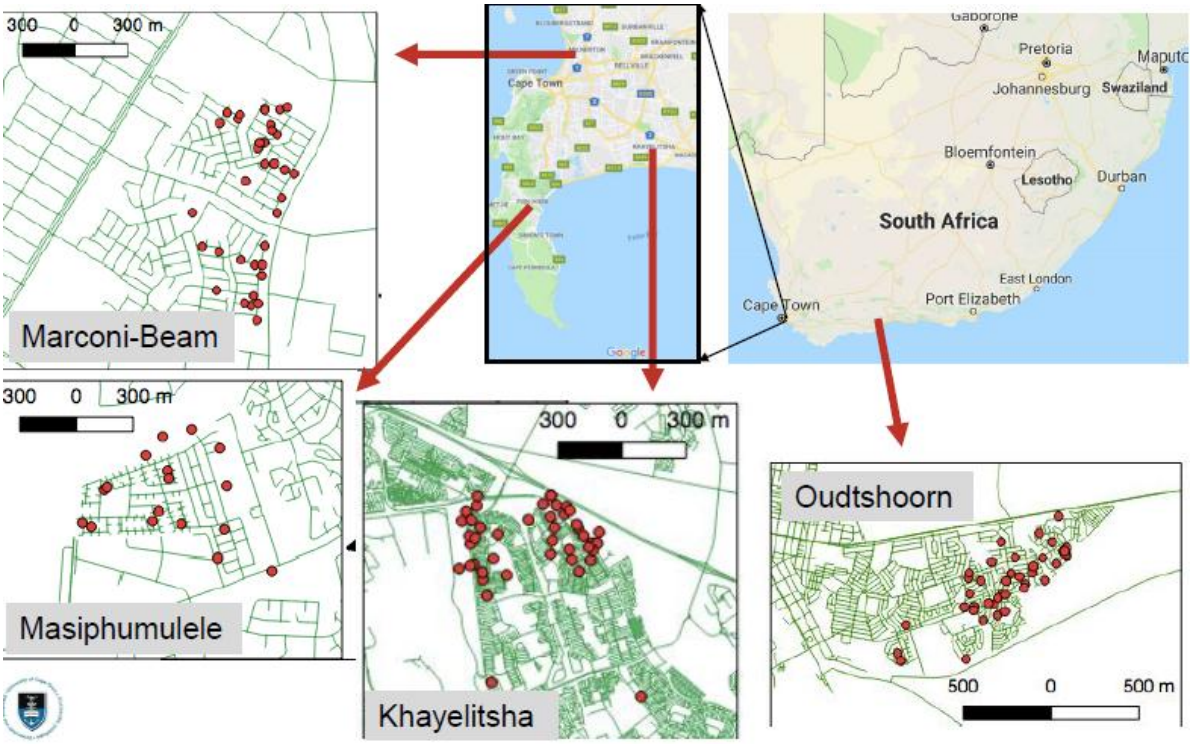


Figure 3.1: Exposure assessment monitoring neighbourhoods

This study included three areas prioritised in a needs analysis study conducted by the Department of Environmental Affairs and Development Planning (DEA&DP) in 2013. The in-cooperated study areas were within the neighbourhoods of the primary school attending children. Additionally, Noordhoek in Masiphumelele was identified as the control area. This area had a low air pollution score ranking in comparison to the other three areas (DEA&DP, 2010).

A total number of 600 school attending children were selected as participants for this exposure assessment study. However, ultimately, from a pool of 600 school attending children only a limited number of 40 households per neighbourhood were considered for air pollution assessments, refer to Figure 3.2. Chosen and selected sampling sites were considered to maximise the spatial distribution of air pollution. Thus, the sampling sites were selected to provide broad coverage of the air pollution variability in the neighbourhoods.

Moreover, chosen areas were selected to maximise contrast exposure levels of various ambient air pollutants in the neighbourhoods. The locations for air pollution exposure assessment include an urban industrialised area (Milnerton/Milnerton Ridge including Phoenix & Joe Slovo), a peri-urban area with a large informal sector Khayelitsha and a rural area Oudtshoorn located on the outskirts of Cape Town. Noordhoek in Masiphumelele was the control area.

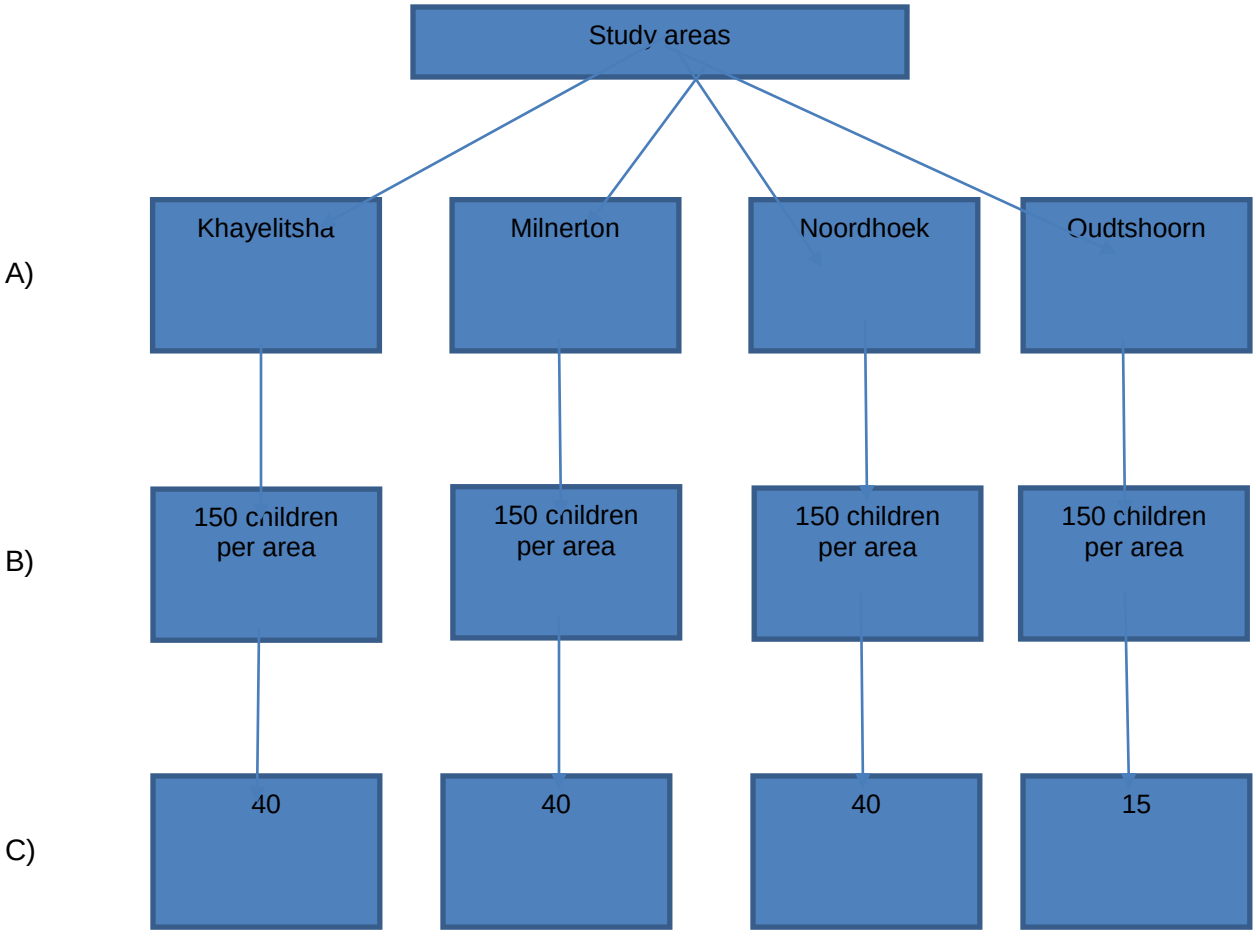


Figure 3.2: Houses considered for exposure assessment

3.2 Description of areas and selection of exposure assessment sites

In 2013, the Western Cape Department of Environmental Affairs & Development Planning (DEADP) undertook human health risk assessment (HRA) studies that identified and prioritised areas in the Western Cape Province. The vulnerability of population groups to poor air quality was assessed. Subsequently, an emission inventory for the Western Cape was compiled and dispersion models for the study of air pollution were developed. Areas were ranked based on the populations' potential for exposure to air pollution as well as their vulnerability to air pollution.

Areas prioritised based on their risk and vulnerability to air pollution for exposure included Khayelitsha, Milnerton and Oudtshoorn. These three study areas had a high priority ranking of air pollution exposure. Additionally, Noordhoek was identified and demarcated as the control area. It was earmarked a control area due to lack of industrial activities within its vicinity that may exacerbate exposure levels of air pollution. The outcome results of the human health risk assessment study have significantly influenced the consideration and selection of these study areas for air pollution exposure assessment.

3.2.1 Khayelitsha

Khayelitsha is a poor urban informal settlement. It approximately has a population of 820, 000 residents, which makes it the biggest township within the metropolis (USB, 2014). It is situated 32 km away from the City of Cape Town. Khayelitsha experiences a high rate of unemployment and poverty, therefore solid fuels are their primary households' energy use (Tessema, 2011). Muchapondwa (2010) corroborated that wood, household waste and used tyres are commonly used as the source of energy in Khayelitsha. Khayelitsha has a fuel storage facility that may serve as a source of fugitive emissions for VOCs and an additional source of pollution exposure in the area (Western Cape Government, 2013). High emissions of PM_{10} are prevalent in Khayelitsha, such emissions are associated with exposure to traffic as one of the main anthropogenic sources (Norman et al., 2007).

3.2.2 Milnerton

Milnerton is a suburb settlement that is situated 12 km away from the Central Business District of Cape Town. Census conducted in 2011 revealed it has a population of 95, 630 (Census, 2011). For environmental studies, Milnerton is a prominent study area due to its vicinity to a

petrochemical refinery that produces complex emissions. The petrochemical refinery produces emissions that include fugitive emissions containing numerous aliphatic and aromatic hydrocarbons as well as sulphur dioxide, particulates and oxides of nitrogen (White et al., 2009). A study conducted around early 2000 in Cape Town revealed that refinery emissions contributed to significant levels of ambient air pollution around the area (White et al., 2003).

3.2.3 Oudtshoorn

Oudtshoorn is the largest town in the Little Karoo region, it is well known for its farming activities. Census conducted in 2011 revealed that it has a population of 95, 933 (Census, 2011). H_2S and CO_2 are considered pollutants of concern in the area and therefore, as a result, they are monitored. During the winter periods, the pollution limit of H_2S is commonly exceeded. The actual cause contributing to H_2S guideline being exceeded is not known (DEA, 2012).

3.2.4 Noordhoek

Noordhoek is the suburb of Cape Town, located west coast of the Cape Peninsula, and approximately thirty-five kilometres to the south of the city. Census conducted in 2011 revealed it has a population of 31, 980 (Census, 2011). This area is considered a control area because air pollution around this area is assumed to be low in comparison to other selected study areas due to low industrial activity (DEA&DP, 2010).

3.3 Selection of households for exposure assessment

Air pollution monitoring was conducted in the four above-mentioned study areas. In the main study of asthma exposure-response, 600 primary school pupils were selected as participants based on sample size calculations. From each neighbourhood, a random number of 150 primary school attending pupils were selected from one or 2 schools. Principals of the respective schools gave consent that allowed pupils to participate. Subsequently, their households were visited to request consent to conduct air pollution exposure assessment within their households that form part of the selected neighbourhoods.

Eventually, for the purpose of air pollution exposure assessment, only a total of 135 pupils' households were selected for monitoring within the four neighbourhoods. The 135 pupils sample size households were selected based on the potential to maximise spatial variability and accessibility of the households. In each neighbourhood, 40 households were subsequently assessed for exposure to air pollution with the exception of the control area (Noordhoek) that

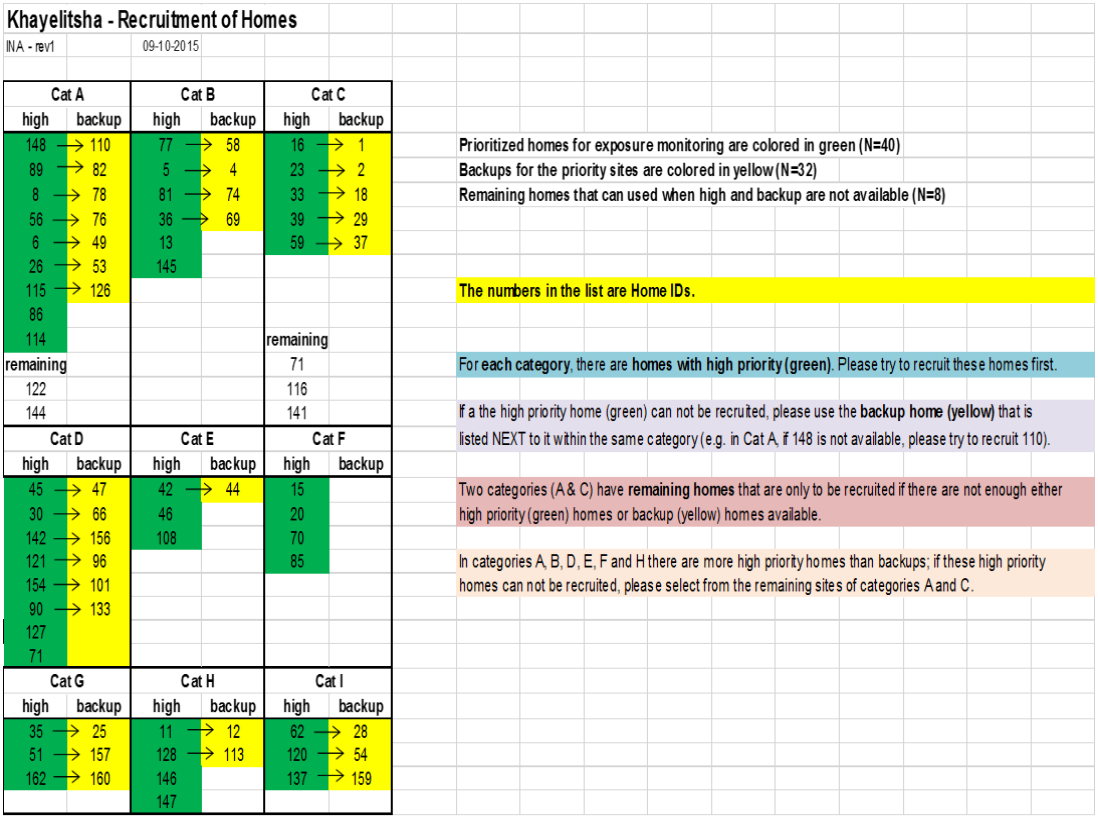
only had 15 households demarcated for exposure assessment. Lastly, these sample size numbers were derived from the main health study of asthma exposure-response that elaborates on random participant's selection rationale and numbers sampled in the neighbourhoods (Olaniyan et al., 2017).

Every monitored neighbourhood had a representative number of 40 households with the exception of the control area Noordhoek (Masiphumelele) that was allotted only 15 households for exposure monitoring. The reason for including few households' numbers for monitoring in Noordhoek (Masiphumelele) is mere because this area was only included in the concluding phases of planning. Therefore, during this phase, there was insufficient funding for a total number of 40 households in this neighbourhood.

The monitored households were selected from a map of the GIS co-ordinates entailing all the houses of participants in each area obtained from house visits during the cohort study. Households selected for monitoring were considered to provide the best image of the spatial distribution of the pollutants within various distances of measured households. The GIS coordinates of the households considered for exposure monitoring were obtained during visits to the main health study of asthma exposure-response. Refer to Annexure A for a home sampling checklist entailing a section for recording household GIS coordinate's information.

A figure below further depicts the selection of the monitored households per neighbourhood (Figure 3.3). During the main health study of asthma exposure-response, detailed information was obtained from the guardian/parents of the children for quality control purposes during visits of households. Detailed information included finding out from the parents or guardian if the household had access to electricity and confirming GIS-coordinates. Furthermore, during visits, a checklist was used to capture the neighbourhood information.

The checklist was used to tick and record information such as GIS coordinates, site type and any nearby possible pollution sources within a range of 1000 meters, amongst other information. GIS co-ordinates aided to circumvent exposure assessment of households clustered in one area because the spatial variation of air pollution has been reported to occur within further distances of households from each other.



Khayelitsha - Recruitment of Homes

INA - rev1 09-10-2015

Cat A		Cat B		Cat C	
high	backup	high	backup	high	backup
148 →	110	77 →	58	16 →	1
89 →	82	5 →	4	23 →	2
8 →	78	81 →	74	33 →	18
56 →	76	36 →	69	39 →	29
6 →	49	13		59 →	37
26 →	53	145			
115 →	126				
86					
114				remaining	
remaining				71	
122				116	
144				141	

Cat D		Cat E		Cat F	
high	backup	high	backup	high	backup
45 →	47	42 →	44	15	
30 →	66	46		20	
142 →	156	108		70	
121 →	96			85	
154 →	101				
90 →	133				
127					
71					

Cat G		Cat H		Cat I	
high	backup	high	backup	high	backup
35 →	25	11 →	12	62 →	28
51 →	157	128 →	113	120 →	54
162 →	160	146		137 →	159
		147			

Prioritized homes for exposure monitoring are colored in green (N=40)

Backups for the priority sites are colored in yellow (N=32)

Remaining homes that can used when high and backup are not available (N=8)

The numbers in the list are Home IDs.

For **each category**, there are **homes with high priority (green)**. Please try to recruit these homes first.

If a the high priority home (green) can not be recruited, please use the **backup home (yellow)** that is listed NEXT to it within the same category (e.g. in Cat A, if 148 is not available, please try to recruit 110).

Two categories (A & C) have **remaining homes** that are only to be recruited if there are not enough either high priority (green) homes or backup (yellow) homes available.

In categories A, B, D, E, F and H there are more high priority homes than backups; if these high priority homes can not be recruited, please select from the remaining sites of categories A and C.

Figure 3.3: Prioritised home for exposure monitoring coloured in green, backups coloured in yellow and remaining homes to be used when prioritised and backup are not available.

Furthermore, households were selected and prioritised based on the following characteristics: the main criterion for selecting houses was the density of buildings and site types. Site types were distinguished into three, the street type which is less than 50 meters from a major road, an urban background which is 100 meters away from the major road and the regional background which is further 200 meters away from the major road (Beelen et al., 2013). Furthermore, Eeftens et al. (2012) and (2013) adopted similar methodological approaches in the studies of land use regression model development. Therefore it was appropriate for this study to adopt similar methodological approaches that have included determining exposure by site types and considering the land use activities that pose as predictor variables for air pollution in the neighbourhoods.

The households meeting above-mentioned criterions were analysed and prioritised using a GPS device. GIS device was used to prioritise the houses with the intention to maximise spatial variation and to increase contrast in exposure. Baxter et al. (2013) corroborated that in order to achieve variability of populations exposure, monitoring instruments should be 10 miles away from each other.

The number of households included per neighbourhood for monitoring was derived based on a strategy described in the paper of Lee et al. (2014). The strategy suggested that in order to achieve an enhanced spatial variation of air pollution, a minimum number of forty (40) sampling sites is required. Thus, a minimum number of 40 sampling sites were considered for monitoring in the three neighbourhoods.

Subsequently, air measurements exposures were conducted in the selected households. Gases were sampled both indoor and outdoor with the intentions of determining exposure pollutants variability in the selected households. Sampling measurements were conducted seasonally during summer and winter in every neighbourhood to increase chances of determining seasonal variability within monitored neighbourhoods.

The coordinates of each monitored location were determined and geocoded using GPS and linked to their respective neighbourhood. Monitoring was conducted for a period of 4 weeks in each neighbourhood per season. During this 4 week period, 10 households were monitored per week. Sampling checklists were used as recording tools for ensuring consistency and record keeping for both particles and gases at the monitoring sites, refer to Annexure: B, C, D, E and F. Lastly, out of the ten possible households monitored per week in each area, one household was randomly selected for monitoring both indoor and outdoor air pollution, while ambient monitoring of criteria pollutants was conducted in other houses.

3.4 Air pollution exposure measurements

3.4.1 Gases

Gases were measured using passive passam samplers, see Figure 3.4. The passam passive samplers are capable of collecting integrated (one average concentration value) indoor and outdoor data with the averaging time being the same as exposure time. Gases were sampled both indoor and outdoor, with the intentions of determining pollutants variability in the monitored households (Figure 3.7). To ensure quality control field blanks and duplicates samplers were

part of monitoring samples in the monitored environment. The field blanks were exposed for a few seconds in the sampling environment.

Additionally, “the diffusive passive samplers of ozone, sulphur dioxide, nitrogen dioxide and carbon monoxide have distinguished characteristics. For instance, the ozone diffusive sampler is based on the diffusion of ozone along a tube to an absorbing medium. The chemisorption of ozone takes place by reaction with Sodium nitrite. In the presence of ozone, the nitrite ion is oxidized to nitrate ions. The passive samplers are constructed with a polypropylene housing with an opening of 20 mm in diameter. To reduce wind disturbance a membrane is attached, supported by a wire net. At the closed end, there is a glass fibre filter dipped in a solution of sodium nitrite in acetic acid. The amount of nitrate is determined by ion chromatography” (Passam ag, 2017).

