QUANTIFICATION OF EMISSIONS GENERATED FROM DOMESTIC BURNING ACTIVITIES FROM TOWNSHIPS IN JOHANNESBURG

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in the School of Geography, Archaeology and Environmental Studies at the University of the Witwatersrand, Johannesburg. It has not been submitted previously for any degree or examination in any other university.

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ABSTRACT

Domestic fuel burning activities have become a major source of urban air pollution. Studies have indicated that domestic burning activities, specifically in low-income settlements and townships, contribute greatly to the air quality problems experienced by most developing urban centres. Low-income households that exist within townships in South Africa, house a large portion of the South African population. These households burn vast quantities of coal, wood, paraffin as well as other substances in order to provide for their energy needs. Pollution emitted as a result of domestic burning activities is estimated to be one of the leading causes of respiratory illnesses, prevalent in inhabitants of low-income settlements. To better understand the relationship that exists between domestic burning and the resultant pollutants, a method of quantifying these pollutants has been developed for a completely un-electrified settlement, near Johannesburg, using the quantities and type of fuel consumed. A study, carried out in Zenzele during the winter months, in addition to a month before and a month after this period, allowed for the analysis of some of the more harmful winter fuels. Common fuel types consumed were identified through the analysis of census data and information gathered from questionnaires. In un-electrified households, paraffin and liquid petroleum gas (LPG), used specifically for cooking and lighting, are the most commonly used fuel types during the warmer months. During the colder months, however, residents of households in low-income settlements prefer to use solid fuels such as wood and coal. Factors such as seasonality, the availability and price of fuels as well as cultural aspects all have a bearing on residents' fuel choices and the quantity consumed. Emissions were quantified based on the quantities of wood and coal burnt in 15 households in Zenzele, using emission factors for SO_2, PM_{10}, CO_2 and CO. As the temperature declines, the rate at which these solid fuels are consumed increases. The most significant observations identified in this study are the diurnal and seasonal trends associated with domestic burning.

Key words: Domestic burning, domestic energy, low-income settlements, urban air pollution.

PREFACE

Domestic fuel combustion is an issue that has been gaining increasing concern over the past few decades. In developing countries, where much of the developing world still participates in various combustion processes on a daily basis, problems arise in the emissions released from these processes. A variety of fuels, burnt to supply energy for cooking, heating as well as lighting purposes, generates a range of trace gases and associated particulate material. Evidence has suggested that the combustion of domestic fuels release pollutants that can potentially be harmful.

Although a pressing issue, not many strides have been taken to fully understand and further quantify the emissions resulting from these burning activities. Studies undertaken in various developing countries worldwide have indicated either the environmental significance or the health risks associated with the combustion of domestic fuels, but very seldom have these matters been dealt with simultaneously. With the case of South Africa, only a small portion of work has been done in trying to estimate the total emissions generated from the combustion of domestic fuels.

Low-income settlements in South Africa account for a large portion of South Africa’s informal population. Usually residing in one of the many forms of informal dwellings, inhabitants of these households do not always have access to basic services such as electricity. Low-income communities based in informal settlements therefore seek alternative sources of fuels to provide for their energy producing needs. An abundance of coal reserves in South Africa will play a role in influencing the burning behaviour of low-income communities that do not have access to electricity.

Although a large number of both formal and informal settlements in South Africa have had access to electricity for a while, research has shown that some people living in these electrified households will continue to use fuels such as coal, wood, liquid petroleum gas (LPG), paraffin and other substances for domestic burning.

This research project has been reviewed by the Human Research Ethics Committee (Non-Medical) at the University of the Witwatersrand. A clearance certificate has been granted with the Protocol Number H1 10207.

This dissertation consists of seven chapters. Chapter 1 introduces the topic of domestic burning activities on a global scale and also identifies the objectives of the study, together with the research questions. Chapter 2 focuses on domestic burning in a South African context and gives a detailed list of the fuel types utilised and their associated pollutants and greenhouse gases. The related effects, both in the context of climate and health impacts, associated with these emissions are also discussed in Chapter 2. Chapter 3 provides a detailed description of the study site as well as the methodological approaches applied in this study. The results of this study are presented and discussed thoroughly in Chapters 4 and 5. Chapter 6 explores the conclusions of this study as well as the accompanying recommendations. Chapter 7 gives a list of all the reference papers and material used throughout this project.

Sections of this dissertation have been presented at the National Conference of the South African Society for Atmospheric Sciences held in the Free State in September 2010, at the International Conference on the Domestic Use of Energy held in Cape Town in April 2011 and at the 16th International Union of Air Pollution Prevention and Environmental Protection Associations Congress held in Cape Town in October 2013.

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ABBREVIATIONS AND ACRONYMS

APPA	Air Pollution Prevention Act
AQG	Air Quality Guideline
BNM	Basa Njengo Magogo
CO	Carbon monoxide
CO_2	Carbon dioxide
DME	Department of Minerals and Energy
DoE	Department of Energy
DEA	Department of Environmental Affairs
EJ	Exajoule
FRIDGE	Fund for Research into Industrial Development, Growth and Equity
IAP	Indoor Air Pollution
INEP	Integrated National Electrification Programme
LPG	Liquid Petroleum Gas
NAAQS	National Ambient Air Quality Standards
NEMAQA	National Environmental Management Air Quality Act
PM_{10}	Particulate matter (with aerodynamic diameter of less than 10um)
ppb	Parts per billion
ppm	Parts per million
RDP	Reconstruction and Development Programme
RLM	Randfontein Local Municipality
SO_2	Sulphur dioxide
Stats SA	Statistics South Africa
$\mu g/m^3$	micrograms per cubic metre
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
WHO	World Health Organisation

CHAPTER 1: INTRODUCTION

Overview

> *This chapter provides a brief background of the state of domestic burning on both a national and a global scale. The objectives of the study and the key research questions are also stated in this chapter.*

1.1. Background

Domestic burning is an activity that has been exercised for centuries and for a range of functions. There are large parts of both the developed and developing world that rely on some sort of domestic burning as a source of energy. Estimates have suggested that the carbon emissions generated from the combustion of domestic fuels in Africa is significant on a global scale (Bertschi *et al.* 2003).

The last few decades have witnessed a rapid increase in the world's urban population. This urbanisation has led to increased energy use, industrial activity and transportation and comes with a long list of associated problems, one of them being the quality of urban air. Related to this are factors pertaining to the environment, human health and wellbeing and even property damage. Gurjar *et al.* stated in 2008 that "the United Nations (UN) estimates that 4.9 billion inhabitants out of 8.1 billion will be living in cities by 2030". This is an estimation that suggests that more than half of the world's population will be concentrated in the smaller metropolitan areas around the globe. As a result an exponential growth in low-income settlements will be witnessed, accompanied by a backlog in the distribution of basic services such as electricity provision, amongst many others.

In South Africa, and more specifically the city of Johannesburg, there has been a significant flux of people into the city from the surrounding rural areas, in an attempt to find employment opportunities. The most recent census study of 2011 has indicated that there has been a positive net migration of people into the province of Gauteng. Statistics SA has explained this concept as being "the difference between the number of persons settling in a province and those moving out" (Stats SA, 2011a). With an influx of about 1 million people into the province in the last 10 years, Gauteng has the highest levels of migration and attracted more people than all the other provinces have lost. This, in turn, places enormous pressure on already dense low-income settlements and a resultant increase in domestic burning and associated pollutant emissions are witnessed.

1.2. Global Domestic Fuel Use

Extensive research has been carried out in this field of study. Previous studies have focused on the emissions generated from various burning activities in informal regions of both urban and rural areas. These studies, although carried out at different times, both nationally and internationally, covered similar aspects of domestic burning activities, including the use of domestic biomass fuels**.** Yevich and Logan indicate that the domestic combustion of biomass is prevalent in the rural parts of developing countries and have identified that it can be divided into two distinct parts. The first of these deals with the combustion of charcoal, wood and agricultural by-product for domestic use and, secondly, includes the combustion of other crop residue in the clearing of fields (Yevich and Logan, 2003). As Table 1.1 indicates, considerable domestic emissions are emerging from the developing countries of Africa, Asia and Latin America.

Table 1.1. Inventory of global biofuel and corresponding emissions (Ludwig *et al.* 2003).

Region	Population (1995) Millions	Biofuel Consumption			Emission		
		Ia	Ib	II	CO_2	CO	NO
		Tg dm yr $^{-1}$			Tg C or N yr^{-1}		
Africa	728	265	11.5	633	296	28	0.50
Asia	3386	517	3.8	1896	886	84	1.51
Latin America	482	157	8.0	236	110	10	0.19
Oceania	29	5	0.0	6	3	0	0.00
N. America	293	59	0.5	243	114	11	0.19
Europe	506	29	0.4	86	40	4	0.07
Former USSR	292	30	0.1	99	46	4	0.08
World Total	5716	1062	24.3	3199	1495	141	2.54
All anthropogenic sources					7100	925	34

Notes: Biofuel consumption :Ia, fuelwood for the year 1993 as given by FAO production statistics (1995) and converted to dry mass units with FAO conversion factors and a moisture content of 20% mcdb; Ib, charcoal for the year 1993 as given by FAO production statistics (1995); II, all biofuel types for the population of 1995 (United Nations, 1995) calculated with per capita consumption rates given on a national basis by Hall *et al.* (1994) for the reference year 1987. Initial energy consumption figures were converted to dry mass units with the conversion factor and the moisture content (20% mcdb) as suggested by Hall *et al.* (1994). The resulting consumption rates (in dm cap−1 yr−1), including all forms of biomass, are 0.87 (Africa), 0.56 (Asia), 0.49 (Latin America), 0.19 (Oceania), 0.83 (N. America), 0.17 (Europe), and 0.34 (former USSR). Emissions were estimated with our emission factors given in Table I and biofuel consumption in column II under the assumption that 80%, 15%, 2.5%, and 2.5% of the total consumption is in form of wood, residues, dung, and charcoal, respectively. Data on emissions from all anthropogenic sources are taken from M. Prather *et al.*, 1995; D. Schimel *et al.*, 1996)

Karekezi explains that energy usage on the African continent can be examined based on three separate areas. These regions include North Africa, where countries primarily use oil and gas, South Africa which is reliant mainly on coal and finally the sub-Saharan countries of Africa that rely heavily on the combustion of biofuels (Karekezi, 2002). The combustion of a range of domestic fuels releases extensive quantities of various trace gases into the atmosphere, leading to subsequent environmental, climatic and health impacts (Levine, 2003).

Research undertaken in Southern Africa, includes the Qalabotjha study, a low-smoke fuels macro scale experiment. This experiment, carried out in 1997, examined the changes in air quality, with the use of different fuels. The study also investigated the concentrations of particulate matter, both $PM_{2.5}$ and PM_{10} released into the atmosphere (Engelbrecht *et al.* 2000). A Zimbabwean study, highlighted similar aspects of domestic burning activities, but focused specifically on the domestic combustion of biofuels. This study carried out in 2005, involved a survey in which the burning of domestic biofuels was investigated to establish the impact that these fuels have on the atmospheric trace gas budget. This study included both urban and rural areas (Marufu *et al.* 1997). In most African countries, wood is used as a major fuel type to support primarily cooking and heating purposes (Brocard *et al.* 1998). Internationally, similar studies have also occurred in both China (Yan *et al.* 2006) and Mexico City (Adachi and Buseck, 2008), amongst many others.

China has a significantly large population of approximately 1.357 billion people, as recorded by the World Bank in 2013 (The World Bank, 2014b). A substantial portion of this population can be classified as rural (47%), living in informal or low-income housing (The World Bank, 2014a). The main source of energy for domestic use in these regions is derived from the combustion of biofuels. Yan *et al.* (2006), however, indicates that recent economic development in China has subsequently decreased the amount of biofuels being burnt as a greater portion of the rural population has access to electricity. The combustion of solid domestic fuels contributes to the deteriorating state of indoor air pollution in China (Foell *et al.* 1995; Mestl *et al.* 2007). After China, India displays the highest biofuel use (Joshi, 1991; Yevich and Logan 2003). A study presented by Streets and Waldhoff estimates that amount of biofuels consumed throughout Asia in the year 1990 was about 22EJ (1EJ = 10^{18} J) and account for about 24 % of the total energy use for Asia (Streets *et al.* 1999).