The passive sampler of sulphur dioxide is based on the principle of “diffusion of sulphur dioxide molecules onto the absorbent made out of potassium carbonate and glycerin. The quantification is done by ion-chromatography. The samplers are composed of a polypropylene housing with an opening of 20 mm in diameter. To exclude wind and weather disturbances, a glass fibre membrane supported by a wire net is attached and set up in an especially designed protective suspension device. In contrast, the passive samplers to measure nitrogen dioxide are based on the principle of the NO_2 diffusion onto the absorbent triethanolamine. The collected NO_2 is then determined spectrophotometrically by the well-established Saltzmann method. Being designed for running without power supply, the samplers are optimized to operate in challenging environments” (Passam ag, 2017).

Lastly, the passive samplers to measure carbon monoxide is based on “the principle of the diffusion of CO molecules onto the absorbing medium Palladium chloride. The formed metallic Palladium can then photometrically be determined by a specific reaction. The samplers are composed of a polypropylene housing with an opening of 20 mm in diameter. To exclude wind and weather disturbances, a glass fibre supported by a wire net is attached and set up in a protective shelter” (Passam ag, 2017).

3.4.2 Particulate Matter

To determine exposure assessment for particulate matter, active sampling methods were used for indoor and outdoor measurements (Figure 3.7). All particulate matters were collected using centrifugal cyclone particle size cut $PM_{2.5}$ at 4 LPM (Figure 3.5). $PM_{2.5}$ was measured using Mesa Labs GK2.05 (KTL) cyclone with the GilAir Plus Air Sampling Pump from Sensidyne. The centrifugal cyclone instrument conforms to US EPA (PM) 2.5 Standard with a 50% cut point of 2.5. As filters, the SKC, PTFE, 2.0, 37MM were used in leak-free 3PCS filter cassettes. The filter was weighted at Swiss TPH using a custom made weighing chamber and a Mettler UMX2 microbalance. The pumps were programmed to operate 15 minutes per hour.

Figure 3.4: Samplers

Figure 3.5: Tubing attached to centrifugal cyclone used for particulate matter

The centrifugal cyclone collected particles smaller than 2.5 mm ($PM_{2.5}$) or smaller than 10 mm (PM_{10}) at a flow rate of 4 litres per minute (Eeftens et al., 2012). To circumvent overload of filters the pumps were programmed to operate 15 minutes per hour for a period of 7 days. To avoid a shortage of power and or power failure during sampling activities sampling pumps were attached to docking stations and connected to the main power plug supply. Airflow was measured before and after sampling using the same type of rotameters in Cape Peninsula University of Technology's occupational health and safety laboratory.

3.4.3 Quality Control

Teflon Filters were transported from the Swiss Tropical Public Health Institute (STPH), having been pre-weighed, stored and shipped cold (4 Degrees Celsius) to South Africa. Prepared samplers from Swiss Tropical Health Institute were kept in the refrigerator to sustain cold chain in the occupational health and safety laboratory in the Cape Peninsula University of Technology.

Samples were carried in the cooler box with ice blocks to the designated sampling environment to ensure cold chain is sustained and not compromised. Sampling pumps were calibrated in the occupational health and safety laboratory using Gillibrator-2 (Sensidyne, 2016). Rotameters

based only in occupational health and safety laboratory were used to confirm the accurate flow rate of 4 litres per minute in the laboratory after calibration of pumps, see Figure 3.6.

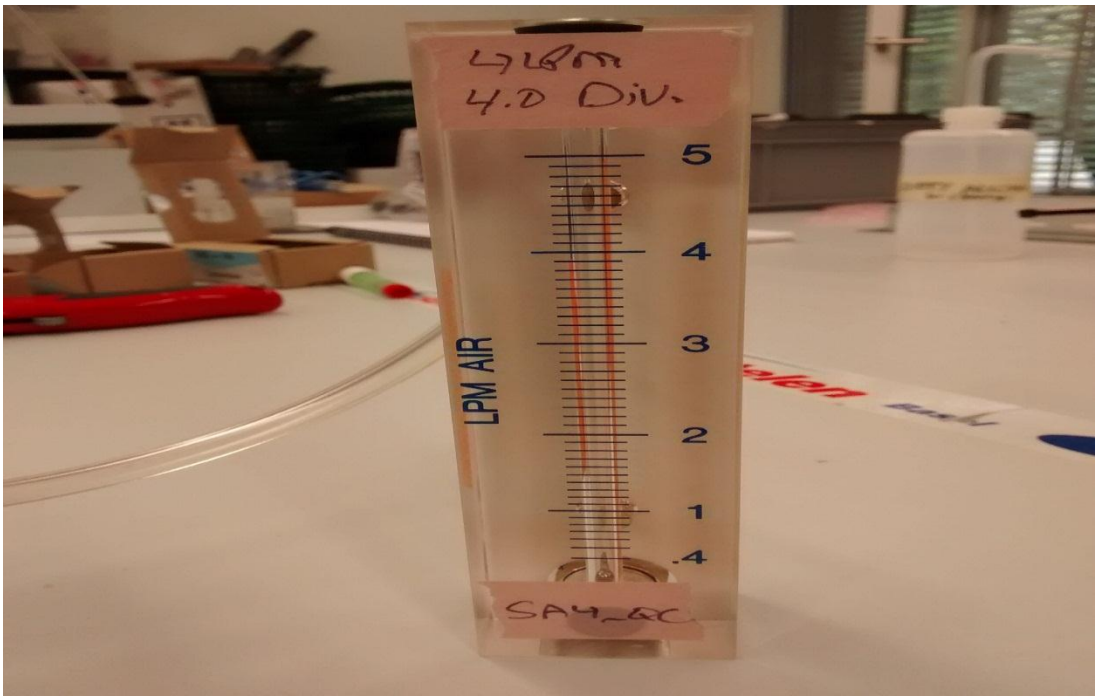


Figure 3.6: Rotameters used for volumetric flow

Field assigned rotameters were taken to the sampling field to re-test and ensure that the accuracy of flow rate is still within 4 litres per minute. A Gillibrator-2 primary calibrator uses a mild soap solution to create a bubble inside an internal chamber. The bubble is pulled from the bottom of the chamber to the top by the air-flow created by the sampling pump. The bubble is timed by the Gillibrator-2 and a flow rate is calculated by the amount of time it takes the bubble to travel from the bottom of the chamber to the top (Sensidyne, 2016).

Always before and after sampling, the sampling pump program was reinstalled in the lab to ensure that the pump only runs for 15 minutes per hour for a period of seven days. Samples from the monitored area were kept in the cooler box during transportation to the health and safety laboratory in the Cape Peninsula University of Technology where they were subsequently stored in the refrigerator to maintain cold chain before being shipped back to the Swiss Tropical Public Health Institute.

Subsequently, the samples were shipped to Switzerland laboratory for analysis. Samples were analysed by Passam ag, an accredited testing laboratory for air quality based in Switzerland. Samples were analysed using spectrophotometry, gas and ion chromatography in accordance with the standard ISO/IEC 17025 (Passam ag, 2017).

Figure 3.7: Example of indoor and outdoor setup

3.4.4 Exposure predictor variables

There are several variables that are associated with exposure to air pollutants. Pratt et al. 2014 demonstrated that emissions from traffic-related sources (e.g. distance to major roads) were important predictors of associated with $PM_{2.5}$ and NO_2 exposure. GIS data on road networks were available in the form of shape-files received from the City of Cape Town for three of the four study areas. Road networks were categorized into three groups: major roads, medium roads and smaller roads based on size and location. However, parts of these data files were

incomplete, with respect to households and more specifically road categorization. Additional information was sourced from the City of Cape Town with regards to the following – bus routes and stops (separated into two categories between “IRT” (Integrated Rapid Transfer bus system, and “GA” Golden Arrow, older bus system and taxi routes.

Furthermore, data on specific point sources of air pollution that are important within these areas and not presented in GIS information were collected during the weeks of assessment (Annexure I). A separate protocol was developed for collection of specific point sources of air pollution, which are rather informal and therefore not accounted for in the usual GIS datasets and which could explain part of the spatial variation of NO_2 and $PM_{2.5}$. These data have an important impact on the variation of air pollution within these areas and included the following, such as open grills, waste collection or burning sites and construction sites. These predictor variables were categorised within the proximity radius (buffer zones) of 25, 50, 100, 300, 500 and 1000 meters based on geographical coordinates.

3.5 Data management

Environmental sampling data collection sheets were coded for double entry. All data collection sheets were stored in confidential files until the completion of the study and then destroyed. Independent checks of range, validity, consistency and missing data were performed.

3.6 Statistical analysis and modelling

All statistical analyses were performed using Stata V12 and SAS software. Exposure values below the limit of detection were replaced by two-thirds of the limit. Descriptive univariate statistics were generated for the total sample distribution. Linear regression models were developed to describe the determinants of variability of the various exposure metrics. Environmental data normally follows a lognormal distribution; thus, the natural logarithm of the measured air pollution was used as the dependent variable. The units of measurements for concentration levels are ug/m^3 for O_3, PM, NO_2 and SO_2 respectively, except the units of measurement for CO which is mg/m^3 respectively. Simple linear regression was used to evaluate the relationship between continuous ambient outdoor exposure levels and the respective predictor variables. Each predictor variable was modelled separately with NO_2 and $PM_{2.5}$ to explore the associations and identify the most important predictors of variability in exposure within these areas. Predictors were considered significant at a 5% and 10% level, due to small sample sizes.

CHAPTER FOUR:
RESULTS

4.1 Introduction

This chapter provides an overview of the results for exposure assessment levels and the predictor variables that influence exposure concentrations. The results are presented for each criteria pollutant overall and stratified per neighbourhood and season. The main pollutants of interest were $PM_{2.5}$, NO_2, SO_2, O_3 and CO's. The analysis also focussed on a selection of indoor and outdoor measurements within these neighbourhoods. Overall, a total of 135 households were selected based on specific criteria discussed in the previous chapter for exposure assessment. For PM2.5 missing data was recorded for 23 and 35 samples for summer and winter respectively. Missing data for NO_2 was recorded in 8 households in summer and 22 in winter. For SO_2 the total missing data samples for 9 households during summer and 33 in winter season were noted.

4.1.1 Summer and winter ambient air pollution measurements

4.1.1.1 Summer and winter exposure levels of $PM_{2.5}$

The overall average weekly $PM_{2.5}$ exposure concentration for summer period was 7.67 µg/m^3, with the highest mean recorded in Milnerton (8.76 µg/m^3) and the lowest in Noordhoek (5.77µg/m^3). An important observation for winter exposure estimates was the heterogeneity of exposure levels in contrast to summer concentrations. The weekly average $PM_{2.5}$ during this season was notably higher and almost double (13.14 µg/m^3) in comparison to the summer season exposure concentration (Table 4.1). Oudtshoorn recorded the highest mean concentration of 16.07 µg/m^3, and Noordhoek the lowest average mean of 7.75 µg/m^3.

Table 4.1: Actual monitored environmental exposure levels of $PM_{2.5}$ µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER					WINTER				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	37	7.06	5.93	1.87	1.12 – 16.18	31	13.37	8.81	2.79	0.98 – 43.39
Milnerton	33	8.76	7.49	1.72	2.25 – 35.42	29	11.71	9.71	2.06	0.82 – 24.32
Noordhoek	14	5.77	5.22	1.63	2.19 – 8.79	10	7.75	6.94	1.82	1.39 – 10.99
Oudtshoorn	28	8.13	6.11	2.21	1.03 – 27.09	30	16.07	11.64	3.19	0.05 – 52.36
Overall	112	7.67	6.29	1.89	1.03 – 35.42	100	13.14	9.62	2.61	0.05 – 52.36

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

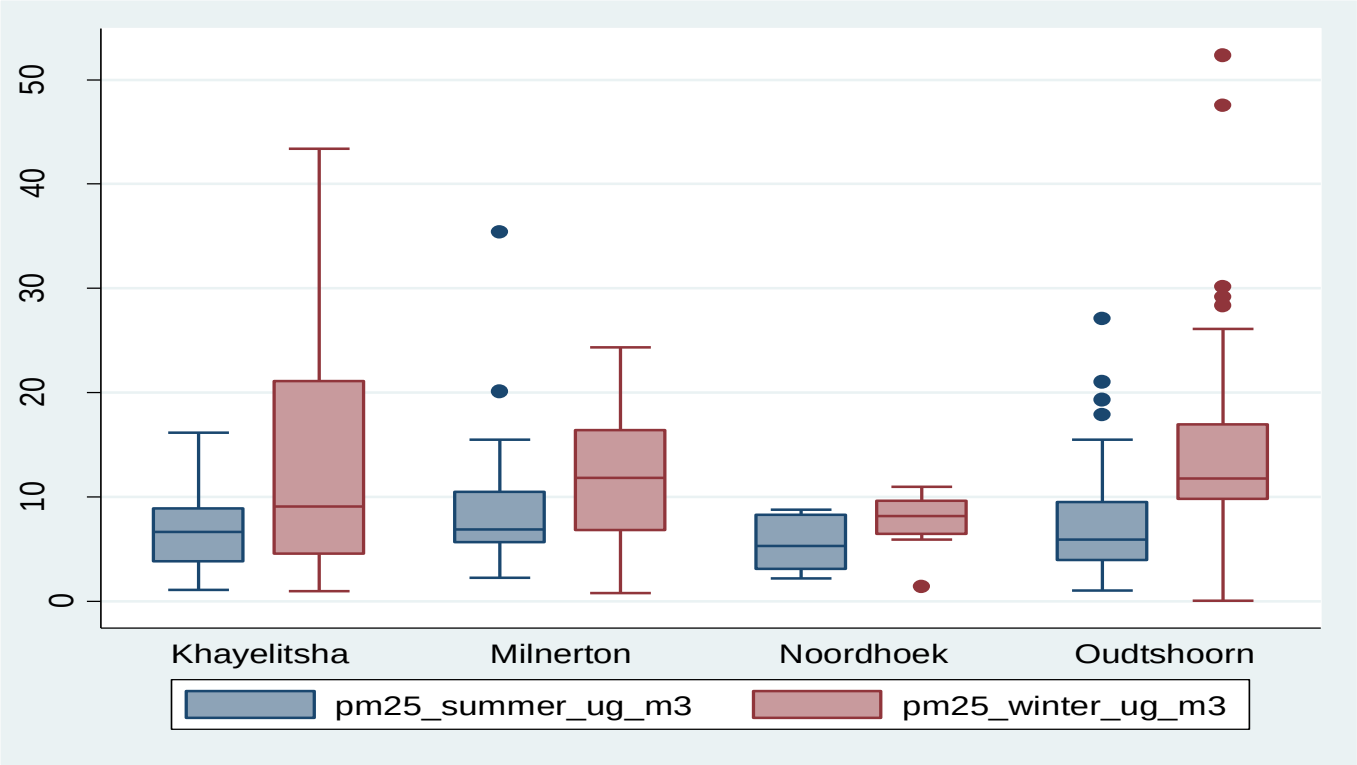


Figure 4.1: Box-and-whisker plot of exposure levels for $PM_{2.5}$ ($\mu g/m^3$) according to seasons

4.1.1.2 Summer and winter exposure levels of NO_2

Winter exposure levels of nitrogen dioxide were higher than the summer season concentrations. Notably, Khayelitsha recorded the highest winter concentration of 35.69 $\mu g/m^3$ compared to other neighbourhoods (Table 4.2). The overall average weekly exposure to NO_2 was 13.27 $\mu g/m^3$, with the highest exposure concentration of 16.32 $\mu g/m^3$ recorded in Milnerton and the lowest observed in Noordhoek and Oudtshoorn.

Table 4.2: Actual monitored environmental exposure levels of NO_2 µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER					WINTER				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	40	15.73	13.62	2.03	0.4 – 28.4	36	35.69	35.29	11.64	25.2 – 50.2
Milnerton	35	16.32	16.00	1.19	11.7 – 22.8	30	29.09	28.72	1.18	19.1 – 38
Noordhoek	15	9.11	7.35	1.71	4.8 – 44.1	14	10.04	9.95	1.15	8.3 – 13.9
Oudtshoorn	37	9.49	9.13	1.33	4.7 – 18.3	33	7.24	6.82	1.41	3.9 – 17.4
Overall	127	13.27	11.78	1.72	0.4 – 44.1	113	22.45	17.67	2.14	3.9 – 50.2

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

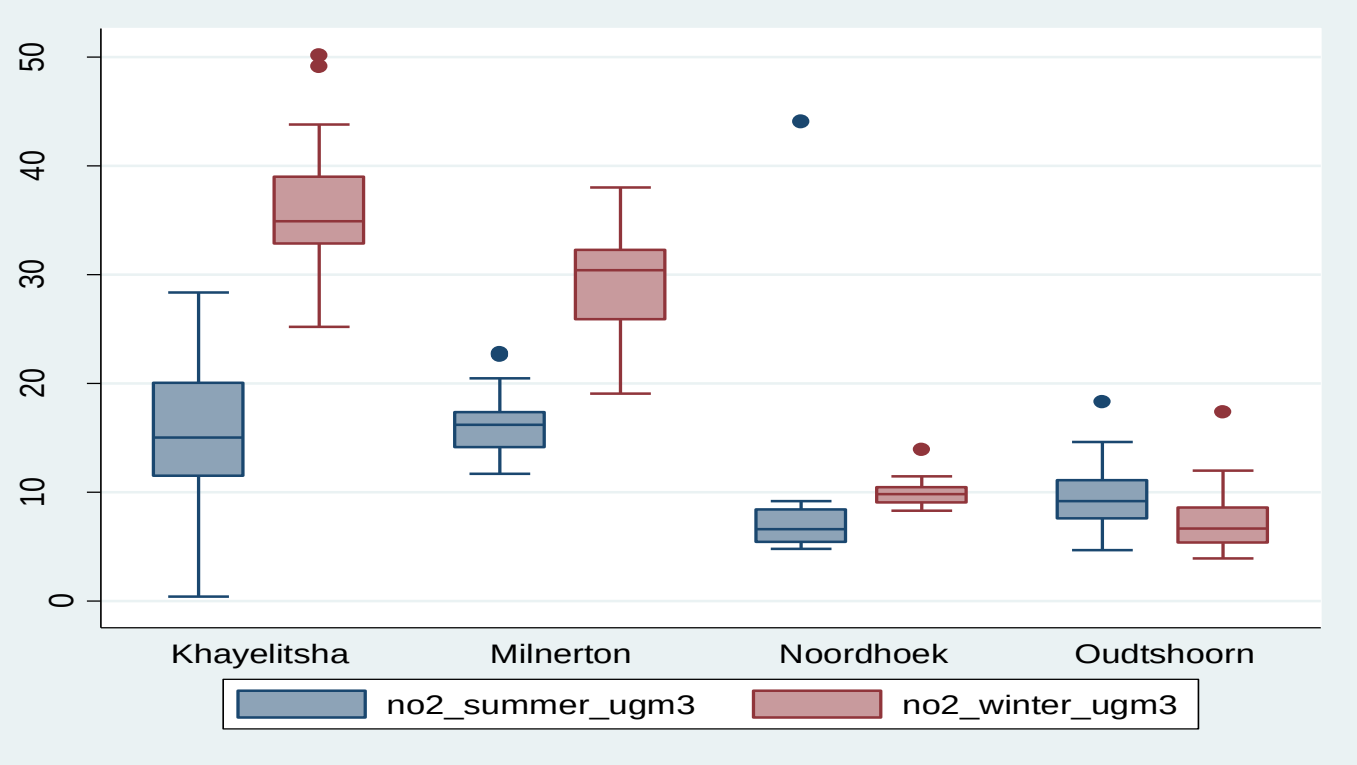


Figure 4.2: Box-and-whisker plot of exposure levels for NO_2 (µg/m^3) according to seasons

4.1.1.3 Summer and winter exposure levels of SO_2

Exposure assessment levels of summer and winter were relatively low. The highest concentration between these two seasons was recorded in Oudtshoorn neighbourhood during summer season (4.52 µg/m^3). Khayelitsha and Noordhoek average concentrations were relatively comparable (Table 4.3). Whereas in winter the average concentration of SO_2 was 1.71 µg/m^3.

Table 4.3: Actual monitored environmental exposure levels of SO_2 µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER					WINTER				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	39	3.14	2.02	1.01	0.5 – 10.1	32	0.81	0.64	0.55	0.5 – 4.7
Milnerton	35	1.43	0.98	0.79	0.5 – 0.6	29	2.31	1.64	0.88	0.5 – 0.9
Noordhoek	14	3.1	3.03	0.22	2.0 – 4.4	12	1.5	0.76	0.96	0.5 – 9.8
Oudtshoorn	38	4.52	2.99	1.11	0.5 – 11.5	29	2.19	1.38	0.95	0.5 – 9.7
Overall	126	3.08	1.94	2.80	0.5 – 11.5	102	1.71	1.06	2.48	0.5 – 9.8

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation; LOD: Limit of Detection SO_2: 0.6 µg/m^3.

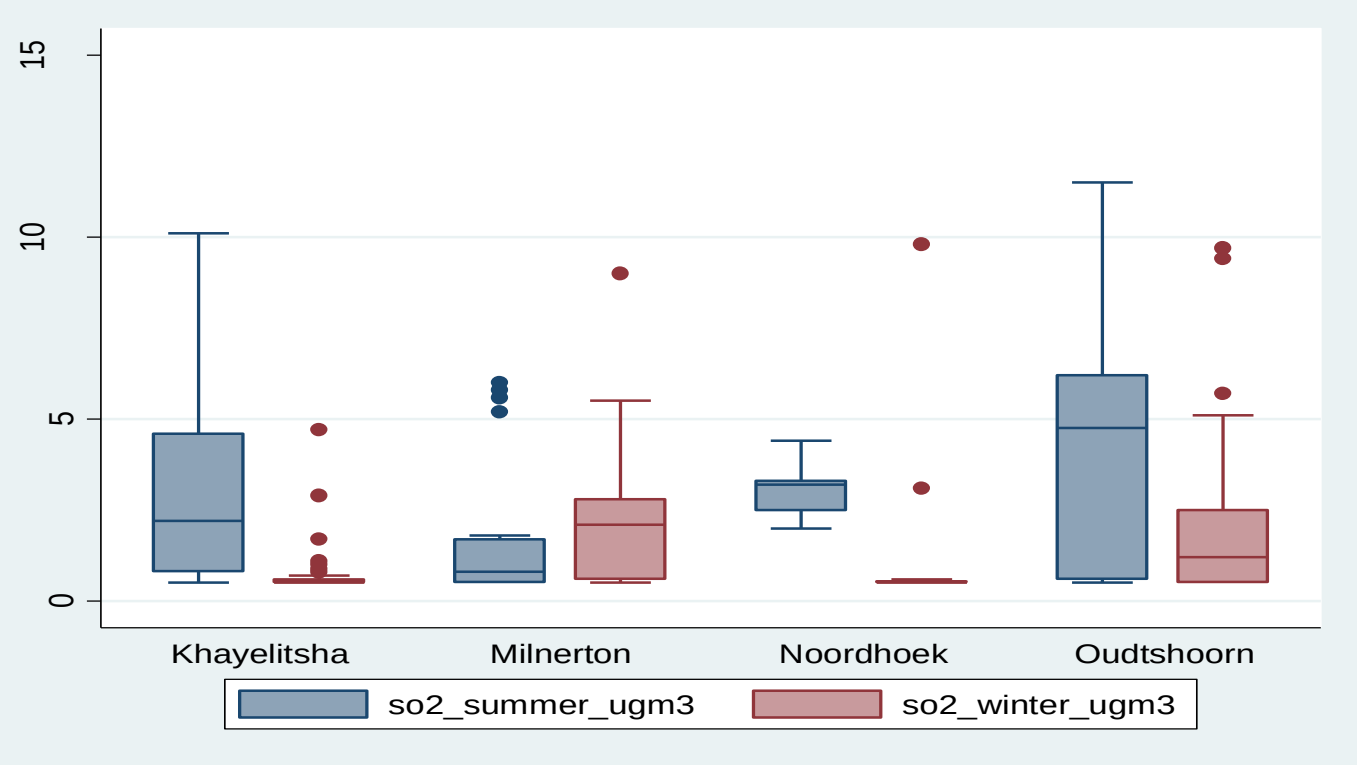


Figure 4.3: Box-and-whisker plot of exposure levels for SO_2 (µg/m^3) according to seasons

4.2 Summer indoor and outdoor air pollution measurements

4.2.1 Summer indoor and outdoor exposure levels of $PM_{2.5}$

The summer $PM_{2.5}$ results reveal relatively comparable indoor (8.35 µg/m3) and outdoor concentrations (7.59 µg/m^3) (Table 4.4). Indoor maximum mean concentrations were detected in Oudtshoorn (9.79 µg/m^3) during summer and Milnerton neighbourhoods (9.83 µg/ m^3) during the winter season.

Table 4.4: Actual monitored environmental exposure levels of $PM_{2.5}$ µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER INDOOR				SUMMER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	10	8.59	7.11	0.71	2.29 – 14.44	10	7.23	6.30	0.58	3.01 – 10.64
Milnerton	3	7.45	6.26	0.71	3.38 – 13.63	4	9.83	9.81	0.07	9.21 – 10.47
Noordhoek	3	5.55	4.69	0.78	1.91 – 7.69	2	6.38	6.24	0.29	5.05 – 7.71
Oudtshoorn	6	9.79	4.58	1.38	1.64 – 34.96	6	7.10	5.03	0.89	1.56 – 21.05
Overall	22	8.35	5.86	0.90	1.16 – 34.96	22	7.59	6.42	0.63	1.56 – 21.05

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation

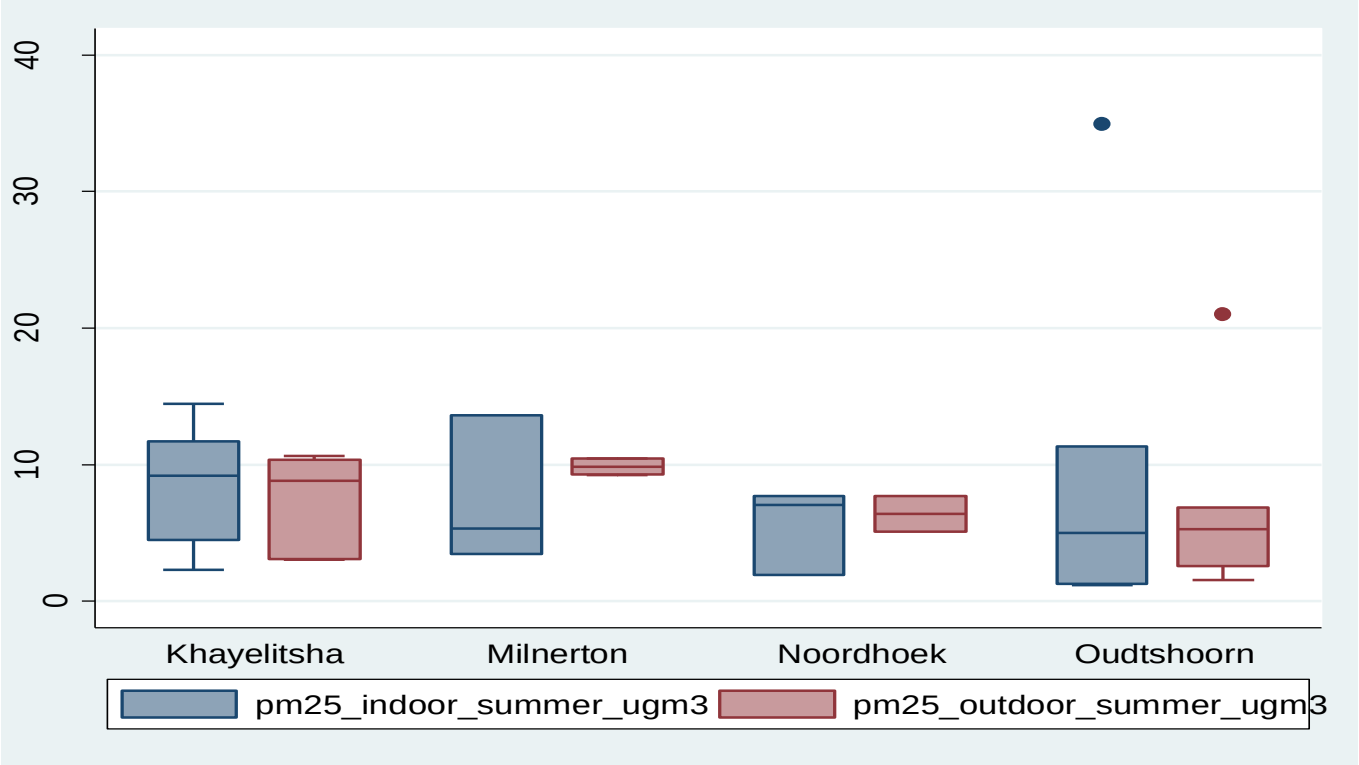


Figure 4.4: Box-and-whisker plot of exposure levels for $PM_{2.5}$ (µg/m^3) according to season

4.2.2 Summer indoor and outdoor exposure levels of NO_2

The indoor exposure assessment levels of NO_2 were assessed in 29 sites amongst the four neighbourhoods. Overall, the summer average indoor NO_2 results between the study areas were 9.24 µg/m^3, with the highest concentration detected in Milnerton neighbourhood (13.86 µg/m^3) and with the lowest concentration recorded in Noordhoek (4.2 µg/m^3). In contrast, observed outdoor levels were slightly higher than the indoor exposure estimates. The outdoor neighbourhood average concentration of NO_2 was 11.99 µg/m^3 (Table 4.5), with the highest recorded concentration observed in Milnerton 15.36 µg/m^3 and Noordhoek recording the lowest concentration of 5.47 µg/m^3.

Table 4.5: Actual monitored environmental exposure levels of NO_2 µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER INDOOR				SUMMER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	11	9.85	6.24	1.39	0.4 – 15.9	12	14.37	8.67	1.48	0.4 – 32.4
Milnerton	5	13.86	13.80	0.10	12.9 – 16.5	5	15.36	15.34	0.59	14.4 – 16.6
Noordhoek	3	4.2	4.13	0.23	3.2 – 5	3	5.47	5.39	0.20	4.8 – 6.8
Oudtshoorn	9	7.6	7.15	0.37	4.5 – 12.6	9	9.14	8.57	0.36	6.1 – 18.3
Overall	28	9.24	7.19	0.94	0.4 – 16.5	29	11.99	9.07	0.99	0.4 – 32.4

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation; LOD: Limit of Detection NO_2: 0.4 µg/m^3.

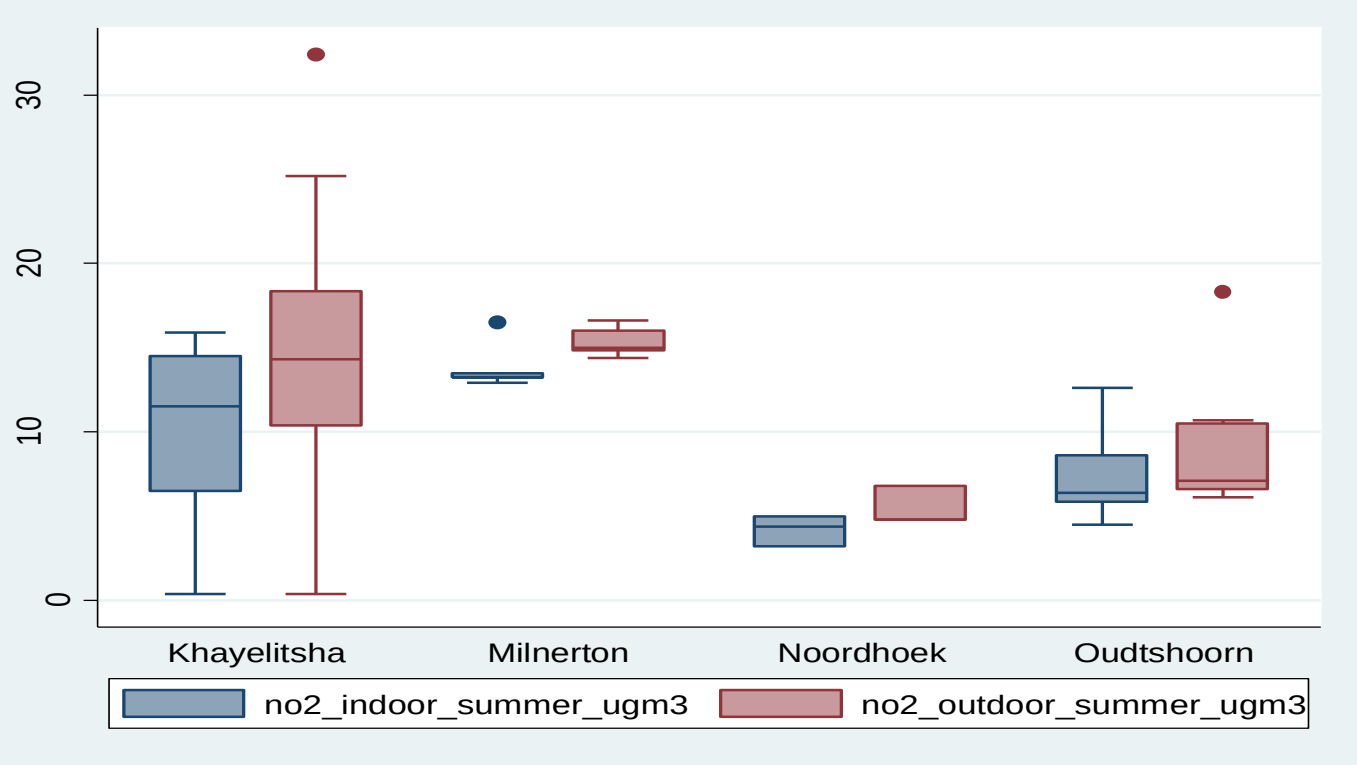


Figure 4.5: Box-and-whisker plot of indoor and outdoor exposure levels for NO_2 (µg/m^3) according to season

4.2.3 Summer indoor and outdoor exposure levels of SO_2

Relatively low exposure concentrations of SO_2 were recorded between indoor and outdoor in the 4 neighbourhoods. The SO_2 exposure levels for indoor were relatively comparable between Oudtshoorn (4.46 µg/m^3) and Noordhoek (3.3 µg/m^3) neighbourhoods, with the exception of Milnerton (0.64 µg/m^3) that recorded lowest concentrations. Whereas outdoor average exposure level (4.5 µg/m^3) of SO_2 almost recorded the double average concentration of indoor exposure (Table 4.6), with the highest concentration recorded in Oudtshoorn (7.38 µg/m^3). Noordhoek and Milnerton detected lowest mean concentrations of 2.43 µg/m^3 and 1.5 µg/m^3 respectively.

Table 4.6: Actual monitored environmental exposure levels of SO_2 µg/m^3 in the Western Cape's four neighbourhoods

	SUMMER INDOOR				SUMMER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	12	2.08	1.52	0.85	0.6 – 0.6	12	4.11	3.23	0.86	0.6 – 7.7
Milnerton	5	0.64	0.64	0.13	0.6 – 0.8	5	1.5	1.41	0.42	0.7 – 2.1
Noordhoek	3	3.3	2.57	0.84	1.4 – 6.7	3	2.43	2.43	0.62	2.3 – 2.6
Oudtshoorn	9	4.46	4.24	0.32	2.9 – 7.5	9	7.38	6.95	0.38	3.5 – 10.2
Overall	29	2.69	1.89	0.90	0.6 – 7.5	29	4.5	3.45	0.82	0.6 – 10.2

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation; LOD: Limit of Detection SO_2: 0.6 µg/m^3.

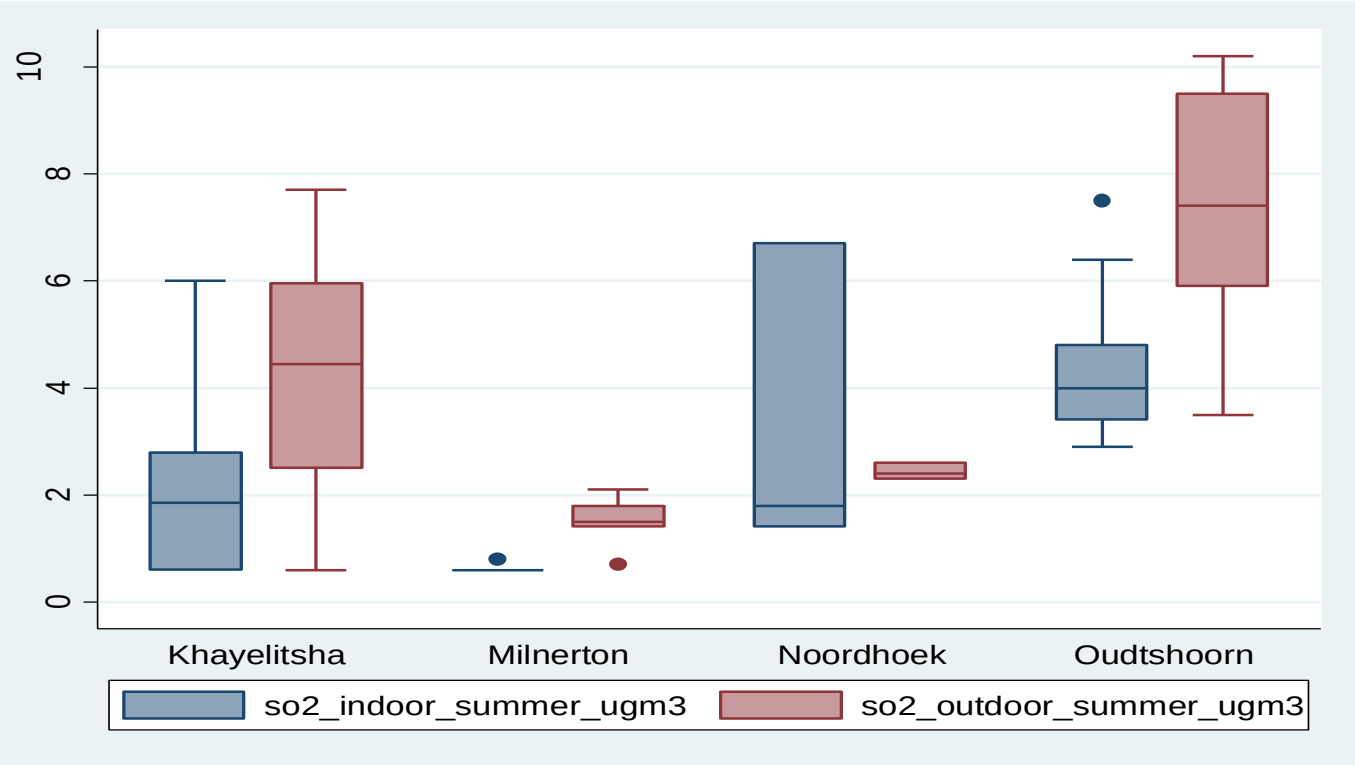


Figure 4.6: Box-and-whisker plot of indoor and outdoor exposure levels for SO_2 (µg/m^3) according to season

4.2.4 Summer indoor and outdoor exposure levels of O_3

The indoor exposure assessment levels of Ozone indicated the low average concentration of 1.19 µg/m^3. Noordhoek neighbourhood compared to Milnerton (1.55 µg/m^3) and Oudtshoorn (1.09 µg/m^3) recorded relatively slightly higher concentration (1.83 µg/m^3). However, the lowest exposure concentration of 0.89 µg/m^3 was observed in Khayelitsha (Table 4.7). The outdoor average O_3 concentration (14.25 µg/m^3) results were high compared to indoor exposure levels. The highest mean concentration was recorded in Noordhoek (20.72 µg/m^3), and the lowest mean concentration was detected in Oudtshoorn (11.66 µg/m^3).

Table 4.7: Actual monitored environmental exposure levels of O_3 µg/m^3 in the Western Cape's four neighbourhoods

		SUMMER INDOOR				SUMMER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	8	0.89	0.74	0.65	0.3 – 1.65	8	14.28	12.65	0.51	6.47 – 32.26
Milnerton	4	1.55	1.29	0.77	0.43 – 2.53	4	14.53	14.44	0.13	12.68 – 16.55
Noordhoek	3	1.83	1.33	1.05	0.44 – 3.53	3	20.72	20.25	0.27	14.86 – 24.46
Oudtshoorn	8	1.09	0.77	0.54	0.44 – 2.06	8	11.66	10.88	0.42	4.61 – 17.91
Overall	23	1.19	0.97	0.68	0.3 – 3.53	23	14.25	13.06	0.43	4.61 – 32.26

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation; LOD: Limit of Detection O_3: 0.3 µg/m^3.