Yevich and Logan suggest that similarly to the countries of sub-Saharan Africa, the main fuel type utilised by the rural population in Latin America is wood. Due to its vast forest resources in the tropical regions, wood is easily accessible and relatively inexpensive. Charcoal is not as commonly used for domestic burning but rather for industrial purposes. Using a dataset from the year 1985, they were able to establish which continents and sub-continents exhibited the highest consumption rates of domestic biofuels. Although Asia, focusing specifically on China and India, came out on top, the countries of Central and South America were given a notable mention with 13% of that year's global domestic biofuel estimate being burnt in Latin America. Brazil is the largest consumer of domestic biofuels amongst the Central and South American countries, followed closely by Mexico (Yevich and Logan, 2003).

In recent years, South Africa has undergone mass electrification, through the Department of Energy's Integrated National Electrification Programme (DoE: INEP) and an exponential increase in the number of electrified households has been witnessed (DoE, 2012). A statement made in line with South Africa's goal to provide some form of energy to the entire country states that "South Africa aims to ensure that by 2030 at least 90% of people have access to grid electricity" (Stats SA, 2011a). The proportion of households using electricity for cooking has increased by 26.4%, from 47.5% in 1993 to 73.9% in 2011. The number of households using electricity for lighting has also increased, from 57% in 1996 to 84% in 2011 (Stats SA, 2011b). It is, however, still difficult to ascertain whether the amount of domestic fuel burning will decrease and if people will change over completely to electricity as their most convenient source of energy (Van Horen *et al.* 1993).

Although previous studies have been carried out within this field of research, relative to the emission inventories that exist for commercial and industrial emissions, little work has been done on domestic burning emissions inventories (Kituyi *et al.* 2001b). The purpose of this study therefore, is to derive a method to quantify the emissions generated from various burning activities of households situated within a completely un-electrified low-income settlement. It will further investigate how different sources of energy contribute to the total amount of emissions released into the atmosphere.

1.3. Rationale for this Study

Only a small amount of work has been done in the way of determining any sort of domestic burning emissions inventory in South Africa. For this reason, a lack of South African literature surrounding this topic breeds uncertainty in not only the various fuel types being utilised but also the quantities of these fuels being consumed in low-income settlements as well as the associated impacts. This work is important not only because it will shed some light on what the major domestic fuel types being utilised are, but it will also provide much needed data on the consumption rates of some of these fuels. It will also enable a better understanding of how these activities affect the atmospheric loading budget. Information on emission calculations and estimates gathered from this study can also be used to improve modelling for future projections.

The World Health Organisation (WHO) estimates that approximately 4.3 million deaths can be caused by household air pollution annually, with approximately 3.5 million deaths occurring as a result of household air pollution directly and 0.5 million deaths occurring as a result of exposure to outdoor air pollution associated with solid fuel combustion (GACC, 2014; WHO, 2014). These figures confirm that there are numerous health risks associated with domestic burning activities that act on both the pulmonary and respiratory systems. Exposure to indoor air pollution as a result of domestic fuel combustion leaves vulnerable communities open to the early onset of acute respiratory illnesses which will inevitably be detrimental to their health and well being (Scorgie *et al.* 2004a).

1.4. Objectives and Research Questions

The main objectives of this study are:

I. To identify the fuels most commonly burnt and the resulting emissions associated with domestic burning activities in a low-income settlement in Johannesburg called Zenzele.
II. To quantify these emissions using a fuel weight approach and emission factors.
III. And finally, to compare the emissions generated in this low-income settlement to a similar settlement in Johannesburg; and in so doing, examine the potential of being able to relate these emissions to sites with similar characteristics.

In order to achieve these specific objectives, the following questions need to be posed:

1. What are the key fuel types being utilised in Zenzele?
2. What are the uncertainties within the emission estimates?

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Extensive research on domestic fuel burning has been undertaken globally, with specific attention paid to developing countries. Within a Southern African context, however, there remains a gap in the literature. Chapter 2 seeks to explore this gap, in addition to examining the climatic and health impacts associated with emissions generated from domestic fuel use.

CHAPTER 2: DOMESTIC BURNING AND RELATED EFFECTS

Overview

This chapter provides a detailed description of the fuels burnt domestically and the associated pollutants and greenhouse gases that are emitted from the combustion processes. It also provides insight into the legislation and regulations surrounding air quality, which identifies national standards and guidelines for the various pollutants. This chapter further discusses the climatic effects and the health risks associated with the resulting emissions, and gives insight into the initiatives aimed at curbing the impacts of these emissions associated with domestic burning.

Townships in South Africa are mainly characterised by low-income households and this type of housing is further characterised by domestic burning activities when examining air quality (Balmer, 2007). A large portion of the South African population (37%) is housed in informal households that exist within low-income settlements in South Africa (The World Bank, 2014a). According to Stats SA’s 2011 census data, 13.6% of households in South Africa are classified as informal. Gauteng has one of the highest percentages of people living in informal housing in relation to the total South African population, when compared to the other eight provinces. 18.9% of houses in Gauteng are classified as informal (Stats SA, 2012). For this reason, Gauteng contributes largely to the emissions generated from townships in South Africa.

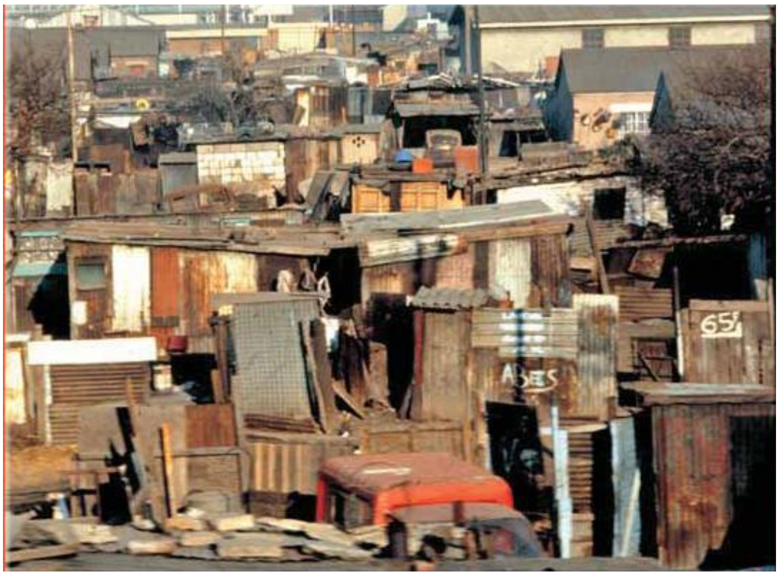


Figure 2.1. Gauteng Low-income Settlement (HSRC, 2005).

Although a large portion of South Africa's settlements have, in recent years, become increasingly electrified, there are still some settlements that are either only partially electrified or completely un-electrified (Bekker *et al.* 2008). In 2012, Stats SA documented that 11% of households in South Africa did not have access to electricity (Stats SA, 2013). Even some of those households that do have access to this basic service, often continue to make use of fuels required for domestic burning to meet some, if not all of their energy needs (Scorgie *et al.* 2003). Madubansi and Shackleton (2006) note that in most South African settlements, households that have gained access to this basic service usually only utilise electricity for lighting and powering electrical appliances but will continue to utilise wood for their thermal requirements. Even the use of electricity in cases such as these is often too costly, as these appliances are energy intensive (White *et al.* 1997).

A variety of fuel types are utilised within low-income settlements in South Africa; and each one is associated with resultant emissions. The fuels utilised by a specific community or within a specific settlement are dependent on a number of factors. These factors relate largely to the availability, accessibility and affordability of the fuels (Hall *et al.* 1994, Wagner *et al.* 2005).

2.1. Fuel Types Utilised

Low income households in South Africa often do not have adequate access to basic services, including energy services. These households that house a large portion of the unemployed population, where poverty is rife, therefore have to, rely on less convenient and often harmful fuels (Balmer, 2007).

Table 2.1. Fuel use in electrified and un-electrified settlements

		Summer	**Winter**
Electrified	**Cooking**	Electricity	Coal and/or wood
	Heating	No Fuel	Coal and/or wood
	Lighting	Electricity	Electricity
Un-electrified	**Cooking**	Gas or paraffin	Coal and/or wood
	Heating	No Fuel	Coal and/or wood
	Lighting	Paraffin or candles	Paraffin or candles

Note: Gas refers to Liquid Petroleum Gas

As highlighted in table 2.1, there are a number of fuels types that are burnt during domestic burning activities in electrified and un-electrified South African settlements. The two major fuels consumed in these areas during winter have been identified as coal and wood, although other substances such as paraffin, liquid petroleum gas (referred to as gas throughout the rest of this dissertation), animal dung and electricity are also utilised to provide for inhabitants of low-income settlements energy needs (Ludwig *et al.* 2003). Common fuels utilised during the warmer summer months are paraffin, candles, electricity and gas. Gas is also a popular choice for cooking purposes but is often too expensive, in relation to paraffin. In electrified households, electricity is the preferred fuel choice to provide for lighting needs; and candles in that of un-electrified. Paraffin is the most common fuel consumed within completely un-electrified settlements, as it is used mainly for cooking but also lighting by means of paraffin lanterns (Muller *et al.* 2003).

Households tend to utilise coal and wood as a result of its multi-functional nature. These fuels can be used for both cooking and lighting functions, as well as, simultaneously, for space heating purposes (Scorgie *et al.* 2003). The use of fuelwood and coal pose both environmental and health concerns for the communities residing in these low-income settlements.

2.1.1. Coal

Low grade, poor quality bituminous coal is used widely by low-income urban communities in South Africa (Formenti *et al.* 1998; Engelbrecht *et al.* 2002). Both coal and charcoal are commonly used fuels within most African countries. Although their names are sometimes used interchangeably, these two fuels are different in the way in which they originate. The formation of charcoal occurs when fuelwood is carbonised and the wood is converted to charcoal through pyrolysis (Delmas *et al.* 1991). Even some electrified households, within settlements continue to use coal, due particularly to its cost effectiveness, cultural attributes and its abundance and availability in South Africa. Scorgie had indicated that “approximately 45% of electrified ‘township’ households and 88% of un-electrified ‘township’ households use coal on a daily basis for cooking and space heating” (Scorgie *et al.* 2003, 3).

Quantities of a range of different fuel types that are utilised during domestic burning are dependent on a number of different factors. Specifically with the case of coal, Scorgie *et al.*

2003 has further indicated that the average coal usage per household will vary, depending on the following factors:

1. Type of house (formal house, planned shack, unplanned shack or backyard shack)
2. Whether or not the household is electrified
3. The number of people living in the house
4. The season
5. The availability of coal
6. The price of coal and the household income

There are three different types of housing; these include formal, informal and traditional housing. Within urban informal settlements, however, traditional dwellings are very seldom built. Urban informal settlements consist mainly of informal housing, with formal housing to a far lesser extent. A formal dwelling is usually described as a brick structure and can range from a small home in an informal settlement, to a flat or apartment to a large free-standing property. Burning behaviours witnessed in formal dwellings are vastly different to that of burning behaviours in informal homes. Formal houses are almost always electrified and therefore rely less on other sources of energy such as coal. These homes tend to be insulated better too and for this reason do not require as much energy for heating purposes (Stats SA, 2012).

Planned shacks, unplanned shacks and backyard shacks are all considered to be informal types of housing. A planned shack is one that is built within an already existing settlement, whereas unplanned shacks are those erected on an ad hoc basis. Backyard shacks are informal dwellings built on the same stand as a formal house. These informal homes, usually existing within an electrified or partially electrified settlement, generally require fuels such as coal to provide for the cooking, heating and sometimes even lighting purposes.

Households in low-income settlements situated within close proximity of coal mines tend to utilise this fuel more as it is relatively inexpensive and readily available. A number of pollutants deemed harmful to human health are emitted when coal is burnt. These include a range of gaseous pollutants, as well as large quantities of respirable particulates (Finkelman *et al.* 1999).