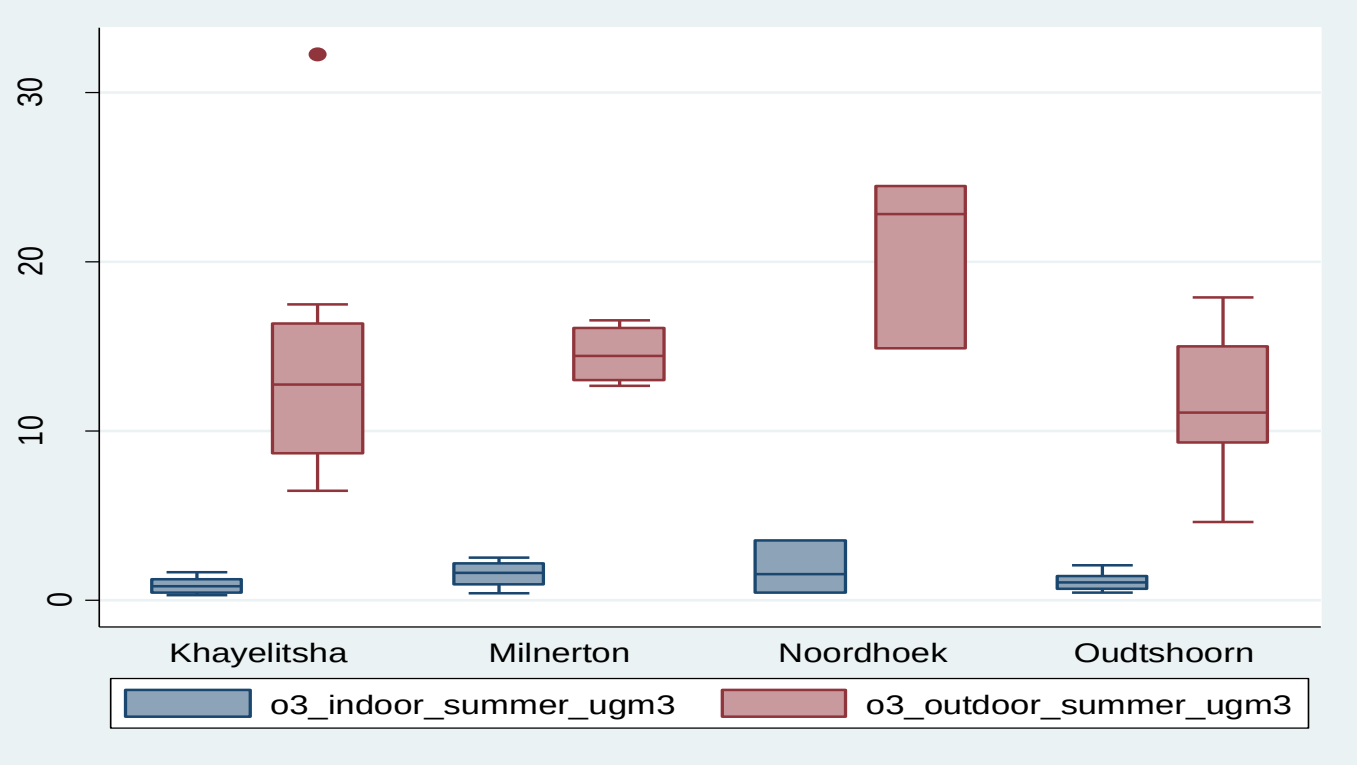


Figure 4.7: Box-and-whisker plot of indoor and outdoor exposure levels for O_3 (µg/m^3) according to season

4.2.5 Summer indoor and outdoor exposure levels of CO

The indoor and outdoor exposure assessment levels of (CO) were comparable. Indoor exposure assessment levels were (5.05 mg/m^3) and outdoor assessment exposure levels recorded (5.65 mg/m^3). The highest mean concentration indoor (5.99 mg/m^3) and outdoor (6.97 mg/m^3) were recorded in Oudtshoorn neighbourhood (Table 4.8).

Table 4.8: Actual monitored environmental exposure levels of CO mg/m^3 in the Western Cape's four neighbourhoods

	SUMMER INDOOR				SUMMER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	8	4.73	4.53	0.31	2.86 – 8.28	8	4.43	4.26	0.30	2.66 – 6.68
Milnerton	4	4.80	4.43	0.44	3.33 – 8.51	4	5.48	5.37	0.24	3.98 – 6.69
Noordhoek	3	3.71	3.61	0.29	2.69 – 4.79	3	5.56	5.34	0.35	3.56 – 6.86
Oudtshoorn	8	5.99	5.53	0.45	2.46 – 9.19	8	6.97	6.82	0.22	4.71 – 9.80
Overall	23	5.05	4.69	0.39	2.46 – 9.19	23	5.65	5.38	0.32	2.66 – 9.80

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation

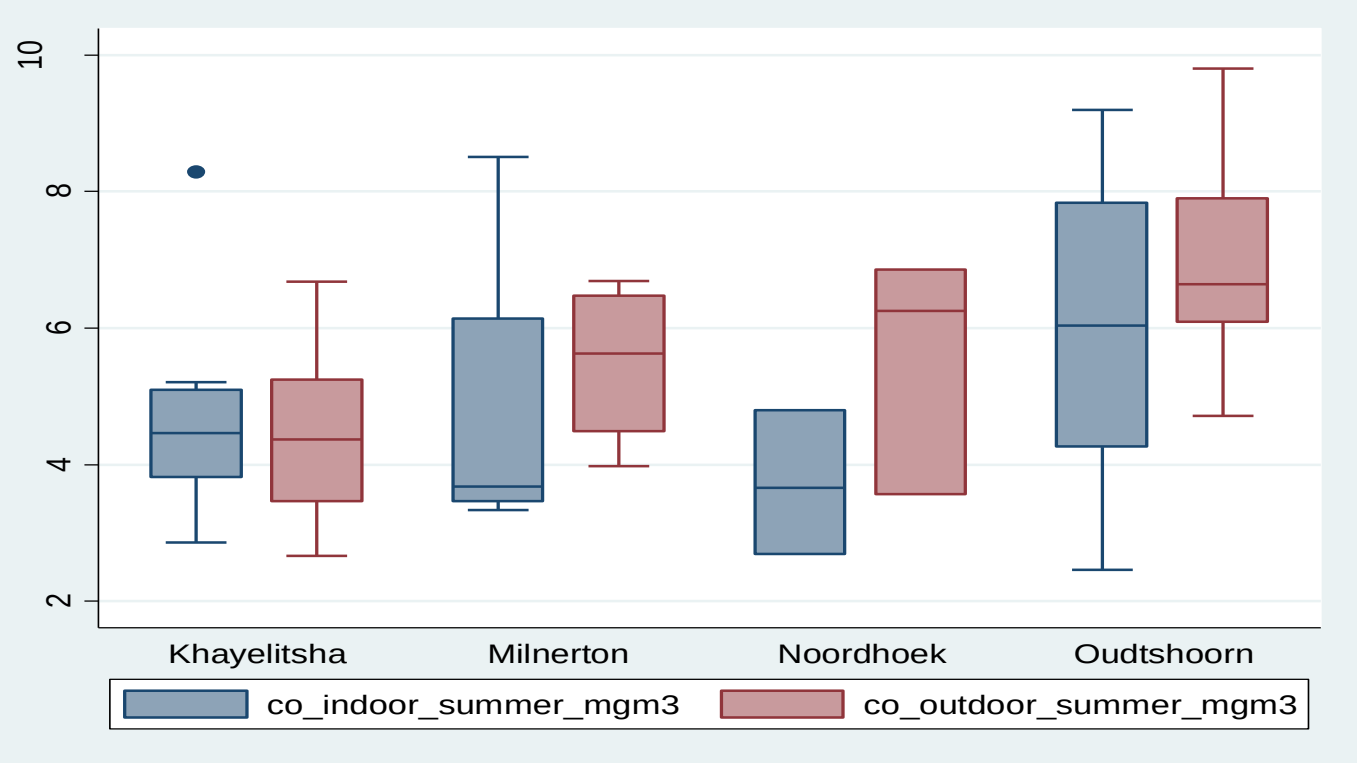


Figure 4.8: Box-and-whisker plot of indoor and outdoor exposure levels for CO (mg/m^3) according to season

4.3 Winter indoor and outdoor air pollution measurements

4.3.1 Winter indoor and outdoor exposure levels of $PM_{2.5}$

The winter exposure assessment results for $PM_{2.5}$ amongst the 4 neighbourhoods reached the exposure average overall concentration of 12.28 µg/m^3 indoors (Table 9). With the highest mean concentration (14.77 µg/m^3) observed in Oudtshoorn neighbourhood. Khayelitsha's neighbourhood recorded 12.26 µg/m^3 of $PM_{2.5}$ exposure levels while the lowest average concentrations of 9.78 and 7.94 µg/m^3 were respectively recorded in the neighbourhoods of Milnerton and Noordhoek respectively. In contrast to indoor, the outdoor exposure overall average concentration was (10.93 µg/m^3), with the highest exposure in Khayelitsha neighbourhood (11.67 µg/m^3). Milnerton (10.99 µg/m^3) and Oudtshoorn (10.84 µg/m^3) recorded comparable exposure levels (Table 4.9).

Table 4.9: Actual monitored environmental exposure levels of $PM_{2.5}$ µg/m^3 in the Western Cape's four neighbourhoods

	WINTER INDOOR				WINTER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	8	12.26	6.80	1.38	0.44 – 33.67	7	11.67	5.78	3.52	1.29 – 36.45
Milnerton	3	9.78	8.74	0.48	5.21 – 13.28	4	10.99	9.38	0.70	3.57 – 18.74
Noordhoek	2	7.94	7.18	0.64	4.55 – 11.33	3	9.27	9.13	0.22	7.19 – 10.99
Oudtshoorn	7	14.77	12.66	0.59	7.10 – 28.22	6	10.84	10.49	1.34	6.53 – 13.91
Overall	20	12.28	8.83	2.63	0.44 – 33.67	19	10.93	8.05	2.31	1.29 – 36.45

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

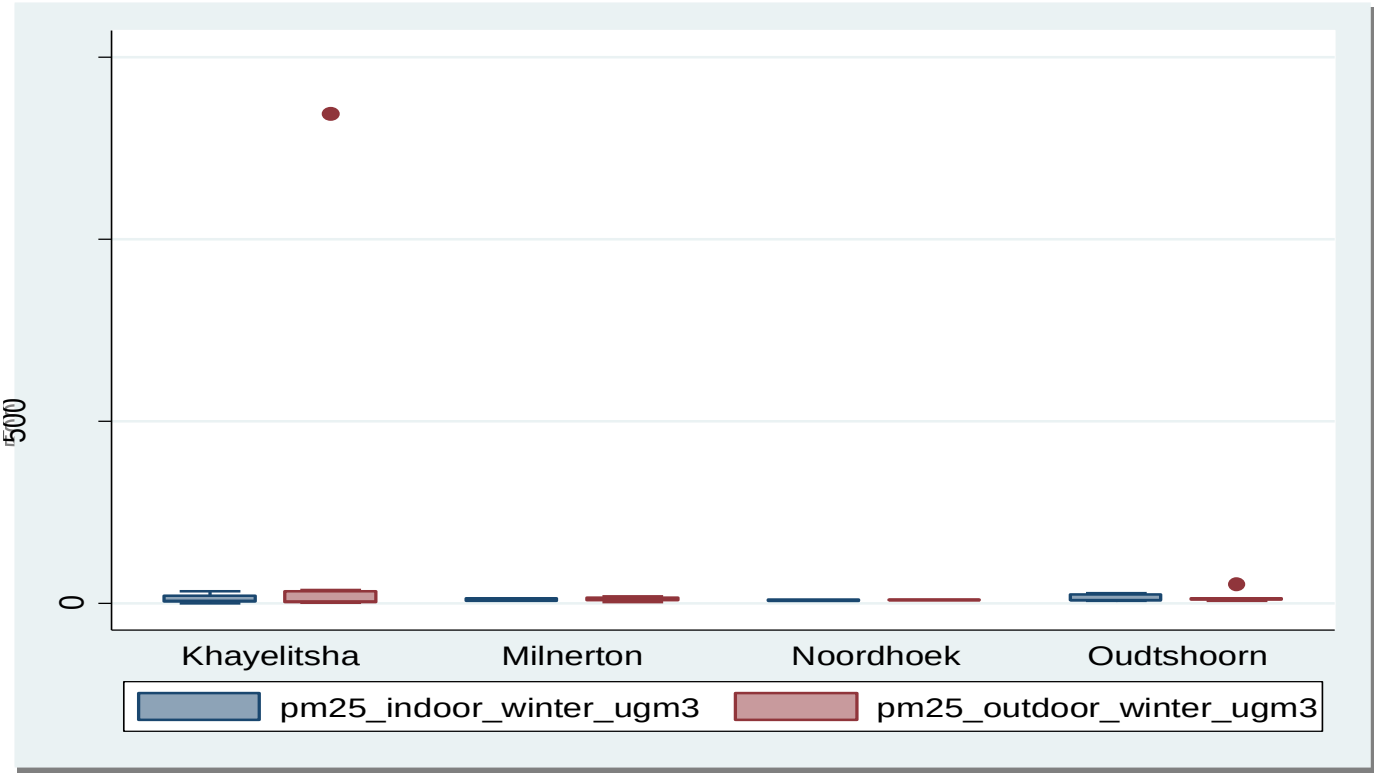


Figure 4.9: Box-and-whisker plot of indoor and outdoor exposure levels for $PM_{2.5}$ ($\mu g/m^3$) according to season

4.3.2 Winter indoor and outdoor exposure levels of NO_2

Nitrogen dioxide indoor and outdoor exposure levels results indicate no substantial difference. The indoor average concentration is (22.03 $\mu g/m^3$) compared to the outdoor average concentration of (24.23 $\mu g/m^3$). However, great exposure level variability is observed between neighbourhoods. Significant indoor and outdoor exposure levels were recorded in Khayelitsha (29.45 $\mu g/m^3$) indoor and Khayelitsha (35.66 $\mu g/m^3$) outdoor respectively (Table 4.10).

Table 4.10: Actual monitored environmental exposure levels of NO_2 µg/m^3 in the Western Cape's four neighbourhoods

	WINTER INDOOR					WINTER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	12	29.45	28.51	0.25	21.3 – 52.6	12	35.66	35.56	0.80	30.1 – 38.7
Milnerton	5	26.46	22.25	0.69	8.2 – 44.6	5	33.58	33.17	0.17	28.3 – 44
Noordhoek	2	19.55	19.53	0.06	18.7 – 20.4	3	12.77	12.24	0.35	9.6 – 18.2
Oudtshoorn	9	10.21	8.00	073	3.6 – 22.3	9	7.6	7.17	0.37	3.9 – 10.2
Overall	28	22.03	17.65	0.76	3.6 – 52.6	29	24.23	19.15	0.78	3.9 – 44

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

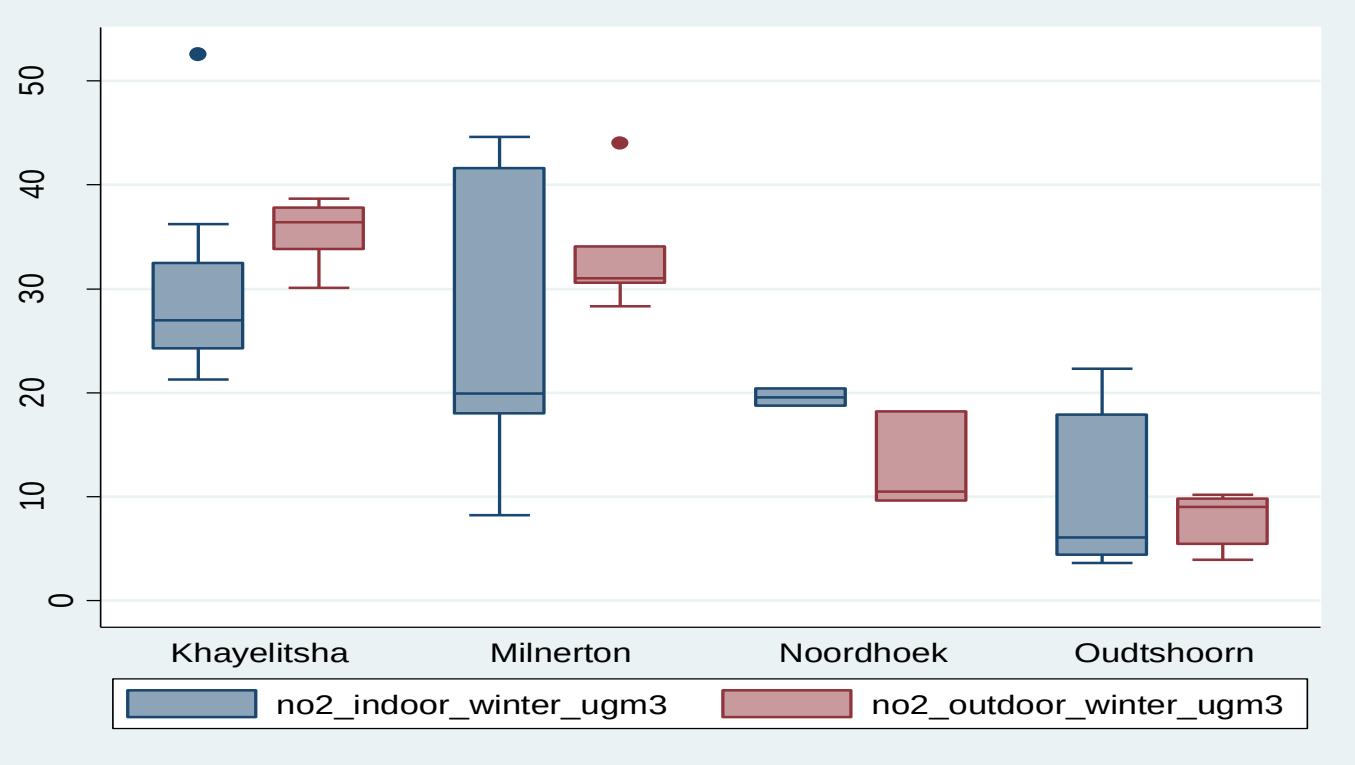


Figure 4.10: Box-and-whisker plot of indoor and outdoor exposure levels for NO_2 (µg/m^3) according to season

4.3.3 Winter indoor and outdoor exposure levels of SO_2

Generally, the exposure assessment concentration of SO_2 indicated indoor and outdoor concentrations. The average indoor concentration was 0.81 µg/m^3, whilst the outdoor average concentration recorded was1.85 µg/m^3 (Table 4.11). The maximum mean concentration for outdoor exposure was recorded in Milnerton neighbourhood with an average of 1.68 µg/m^3.

Table 4.11: Actual monitored environmental exposure levels of SO_2 µg/m^3 in the Western Cape's four neighbourhoods

	WINTER INDOOR					WINTER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	11	0.63	0.62	0.12	0.6 – 0.9	12	0.7	0.68	0.25	0.6 – 1.3
Milnerton	5	0.78	0.72	0.41	0.6 – 1.5	4	1.68	1.27	0.88	0.6 – 3.4
Noordhoek	1	0.6	0.6	0	0.6 – 0.6	3	0.6	0.6	0	0.6 – 0.6
Oudtshoorn	7	1.14	0.90	0.69	0.6 – 2.6	5	0.94	0.78	0.60	0.6 – 14.7
Overall	24	0.81	0.71	0.43	0.6 – 2.6	25	1.45	0.86	0.77	0.6 – 14.7

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation; LOD: Limit of Detection SO_2: 0.6 µg/m^3.

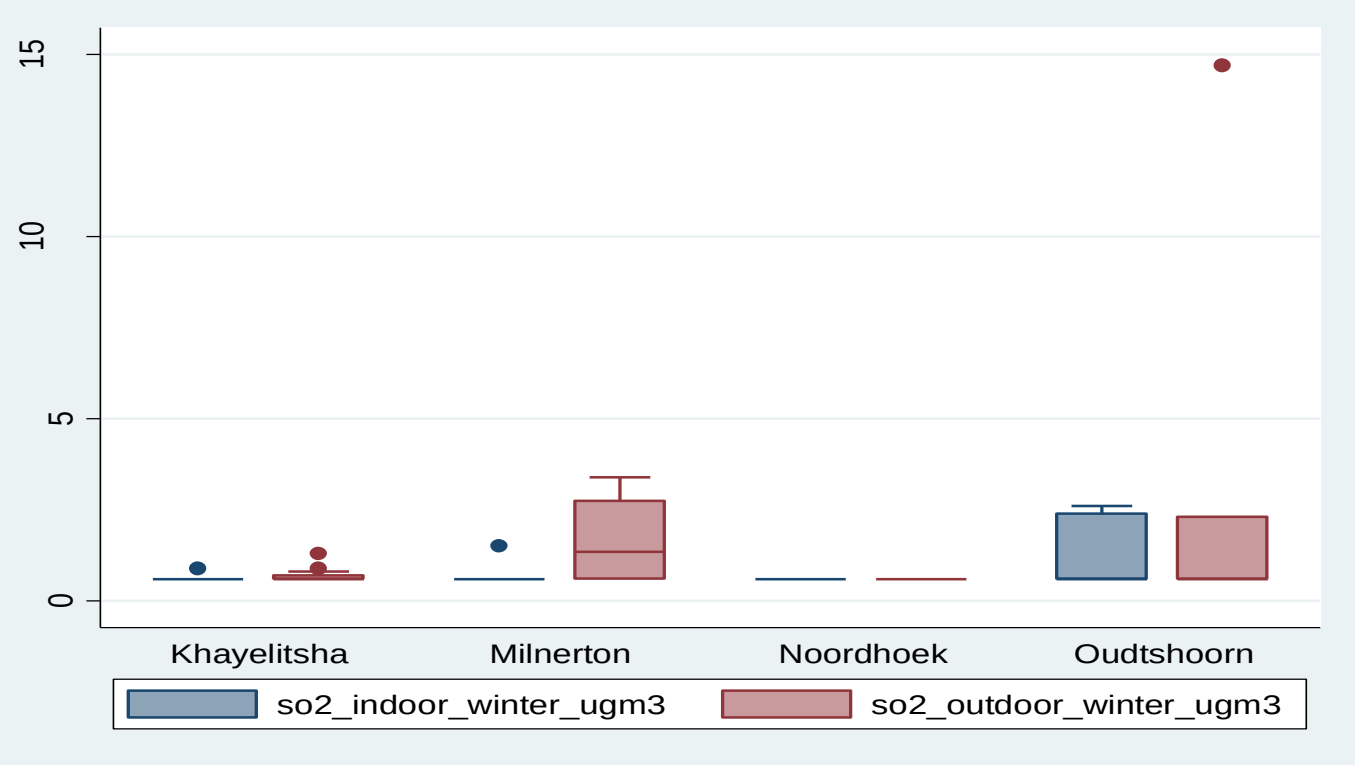


Figure 4.11: Box-and-whisker plot of indoor and outdoor exposure levels for SO_2 (µg/m^3) according to season

4.3.4 Winter indoor and outdoor exposure levels of O_3

Indoor exposure levels of O_3 were considerably low (2.06 µg/m^3) in comparison to outdoor, that was 9 times higher (19.41 µg/m^3) (Table 4.12). The highest indoor mean concentration of 2.74 µg/m^3 was recorded in Khayelitsha neighbourhood. However, in contrast to an indoor, outdoor highest mean concentration between the study areas was recorded in Noordhoek neighbourhood with the average mean concentration of 30.5 µg/m^3 (Table 12).

Table 4.12: Actual monitored environmental exposure levels of O_3 µg/m^3 in the Western Cape's four neighbourhoods

	WINTER INDOOR					WINTER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	8	2.74	1.29	1.27	0.3 – 12.5	8	13.08	8.21	1.56	0.2 - 19
Milnerton	4	1.38	0.55	1.48	2 – 4.6	4	23.92	23.58	0.19	19.8 – 30.5
Noordhoek	2	1.7	1.69	0.08	1.6 – 1.8	3	30.5	30.25	0.16	25.8 – 35.4
Oudtshoorn	3	1.4	1.25	0.57	0.9 – 2.4	4	19.25	18.73	0.28	12.5 – 23.8
Overall	17	2.06	1.08	1.15	0.2 – 12.5	19	19.41	14.98	1.12	0.2 – 35.4

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

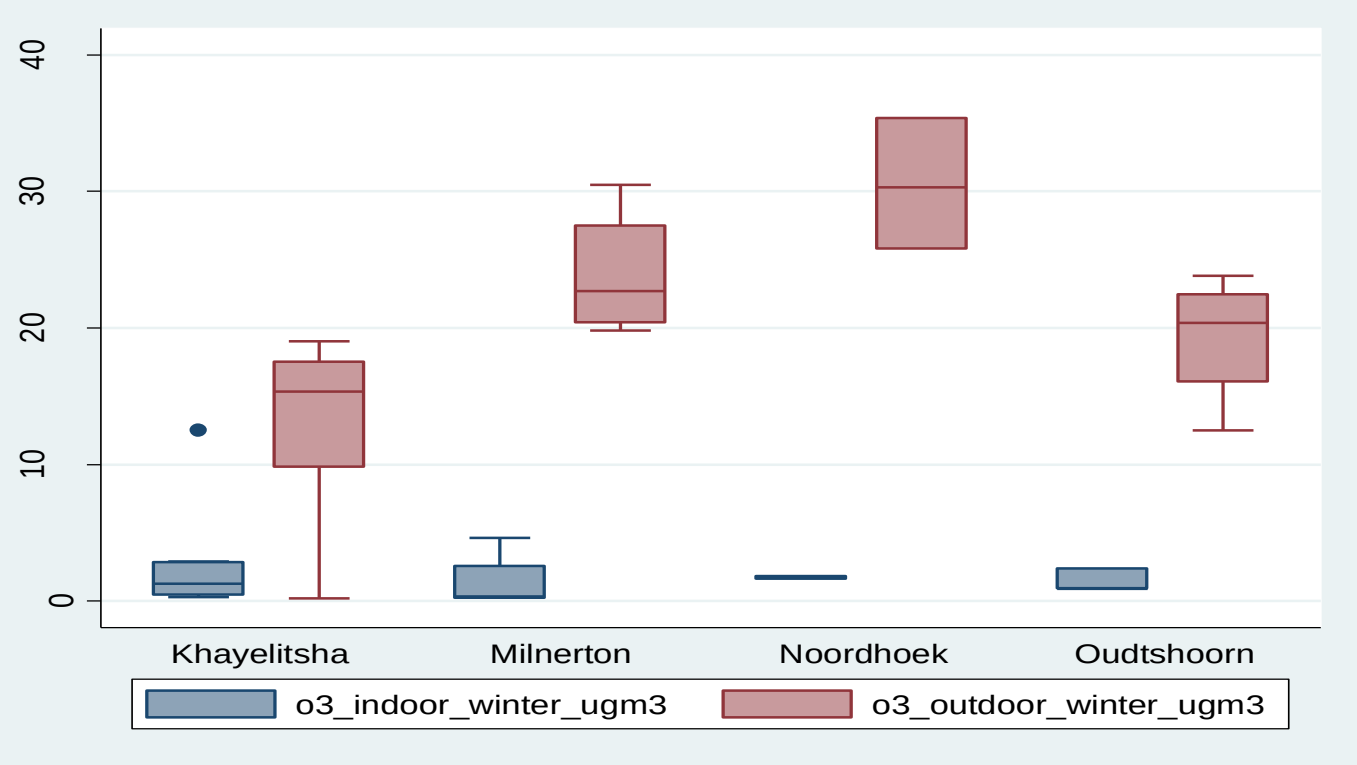


Figure 4.12: Box-and-whisker plot of indoor and outdoor exposure levels for O_3 (µg/m^3) according to season

4.3.5 Winter indoor and outdoor exposure levels of CO

Overall, the winter indoor results indicated a slightly higher mean concentration of 10.83 mg/m^3, compared to outdoors (9.61 mg/m^3). With the highest mean concentration visible in Milnerton neighbourhood (12.62 mg/m^3), whilst the lowest concentration was recorded in Oudtshoorn neighbourhood (9.62 mg/m^3). A highest mean outdoor concentration between the neighbourhoods was observed in Khayelitsha (11.71 mg/m^3), followed by the average mean concentration of Milnerton (10.85 mg/m^3). Oudtshoorn and Noordhoek recorded the lowest average mean concentrations of 10.32 and 4.67 mg/m^3 respectively (Table 4.13).

Table 4.13: Actual monitored environmental exposure levels of CO mg/m^3 in the Western Cape's four neighbourhoods

	WINTER INDOOR					WINTER OUTDOOR				
Neighbourhood	**N**	**AM**	**GM**	**GSD**	**RANGE**	**N**	**AM**	**GM**	**GSD**	**RANGE**
Khayelitsha	2	12.44	11.88	0.43	8.76 – 16.12	2	11.71	11.70	0.05	11.33 – 12.09
Milnerton	4	12.62	11.91	0.42	6.53 – 16.59	4	10.85	10.59	0.26	7.5 – 12.95
Noordhoek	2	9.89	8.78	0.70	5.35 – 14.42	3	4.67	4.59	0.22	3.62 – 5.61
Oudtshoorn	7	9.62	9.28	0.29	5.95 – 15.24	8	10.32	10.17	0.18	8.16 – 13.75
Overall	15	10.83	10.17	0.37	5.35 – 16.59	17	9.61	9.07	0.37	3.62 – 13.75

N: Number of measurements; AM: Arithmetic Mean; GM: Geometric Mean; GSD: Geometric Standard Deviation.

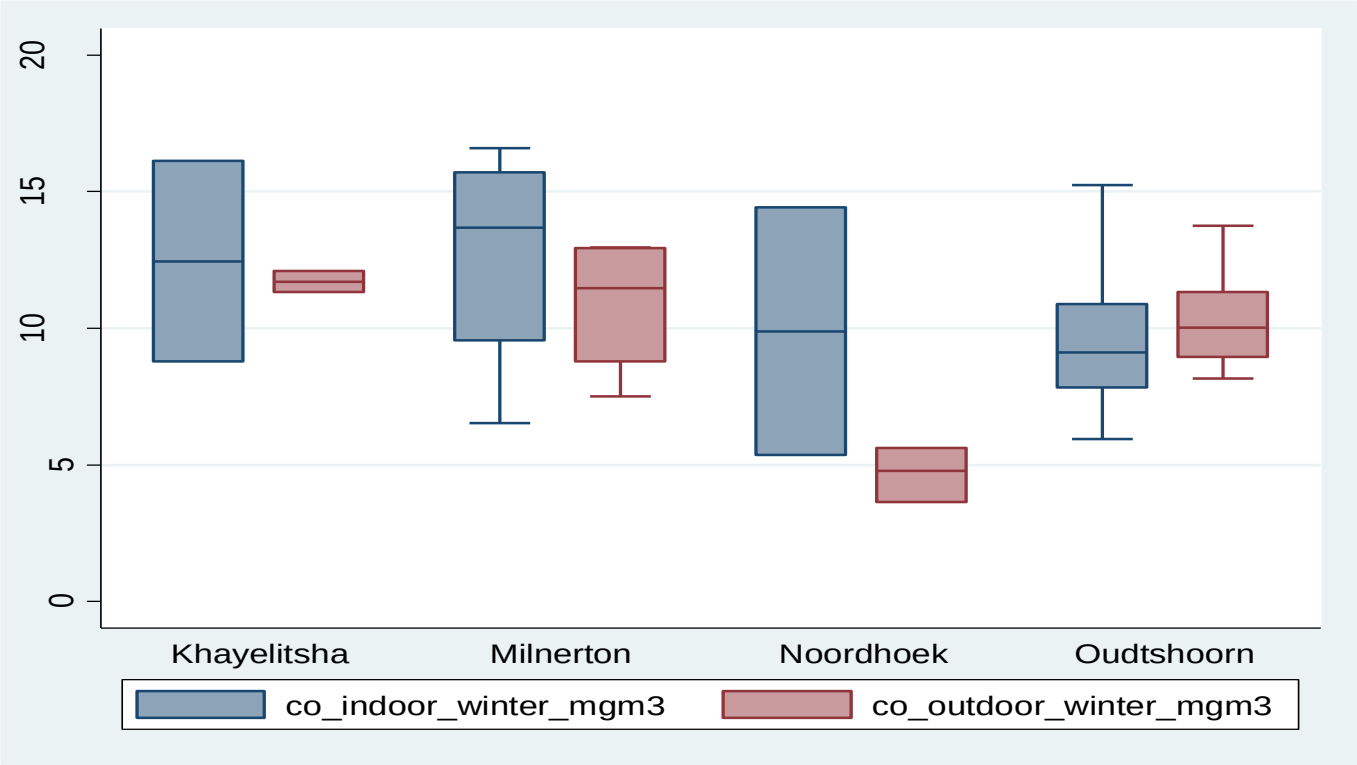


Figure 4.13: Box-and-whisker plot of indoor and outdoor exposure levels for CO (mg/m^3) according to season

4.3.6 Predictor variables of $PM_{2.5}$

Linear regression modelling results revealed that significant predictors of elevated exposure to $PM_{2.5}$ were proximity to construction activities and open grills (Table 4.15). Analysis demonstrated a clear dose-response relationship with distance, with open grills within 1000m associated with a 0.33 µg/m^3 increase in $PM_{2.5}$ to 6.77 µg/m^3 at a distance of 25 meters. A similar pattern was observed for distance to construction activities demonstrating an increase of 0.22 µg/m^3 at 1000m, to 14.67 µg/m^3 at 25 meters (Table 4.15).

Whilst the relationship between exposure levels and the distance in relation to the nearest bus stop was inconsistent, a bus stop within the radius of 25 meters was positively associated with increasing the levels (Table 4.14), though not significant (β=0.93). No clear association could be shown for traffic-related variables such as small and/or major roads, bus/taxi routes and railways (Table 4.16-4.17). However, a similar behaviour pattern of variables was not detected during the winter period. This could partially be explained by more missing data during this

exposure assessment period. Variability in exposure to $PM_{2.5}$ was poorly explained by models of PM2.5, with distance to open grills and construction activities explaining 13-22% (radius of 50 to 25 meters).

4.3.7 Predictor variables of NO_2

Results from the linear regression modelling revealed that significant predictors of exposure to NO_2 were proximity to rapid transport bus stops, bus routes, taxi routes and major routes (Table 4.20). Distance to rapid transport bus stops demonstrated an increase in NO_2 between 0.09 $\mu g/m^3$ (at 1km) to 2.16 $\mu g/m^3$ (at 50m) during summer. However, in comparison to summer, whilst winter results showed a similar trend, the increases in NO_2 exposures were lower (0.04 $\mu g/m^3$ to 1.33 $\mu g/m^3$ at a distance of 1000 and 100 meters respectively).

Distance to construction sites was also positively associated with an increase in NO_2 with a decrease in distance to the household. Furthermore, a similar pattern was observed for taxi routes and bus routes displaying an increase of 6.26 $\mu g/m^3$ and 6.82 $\mu g/m^3$ respectively within the proximity of 1000 meters. However, a similar pattern was not observed during the winter season. Major roads were associated with an increase of NO_2 levels within 100 to 25 meters (0.00 to 0.11). However, seasonal comparisons show that significant positive predictors within 100 to 25 meters were observed in the winter period (0.04 $\mu g/m^3$ to 0.25 $\mu g/m^3$).

Railways variables indicated no significant clear association contributing towards NO_2 exposure in summer but in the winter period, exposure levels within proximity of 100 to 25 meters indicated an increase of 0.03 $\mu g/m^3$ to 0.20 $\mu g/m^3$ NO_2 exposure (Table 4.21). Additionally, activities associated with combusting fuel such as open grills and construction sites significantly recorded a positive increase of exposure levels in summer season compared to the winter season.

Table 4.14: Predictors of exposure variability in $PM_{2.5}$ levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Waste Burning Sites						
- 1000	-0.83	-3.29 : 1.61	0.01	-7.25	-26.1 : 11.56	0.01
- 500	-1.85	-6.89 : 3.18	0.01	-12.1	-47.3 : 23.47	0.01
- 300	-0.75	-6.56 : 5.04	0.00	-12.1	-52.9 : 28.70	0.01*
- 100	[a]	[a]	[a]	[a]	[a]	[a]
- 50	[a]	[a]	[a]	[a]	[a]	[a]
- 25	[a]	[a]	[a]	[a]	[a]	[a]
Waste Collection Sites						
- 1000	0.00	-0.25 : 0.26	0.00	0.77	-1.15 : 2.69	0.00
- 500	-0.34	-1.01 : 0.33	0.01	1.21	-3.68 : 6.12	0.00
- 300	-0.44	-1.52 : 0.63	0.01	-12.1	-8.36 : 7.46	0.00
- 100	-0.88	-2.95 :1.19	0.01	-0.74	-15.44:13.94	0.00
- 50	-2.89	-7.91 : 2.12	0.02*	-4.74	-36.91 :27.42	0.00*
- 25	[a]	[a]	[a]	4.98	-64.93 :74.89	0.00
Bus stop						
- 1000	0.08	-0.04 : 0.21	0.02	0.43	-0.56 : 1.44	0.01
- 500	-0.18	-0.40 : 0.03	0.03	-0.74	-2.43 : 0.94	0.01
- 300	-0.40	-0.78 : (-0.03)	0.06**	-1.23	-4.00 : 1.52	0.01
- 100	-0.73	-2.09 : 0.62	0.01	-4.87	-14.56:4.18	0.01
- 50	-0.50	-3.35 : 2.33	0.00	-6.08	-26.17:14.01	0.01
- 25	0.93	-3.15 : 5.02	0.00	-10.23	-39.02:18.54	0.01
Informal trading						
- 1000	-0.00	-0.00 : 0.00	0.01	-0.00	-0.05 : 0.04	0.00
- 500	-0.01	-0.03 : 0.00	0.02	-0.04	-0.20 : 0.11	0.00
- 300	-0.03	-0.07 : 0.00	0.04*	-0.05	-0.40 : 0.29	0.00
- 100	-0.14	-0.33 : 0.05	0.03	-0.41	-2.61 : 1.79	0.00
- 50	-0.33	-0.91 : 0.24	0.02	-2.65	9.36: 4.05	0.01
- 25	-1.38	-3.59 : 0.82	0.02	-5.07	-19.6 : 9.45	0.01

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.15: Predictors of exposure variability in $PM_{2.5}$ levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Open Grills						
- 1000	0.33	0.04 : 0.63	0.06**	0.90	-1.41 : 3.22	0.01
- 500	0.28	-0.00 : 0.58	0.05*	0.06	-2.18 : 2.31	0.00
- 300	0.30	-0.06 : 0.66	0.03	0.68	-2.09 : 3.45	0.00
- 100	1.77	0.90 : 2.64	0.17**	1.10	-5.38 : 7.59	0.00
- 50	3.01	0.89 : 5.14	0.09**	-0.53	-13.98 :12.91	0.00
- 25	6.77	3.79 : 9.75	0.21**	1.65	-21.94 : 25.25	0.00
Rapid Transport Stop						
- 1000	0.06	-0.00 : 0.13	0.04*	-0.03	-0.56 : 0.49	0.00
- 500	0.16	-0.01 : 0.34	0.04*	-0.31	-1.65 : 1.01	0.00
- 300	0.55	0.21 : 0.90	0.12**	-0.31	-3.09 : 2.47	0.00
- 100	-0.51	-3.03 : 2.01	0.00	1.60	-18.86 : 22.08	0.00
- 50	-1.00	-5.96 : 3.94	0.00	[a]	[a]	[a]
- 25	[a]	[a]	[a]	[a]	[a]	[a]
Construction sites						
- 1000	0.22	-0.13 : 0.58	0.02	-0.27	-2.86 : 2.32	0.00
- 500	0.35	-0.16 : 0.87	0.02	0.32	-3.49 : 4.15	0.00
- 300	0.43	-0.23 : 1.10	0.02	3.58	-1.26 : 8.43	0.03
- 100	3.15	0.15 : 6.16	0.05**	-1.01	-22.96 : 20.94	0.00
- 50	9.24	3.82 : 14.66	0.13**	-1.96	-51.75 : 47.83	0.00
- 25	14.67	8.42 : 20.92	0.22**	-1.96	-51.75 : 47.83	0.00
Small roads						
- 1000	0.00	-0.00 : 0.00	0.01	0.00	-0.00 : 0.00	0.00
- 500	0.00	-0.00 : 0.00	0.00	0.00	-0.00 : 0.00	0.00
- 300	0.00	-0.00 : 0.00	0.01	-0.00	-0.00 : 0.00	0.00
- 100	0.00	-0.00 : 0.00	0.04*	-0.01	-0.03 : 0.01	0.02
- 50	0.00	-0.00 : 0.01	0.02	-0.05	-0.13 : 0.02	0.02
- 25	0.01	-0.01 : 0.04	0.01	-0.09-	-0.34 : 0.15	0.01

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.16: Predictors of exposure variability in $PM_{2.5}$ levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Rapid Transport Routes						
- 1000	0.00	-0.00 : 0.00	0.03	-0.00	-0.00 : 00	0.00
- 500	0.00	-0.00 : 0.00	0.03*	0.00	-0.00 : 0.00	0.00
- 300	0.00	0.00 : 0.00	0.09**	-0.00	-0.00 : 0.00	0.00
- 100	-0.00	-0.00 : 0.00	0.00	-0.00	-0.04 : 0.03	0.00
- 50	-0.00	-0.01 : 0.00	0.01	-0.02	-0.13 : 0.08	0.00
- 25	-0.03	-0.11 : 0.04	0.01	-0.08	-0.66 : 0.50	0.00
Bus Routes						
- 1000	2.79	-3.04 : 3.60	0.00	6.28	-0.00 : 0.00	0.00
- 500	-4.68	-0.00 : 2.30	0.02	-0.00	-0.00 : 0.00	0.01
- 300	-0.00	-0.00 : 2.04	0.04*	-0.00	-0.00 : 0.00	0.01
- 100	-0.00	-0.00 : 0.00	0.01	-4.87	-0.00 : 0.00	0.00
- 50	-0.00	-0.00 : 0.00	0.01	-0.00	-0.00 : 0.00	0.01
- 25	-0.00	-0.00 : 0.00	0.01	-0.00	-0.00 : 0.00	0.00
Taxi Routes						
- 1000	6.26	-1.31 : 0.00	0.03*	-0.00	-0.00 : 0.00	0.00
- 500	-0.00	-0.00 : 0.00	0.00	-0.00	-0.00 : 0.00	0.01
- 300	-0.00	-0.00 : 0.00	0.00	-0.00	-0.00 : 0.00	0.00
- 100	-0.00	-0.00 : 0.00	0.00	0.00	-0.00 : 0.00	0.00
- 50	-0.00	-0.00 : 0 .00	0.01	-0.00	-0.03 : 0.01	0.01
- 25	0.00	-0.01 : 0.00	0.00	-0.01	-0.12 : 0.08	0.00
Major roads						
- 1000	0.00	-0.00 : 0.00	0.02	0.00	-0.00 : 0.00	0.01
- 500	-0.00	-0.00 : 0.00	0.01	-0.00	-0.00 : 0.00	0.00
- 300	-0.00	-0.01 : 0.01	0.00	-0.00	-0.00 : 0.00	0.00
- 100	-0.00	-0.01 : 0.01	0.01	-0.07	-0.42 : 0.27	0.01
- 50	-0.01	-0.04 : 0.01	0.02	-0.10	-0.31 : 0.10	0.01
- 25	-0.05	-0.16 : 0.04	0.01	-0.01	-0.95 : 0.52	0.00