Certain households that have been electrified prefer to retain coal stoves as a cost effective option for space heating as indicated in figure 2.2. In many cases they are passed down from one generation to the next and for this reason, when used, create a strong cultural association to coal burning. In households utilizing coal stoves, they are operated most frequently by an elderly member of the family, it has been reported that the presence of a warm stove creates a pleasant atmosphere conducive to the gathering and socialising of family members (Mdluli, 2007).

Amongst households with both electric and coal stoves, households with higher incomes use coal less frequently and opt preferentially, for electricity. Households with lower incomes, prefer to make use of coal even though it is the lesser convenient of the two options (Van Horen *et al.* 1993).

Figure 2.2. Photographs of coal stoves in houses in Zenzele.

2.1.2. Fuelwood

In a large number of developing countries, fuelwood is a dominant fuel type used in domestic burning activities (Goodman, 1987; Barrefors and Petersson, 1995). In both urban and rural settlements, poor communities utilise wood on a daily basis for their energy requirements. Although large quantities of this fuel type are required around the globe, there is a significant gap in the knowledge that exists in the supply and demand of this fuel in these areas (Banks *et al.* 1996; Madubansi and Shackleton, 2007). Fuelwood use, in areas that are completely rural, differs somewhat from areas such as urban townships. Where rural regions are almost entirely reliant on wood and other non-woody biofuels, settlements based in urban areas do have access to other fuel types (Miah *et al.* 2003). For this reason, a positive correlation can be witnessed between fuelwood use and deforestation in rural areas (Kituyi *et al.* 2001a; Ludwig *et al.* 2003). The annual amount of fuelwood burnt, however, is difficult to estimate due to the varying nature with which firewood is gathered and consumed (Andreae, 1991).

Fuelwood use patterns are also highly dependent on the availability of wood (Xiaohua and Zhenming, 1996). Marufu *et al.* (1997) explain that, often, communities display preferences in the type of wood they choose for combustion, as different types of wood exhibit different burning characteristics. When wood becomes scarce, however, they settle for other biofuels that are available (Marufu *et al.* 1999). The amount of wood burnt for domestic use is also influenced by a number of other factors such as climate, income and the distance that the settlement is located from a source of fuelwood. Fuel types in the form of forests may be limited depending on whether the climate, environment and topography of an area, allows for growth. Wood, being a relatively inexpensive fuel if gathered, could be made use of less if there is more income allocated to domestic fuels. With the increasing growth rate of urban informal settlements, the areas that once possessed an abundant supply of gathering fuelwood becomes populated and collection sites are no longer located within close proximity of those settlements. Subsequently, this has lead to an increase in the number of households purchasing fuelwood as it remains a fuel type that is relatively cheaper than other fuels such as coal (Madubansi and Shackleton, 2007).

As with many other types of fuels, wood is not a generic commodity. It differs in size, type and composition, most importantly moisture content. When burnt, wood can emit pollutants on different scales, depending on these factors. Emissions generated from the combustion of wood, or any other fuel, are not only dependent on the fuel but also on how that fuel it is burnt and the rate at which it is burnt (McDonald *et al.* 2000). Resultant emissions can be inferred by merely looking at what is being generated (Lee *et al.* 2010). Black smoke is usually formed in the regions where a flame exists, whereas a paler white smoke is emitted from regions where a flame does not exist. At adequate temperatures for initial combustion, this whiter smoke is released and contains particles of unburned matter. Products of incomplete combustion are generated when the temperature of the fire does not rise above those experienced in the initial combustion phase and for this reason, the reaction cannot be completed (Bond *et al.* 2004).

In South Africa, however, wood is still widely used as a major fuel type in urban townships. If wood can be sourced, it is usually burnt in these self-made stoves, with attached chimney, as demonstrated in the figure 2.3.

Figure 2.3. Photographs of hand-built stoves with chimneys from households in Zenzele.

2.2. Pollutants and Greenhouse Gases, and their associated National Standards and Regulations

The importance of trace gases, pollutants and greenhouse gases associated with domestic burning activities are well recognised as emissions that have an effect on global climate change; and have also been gaining interest in the context of human health. In order to gauge their effect on the environment and further human health, it is important to take into account the national standards and guidelines developed to regulate these pollutants.

Particulate matter and an array of trace gases are produced and emitted into the atmosphere during domestic burning activities. Some of these trace gases include carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2), amongst many others (Crutzen and Andreae, 1990). Most of these gases are precursors of other gases and pollutants, and together, all have a significant influence on the chemistry of the atmosphere.

Almost all major pollutants emitted as a result of domestic burning activities fall into the category of criteria pollutants. Criteria pollutants are some of the most common pollutants released into the atmosphere. As such, these pollutants have been deemed hazardous and have an impact on both the environment and more specifically human health when examining emissions generated from domestic burning. For this reason, the emission of criteria pollutants into the atmosphere is controlled by national ambient air quality standards (Aneja *et al.* 2001). Fine particulate matter is a criteria pollutant that has become a major problem in many developing countries, where domestic burning is a common practice. It has one of the most stringent set of air quality standards and is regulated most extensively because of its health risks (Bhanarkar *et al.* 2002). With the acute effects being of greatest concern over the last few decades, a smaller portion of work has been done on the long term effects. Some of the short-term effects include; respiratory, cardiopulmonary and cardiac illnesses (Katsouyanni, 2003).

National legislation, in the form of the Department of Environmental Affairs' National Environmental Management: Air Quality Act (Act No. 39 of 2004), prescribes national standards for all the criteria pollutants. This piece of legislation follows on from the Atmospheric Pollution Prevention Act (Act No. 45 of 1965), which was repealed on the 31st of March 2010, allowing for NEMAQA to come into full effect from the 1st of April 2010. Through air quality management plans, the abovementioned standards seek to ensure that the negative impact of poor air quality is reduced with reference to people's health and the environment (RSA, 2009).

Under NEMAQA, South Africa's National Ambient Air Quality Standards have been specified in individual tables for each criteria pollutant. Regulatory concentrations are quoted alongside the averaging period, the frequency of exceedence and the compliance date. The averaging period refers to the period of time over which an average was calculated. A vital piece of information concerning a regulated concentration of a pollutant is the frequency of exceedence. This value refers to the number of times a national standard can be exceeded within one calendar year. If the national standard is exceeded on more occasions than specified by the frequency of exceedence value, then there is no longer compliance with that standard. The compliance date refers to the dates that the standard was promulgated and period over which compliance of the standard is required (RSA, 2005).

The World Health Organisation’s (WHO) air quality guidelines have been developed to regulate air pollution, with a focus on reducing the impacts on human health. With the intention of making its recommendations globally applicable, this set of guidelines differs from national standards set out by individual countries, in that the national standards speak directly to that country’s national environmental policies. The WHO air quality guidelines, on the other hand, provide general information and thresholds for a specific group of pollutants deemed harmful to public health. For this reason, it is important to consider both national legislation and these guidelines when looking at matters of air quality, pertaining to human health and the environment. These guidelines were first released in 1987 and then further updated in 1997 and most recently in 2005 (WHO, 2006).

Set up similarly to that of South Africa’s National Ambient Air Quality Standards, the WHO Air Quality Guidelines are also quoted in tables for individual pollutants. With interim targets, set above the value of the air quality guideline, the table also provides a basis on how these different levels of targets values were selected.

2.2.1. Particulate Matter

Particulate matter is a common pollutant associated with the smoke emitted from domestic burning activities. Particulate matter refers to the microscopic solid particles that are generally emitted into the atmosphere from natural or anthropogenic sources. Particulate matter can consist of a variety of elements, from aerosols, to organic and metallic particles, to traces of dust as well (Garza, 1996). Significant particles included in this type of particulate pollution are those with an aerodynamic diameter of less than 10µm, known as PM_{10}. Contained in this category, are even finer particles with an aerodynamic diameter of less than 2.5µm ($PM_{2.5}$). These particles are of great concern when relating domestic burning to health risks. Small PM_{10} particles and even tinier particles of $PM_{2.5}$ have the ability to penetrate deep into lungs, when inhaled.

The combustion of D-grade, poor quality coal contributes to the release of particulate matter into the atmosphere. Both concentrations of $PM_{2.5}$ and PM_{10} are of great significance with respect to respiratory illnesses (Fullerton *et al.* 2008). Finer particles, such as $PM_{2.5}$, have a longer lifetime in the atmosphere and can therefore be dispersed with ease and over great distances. Coarser particles that remain after the combustion process, however, disperse with the assistance of winds. Lighter winds will therefore disperse a larger portion of the smaller $PM_{2.5}$ particles as opposed to the heavy particles of PM_{10}. Bond *et al.* (2004), explains that the coarser particles that are emitted from a combustion process are more likely to consist of mineral matter and carbon particles from the fuel.

A follow-up study to the Qalabotjha low-smoke fuels macro-scale experiment indicates that air particulate concentrations are highly dependent on the fuel utilised, as well as the wind (Engelbrecht *et al.* 2001). Both of these studies were carried out in an attempt to minimise the exposure of people to the emissions generated from the combustion of poor quality coal. In order to achieve this, alternative fuels in the form of low-smoke fuels were suggested, in a bid to decrease concentrations of air particulates. The national standards for particulate matter, as well as the WHO guidelines, for both sizes PM_{10} and $PM_{2.5}$ are given in tables 2.2, 2.3, 2.4 and 2.5. As already mentioned, all values of national standards were released in 2010, the national standards for $PM_{2.5}$, however, were proposed at a later stage and further promulgated on 29 June 2012.

Table 2.3. National ambient air quality standards for particulate matter (PM_{10}) (after RSA, 2009.)

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
24 hour	120µg/m³	4	Immediate–31 December 2014
24 hour	75µg/m³	4	1 January 2015
1 year	50µg/m³	0	Immediate-31 December 2014
1 year	40µg/m³	0	1 January 2015
The reference method for the determination of the particulate matter fraction of suspended particulate matter shall be EN 12341			

Table 2.4. National ambient air quality standards for particulate matter ($PM_{2.5}$) (after RSA, 2011).

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
24 hour	65 µg/m³	4	Immediate-31 December 2015
24 hour	40 µg/m³	4	1 January 2016-31 December 2029
24 hour	25 µg/m³	4	1 January 2030
1 year	25 µg/m³	0	Immediate-31 December 2015
1 year	20 µg/m³	0	1 January 2016-31 December 2029
1 year	15 µg/m³	0	1 January 2030
The reference method of the determination of $PM_{2.5}$ fraction of suspended particulate matter shall be EN 14907			

Table 2.5. WHO air quality guidelines and interim targets for particulate matter: annual mean concentrations[a] (after WHO, 2006).

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	Basis for the selected level
Interim target-1 (IT-1)	70	35	These levels associated with about a 15% higher long-term mortality risk relative to the AQG level.
Interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% [2-11%] relative to the IT-1 level.
Interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% [2-11%] relative to the IT-2 level.
Air quality guideline (AQG)	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more that 95% confidence in response to long-term exposure to $PM_{2.5}$

[a] The use of $PM_{2.5}$ guideline value is preferred.

Table 2.6. WHO air quality guidelines and interim targets for particulate matter: 24-hour concentration[a] (after WHO, 2006).

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	Basis for the selected level
Interim target-1 (IT-1)	150	75	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short-term mortality over the AQG value).
Interim target-2 (IT-2)	100	50	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short-term mortality over the AQG value).
Interim target-3 (IT-3)*	75	37.5	Based on published risk coefficients from multi-centre studies and meta-analyses (about 1.2% increase of short-term mortality over the AQG value).
Air quality guideline (AQG)	50	25	Based on relationship between 24-hour and annual PM levels

[a] 99th percentile (3days/year).

For management purposes. Based on annual average guideline values; precise number to be determined on basis of local frequency distribution of daily means. The frequency distribution of daily $PM_{2.5}$ or PM_{10} values usually approximates to a log-normal distribution.