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.17: Predictors of exposure variability in $PM_{2.5}$ levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Railways						
- 1000	0.00	-0.00 : 0.00	0.02	-0.00	-0.01 : 0.00	0.01
- 500	-0.00	-0.00 : 0.00	0.01	-0.00	-0.03 : 0.02	0.00
- 300	-0.00	-0.01 : 0.00	0.00	-0.01	-0.07 : 0.05	0.00
- 100	-0.02	-0.07 : 0.02	0.01	-0.07	-0.42 : 0.27	0.00
- 50	-0.05	-0.15 : 0.05	0.01	-0.14	-0.88 : 0.85	0.00
- 25	-0.13	-0.39 : 0.13	0.01	-0.38	-2.26 : 1.49	0.00

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.18: Predictors of exposure variability in NO_2 levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Waste Burning sites						
- 1000	-7.00	-9.38 : (-4.61)	0.29**	-13.65	-17.80 :(-9.51)	0.37**
- 500	-7.26	-12.90 : (-1.62)	0.07**	-18.46	-27.8 1:(-9.10)	0.17**
- 300	-6.31	-12.89 : 0.26	0.04*	-17.62	-28.69 :(-6.55)	0.12**
- 100	[a]	[a]	[a]	[a]	[a]	[a]
- 50	[a]	[a]	[a]	[a]	[a]	[a]
- 25	[a]	[a]	[a]	[a]	[a]	[a]
Waste Collection Sites						
- 1000	0.31	0.01 : 0.60	0.05**	1.24	0.77 : 1.71	0.28**
- 500	0.41	-0.35 : 1.17	0.01	2.08	0.78 : 3.38	0.12**
- 300	1.18	-0.01 : 2.38	0.05**	4.54	2.58 : 6.5	0.22**
- 100	-0.84	-3.17 : 1.47	0.01	-0.29	-4.72 : 4.13	0.00
- 50	0.33	-4.93 : 5.61	0.00	4.74	-4.45 : 13.94	0.01
- 25	-8.32	-19.68 : 3.04	0.03	7.53	-12.5 : 27.61	0.01
Bus Stop						
- 1000	0.13	-0.01 : 0.28	0.04*	0.31	0.04 : 0.58	0.07**
- 500	-0.25	-0.50 : (-0.00)	0.05**	-0.16	-0.63 : 0.31	0.01
- 300	-0.34	-0.78 : 0.09	0.03	0.20	-0.59 : 1.00	0.00
- 100	-0.49	-2.07 : 1.09	0.00	0.23	-2.56 : 3.03	0.00
- 50	-1.55	-4.83 : 1.72	0.01	-0.97	-6.76 : 4.82	0.00
- 25	-4.31	-8.96 : 0.33	0.04*	-4.43	-12.69:3.82	0.02
Informal Trading						
- 1000	0.00	-0.00 : 0.01	0.03	0.02	0.01 : 0.03	0.25**
- 500	0.01	-0.00 : 0.04	0.03	0.09	0.05 : 0.12	0.26**
- 300	0.02	-0.02 : 0.07	0.01	0.17	0.09 : 0.24	0.23**
- 100	0.11	-0.11 : 0.33	0.01	0.52	0.14 : 0.90	0.09**
- 50	-0.06	-0.74 : 0.60	0.00	0.98	-0.17 : 2.14	0.04*
- 25	-1.03	-3.40 : 1.34	0.01	0.20	-3.99 : 4.40	0.00

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.19: Predictors of exposure variability in NO_2 levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Open Grills						
- 1000	0.87	0.58 : 1.17	0.30**	1.31	0.75 : 1.87	0.23**
- 500	0.49	0.16 : 0.81	0.09**	0.13	-0.49 : 0.76	0.00
- 300	0.52	0.12 : 0.93	0.08**	-0.00	-0.77 : 0.76	0.00
- 100	1.20	0.18 : 2.21	0.06**	1.29	-0.55 : 3.14	0.03
- 50	1.30	-0.85 : 3.45	0.02	0.46	-3.39 : 4.33	0.00
- 25	2.79	-1.03 : 6.62	0.03	2.99	-3.76 : 9.76	0.01
Rapid Transport Stop						
- 1000	0.09	0.01 : 0.17	0.07**	0.04	-0.11 : 0.19	0.00
- 500	0.27	0.07 : 0.46	0.09**	0.01	-0.36 : 0.39	0.00
- 300	0.61	0.21 : 1.00	0.10**	0.18	-0.60 : 0.98	0.00
- 100	3.54	0.72 : 6 .37	0.07**	1.33	-3.79 : 6.47	0.00
- 50	2.16	-3.56 : 7.89	0.01	-0.89	-10.97:9.18	0.00
- 25	[a]	[a]	[a]	[a]	[a]	[a]
Construction						
- 1000	0.16	-0.24 : 0.57	0.01	-0.72	-1.45 : (-0.00)	0.05**
- 500	0.36	-0.23 : 0.96	0.02	-0.97	-2.04 : 0.09	0.04*
- 300	0.41	-0.35 : 1.17	0.01	-0.73	-2.09 : 0.62	0.02
- 100	3.56	0.20 : 6.92	0.05**	0.28	-6.24 : 6.81	0.00
- 50	3.43	-3.24 : 10.11	0.01	2.45	-11.89:16.79	0.00
- 25	5.40	-2.69 : 13.50	0.02	2.45	-11.89:16.79	0.00
Small roads						
- 1000	0.00	0.00 : 0.00	0.15**	0.00	0.00 : 0.00	0.36**
- 500	0.00	-0.00 : 0.00	0.04*	0.00	0.00 : 0.00	0.07**
- 300	0.00	-0.00 : 0.00	0.02	0.00	-0.00 : 0.00	0.02
- 100	0.00	-0.00 : 0.00	0.00	0.00	-0.00 : 0.00	0.00
- 50	-0.00	-0.01 : 0.06	0.02	-0.00	-0.02 : 0.01	0.00
- 25	0.02	-0.01 : 0.04	0.01	0.02	-0.04 : 0.09	0.01

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.20: Predictors of exposure variability in NO_2 levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Rapid Transport Routes						
- 1000	0.00	0.00 : 0.00	0.09**	0.00	-0.00 : 0.00	0.04*
- 500	0.00	-0.00 : 0.00	0.12**	0.00	-0.00 : 0.00	0.02
- 300	0.00	0.00 : 0.00	0.14**	0.00	-0.00 : 0.00	0.03
- 100	0.00	-0.00 : 0.01	0.04*	0.00	-0.00 : 0.01	0.03
- 50	0.01	-0.00 : 0.03	0.04*	0.02	-0.00 : 0.05	0.03
- 25	0.11	0.02 : 0.21	0.07**	0.19	0.02 : 0.35	0.07**
Bus Routes						
- 1000	6.82	3.23 : 0.00	0.15**	0.00	0.00 : 0.00	0.52**
- 500	2.91	-5.31 : 0.00	0.01	0.00	0.00 : 0.00	0.20**
- 300	8.32	-9.30 : 0.00	0.01	0.00	0.00 : 0.00	0.19**
- 100	0.00	-0.00 : 0.00	0.01	0.00	0.00 : 0.00	0.09**
- 50	0.00	-0.00 : 0.00	0.00	0.00	0.00 : 0.00	0.08**
- 25	0.00	0.00 : 0.00	0.07**	0.00	0.00 : 0.00	0.06**
Taxi Routes						
- 1000	6.26	4.91 : 0.00	0.11**	7.92	-8.66 : 0.00	0.01*
- 500	0.00	-9.50 : 0.00	0.03	0.00	-0.00 : 0.00	0.01
- 300	0.00	-0.00 : 0.00	0.04*	0.00	-0.00 : 0.00	0.04*
- 100	0.01	-0.00 : 0.00	0.03*	0.00	-0.00 : 0.00	0.04*
- 50	0.00	-0.00 : 0.00	0.02	0.00	-0.00 : 0.01	0.03
- 25	0.01	-0.00 : 0.02	0.04*	0.01	-0.01 : 0.04	0.02
Major roads						
- 1000	0.00	0.00 : 0.00	0.31**	0.00	0.00 : 0.00	0.42**
- 500	0.00	0.00 : 0.00	0.12**	0.00	0.00 : 0.00	0.33**
- 300	0.00	0.00 : 0.00	0.09**	0.01	0.00 : 0.01	0.34**
- 100	0.01	-0.00 : 0.02	0.03	0.04	0.02 : 0.06	0.18**
- 50	0.01	-0.01 : 0.00	0.01	0.08	0.02 : 0.14	0.11**
- 25	0.12	0.00 : 0.24	0.05**	0.25	0.04 : 0.46	0.07**

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

Table 4.21: Predictors of exposure variability in NO_2 levels within the neighbourhoods, in the Western Cape

	Summer			Winter		
Predictor	β	95% CI	R^2	β	95% CI	R^2
Railways						
- 1000	0.00	0.00 : 0.00	0.21**	0.00	0.00 : 0.01	0.34**
- 500	0.00	-0.00 : 0.00	0.01	0.01	-0.00 : 0.01	0.10**
- 300	0.00	-0.00 : 0.01	0.00	0.01	0.00 : 0.03	0.06**
- 100	0.00	-0.05 : 0.06	0.00	0.03	-0.06 : 0.14	0.01
- 50	0.01	-0.10 : 0.13	0.00	0.07	-0.13 : 0.29	0.01
- 25	0.02	-0.28 : 0.33	0.00	0.20	-0.34 : 0.75	0.00

All predictor variables refer to distance in relation to households; [a] = Not calculable, no households within this range; **p<0.05 ; *p<0.1

CHAPTER FIVE:
DISCUSSION

5.1 Introduction

The aim of this study was to examine the exposure to indoor and outdoor air pollution of households from four informal settlements in the Western Cape, South Africa. The 3 criteria pollutants, particulate matter, sulphur dioxide and nitrogen dioxide were measured outdoor in all households. Indoor and outdoor exposure assessments were conducted on a smaller number of households. Indoor and outdoor measurements included particulate matter, ozone, carbon monoxide, nitrogen dioxide, and sulphur dioxide. The study further sought to determine whether observed levels of air pollutants in the study areas pose a risk of exceeding or necessarily complies with the National Ambient Air Quality Standards (NAAQS).

Spatial variation of exposure levels within neighbourhoods are influenced by different emission sources. Findings indicate a seasonal distinct pattern of environmental exposure levels. Specific environmental air pollutants such as NO_2 and PM are associated with traffic emissions, while others are associated with industrial sources thus emitting SO_2, and other smaller localised activities such as informal settlement combustion as reported by Levy et al. (2014).

5.2 Ambient air pollution levels

The results of this study indicate that weekly ambient $PM_{2.5}$ levels were relatively higher in winter (mean concentration of 13.14 µg/m^3) than in summer (mean concentration of 7.67 µg/m^3). Interestingly, though, the highest $PM_{2.5}$ level was recorded in Milnerton during summer (8.76 µg/m^3) and the highest weekly $PM_{2.5}$ level was detected in Oudtshoorn (16.07 µg/m^3) during winter. The spatial variability results show that in summer sampling campaign Milnerton and Oudtshoorn were the most polluted neighbourhoods with PM concentrations of (8.76 µg/m^3) and (8.13 µg/m^3) respectively. In winter highest weekly exposure levels that displayed spatial variability for $PM_{2.5}$ were detected in Oudtshoorn (16.07 µg/m^3) and Khayelitsha (13.37 µg/m^3), refer to Table 4.2. Noordhoek neighbourhood spatial concentrations were relatively lower in summer and winter, for the PM substance.

The levels of $PM_{2.5}$ during summer (geometric mean = 7.67 µg/m^3) and winter (geometric mean = 9.62 µg/m^3) measured in this study were relatively low when compared to those in other African countries of South Africa (Rustenburg) and Ghana (Accra) that exceeded WHO's guidelines (Dionisio et al., 2010 & Venter et al., 2012). Weekly geometric means of 21 µg/m^3

and 39 µg/m^3 were recorded in the study of air pollution in four Accra neighbourhoods of low income in Ghana and exposure levels were attributed to combustion of fossil fuel, biomass and traffic emissions (Dionisio et al., 2010). Furthermore, dry season weekly exposure levels recorded in the urban neighbourhoods of Bafoussam (67 µg/m^3), Bamenda (132 µg/m^3), and Yaoundé (49 µg/m^3) in Cameroon were substantially higher than levels measured in Khayelitsha (7.06 µg/m^3), Milnerton (8.76 µg/m^3) and Oudtshoorn (8.13 µg/m^3) during summer. However, the Cameroonian study used at least ten and at most 14 samples per neighbourhood to measure for $PM_{2.5}$ exposure. The high levels of particulate matter measured in the Cameroonian study were attributed to combustion practices by informal food vendors, burning of waste and suspension of dust from unpaved roads as reported by Antonel and Chowdhury (2014). These findings are consistent with Reynolds (2012) and other studies conducted within the African continent that established high $PM_{2.5}$ exposure concentrations in neighbourhoods associated with similar predictor variables (Kirenga et al., 2015).

The results of the current study demonstrate a spatial seasonal trend for pollutants, with levels generally increasing during the winter season in all neighbourhoods for $PM_{2.5}$. A similar pattern was observed for particulate matter levels significantly increasing in winter in a study of exposure seasonal variation conducted by Chen et al. (2013) in Chinese cities. Likewise, neighbourhoods that demonstrated the variation of $PM_{2.5}$ also indicated the seasonal variation of NO_2. This is evident because areas that recorded significant particulate matter exposure levels are found to have recorded high exposure concentrations of nitrogen dioxide. Nevertheless, in contrast, spatial variability for NO_2 revealed that Khayelitsha and Milnerton neighbourhoods were most polluted for both winter and summer season. Furthermore, NO_2 pollutant spatial exposure increase was observed during the summer and winter period. While emissions of sulphur dioxide proved to be relatively low in winter (1.71 µg/m^3) compared to summer season (3.08 µg/m^3).

The observation of increasing $PM_{2.5}$ and NO_2 across neighbourhoods could possibly imply that a correlation exists between $PM_{2.5}$ and NO_2 exposure. Nitrogen dioxide has been reported as a secondary precursor for particulate matter (Hodan, and Barnard 2004 & Pineda et al. 2018). The results of this study corroborate this finding. Since nitrogen dioxide exposure levels were consistently high in neighbourhoods that had recorded a high concentration of $PM_{2.5}$, see Table 4.1 and 4.2. However, overall, environmental exposure levels of NO_2 were relatively higher.

In the current study, higher nitrogen dioxide levels were recorded during the winter season compared to the summer season in the neighbourhoods of Milnerton and Khayelitsha. Exposure assessment results indicate that NO_2 exposure trend is comparable to results obtained by Levy et al. (2014) who discovered high exposure levels of NO_2 across neighbourhoods during winter season compared to the summer season. These high exposure levels are likely influenced by the common land use activities between the two neighbourhoods of Khayelitsha and Milnerton, such as combustion of wood, biomass and vehicular traffic emissions. In these neighbourhoods, the aforementioned activities are significantly common.

The average summer concentration of NO_2 (13.27µg/m^3) is comparable to exposure levels of 13.3 µg/m^3 recorded in the South of Italy's neighbourhoods (Ielpo et al., 2019), but lower than exposure levels of 24 µg/m^3 reported by Javis et al. (2010). It is worth to note that, exposure levels of NO_2 in the neighbourhoods of South Italy are characterised by few quantified sites of the Taranto that city. Moreover, comparisons indicate that the average winter NO_2 (22.45 µg/m^3) was comparable to exposure levels of 24.2 µg/m^3 observed in Mažeikiai, Lithuania (Šerevičienė et al., 2014), higher than estimated exposure levels of 17 µg/m^3 recorded in KwaGuqa, Mpumalanga province (Pauw et al., 2011), but lower than levels of 36.5 µg/m^3 recorded in Barcelona (Schembari et al., 2013). The weekly exposure assessments in KwaGuqa Mpumalanga province were conducted in three neighbourhoods of informal settlement and low-cost housing using passive samplers. Notably, the population size of the three measured neighbourhoods combined is significantly lower than the Oudtshoorn neighbourhood alone and or any of the other three neighbourhoods covered by this study.

The results indicate that levels of SO_2 were relatively low across all the neighbourhoods in different seasons. Sulphur dioxide exposure levels were very low and frequently below the detection of limit for sampling and analysis purposes. The concentrations of SO_2 assessed over the neighbourhoods were much lower (1.7 – 3.1 µg/m^3) than the 24-hour average concentrations prescribed by SANAQQS (125 µg/m^3). The SO_2 levels measured in this study, however, are comparable to Ugandan study that recently recorded 3 µg/m^3 sulphur dioxide (Kirenga et al., 2015) but significantly lower than sulphur exposure levels of 24.2 µg/m^3 observed in Balikesir, Turkey (Tecer and Tagil, 2013) and 84 µg/m^3 observed in Emalahleni, Mpumalanga (Olufemi et al., 2018). The relatively high exposure levels in these neighbourhoods are exacerbated by industrial activities within the neighbourhood proximity, whereas in contrast

neighbourhoods with non-industrial activities within their precinct recorded relatively low exposure concentration of sulphur dioxide.

Sulphur dioxide exposure results may be influenced by the fact that the participating neighbourhoods are not within the proximity of industrial activities, rather to roadways used by motor vehicles. Motor vehicles may not contribute much towards high exposure levels of SO_2. Mainly because South Africa has fuel that contains low sulphur content and the majority of the vehicles are using petrol engines compared to diesel engines, nationally (DoE, 2014). Additionally, the absence of significant coal combustion activities in the Western Cape possibly reduces high exposure levels of SO_2. Low SO_2 levels were also measured by Arku et al. (2008) who recorded significantly low variation and exposure levels of SO_2 in the neighbourhoods of Accra where reduction of sulphur content in petrol fuel was cited as the major contributor towards recording low SO_2 levels.

5.3 Indoor and outdoor air pollution exposure levels

The overall study results indicate that summer indoor and outdoor observed results of particulate matter demonstrate comparability of exposure levels. In general, the results indicate that $PM_{2.5}$ exposure levels were slightly higher indoors (8.35 µg/m^3) compared to outdoors (7.59 µg/m^3) in the summer season. Indoor and outdoor exposure levels of particulate matter, when compared to other studies in the African continent, were lower than levels of 108.9 µg/m^3 recorded indoors and outdoors (166 µg/m^3) in the neighbourhoods of Nairobi, Kenya by Muindi et al. (2016). The reason for the relatively high indoor and outdoor $PM_{2.5}$ levels measured in the Kenyan study was that the majority of the households in the Kenyan study had no windows. The entrance door was used as the means of venting indoor pollutants. Furthermore, the study established that a considerable proportion of households that participated in the study do not open windows and doors during cooking practices. But comparable to weekly exposure levels of 8.4 µg/m^3 indoor and 9.3 µg/m^3 outdoor exposure levels observed in thirty-four suburban neighbourhoods of Stockholm, Sweden (Wichmann et al., 2010).

In contrast, winter seasonal comparisons of indoor and outdoor exposure levels reveal slightly higher $PM_{2.5}$ in comparison to summer exposure. However, there is no substantial difference between these indoor (12.28 µg/m^3) and outdoor (10.93 µg/m^3) exposure levels, thus they are comparable. Likewise, winter estimated exposure levels of indoor air quality (12.28 µg/m^3) were

lower than that reported winter indoor exposure levels of 22.20 μg/m^3 observed in Ibadan, South-western of Nigeria (Onabowale et al., 2015) and 416 μg/m^3 recorded by Song et al.(2015) in Xicheng district, Beijing. Nevertheless, the $PM_{2.5}$ levels were higher than the weekly indoor exposure levels of 8.7 μg/m^3 reported in four neighbourhoods of Switzerland households (Meier et al., 2015).

Meier et al. (2015) further established that the lowest indoor levels were recorded in the rural area in contrast to an urban area. Onabowale et al. (2015) in Ibadan, South-western of Nigeria attributes $PM_{2.5}$ high exposure levels from the two monitored densely populated residential sites due to the use of firewood in the precincts. However, in contrast, Song et al. (2015) in Xicheng district, Beijing associated high indoor $PM_{2.5}$ levels with cooking and cleaning activities as significant contributors to indoor exposure sources. Similarly, as in the studies discussed above, observed particulate matter outdoor concentrations (10.93 μg/m^3) were lower than exposure levels reported in Kwadela (27 μg/m^3) in Mpumalanga province and 44 μg/m^3 recorded by Huang et al. (2015) in the study characterising indoor and outdoor relationship of particulate matter in Beijing. Furthermore, exposure levels of 150 μg/m^3 were also reported in Beijing (Deng et al., 2017). The Kwadela study discovered that the outdoor average concentration of $PM_{2.5}$ was significantly high in winter compared to indoor summer exposure (Wernecke et al., 2015). Exposure sources to air pollution in Kwadela include practices of combusting solid fuel because of cooking and space heating. Furthermore, Deng et al. (2017) found that outdoor concentrations influence indoor exposure levels of $PM_{2.5}$.

In essence, significant indoor exposure levels are likely to be influenced by ambient air pollution concentrations and individual behaviour amongst other factors. Song et al. (2015) attribute high indoor concentrations of $PM_{2.5}$ to anthropogenic activities such as cleaning, smoking, ambient spatial concentration of air pollution in the background and is further associated with the use of certain fuel type for cooking. However, it is important to note that significant indoor air pollution has been reported even in households that make use of clean fuel for cooking purposes (Gurley et al., 2013). Therefore, when dealing with indoor air pollution exposure levels the significance of the air pollution levels in the background cannot be disregarded. Diapouli et al. (2008) corroborate that significant indoor air pollution is exacerbated by significant levels of outdoor air pollution concentrations. Hence, the agricultural and combustion practices observed in some vicinity of the neighbourhoods may have contributed to significant levels of ambient air pollution that subsequently impact the air quality indoors. Furthermore, it has been found that poor

households are exposed to higher indoor air pollution levels in developing countries compared to countries that are developed (Nasir et al., 2015).

The increase in $PM_{2.5}$ levels during the winter season is predominantly due to the combustion of biomass, tyre burning and motor vehicle traffic emissions. A similar study conducted by Lodhi et al. (2009) attributes winter exposure levels to these sources. Similarly, there may be a probability of seasonal disparity of ambient air pollution sources in different seasons arising to meet the cold weather demands during the winter season as Gurley et al. (2013) suggested that different season may be associated with different ambient air pollution sources. Furthermore, air pollution levels increased during the winter season; however, Gurley et al. (2013) indicated that the cause of exposure increase was ambiguous. For instance, it is common practice in the informal settlement to burn tyres during winter as a means of space heating (Mahlangu, 2009). Additionally, temperature inversions and relatively below average rainfall experienced recently may have contributed to significant outdoor exposure levels of $PM_{2.5}$.

5.3.1 Sulphur dioxide and carbon monoxide

Results indicate that SO_2 indoor and outdoor average concentrations were significantly low in the observed neighbourhoods of Western Cape during summer and winter season. Sulphur dioxide exposure levels were very low and frequently below the detection of limit for sampling and analysis purposes. This study is congruent with other African studies that have previously reported relatively low weekly exposure concentrations of SO_2 (Arku et al., 2008, Moodley et al., 2011 and Kirenga et al., 2015).

However, in this study findings indicate that the recorded summer SO_2 levels were relatively high in comparison to winter levels, see Table 4.6 and 4.11. Summer indoor sulphur dioxide concentrations were three times higher than exposure levels recorded in winter. These seasonal trend distinctions are consistent with the findings reported by Bralić et al. (2012) in the study of sulphur dioxide seasonal variation in Split, Croatia. Furthermore, Bralic et al. (2012) study presented monthly and seasonal variation of SO_2 levels in the neighbourhood characterised with air pollution predictor variables such as vehicular traffic and industrial activities.

In summer season Khayelitsha and Oudtshoorn recorded moderate indoor and outdoor concentrations of sulphur dioxide in contrast to other neighbourhoods. On the contrary, in the winter season, moderate SO_2 exposure levels were recorded in Milnerton and Oudtshoorn

neighbourhoods. The winter indoor (0.81 µg/m^3) and outdoor (1.45 µg/m^3) SO_2 exposure levels results were lower than indoor (4.8 µg/m^3) and outdoor (17 µg/m^3) exposure concentrations reported in Emalahleni, Mpumalanga which were measured within the proximity of coal mines. In contrast, summer indoor (2.69 µg/m^3) exposure concentrations were comparable to summer indoor exposure levels of 2.5 µg/m^3, however, outdoor (4.5 µg/m^3) exposure concentrations were lower than outdoor (14.2 µg/m^3) concentrations recorded in Kocaeli industrial neighbourhood, Turkey (Bozkurt et al., 2015). High levels of air pollution in Kocaeli neighbourhoods is credited to industries, fossil fuel with high sulphur content such as coal and vehicles using diesel fuel.

Fazlzadeh et al. (2015) suggest that exposure to significant levels of indoor carbon monoxide is not common, not unless there is a CO, emitting source within close proximity. In the absence of the indoor emission source, significant exposure levels are attributed to outdoor air pollutants concentrations. Results reveal that CO exposure levels were significantly higher than SO_2 exposure concentrations discussed above. Seasonal contrast reveals that indoor and outdoor exposure concentrations of CO in winter were almost two times higher than that recorded in summer (refer to Table 4.8 and Table 4.13. Significant winter indoor exposure levels are associated with practices such as not opening windows during cold winter and combustion of fuels in the household for space heating purposes (Mehta, 2007). These practices exacerbate significant exposure to carbon monoxide.

In summer, CO outdoor exposure levels (5.65 mg/m^3) were comparable in contrast to indoor concentration (5.05 mg/m^3). The summer indoor air concentrations are higher than those exposure levels of 0.27 mg/m^3 reported in eight hundred and seventy-six England homes in summer (Raw et al., 2002). While summer outdoor concentrations were almost two times higher than CO exposure levels reported in Blantyre city, Malawi (Mapoma et al., 2014). The Malawian study in Blantyre city measurements was conducted in a vicinity characterised with an industrial site, vehicle and motorcycle traffic.

These findings are consistent with Darus et al. (2011) who experienced similar observation in the study of indoor and outdoor air quality in Shah Alam, Malaysia. Additionally, on contrary in winter period indoor concentrations (10.83 mg/m^3) were higher than outdoor (9.61 mg/m^3) exposure levels see Table 4.13. These indoor exposure levels are significantly higher than

winter weekly indoor CO concentrations (0.62 mg/m^3) reported in England homes and 2.81 mg/m^3 monthly outdoor exposure levels recorded in Blantyre city, Malawi.

5.3.2 Nitrogen dioxide and ozone

There is an existing relationship between nitrogen dioxide and surface ozone pollutant. The photochemical reaction is necessary for nitrogen dioxide and surface ozone pollutant formation. Nitrogen dioxide is considered a precursor pollutant for surface ozone. Ozone pollutant is formed in the photochemical reaction presence of nitrogen dioxide and sunlight. Lee et al. (2002) in the Southern California study of examining indoor and ambient concentrations of nitrogen dioxide and ozone pollutant discovered that indoor ozone exposure levels were lower than outdoor concentrations, significantly. While on the contrary NO_2 indoor concentrations were significantly higher than outdoor.

Similarly, the results of this study indicate that ambient O_3 exposure concentrations were significantly higher than indoor ozone concentrations. While on the contrary, NO_2 exposure level results indicate that ambient concentrations were higher than levels recorded outdoor in both seasons of summer and winter. Furthermore, results indicate that exposure levels of NO_2 were relatively high in comparisons to other pollutants, which were assessed. Seasonal exposure levels show that summer NO_2 exposure concentrations were relatively low compared to winter levels.

This finding is consistent with studies of Lourens et al. (2011) conducted in the Highveld of South Africa and Kaunas city, Lithuania in Europe by Dėdelė and Miškinytė (2016) that noted an increase of NO_2 exposure concentration during winter. Both studies exposure sources include road transport and industry amongst other contributors. Winter exposure levels were significantly high both indoor and outdoor in contrast to summer exposure levels.

Significant nitrogen dioxide concentrations for winter are exacerbated by traffic emissions. Jarvis et al. (2010) suggest that significant winter exposure levels of nitrogen dioxide are associated with traffic emissions. Furthermore, winter meteorological conditions are associated with limiting dispersion of air pollutants, thus, resulting in significant exposure levels of nitrogen dioxide in winter (Lourens et al., 2011).

In essence, summer indoor nitrogen dioxide exposure levels of 9.24 µg/m^3 and 11.99 µg/m^3 outdoor concentration were lower when compared to exposure observation that recorded exposure levels of 33 µg/m^3 indoor and outdoor exposure levels of 39 µg/m^3 reported in Antwerp, Belgium (Stanger et al., 2007). However, nitrogen dioxide winter outdoor concentrations of 24.23 µg/m^3 were significantly higher than winter outdoor exposure levels of 8 µg/m^3 recorded in north London and indoor exposure levels of 22.03 µg/m^3 were significantly higher than outdoor concentrations of 7 µg/m^3 (Kornartit et al., 2010).

Additionally, summer indoor ozone exposure levels of 1.19 µg/m^3 were significantly lower than indoor exposure concentrations of 3.2 µg/m^3; Furthermore, summer ambient exposure levels of 14.25 µg/m^3 were lower than summer outdoor concentrations of 28 µg/m^3 reported in Antwerp, Belgium by Stanger et al. (2007). However, winter indoor ozone concentrations (2.06 µg/m^3) were comparable to indoor winter exposure levels recorded by Bozkurt et al. (2015) in Turkey. While winter ambient concentrations (19.41 µg/m^3) were significantly higher than Turkey's outdoor exposure levels of 6.9 µg/m^3 (Bozkurt et al., 2015).

The reason behind recording high exposure ozone levels in winter is not clear. Because ozone formation requires photochemical production processes. In fact, the seasonal variability pattern indicates that high O_3 levels were observed in winter season compared to the summer season, refer to Table 4.7 and 4.12. Additionally, the results of this study indicate no correlation and influence between NO_2 and O_3 considering that NO_2 is a precursor for ozone pollutant. Thus, neighbourhoods that recorded significant levels of NO_2 did not necessarily record high levels of O_3 pollutant, even though NO_2 is a precursor pollutant for O_3.

5.4 Predictors of exposure

The results from the linear regression modelling indicate that construction activities and open grills are variables that have influenced spatial $PM_{2.5}$ exposure levels. In the current study, a number of potential predictors were unable to be modelled and discarded due to no observations or substantial zero (0) values over-represented in the database. Therefore, predictor variables that displayed a considerable number of zeros within the buffer zone of 1000 to 25 meters radius were overlooked. This is consistent with Dirgawat et al. (2016) who discarded a great number of potential $PM_{2.5}$ exposure sources (predictor variables) with zero values within the radius of 300 to 25 meters in the study of particulate matter and associated components.

The $PM_{2.5}$ exposure levels increased with a decrease in the proximity of the exposure source. This was observed in both scenarios for open grills and construction activities. This finding is consistent with the Johannesburg study conducted by Venter et al. (2015) that recorded a significant increase of particulate matter exposure during open grilling activities. And incongruent with a Korean study that reported higher $PM_{2.5}$ levels within neighbourhoods that use open grilling method in comparison to neighbourhoods without open grilling activities (Kim and Lee, 2012). Several studies reported that construction activities in the neighbourhood increase exposure levels of $PM_{2.5}$ (Araújo et al., 2014; Azarmi et al., 2016 and Payus et al., 2017). The increase of $PM_{2.5}$ exposure levels with proximity to construction activities was observed by Azarmi et al. (2014). This study demonstrated a 15-fold increase in exposure to $PM_{2.5}$ within the vicinity of construction activities, whilst in their 2016 study, the authors showed a decline with an increase in distance. Font et al. (2014) in their study conducted in South East London in England discovered similar observations; construction activities were responsible for the increment of particulate matter exposure leading to exceedances of recommended limits. Rapid transport also appeared to be a good predictor for $PM_{2.5}$ concentrations, possibly due to the common use of diesel-consuming vehicles.

Whilst distance to construction sites and open grills were significantly associated with exposure, variability in $PM_{2.5}$ exposure was poorly explained by these models, only explaining 13-22% (radius of 50 to 25 meters). Small local sources in these informal areas that seemed to have a more substantial impact on $PM_{2.5}$, since these types of combustion are well-known sources of fine particles. Informal emission sources are generally not registered in any GIS database and can, therefore, be difficult to model, particularly since these activities are temporary in nature. Furthermore, spatial variability in $PM_{2.5}$ is generally low within small distances and therefore also more difficult to model (Fruin et al., 1994 & Kendrick et al., 2015). A recent study by Park et al (2018), regression models also performed poorly and was only able to explain 10.7% of the variability in $PM_{2.5}$. Notably, these models included a number of categories of predictor variables, which included land use (eg industrial, green area) transportation (eg bus routes, bus stop, major roads), housing types (single family, multiple families) and development density (gross commercial, gross residential). In light of the above, the individual models in the current study, performed better on its own, in comparison to the combined models in the Park study.

Traffic is a well-established indicator of NO_2 exposure. In the current study, proximity to rapid transport stops, bus routes, taxi routes and major routes were significant predictors of NO_2 exposure. These observations are consistent with Lee et al. (2017) findings who used traffic-related variables such as road lengths and distance to the nearest roads, to establish that NO_2 significant exposure levels are linked to these variables. Furthermore, Yang et al. (2017) discovered a similar impact of traffic-related variables mainly influencing nitrogen dioxide exposure. Muttoo et al. (2018) corroborated that nitrogen dioxide exposure is strongly influenced by traffic demonstrating a 59% increase of NO_2 exposure levels with proximity to traffic-related variables.

Additionally, linear regression model shows that nitrogen dioxide demonstrates spatial variability in close proximity to open grills and construction sites. This finding could be partially explained by the fact that these activities are associated with the combustion of fuel. Venter et al. (2015) confirmed that open grills significantly increase exposure levels of nitrogen dioxide. A significant change in the quality of the air was recorded during the duration of open grilling, revealed the outdoor experiment. However, after open grilling activities, the ambient air concentrations of nitrogen dioxide normalised. Furthermore, Ioana-Alina and Nicoleta (2017) discovered high levels of NO_2 pollutants in the vicinity of the activities related to construction sites. Likewise, the results of this study are consistent with several studies that have conducted exposure assessment using the same NO_2 predictors as independent variables (Choi et al., 2017; Larkin et al., 2017 and Habermann, 2018).

The individual models for NO_2 poorly explained variability in exposure, with the most variability explained by transport-related predictors such as rapid transport routes (7% - 10%), taxi routes in 1km (11%) bus routes in 1km (15%) and open grills (30%). The findings are consistent with studies, demonstrating mostly traffic predictors as good predictors for spatial variability in NO_2 (Beelan et al., 2013, van der A, 2008). A study by Gebreab et al. 2015 was only able to explain 4% of the variability in NO_2 using all types of the road with 200m as a predictor, whilst the current study shows slightly improved R^2 traffic related predictors such as road types (7% - 15%). Similarly, our study findings are comparable with a study by Gilbert et al. 2005, demonstrating that traffic-related predictor variables, such as highways within 100m (10%), major roads within 750m (16%), and the minor road within 500m (6%) only partially explained the variability.

5.5 Limitations of the study

Despite assessing exposure levels of air pollution for the long term and determining seasonal exposure variability of neighbourhoods, there are limitations associated with this study. Due to budget constraints, indoor exposure assessment was only conducted on a smaller scale. Therefore, the indoor assessment was not conducted for each household that measured outdoor air pollution. Additionally, the household's structure, the nature of fuel used indoors and indoor activities that could possibly influence air pollution were not recorded. Furthermore, limitations in terms of monitoring include the inability of the instruments to read the atmospheric meteorology that influences air pollutants behaviour. Thus, wind speed and direction of the air pollutants could not be determined.

Lastly, the measurement periods of exposure assessments per neighbourhood only lasted for a few weeks. Therefore, results cannot be directly compared with the SANAAQS. Land use regression modelling (LUR) has recently been reported as a common approach used in air pollution studies to assess exposures related to urban and traffic-related air pollution. This type of modelling uses a limited number of air pollution measurements at specific locations as proxies for emission sources, in order to predict concentrations of pollutants at unmeasured locations. In the current study, we were unable to further investigate this type of modelling due to limited data points and lack of availability of reference data from monitoring stations within these neighbourhoods.

5.6 Future research

There is a need for long-term exposure assessment studies for air pollution in the Western Cape that will monitor indoor and outdoor air pollution at least annually and constantly, in a larger scale to determine spatial and seasonal variability. Future studies should consider including atmospheric meteorological conditions and how the atmospheric conditions influence air quality according to the neighbourhoods. Instruments used for exposure assessment should be capable to read and record (equipped with real-time) 1-hour and 24-hour average concentrations of pollutants to enable comparisons with the regulation. This will provide a clear picture of whether average exposure levels of pollutants exceed recommended limits or not. Furthermore, exposure assessment of indoor air pollution should cover a significant number of households and factor in the household structure, household activities and different types of fuel used by different households and document the increase and decrease of indoor/outdoor concentration with respect to time. Development of LUR models for these neighbourhoods

would also provide a greater understanding of the spatial variability of air pollutants within these areas. This would be a cost-effective approach in determining the spatial distribution of air pollution, which could inform and assist in local policy development and guidelines.

5.7 Conclusion

The ambient air concentrations demonstrate seasonal and spatial heterogeneity in exposure levels. Milnerton had the highest outdoor $PM_{2.5}$ and NO_2 concentrations for summer while Oudtshoorn had the highest outdoor concentrations during winter for $PM_{2.5}$ and Khayelitsha for NO_2. SO_2 levels were consistently low during both seasons. Noordhoek had the lowest average levels for all pollutants. Winter average weekly concentrations were generally higher than the levels recorded in summer overall for all pollutants. The $PM_{2.5}$ average exposure levels in the current study, was lower compared to other African countries and international studies. Whilst the average NO_2 exposures were comparable to international studies, the average SO_2 exposure was lower than levels reported in other African studies. Whilst there are no legislative guidelines to compare the current study weekly averages, the concentrations for $PM_{2.5}$ and NO_2 were lower than the World Health Organisation (WHO) ($PM_{2.5}$: 24hour = 25µg/m^3, NO_2:1hour =200 µg/m^3) and South African Air Quality Standards values (NO_2:1hour =200 µg/m3).

In a sub-sample of indoor and outdoor measurements, the results were comparable for $PM_{2.5}$, NO_2 and CO. However, the results of Ozone (O_3) were relatively higher (~10 times) for outdoor compared to indoor levels. This study was able to show relationships between various potential sources of air pollution within these neighbourhoods. The sources and spatial distribution of these pollutants can be very different in African countries, from European counterparts. Significant predictors of $PM_{2.5}$ exposure were the distance to open grills and construction, though the models performed poorly. Rapid transport bus stops, bus routes, taxi routes and major routes were predictors of NO_2 exposure. The poor performance of regression models underscores the notion of possibly fundamental differences in the spatial determinants of particles in this African context and the challenges faced in terms of data availability and reference measurements from monitoring sites. Thus, applicability to health studies may be limited and further research is needed to better understand the spatial patterns and determinants of air pollution levels in these areas of South Africa.