2.2.1.1 Carbonaceous Aerosols

Almost all carbonaceous aerosols are of anthropogenic origin. They include black carbon and organic carbon which arise from two main sources, namely industrial activities which includes the combustion of fossil fuels, and biomass burning (Molnár *et al.* 2005). The largest portion of the global emission of BC is derived from the combustion of either biomass or domestic fuels (Saud *et al.* 2013). Black carbon or soot, as it is commonly referred to, is a product of an incomplete combustion process (Penner *et al.* 1993; Haywood *et al.* 2000). The complete combustion of carbon–based fuels generates CO_2 but an inefficient combustion process will generate BC (Streets *et al.* 2004; Bond *et al.* 2005). If the temperature of the fire is too low or there is an inadequate amount of oxygen, the fuel will not be burnt completely, therefore forming soot instead of carbon dioxide. Incomplete combustion usually occurs during the flaming stages for the fire and these conditions are most conducive to the production of soot. Finer particles are produced during the smouldering stages of the fire (Gwaze *et al.* 2006). When a sufficient amount of oxygen is present, the soot created in the initial stages of combustion will burn out, forming carbon dioxide (Bond *et al.* 2004).

Inefficient combustion technologies give rise to a range of chemical products, the most significant of which is black carbon. Biomass burning, particularly during the drier seasons, also produces large amounts of both black and organic carbon (Ramanathan *et al.* 2001). The combustion of biomass for domestic energy use produces large amounts of organic aerosols. In recent decades, particular attention has been paid to pollutants such at organic and black carbon due to their atmospheric warming potential. Previous studies indicate that smoke particles emitted from fires comprise of approximately 60% organic carbon (OC) and 5-10% black carbon (BC) (Saud *et al.* 2012). Table 2.6 illustrates that, globally, the largest sources of BC and OC from open burning comes from Africa, where the combustion of domestic fuels is a common practice with reference to open burning.

Table 2.7. Emissions of black and organic carbon from open burning[a] (Bond *et al.* 2004).

	Black Carbon			Organic Carbon		
Region	Central	(Low-High)	Previous96 (Ratio)[b]	Central	(Low-High)	Previous96 (Ratio)[b]
North America	116	(49-494)	283 (2.4)	1473	(599-3745)	2126 (1.4)
Central/South America	910	(487-2581)	1812 (2)	6727	(3929-14026)	13074 (1.9)
Europe	59	(29-229)	132 (2.2)	691	(300-1705)	976 (1.4)
Former USSR	100	(44-416)	240 (2.4)	1245	(516-3139)	1787 (1.9)
China	124	(72-282)	160 (1.3)	713	(410—1483)	909 (1.3)
India	92	(49-224)	127 (1.4)	505	(260-1126)	155 (1.5)
Other Asia	275	(127-896)	546 (2)	1962	(1006-4453)	3970 (2)
Pacific	165	(75-469)	275 (1.7)	1132	(523-2720)	1786 (1.6)
Africa	1472	(675-4223)	2628 (1.8)	10540	(5116-24567)	17862 (1.7)
Middle East	11	(6-29)	15 (1.3)	60	(31-134)	90 (1.5)
Total	3325	(1614-9842)	6217 (1.9)	25013	(12691-57099)	43334 (1.7)

[a]Units are Gg/yr.

[b]Previous96 applies emission factors from *Liousse et al.* [1996] to our estimates of dry matter burned.

2.2.2. Carbon Dioxide

Carbon dioxide is another key pollutant emitted as a result of domestic burning activities. This greenhouse gas is emitted as a by-product of a complete combustion process (Bhattacharya *et al.* 2002a). As indicated in equation 1 below, CO_2 and water vapour (H_2O)

are the resultant products emitted from a complete combustion process, where there is sufficient oxygen for the reaction to occur (Lemieux *et al.* 2004). Although the impact of these products on human health, are not as harmful as those products generated from an incomplete combustion process, they do still have a significant climatic impact (Bhattacharya *et al.* 2000). Carbon dioxide together with other carbon based pollutants, which are emitted as a result of domestic burning activities, play a major role in the changes to the global carbon cycle. As with the case of coal burning, wood burning too has a major influence on the emission of carbon species. The type of wood and the size of the log that is burnt will affect the amount or type of carbon released into the air. Owing to the fact that this process, in itself, produces charcoal, the by-products are produced two-fold (Gustafson *et al.* 2006).

$$(\mathrm{CH_2O}) + \mathrm{O_2} = \mathrm{CO_2} + \mathrm{H_2O} \qquad (1)$$

Where (CH_2O) represents the typical composition of organic matter, O_2 represents the oxygen required for combustion and CO_2 and H_2O are the by-products of complete combustion (Delmas *et al.* 1995).

Figure 2.4 shows the CO_2 emissions generated from a fire as a function of time. It is apparent that these two parameters are directly related. Concentrations of carbon dioxide are highest when the temperature of the fire is at its highest, and this occurs during the flaming stage of the fire. It is therefore clear that the largest amounts of carbon dioxide generated during combustion, are released in the initial stages when combustion is complete.

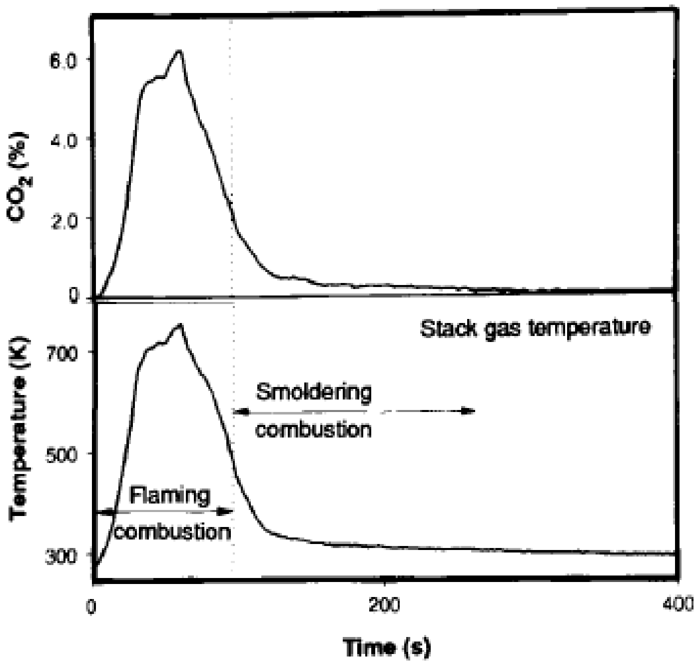


Figure 2.4. Concentrations of CO_2 from an experimental fire as a function of time (adapted from Crutzen and Andreae, 1990).

2.2.3. Products of Incomplete Combustion (PIC)

The three main products, after carbonaceous aerosols, yielded from an incomplete combustion process are carbon monoxide (CO), methane, (CH_4) and polycyclic aromatic hydrocarbons (PAHs) (Smith, 1994; Streets and Waldhoff, 1999). Owing to the fact that most forms of domestic burning occurs in rural or informal urban areas, where burning techniques are poor, there are more instances of the production of incomplete combustion products (Smith *et al.* 1993; Singh *et al.* 2013). Streets and Waldhoff (1999) have also specified that the formation of products of incomplete combustion are inversely related to the combustion efficiency. For this reason, inefficient stoves that often exist in low-income settlements, coupled with poor burning practices will produce greater amounts of these pollutants.

Although studies have revealed that all of the products mentioned above have an impact on human health, Lohmann *et al.* (2000) has indicated that the emission of PAHs are the most difficult to manage and reduce. They explain that the release of PAHs during domestic burning is often inadvertent, due largely to poor burning techniques and for this reason is difficult to control, without guidelines. CO and CH_4 are both greenhouses gases with their own set of greenhouse gas regulations, but amongst these three pollutants, CO is the only substance with national ambient air quality standards, as specified in the table 2.7. Taken from another set of WHO guidelines, the WHO guideline for indoor air quality specifies threshold guidelines for four different averaging times (table 2.8).

Table 2.8. National ambient air quality standards for carbon monoxide (CO) (after RSA, 2009).

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
1 hour	30 mg/m³ (26 ppm)	88	Immediate
8 hour (calculated on 1 hourly averages)	10 mg/m³ (8.7 ppm)	11	Immediate
The reference method for analysis of Carbon Monoxide shall be ISO 4224			

Table 2.9. WHO indoor air quality guidelines for CO (after WHO, 2010).

Averaging Time	Concentration (mg/m³)	Comments
15 minutes	100	Excursions to this level should not occur more than once per day
1 hour	35	Excursions to this level should not occur more than once per day
8 hours	10	Arithmetic mean concentration
24 hours	7	Arithmetic mean concentration

2.2.4. Trace Gases

Sulphur, contained in variety of fuels such as low-grade coal, is oxidised to form sulphur dioxide (SO_2). A major concern with the emission of oxides of sulphur, specifically sulphur dioxide, is its transformation into acidic precipitation. Although sulphur dioxide may be emitted on a lesser scale during domestic burning, in comparison to some of the other pollutants that have already been mentioned, its remains a concern as its impact is two-fold. Table 2.9 provides a breakdown of South Africa’s national ambient air quality standards for four different averaging periods. Sulphur dioxide, however, has been recorded as having significantly exceeded the WHO guidelines in a few instances, within developing countries. Some of these cases include Chongqing and Beijing in 1994, where the annual mean concentrations of SO_2 were recorded at 330µg/m³ and 100µg/m³ respectively (WHO, 2000).

Table 2.10 makes reference to these guidelines, indicating regulatory concentrations for both the 24-hour averaging period as well as the 10-minute averaging period. The highest concentrations of SO_2 have been experienced in these developing countries during extreme winters.

Table 2.10. National ambient air quality standards for sulphur dioxide (SO_2) (after RSA, 2009).

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
10 minutes	500 µg/m³ (191ppb)	526	Immediate
1 hour	350 µg/m³ (134 ppb)	88	Immediate
24 hours	125 µg/m³ (48ppb)	4	Immediate
1 year	50 µg/m³ (19ppb)	0	Immediate
The reference method or the analysis of sulphur dioxide shall be ISO 6767			

Table 2.11. WHO air quality guidelines and interim targets for SO_2: 24-hour and 10-minute concentrations (after WHO, 2006).

	24-hour average (µg/m³)	10-minute average (µg/m³)	Basis for selected level
Interim target-1 (IT-1)[a]	125	-	
Interim target-2 (IT-2)	50	-	Intermediate goal based on controlling either motor vehicle emissions, industrial emissions and/or emissions from power production. This would be a reasonable and feasible goal for some developing countries (it could be achieved within a few years) which would lead to significant health improvements that, in turn, would justify further improvements (such as aiming for the AQG value).
Air quality guideline (AQG)	20	500	

[a] Formerly the WHO Air Quality Guideline (WHO, 2000).

Smaller amounts of nitrogen oxides (NO_x), ozone (O_3) and volatile organic compounds (VOCs) are also released into the atmosphere during the combustion process. The emission of NO_x occurs primarily as nitric oxide (NO), as well as, smaller quantities of nitrogen dioxide (NO_2) and nitrous oxide (N_2O). The oxides of nitrogen are another set of pollutants that are not emitted in extremely large quantities during domestic fuel combustion. Nitrogen dioxide is formed during the combustion process, when nitrogen oxide combines with oxygen (Streets *et al.* 2003). Like SO_2, however, NO_2 (or in the form of NO) is also an acid-deposition precursor and can be transformed into nitric acid. NO_2 also acts as a precursor for tropospheric ozone. In the presence of sunlight, NO_2 is broken down photochemically to form NO and a single oxygen atom. This oxygen atom then combines with a molecular oxygen atom, forming O_3 (Crutzen *et al.* 1979; Seinfeld and Pandis, 2006). Although the impact of oxides of nitrogen, specifically NO_2, may not be as great on human health as some of the other pollutants mentioned above, the health risks associated with the exposure to ozone is still of concern and includes and range of both short- and long-term illnesses. Tables 2.11 to 2.14, offer South African national standards and WHO guidelines for other trace gases that occur in smaller concentrations during combustion processes.

Table 2.12. National ambient air quality standards for Nitrogen Dioxide (NO_2) (after RSA, 2009).

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
1 hour	200 µg/m³ (106ppb)	88	Immediate
1 year	40 µg/m³ (21ppb)	0	Immediate
The reference method for the analysis of nitrogen dioxide shall be ISO 7990			

Table 2.13. WHO air quality for NO_2: annual mean and 1-hour mean concentrations (after WHO, 2005).