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ANNEXURE A: HOME SAMPLING CHECKLIST

Western Cape Home Sampling Siting Checklist
25 June 2015 - INA

Date of visit		**Fieldworker initials**			
Informed the parents about the measurements? (tick X)	YES ☐	**Willing to participate?** (tick X)	YES ☐	NO ☐	
Home ID (Study Number):		**Home Address**			
Study Location		**Participant Name & Phone #**			
GPS Lat		**GPS Long**			
Site Type (tick X):	**Street Site** ☐	**Urban Background** ☐	**Regional Background** ☐		

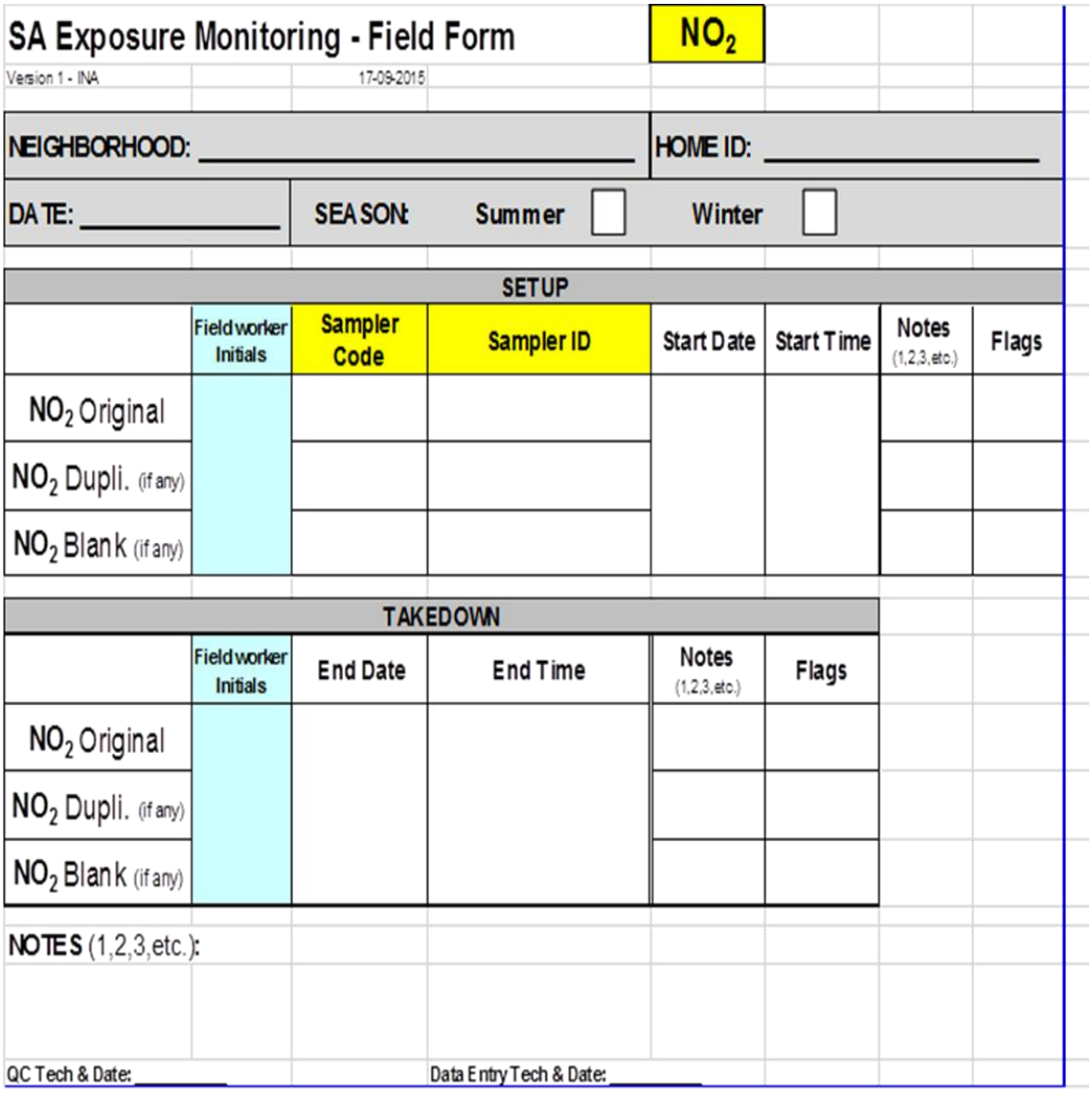
-Street sites: home is very close (<20m) from a major road with lots of traffic; high building density, highly populated surroundings, other sources than traffic possible
- Urban background: Not located at a major street (>100m away) with medium traffic intensity, moderate building density, other sources outside vicinity
- Regional background: Not affected by traffic (>200m from major street), low building density, no other potential sources of pollution, located just outside of the city

Electricity available at home (can it be pulled from inside)? (tick X)	YES ☐		NO ☐		
Nearby sources (<100m) of air pollution (e.g. garage, gas-station, bus stop, industry, factory, informal food catering-Braai, mines) **Other non-cooking home emissions** (e.g. burning of waste)					
Site Pictues (tick X)	**Sampling location** ☐	**View to the left** ☐		*Instructions:* take four pictures standing at potential location, make sure that the entire surroundings of sampling location are visible	
	View to the right ☐	**Straightahead** ☐			
Distance of sampling location from nearest house (m)				*Instructions*: pace it out (1 pace = 1m)	
Potential location of sampler outside of the house (tick X)	**In front of house** ☐	**Side of house** ☐	**Behind house** ☐	**On the roof** ☐	**Other*** ☐
Location access and security situation / concerns (e.g. locked doors or gates, theft, damage)					
Distance to nearest street (m) and **street name**					*Instructions*: pace it out (1 pace = 1m)
Traffic intensity on nearby street (tick X)	**low** ☐	**medium** ☐	**high** ☐	*low*: almost no traffic *high*: constant traffic flow	
Sketch of potential site:					

* If OTHER location: please discribe:

☐ More notes and information on the back of this page

ANNEXURE B: NITROGEN DIOXIDE EXPOSURE MONITORING FIELD FORM



SA Exposure Monitoring - Field Form NO_2

Version 1 - INA 17-09-2015

NEIGHBORHOOD: _____ HOME ID: _____

DATE: _____ SEASON: Summer ☐ Winter ☐

SETUP

	Fieldworker Initials	Sampler Code	Sampler ID	Start Date	Start Time	Notes (1,2,3,etc.)	Flags
NO_2 Original							
NO_2 Dupli. (if any)							
NO_2 Blank (if any)							

TAKEDOWN

	Fieldworker Initials	End Date	End Time	Notes (1,2,3,etc.)	Flags
NO_2 Original					
NO_2 Dupli. (if any)					
NO_2 Blank (if any)					

NOTES (1,2,3,etc.):

QC Tech & Date: _____ Data Entry Tech & Date: _____

ANNEXURE C: OZONE EXPOSURE MONITORING FIELD FORM

SA Exposure Monitoring - Field Form O_3

Version 1 - INA 17-09-2015

NEIGHBORHOOD: _____ HOME ID: _____

DATE: _____ SEASON: Summer ☐ Winter ☐

SETUP

	Field worker Initials	Sampler Code	Sampler ID	Start Date	Start Time	Notes (1,2,3,etc.)	Flags
O_3 Original							
O_3 Dupli. (if any)							
O_3 Blank (if any)							

TAKEDOWN

	Field worker Initials	End Date	End Time	Notes (1,2,3,etc.)	Flags
O_3 Original					
O_3 Dupli. (if any)					
O_3 Blank (if any)					

NOTES (1,2,3,etc.):

QC Tech & Date: _____ Data Entry Tech & Date: _____

ANNEXURE D: SULPHUR DIOXIDE EXPOSURE MONITORING FIELD FORM

SA Exposure Monitoring - Field Form **SO_2**

Version 1 - INA 17-09-2015

NEIGHBORHOOD: _____	HOME ID: _____
DATE: _____	SEASON: Summer ☐ Winter ☐

SETUP

	Field worker Initials	Sampler Code	Sampler ID	Start Date	Start Time	Notes (1,2,3,etc.)	Flags
SO_2 Original							
SO_2 Dupli. (if any)							
SO_2 Blank (if any)							

TAKEDOWN

	Field worker Initials	End Date	End Time	Notes (1,2,3,etc.)	Flags
SO_2 Original					
SO_2 Dupli. (if any)					
SO_2 Blank (if any)					

NOTES (1,2,3,etc.):

QC Tech & Date: _____ Data Entry Tech & Date: _____

ANNEXURE E: PARTICULATE MATTER EXPOSURE MONITORING FIELD FORM

SA Exposure Monitoring - Field Form		
Version 2 - INA/MED	09-10-2015	
NEIGHBORHOOD: _____		HOME ID: _____
DATE: _____	SEASON:	Summer ☐
Fieldworker Initials:		
Pump ID :		
Cyclone ID :		
Sampler ID :		
Sampler Code :		
Start Time :		
Start Time Counter :	0.0	
Rotameter ID :		
Pump Test Flow:		
Sample Start Flow :		
End Date :		
End Time :		
End Time Counter :		
Rotameter ID :		
Sample End Flow :		

ANNEXURE F: CARBON MONOXIDE EXPOSURE MONITORING FIELD FORM

SA Exposure Monitoring - Field Form **CO**

Version 1 - INA 17-09-2015

NEIGHBORHOOD: _____ HOME ID: _____

DATE: _____ SEASON: Summer ☐ Winter ☐

SETUP

	Field worker Initials	Sampler Code	Sampler ID	Start Date	Start Time	Notes (1,2,3,etc.)	Flags
CO Original							
CO Dupli. (if any)							
CO Blank (if any)							

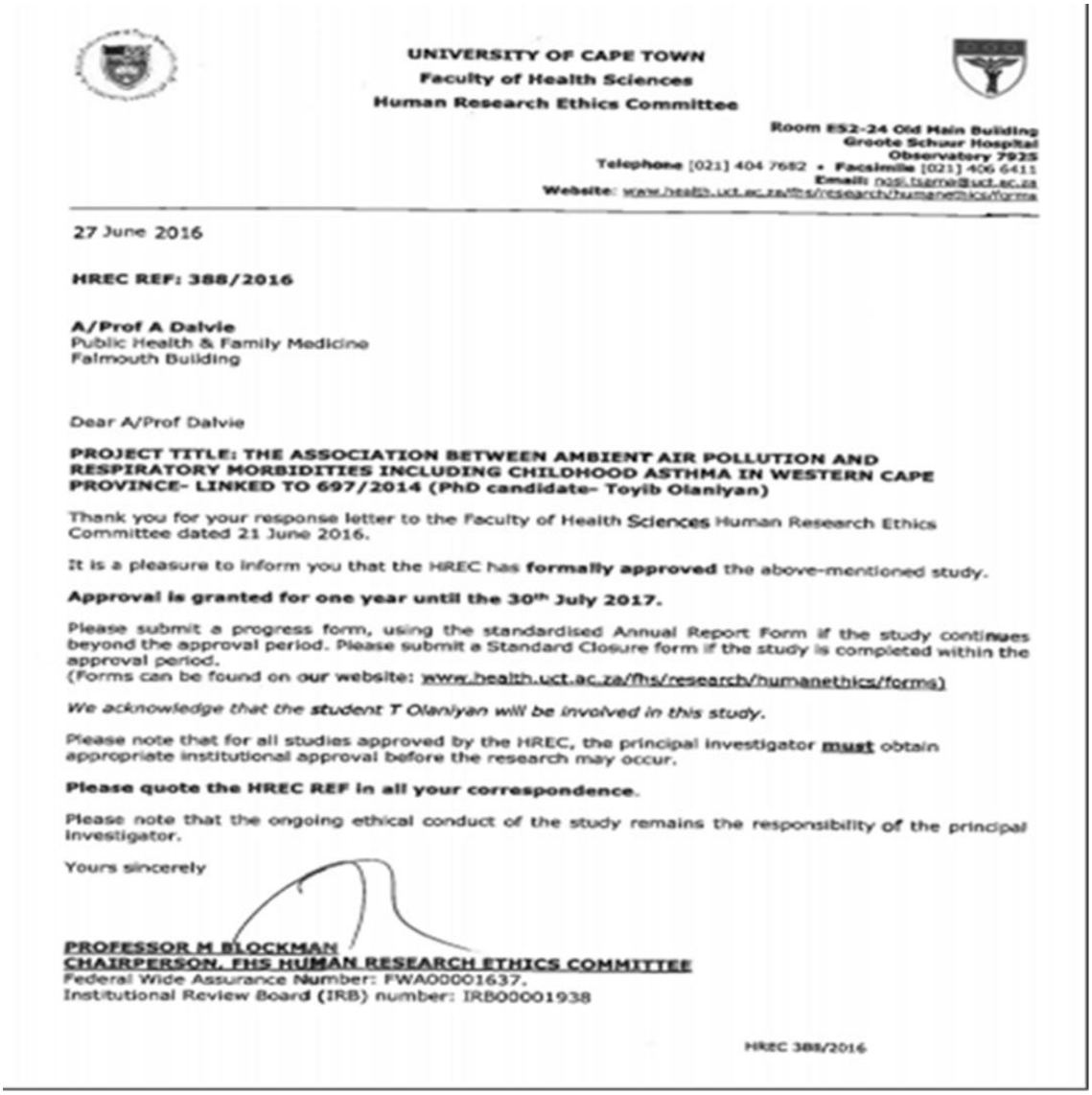
TAKEDOWN

	Field worker Initials	End Date	End Time	Notes (1,2,3,etc.)	Flags
CO Original					
CO Dupli. (if any)					
CO Blank (if any)					

NOTES (1,2,3,etc.):

QC Tech & Date: Data Entry Tech & Date:

ANNEXURE G: ETHICS APPROVAL LETTER



UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room ES2-24 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 404 7682 • **Facsimile** [021] 406 6411
Email: nosi.tsarne@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

27 June 2016

HREC REF: 388/2016

A/Prof A Dalvie
Public Health & Family Medicine
Falmouth Building

Dear A/Prof Dalvie

PROJECT TITLE: THE ASSOCIATION BETWEEN AMBIENT AIR POLLUTION AND RESPIRATORY MORBIDITIES INCLUDING CHILDHOOD ASTHMA IN WESTERN CAPE PROVINCE- LINKED TO 697/2014 (PhD candidate- Toyib Olaniyan)

Thank you for your response letter to the Faculty of Health Sciences Human Research Ethics Committee dated 21 June 2016.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

Approval is granted for one year until the 30th July 2017.

Please submit a progress form, using the standardised Annual Report Form if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.
(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

*We acknowledge that the **student T Olaniyan** will be involved in this study.*

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval before the research may occur.

Please quote the HREC REF in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Yours sincerely

PROFESSOR M BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS COMMITTEE
Federal Wide Assurance Number: FWA00001637.
Institutional Review Board (IRB) number: IRB00001938

HREC 388/2016

This serves to confirm that the University of Cape Town Human Research Ethics Committee complies to the Ethics Standards for Clinical Research with a new drug in patients, based on the Medical Research Council (MRC-SA), Food and Drug Administration (FDA-USA), International Convention on Harmonisation Good Clinical Practice (ICH GCP), South African Good Clinical Practice Guidelines (DoH 2006), based on the Association of the British Pharmaceutical Industry Guidelines (ABPI),and Declaration of Helsinki (2013) guidelines.
The Human Research Ethics Committee granting this approval is in compliance with the ICH Harmonised Tripartite Guidelines E6: Note for Guidance on Good Clinical Practice (CPMP/ICH/135/95) and FDA Code Federal Regulation Part 50, 56 and 312.

HREC 388/2016

ANNEXURE H: CONSENT LETTER FROM THE DEPARTMENT OF EDUCATION

Western Cape Government
Education

Directorate: Research

Audrey.wyngaard@westerncape.gov.za
tel: +27 021 467 9272
Fax: 0865902282
Private Bag x9114, Cape Town, 8000
wced.wcape.gov.za

REFERENCE: 20140917-36653
ENQUIRIES: Dr A T Wyngaard

Prof Mohamed Aqiel Dalvie
School of Public Health and Family Medicine
Health Sciences Faculty
Anzio Road
Observatory
7729

Dear Prof Mohamed Aqiel Dalvie

RESEARCH PROPOSAL: AN EPIDEMIOLOGICAL COHORT STUDY OF SCHOOL CHILDREN INVESTIGATING ASTHMA AND OF ADULTS INVESTIGATING CARDIOPULMONARY OUTCOMES

Your application to conduct the above-mentioned research in schools in the Western Cape has been approved subject to the following conditions:

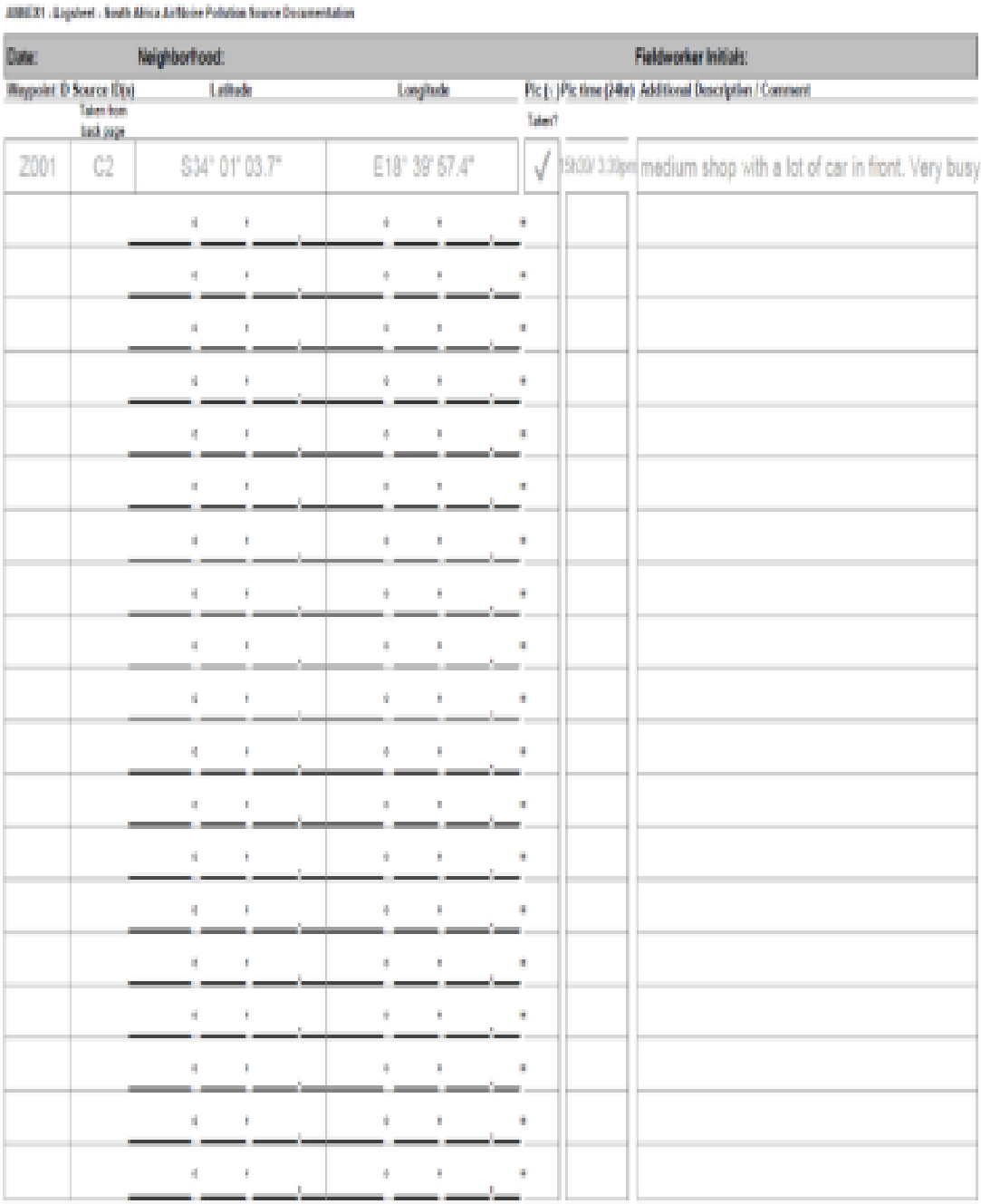
1. Principals, educators and learners are under no obligation to assist you in your investigation.
2. Principals, educators, learners and schools should not be identifiable in any way from the results of the investigation.
3. You make all the arrangements concerning your investigation.
4. Educators' programmes are not to be interrupted.
5. The Study is to be conducted from **01 April 2014 till 30 April 2017**
6. No research can be conducted during the fourth term as schools are preparing and finalizing syllabi for examinations (October to December).
7. Should you wish to extend the period of your survey, please contact Dr A.T Wyngaard at the contact numbers above quoting the reference number?
8. A photocopy of this letter is submitted to the principal where the intended research is to be conducted.
9. Your research will be limited to the list of schools as forwarded to the Western Cape Education Department.
10. A brief summary of the content, findings and recommendations is provided to the Director: Research Services.
11. The Department receives a copy of the completed report/dissertation/thesis addressed to:

    The Director: Research Services
    Western Cape Education Department
    Private Bag X9114
    CAPE TOWN
    8000

We wish you success in your research.

Kind regards.
Signed: Dr Audrey T Wyngaard
Directorate: Research
DATE: 17 September 2014

ANNEXURE I: LOGSHEET



Date:	Neighborhood:				Fieldworker Initials:
Waypoint ID	Source ID (Do) Taken from back page	Latitude	Longitude	Pic ( ) Taken?	Pic time (24hr)	Additional Description / Comment
Z001	C2	S34° 01' 03.7"	E18° 39' 67.4"	√	15h00/ 3.30pm	medium shop with a lot of car in front. Very busy
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		° ' "	° ' "			

ANNEXURE J: SOURCES OF AIR POLLUTION IN THE NEIGHBOURHOOD

Source name	Description	To avoid	Source ID
Grill	Open air restaurant or grill. Any place where food is cooked outside, for selling 	Personal or very small grills or cooking that doesn't emit any smoke. 	**F3**
Construction	Any construction site (road or habitation) that is big and is meant to last, such as building of new habitations, important road construction or repair. With construction machines. 	Small work on a single house, house repair or extension, any work that is not meant to last.  	**C5**

Source name	Description	To avoid	Source ID
Garage	Formal or informal garage or vehicle repair. Only big or very noisy garages (ex. welding)	Small garages or simple vehicle storage places. Damaged cars that lay on the side of the road.	**C6**
Waste	Any waste collection or burning site, such as big waste gathering or   containers	Small waste collections or small burned spots on the floor, that are not permanent or no frequently used waste collection or burning sites. 	**W2**