	NO_2 annual mean (µg/m³)	NO_2 1-hour mean (µg/m³)
Air quality guideline (AQG)	40	200

Table 2.14. National ambient air quality for Ozone (O_3) (after RSA, 2009).

Averaging Period	Concentration	Frequency of Exceedence	Compliance Date
8 hour (running)	120 µg/m³ (61ppb)	11	Immediate
The reference method for the analysis of ozone shall be UV photometric method as described in SANS 13964			

Table 2.15. WHO air quality guideline and interim target for ozone: 8-hour concentrations (after WHO, 2006).

	Daily maximum 8-hour mean (µg/m³)	Basis for selected level
High Levels	240	Significant health effects; substantial proportion of vulnerable populations affected.
Interim target-1 (IT-1)	160	Important health effects; does not provide adequate protection of public health. Exposure to this level of ozone is associated with: Physiological and inflammatory lung effects in healthy exercising young adults exposed for periods of 6.6 hours; Health effects in children (based on various summer camp studies in which children were exposed to ambient ozone levels). An estimated 3-5% increase in daily mortality[a] (based on findings of daily time-series studies).
Air quality guideline (AQG)	100	Provides adequate protection of public health, though some health effects may occur below this level. Exposure to this level of ozone is associated with: An estimated 1-2% increase in daily mortality[a] (based on findings of daily time-series studies). Extrapolation from chamber and field studies based on the likelihood that real-life exposure tends to be repetitive and chamber studies exclude highly sensitive or clinically comprised subjects, or children. Likelihood that ambient ozone is a marker for related oxidants.

[a] Deaths attributable to ozone. Time series studies indicate an increase in daily mortality in the range of 0.3-0.5% for every 10µg/m³ increment in 8-hour ozone concentrations above an estimated baseline level of 70 µg/m³.

2.3. Climate Effects

2.3.1. Atmospheric Chemistry and the Loading Budget

A vast range of pollutants have gained increasing attention with regard to their influences on the globe's atmospheric chemistry and loading budget. A host of trace gases, the major greenhouse gases as well as atmospheric aerosols can all be associated with biomass burning and on a lesser scale, domestic burning. Atmospheric aerosols have an important influence on the earth's radiative budget in that their radiative forcing acts in the opposite direction to greenhouse gases present in the atmosphere (Charlson *et al.* 1992; Anderson *et al.* 1996).

Carbon dioxide, a greenhouse gas, has, in recent years, become notorious for its heating abilities and associated impact on the greenhouse effect. As already mentioned, this greenhouse gas is one of the by-products released from a combustion process. The combustion of biofuels produces carbon dioxide and water. Owing to the fact that the majority of domestic burning is performed in rural or informal areas, where burning techniques are poor, there are more instances of incomplete combustion processes, yielding products such as carbon monoxide (CO) and black carbon (BC) (Smith *et al.* 1993). There are still, however, large amounts of carbon dioxide released into the atmosphere, even in cases of incomplete burning, thereby enhancing the warming of the atmosphere and contributing to both global warming and climate change. The burning of domestic biomass fuels plays a key role in the global carbon cycle. The burning of biomass that was produced sustainably, will not necessarily contribute to the net increase of carbon dioxide in the atmosphere (Smith *et al.* 1993; Sajjakulnukit *et al.* 2003).

Methane (CH_4), another carbon compound and nitrous oxide (N_2O) are other greenhouse gases that contribute to the heating of the atmosphere (Scholes and van der Merwe, 1996). The burning of biofuels influences the atmospheric chemistry and biogeochemical cycles of both carbon and nitrogen (Crutzen and Andreae, 1990). Nitrous oxide, methane and carbon monoxide have a hand in producing traces of ozone in the troposphere, through photochemical reactions. Ozone too, is recognised as one of the primary greenhouse gases (Levine, 2003).

Carbonaceous aerosols too, have an impact when released into the atmosphere. Although this aerosol type includes both organic carbon (OC) and black carbon (BC), these two species act very differently from one another, in the way they interact with solar radiation. Organic carbon scatters solar radiation, whereas black carbon absorbs solar radiation (Reddy and

Venkataraman, 2002). With regards to domestic burning, however, black carbon and organic carbon are important atmospheric aerosols that are released into the atmosphere during combustion processes. Although a large portion of combusted fossil fuels are strongly related to industrial activities and concentrated in developed countries, a considerable amount of black carbon can also be attributed to the combustion of biofuels, particularly, for domestic burning in developing countries (Reddy and Boucher, 2007).

Soot or black carbon particles possess the ability to absorb visible light, whereas, most other elements of atmospheric aerosols are only capable of scattering this incoming light (Andreae, 1983, Adachi and Buseck, 2008). The high absorption efficiency of black carbon significantly enhances the heating of the atmosphere, further adding the warming effect, already established by greenhouse gases (Wentzel *et al.* 2003). Subsequent changes occur in cloud cover and surface albedo, in that, the Earth's radiative budget is affected both directly and indirectly (Power, 2003; Gwaze *et al.* 2006). Aerosols such as these exert a positive forcing on the earth's radiation budget, thereby promoting global warming. These aerosols, not only influence atmospheric temperature, but cause considerable changes in the atmospheric chemistry. Black carbon particles have a relatively short lifespan within the atmosphere and, for this reason, tend to have more localised effects, impacting the regions closest to the source (Bond, 2007).

2.3.2. Atmospheric Transport

The impact of aerosols, particulate matter and a range of other pollutants on the climate and environment can also be widespread. Air pollution is not always restricted by national boundaries and, in many instances, continental boundaries. The United Nations Economic Commission for Europe (UNECE) established the Convention on Long-Range Transboundary Air Pollution in 1979. This convention seeks not only to reduce air pollution but also pollutants that are transported horizontally over large distances, by drawing up policies that outline the changes that need to made in the release of pollutants. With 51 parties already involved and 8 protocols that have been developed, the aim to get intergovernmental cooperation in a bid to solve some of the environmental and health issues associated with tranboundary air pollution, is well on its way to being achieved (http://www.unece.org/env/lrtap/).

The gaseous emissions and particulates associated with domestic burning activities tend to have a localised impact due to their low dispersion potential and short residence times. For this reason, they are deemed hazardous substances in light of human health. Pollutants associated with biomass burning, for instance, as opposed to domestic burning, often have a longer lifespan and the ability to cross boundaries into neighbouring regions or even across continents. Pollutants such as these can have residence times of anywhere between days to months (UNEP, 2007). Figure 2.5 highlights the relationship that exists between residence times and transboundary air pollution. It is evident that they are directly related; as the residence time increases, so does the extent to which the pollutant will travel.

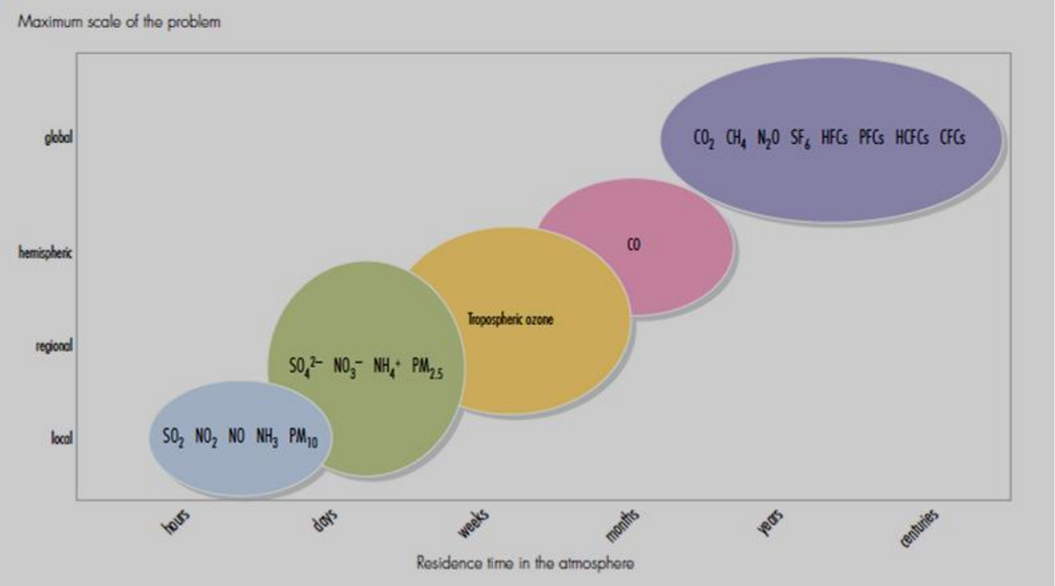


Figure 2.5. Selected pollutants, their average residence times in the atmosphere and the maximum extent of their impact (UNEP, 2007).

Smaller particles that have a longer lifespan in the atmosphere can travel, with their effects being relatively extensive (Andreae and Merlet, 2001). The long-range transport of pollutants, emitted as a result of different forms of burning, is highly dependent on a number of factors. Global winds are, by and large, the most important factor, as this will determine in which direction the pollutants are transported as well as how far they will go, and where they eventually settle. Regional factors such as the topography, amongst many others, of an area are other significant influences (Kukkonen *et al.* 2005). Seasonal variations in the transport of these pollutants are also evident in much of the literature (Crutzen and Andreae, 1990).

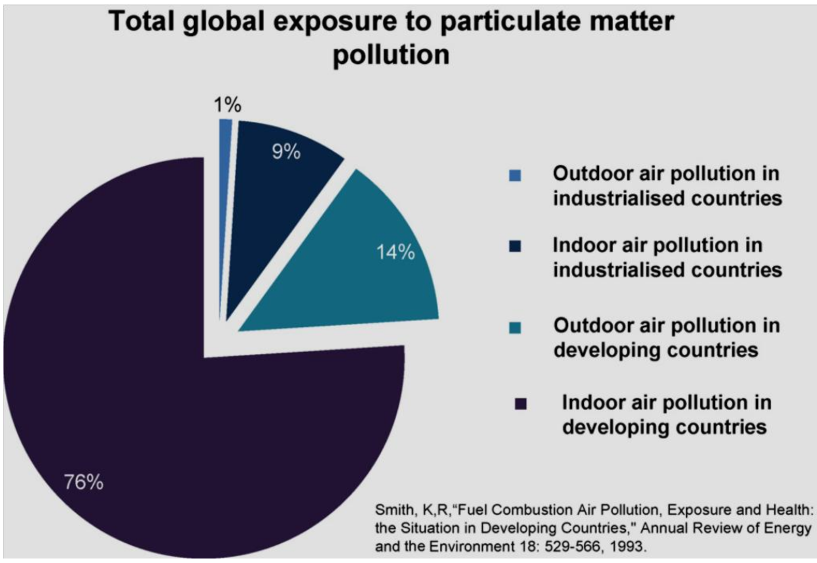
On a more local scale, pollutants emitted into the atmosphere over Southern Africa, have the potential to be transported widely, across both the Atlantic and Indian oceans, or even re-circulated over the region (Tyson *et al.* 1996; Piketh *et al.* 1999b). Piketh *et al.* (1999a), have stated that the semi-permanent subtropical anticyclones, the transient mid-latitude ridging anticyclones, the westerly baroclinic disturbances and the barotropic quasi-stationary tropical easterly disturbances are the most important synoptic systems governing atmospheric transportation over Southern Africa. Vertical and horizontal transportation is dependent not only on the atmospheric circulation of air, but also the stability of the atmosphere. Vertical transportation over this region is highly influenced by the common occurrence of three distinct stable layers, particularly during the dry periods. Horizontally, subsidence within the very prominent Hadley cell controls the departure of pollutants from the anticyclonic system. Circulation occurring in the northern part of the system is transported over the Atlantic Ocean and the southern part, over the Indian Ocean (Garstang *et al.* 1996; Tyson *et al.* 1996).

2.4. Health Risk Potential

Domestic burning activities not only influence climatic cycles on a regional and global scale, but they also have an impact on indoor air quality (Schneider *et al.* 2006). Mestl *et al.* (2007, 12) indicate that "indoor air pollution (IAP) from solid fuel use in developing countries is estimated by the World Health Organisation to be the eighth leading health risk worldwide". Rehfuess *et al.* (2011) have highlighted the range of illnesses that are associated with poor air quality as a result of domestic burning activities and these include; acute respiratory diseases, cardiovascular diseases, chronic obstructive pulmonary disease, different types of cancers, tuberculosis as well as many cases of asthma and pneumonia in children.

Common fuel types utilised during domestic or residential combustion, include coal, wood, candles and kerosene. There are numerous health risks associated with the use of kerosene in low-income settlements, however, this topic does not fall within the scope of this study. An increase in its usage has been witnessed in these areas recently. Davis (1998) describes kerosene as a "transitional fuel" that is being made use of more often as a larger percentage of low-income settlements become electrified, and as people slowly start moving over to electricity usage. Better known as paraffin, this fuel generate sizeable amounts of a variety of pollutants, which include carbon monoxide, nitrogen dioxide and a host of hydrocarbons and volatile organic compounds (Muller *et al.* 2003).

Perhaps the most influential pollutant generated from domestic burning activities, with respect to its effect on human health, is particulate matter. Figure 2.6 highlights the extent to which particulate matter and indoor air pollution affect the developing world. Although identified as a huge problem, there are, however, great uncertainties in trying to quantify pollutants associated with residential fuel combustion. A large portion of this uncertainty lies in the lack of data surrounding the amount of fuel consumed (Jones, 1999).



Smith, K,R,"Fuel Combustion Air Pollution, Exposure and Health: the Situation in Developing Countries," Annual Review of Energy and the Environment 18: 529-566, 1993.

Figure 2.6. Pie chart showing the total global exposure to particulate matter air pollution (Fullerton *et al.* 2008).

Particulate matter of less than 10 micrometres (PM_{10}) and even finer, of less than 2.5 micrometres ($PM_{2.5}$) are easily inhalable. Their size allows them to travel through the body with minimal resistance, where they settle in the cardiovascular and respiratory systems. This can lead to a variety of health impacts, including respiratory illnesses and the associated reduced lung function, pulmonary and cardiovascular diseases.

The impacts that particulate matter have on human health are influenced by a number of factors associated with the physical and chemical properties of every particle. The size of the particle is one of the major factors as this determines, to what extent, the particle can penetrate the lungs and other components of the respiratory system. Both size and chemical composition dictate the residence time of the pollutants in the atmosphere and, in relation to this, whether the particle is inhalable.

Bølling *et al.* (2009) note that amongst inhalable particles, the extent to which these particles have a negative effect on human health is dependent on a different list of elements. These include where the particle settles and how long it is preserved in the lung. Factors such as shape, size and density will have a large influence on where the particle is deposited. Figure 2.7 describes the process with which inhalable particles are deposited in the lungs of humans.

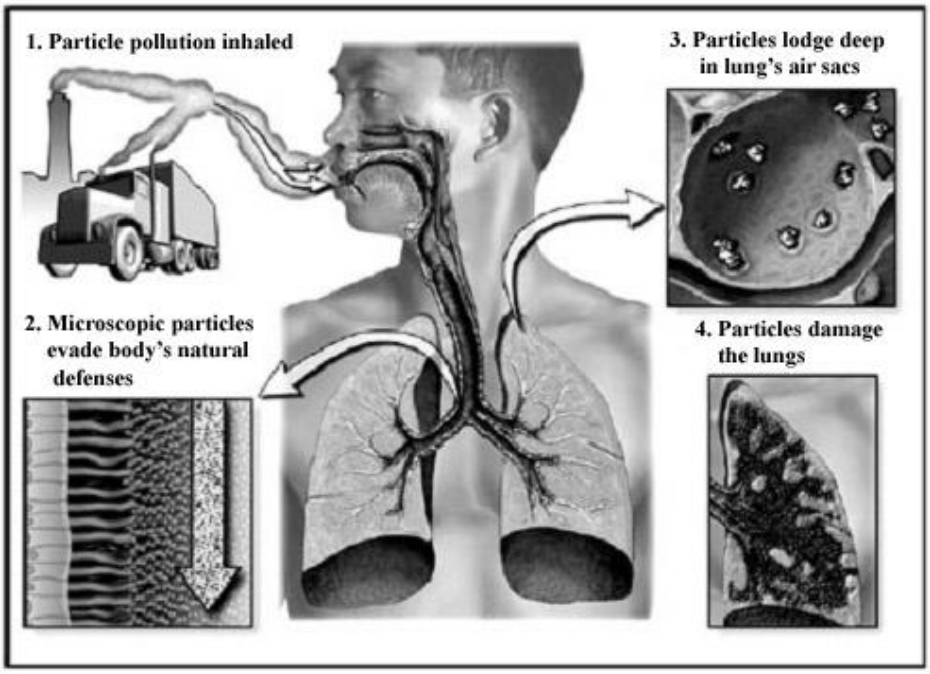


Figure 2.7. The health effects of air pollutants on the respiratory system (www.indoorquality.org).

The occurrence of respirable particulates is, in large part, attributable to wood burning. In South Africa, the worst cases of poor air quality arise from the combustion of wood, dung or coal. These fuel types burnt in open fires, in poorly ventilated low-income households, provide energy for cooking, heating and lighting purposes. Large quantities of particulates are released from combustion processes such as these and are often responsible for the illnesses experienced by the inhabitants of these households (Bruce *et al.* 2000).

The production of inhalable particles, those with an aerodynamic diameter of <10µm (PM_{10}), including $PM_{2.5}$ have been classified as harmful and are associated with adverse health effects on the pulmonary system (Fullerton *et al.* 2008). Figure 2.8 illustrates how different sizes of particulate matter impact different parts of the respiratory system.

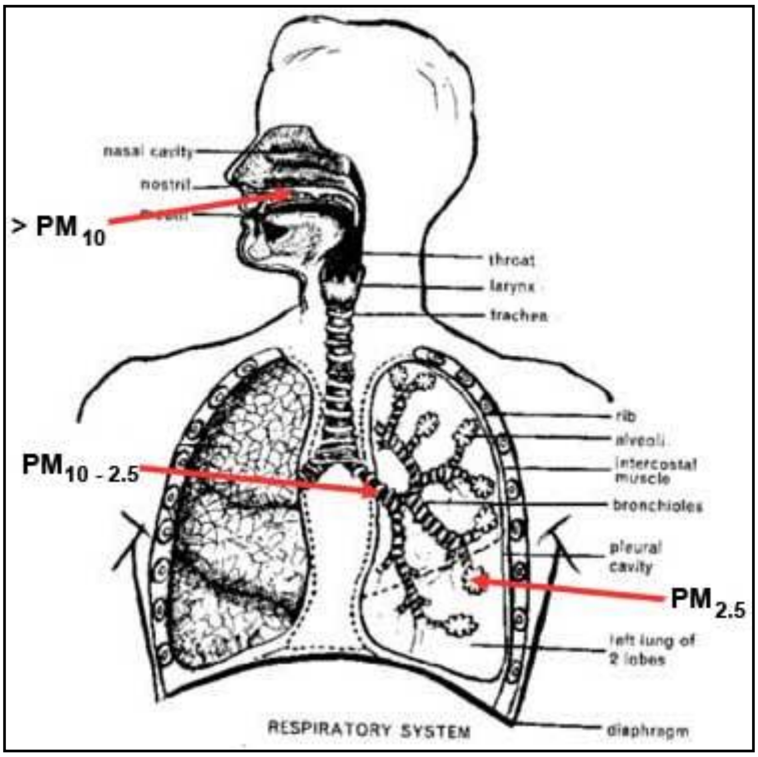


Figure 2.8. The effect of particulate matter on the respiratory system (www.pca.state.mn.us).

As mentioned above, some of the criteria pollutants that exist in the ambient air, that are associated with domestic burning activities and that are regulated by the NAAQS and WHO guidelines, often do not exceed these thresholds and for this reason are not as of great concern to human health. These sources, however, are different to those that are associated with indoor air quality and are not regulated by the NAAQS. Although not regulated as stringently, the WHO has created guidelines for certain indoor air pollutants (WHO, 2010). Instances in which these guidelines are exceeded will pose more of a threat in light of human health. Very high concentrations of both SO_2 and NO_2 can have harmful effects on both the respiratory and pulmonary systems and are more likely to occur in people with pre-existing respiratory illnesses. These pollutants still require regulation, however, because they are precursors to products that are hazardous to human health and the environment and have the ability to be transformed or broken down with relative ease. Ozone, also controlled by NAAQS and WHO guidelines, is one of these products and does in fact have a greater bearing on health risks. The short-term effects of ozone are more pronounced on the respiratory system and show a decrease in lung function (Katsouyanni, 2003).

The combustion of coal for domestic consumption has had significant harmful effects on the health of people globally, with large amounts of toxic metals and other compounds being emitted from combustion processes. Poor quality coal and even wood, burnt in “unvented” stoves, allows for the resulting pollutants to permeate through homes, exposing people to the hazardous substances. Rural homes, with inadequate ventilation, are likely to experience higher levels of these toxic elements (Joshi *et al.* 1989; Finkelman *et al.* 1999).

In developing countries, the burning of coal and biofuels contribute largely to a range of pollutants that lead to pulmonary and related respiratory diseases (Boleij *et al.* 1989). Carbon monoxide poisoning and respiratory illnesses occur as a result of these burning activities, together with poor ventilation, which is a characteristic feature in informal housing (Balmer, 2007). A considerable amount of literature suggests that with respect to domestic burning, the burden of some of these illnesses fall on women and young children that reside in low-income settlements. They are exposed to the highest levels of resultant pollutants when cooking (Rehfuess, 2006).

2.5. Interventions

In an attempt to reduce the harmful impacts associated with domestic burning, several interventions have been suggested. Although these interventions could be met with great success, they are all heavily reliant on the mind-set and behaviours of the people living within these communities. A number of emission reduction strategies associated with residential fuel burning were suggested in the FRIDGE report, and these were selected and prioritised according to the options most viable for reducing the human health risks. Some of these measures included the top down ignition of fires, stove maintenance and replacement, insulation of existing home, electrification, low smoke fuel implementation and switching to LPG and natural gas (Scorgie *et al*. 2004c). These interventions have been established in order to curb the emissions associated with domestic burning activities in South Africa; and they include fuel substitution and the improvement of stove efficiency and ventilation (Röllin *et al.* 2004). Clean coal technologies in the form of the national low smoke fuel programme, is an example of this. Efforts have also been taken to improve housing insulation, thereby assisting in keeping homes warmer for longer, which in turn decreases the amount of fuel being consumed.

2.5.1. National Electrification

As mentioned in Chapter one, South Africa has embarked on a nationwide electrification programme, targeting large settlements and towns on the outskirts of big urban centres, which are either only partially electrified or completely un-electrified. Providing people with a basic service such as electricity, not only allows them to provide for their energy needs with ease, but also reduces air pollution and the health impacts associated with these emissions. In their paper, Spalding-Fecher and Matibe (2003), draw attention to both the negative and positive externalities associated with power generation and electricity supply. They highlight that the negative externalities emerging from industrialised countries are sometimes seen as positive externalities in developing countries. Although electricity generation has atmospheric and environmental consequences, the provision of this basic service to those who do not have access to it, in developing countries, has a positive impact in that it reduced the health costs linked to the combustion of coal, wood and other “dirtier” fuels (Spalding-Fecher, 2005).

2.5.2. Clean Coal Technologies

Basa Magogo and Basa Mama were projects carried out in 1998 and 2003 respectively, as a joint initiative between Sasol and the NOVA Institute. Basa Magogo took place in eMabalenhle, close to Secunda and Basa Mama took place in Zamdela, both areas with large low-income settlements and high levels of domestic burning. The main objective of both these projects was to reduce the concentration of smoke emitted from these fires considerably by changing the way in which these fires were lit and subsequently burnt. Conventional coal fires that are lit from the bottom up, allows for smoke to disperse through the colder pieces of coal at the top, that have not yet been burnt. Whereas with the top-down method, the already ignited coal burns the generated smoke that it emitted, thereby reducing the amount of smoke released into the atmosphere. The difference in these two processes is highlighted in figure 2.9 (Wagner *et al.* 2005).

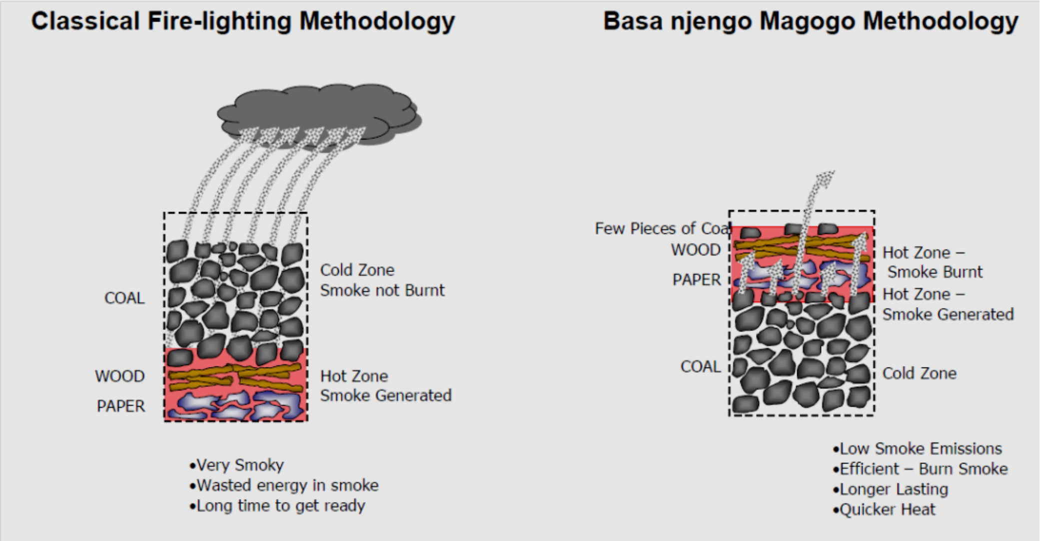


Figure 2.9. The difference between the Classical Fire-Lighting methodology and the Basa Njengo Magogo methodology (DEAT, The 2nd Annual Air Quality Governance Lekgotla).

The Basa Njengo Magogo (BNM) project is an initiative that falls under the Department of Minerals and Energy's National Low-Smoke Fuels Programme. This initiative promotes the top-down ignition of coal fires and has the potential to reduce the concentration of smoke emissions of a conventional fire by up to 50%. As illustrated in the figure 2.10, the fire on the left has been lit using the top-down, less smoke method and the one on the right is a conventional coal fire. This technique addresses particulate emissions in the way domestic fires are lit. It can, significantly, reduce the concentration of smoke emitted during the combustion process (Wentzel, 2006a).

Figure 2.10. The difference between the top-down method and the conventional bottom-up method of lighting a coal fire (Wagner *et al.* 2005).

2.5.3. Improved Wood Stoves

Residential fuel combustion in a large portion of un-electrified low-income settlements and even in some electrified settlements is characterised by poor burning techniques, in inefficient cookstoves. Known by a variety of names, from one country to the next, an example of this type of stove used in South African townships, are called “Imbaulas”. These are generally hand-built stoves, constructed from a metal drum, with strategically placed holes to filter in air to aid in the combustion process (figure 2.11). Characteristically, imbaulas will differ depending on the number and size of these holes (Kimemia and Annegarn, 2011). Often inefficient during combustion, they require that the fuel be replenished at regular intervals and release vast amounts of hazardous pollutants into the air (Bhattacharya *et al.* 2002b).

Figure 2.11. Photograph of an Imbaula.

With a few technological advances, these stoves can be transformed into more effective means of combustion (Williams and Shackleton, 2002; Zhang *et al.* 1999). Examples of these stoves (figure 2.12) with a greater burning efficiency design are also being mass produced and either sold or distributed to people living in low-income settlements. Stoves that burn more efficiently require less fuel, thereby reducing consumption as well as the effect that these pollutants have on human health (Brocard *et al.* 1998; Rehfuess, 2006).

Figure 2.12. Photograph of a low smoke "Imbaula".

2.5.4. Housing Insulation

Proper insulation of houses reduces energy consumption in that a properly insulated home retains far more heat. Generally, in an informal home, up to 60% of the heat-loss is through the roof. Houses with proper insulation lose less heat, thereby, retaining more of the heat generated from combustion. In turn, the amount of fuel required for space heating is reduced; emitting lower levels of pollution and money saved can be used to purchase other more cleaner, convenient fuels that are often more expensive (Wentzel, 2006b). A list of interventions covered in the Vaal Triangle Airshed Priority Area air quality management plan, and published in the Government Gazette in 2009, highlighted the need for a more efficient and cost effective alternative for housing insulation substances to be implemented (DEAT, 2009).

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There are a host of pollutants associated with the range of fuel types such as coal, wood, paraffin and gas that are utilised in domestic burning activities. Many of these pollutants that fall into the categories of particulate matter, carbonaceous aerosols, products of incomplete combustion and various trace gases are regulated by stringent national and international air quality guidelines and standards. The literature explains that a large portion of these pollutants have a negative impact not only on the atmosphere and climatic systems, but also very importantly on human health and wellbeing.

CHAPTER 3: DATA AND METHODOLOGY

Overview

Chapter 3 offers a detailed description of the study site at which this research was conducted. It describes the processes and methodologies involved in conducting this research as well as the materials and instrumentation that were used.

This study consists of four separate components, as highlighted below:

- Questionnaires were distributed to residents of Soweto and Orange Farm in Johannesburg that were selected for a pilot study, as well as to residents from Zenzele where the field study was conducted. The responses to these questionnaires provided information on the burning practices associated with the respective townships and were therefore representative of the entire settlement.
- 15 households in Zenzele were selected to weigh the amounts of wood and/or coal they consume for a 5 month period. These data were used to quantify the emissions associated with the combustion of these solid fuel types.
- Air quality monitoring instruments were temporarily installed in one of the 15 households that participated in the field study in Zenzele and measurements of CO_2 and CO were recorded for one full day within the 5 month period to examine the household air pollution associated with domestic combustion.
- The air quality modelling system CALPUFF was used to determine the fate of the emissions released during the 5 month study period. The emissions from the 15 households were scaled to represent the whole settlement.

3.1. Study Site Description

The site at which to conduct this research was only chosen after an initial pilot study was conducted, in order to establish whether certain assumptions that were made, were correct. The pilot study was conducted in two small sub-sections of Orange Farm and Soweto. Upon further research and results drawn from the pilot study, the low-income settlement known as Zenzele was then chosen as the site at which to conduct this research project.

Although Gauteng exhibits the smallest surface area when compared to the other 8 provinces, it is the most populated province in South Africa and has also been identified as the wealthiest province. For this reason, Gauteng has, in recent years, witnessed increasing levels of mass migration of the poor into the large city centres or commercial hubs such as Johannesburg and Pretoria. Migration of the poor from surrounding rural areas into cities occurs in an attempt to find employment opportunities. Often there is insufficient infrastructure to support this influx of people. As a result, informal housing, in low-income settlements, is then the only option available to these people (HSRC, 2005).

The West Rand District Municipality is situated in the South-West of Gauteng and is home to the Cradle of Humankind World Heritage site. It consists of four local municipalities, as indicated in the figure 3.1. These include the Mogale City Local Municipality, the Merafong Local Municipality, the Randfontein Local Municipality and the Westonaria Local Municipality.

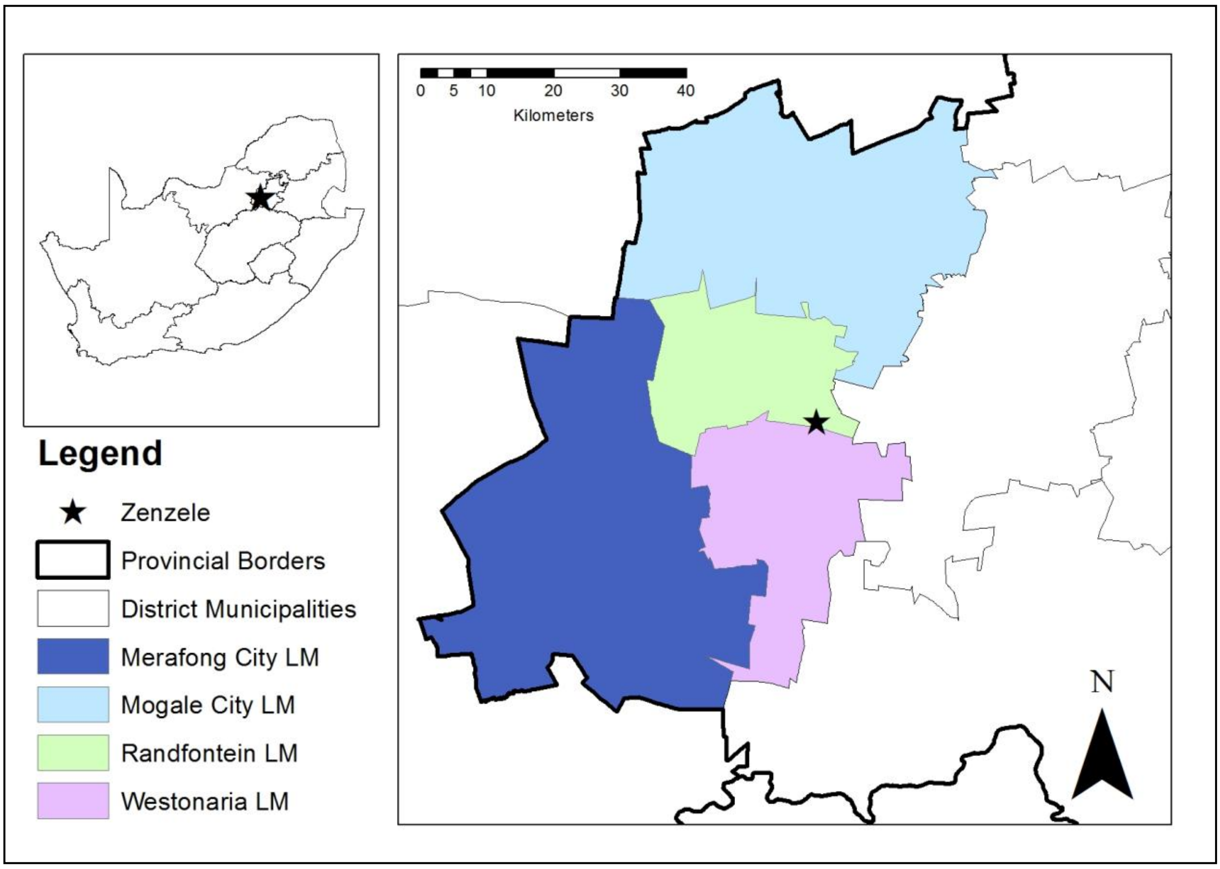


Figure 3.1. Map showing the location of Zenzele.

The Randfontein Local Municipality is relatively small in relation to the other three local municipalities but presents high levels of unemployment and poverty. Zenzele is a small low-income settlement situated in the south of the Randfontein Local Municipality, as indicated in figures 3.1 and 3.2. The Integrated Development Plan for the Randfontein Local Municipality states that Zenzele has one of the highest percentages of informal housing and no access to electricity. A survey conducted in 2010 by the Randfontein Local Municipality highlighted that 98.7% of households in Zenzele are classified as “informal” and 98.8% of the households do not have access to electricity. These statistics illustrate that Zenzele is an almost completely un-electrified low-income settlement (RLM, 2010).

Figure 3.2. Google Earth image of Zenzele.

3.2. Pilot Study

A pilot study, carried out at two separate townships in South Africa, Orange Farm and Soweto, highlighted burning behaviours somewhat different to that expected and brought to light in the literature. The literature gave an insight into the burning behaviours of people living in settlements that were more diverse in nature, where researched settlements were either partially or almost completely electrified. For this reason, it was decided that a pilot study would have to be conducted in order to gather further insight into the burning behaviours witnessed in settlements with different characteristics.

For ethical considerations, a participant information sheet (see Appendix A) had to be developed in addition to the participant questionnaire. The participant information sheet provided a detailed explanation of the research study and covered aspects of confidentiality and what the information provided would be used for.

To gather this information, a questionnaire was developed (see Appendix B) and distributed randomly to 10 people residing in Orange Farm as well as 10 people living in Soweto. Participants from these settlements were asked questions pertaining to, in large part, their seasonal burning behaviours. They were asked to provide information of what types of fuel they consumed during the four different seasons, for the activities of cooking, heating and lighting. In cases where the fuel type consumed changed from one season to the next, they were also requested to present reasons as to why this change occurred.

Characteristically, Soweto is very similar to settlements highlighted in the literature, in that it, too, is diverse in terms of land use. Soweto is comprised of areas that are used for residential and commercial purposes. Orange Farm on the other hand is relatively large in terms of surface area but is characteristic of a more residential low-income settlement.

3.3. Analysis of Census Data

Analysing and reviewing the census data collected and compiled in 2001, allows for an initial assessment of similar data pertaining to low-income settlements, such as population density and the provision of basic services. Sieving through these data, further allows for an in-depth look at the province of Gauteng and more specifically the area of study, Zenzele.

It is also important to note that since 2001, a more recent Census study has been conducted. This study carried out in 2011, focused on the same measurement parameters used in 2001 but generated updated results. However, when this research project commenced, the Census 2011 study had not yet begun and the 2001 Census data for Zenzele had already been analysed. For this reason statistics for parameters that were examined may be slightly under predicted for the current period.

All data pertaining to Zenzele with regards to population, informal housing and fuel types used for various combustion purposes were analysed. All datasets, with the exception of population, used a count according to the number of households. The number of households using different fuels for cooking, heating and lighting purposes were counted in the census study and given in relation to the total number of households within that specific sub-section of the settlement.

The results of these analyses were at a later stage, compared with the information that was acquired from the responses to the questionnaires. Although the questionnaires were not able to assign numerical figures to the consumption of the different fuel types, they did provide enough information to support the census data, in terms of burning behaviours.

3.4. Domestic Fuel Use and Quantification

3.4.1. Scale Measurements

Questionnaires and hanging scales, distributed to a number of randomly selected households within Zenzele, were used to identify and measure the quantities of various fuels being burnt. These hanging scales measure a maximum weight of up to 50kg (figure 3.3). The measurements of quantities of fuel burnt, and the emission factors for these selected fuels and pollutants, allows for the emissions to be quantified over that specific area. The questionnaires (see Appendix C) are designed to gather information on the specific types of fuels utilised and also allows for the most dominant fuel types to be identified. The questionnaire developed for the pilot study was also used for this part of the project as it was successful in providing the necessary information on burning behaviours in Orange Farm and Soweto.

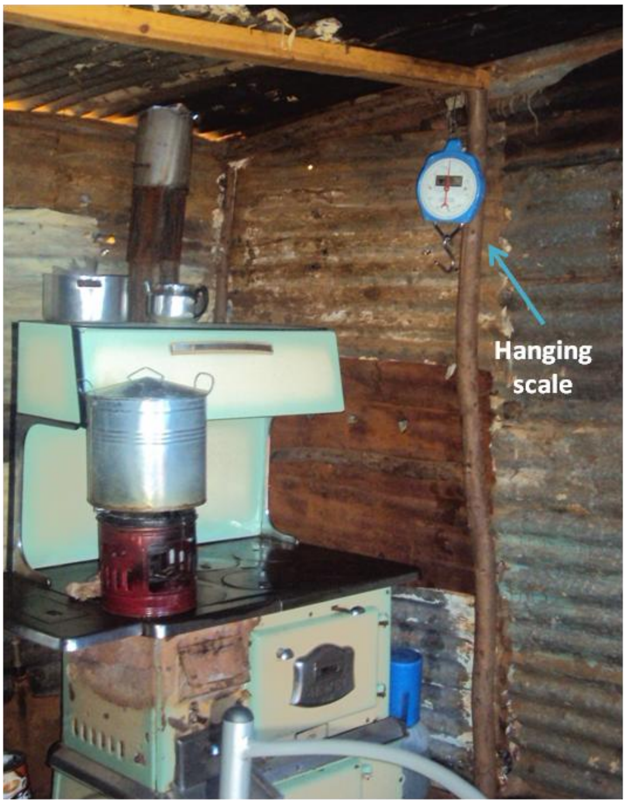


Figure 3.3. Hanging scale set up in a kitchen of one of the 15 study households in Zenzele, used to weigh fuels.

The combustion of residential fuel comprises of a variety of components, from the diverse burning practices to the different types of fuel being used. Mulaudzi (2006) explains that two different methods can be used to determine emissions. The more basic of the two methods, as indicated by equation 2, requires that the fuel consumption and the emission factors for that specific fuel are known. This equation states that the emissions of a specific pollutant can be calculated by multiplying the amount of fuel consumed or burnt by the emission factor for that pollutant, for that specific fuel (Mulaudzi, 2006). The emission factors for both particulate and trace emissions will vary, depending on these different components (Delmas *et al.* 1995).

$$Emissions = Fuel\ consumption\ \times Emission\ Factor \quad (2)$$

Mulaudzi has indicated further that this method has been employed in previous studies by a number of authors. In 2001, Andreae and Merlet (2001) published a paper containing an equation for calculating an emission factor (equation 3). This estimate requires that the amount of fuel consumed as well as the amount of compound released is known. Rearranging this formula presents an equation similar to the one shown above.

$$EF_x = \frac{M_x}{M_{biomass}} = \frac{M_x}{M_C} \cdot [C]_{biomass} \qquad (3)$$

Where EF_x is the emission factor in g kg^{-1}, (M_x) is the amount of compound released and ($M_{biomass}$) is the amount of fuel consumed.

Fifteen households in Zenzele were selected to participate in the fieldwork study. At the first meeting, participants were issued a participant information sheet. Translators were available if needed. Once the participants had agreed to take part in the study, they were then given a participant questionnaire. The questionnaires were read and answered immediately and a hanging scale together with a log book was then distributed to each participant. Participants were required to weigh the amounts of wood and/or coal they used on a daily basis for both the morning and evening burning sessions. Although the questionnaires highlighted paraffin as another common fuel, used widely for both cooking and lighting purposes, it was decided that the emissions associated with paraffin would not be calculated and included as part of this study. The intention of this study was to examine the fuels most commonly used during winter; paraffin is used less frequently during the colder months and for this reason, it was decided that only the use of solid domestic fuels wood and coal would be examined. This decision was also made for the sake of simplicity for the participants, who would potentially have had to decant the paraffin into a separate container in order to weigh it before transferring it into a device to be used for cooking or lighting.

This study was conducted over a 5 month period, from the beginning of May 2011 until the end of September 2011. The winter months were used and a month on either side of the winter period as the literature and the pilot study showed that the largest amounts of coal and wood were burnt during the colder months. Data collected after the 5 month period were analysed and emissions were calculated using emission factors presented in table 3.1, from the 2004 FRIDGE (Fund for Research into Industrial Development, Growth and Equity) Report. The concentrations of SO_2, PM_{10}, CO_2 and CO were calculated for coal and wood, using these emission factors.

Table 3.1. Emission factors used to calculate emission estimates (adapted from the FRIDGE Report; Scorgie *et al*. 2004b).

	Units	SO_2	PM_{10}	CO_2	CO
Coal	g/kg	19	4.1	2997.6	187.4
Wood	g/kg	0.18	15.7	1542.2	114.6

The emission factors presented in table 3.1 were identified specifically for the estimation of domestic fuel combustion in the FRIDGE report. In order to obtain the most relevant and appropriate set of emission factors to represent the state of household fuel combustion in South Africa, reference was made to a number of sources, including the US-EPA emission factors as well as many local sources (Scorgie *et al*. 2004b). Domestic burning activities and combustion processes will vary from one country to the next and for this reason; it is necessary and important to make use of local emission factors as far as possible when estimating the emissions associated with domestic burning. It is on this basis that the FRIDGE emission factors were chosen to be used in this study.

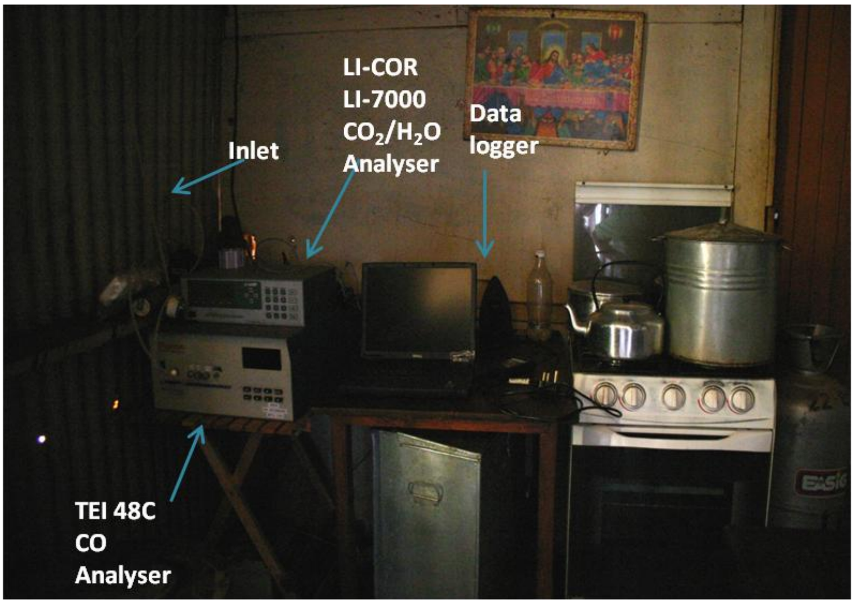
An additional 20 questionnaires were also distributed randomly to other inhabitants of Zenzele, who did not participate in the weighing of fuels. This was done in an attempt to increase the sample size and improve the representativeness of the results.

3.4.2. Patterns of Combustion

Levels of carbon dioxide and carbon monoxide were also monitored at one of the 15 households as part of this study on the 30th of August 2011. Monitoring instruments were run over the course of one full day. This was done in an attempt to examine the indoor concentrations associated with domestic burning activities; and further to examine any diurnal trends associated with this combustion.

As the settlement in which the study took place was completely un-electrified, the two analysers were connected to a generator, and installed into one of the 15 study households, as indicated in figures 3.4 (a) and (b). A LI-COR LI-7000 CO_2/H_2O analyser was installed to measure the concentrations of CO_2. For the measurement of CO, a TEI 48C CO analyser was used. Both instruments were attached to a data logger, recording real time data. All inlets were positioned not more than 10 centimetres from the chimney of the stove.

a



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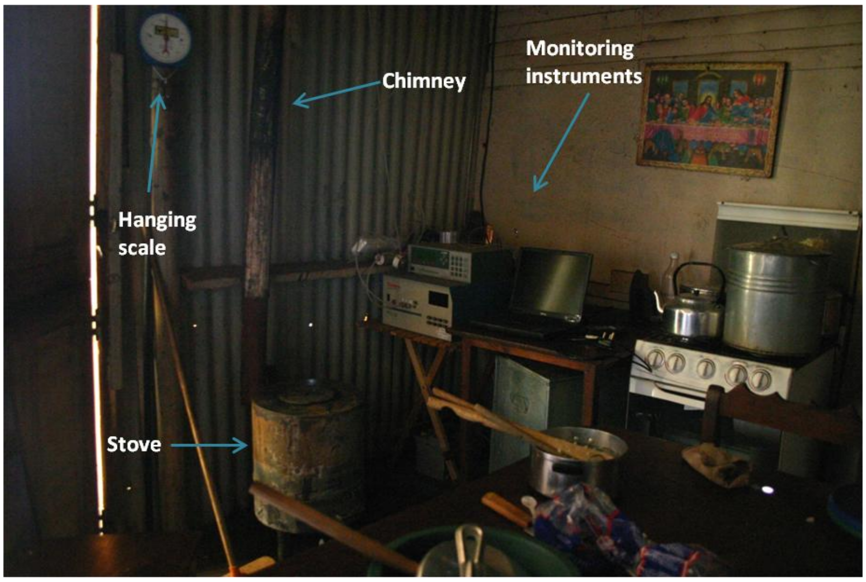

Figure 3.4. Monitoring and measuring instruments set up in one of the 15 study households in Zenzele; where (a) shows the CO and CO_2 analysers, data logger and inlet and (b) shows the chimney, hanging scale and stove.

The LI-COR LI-7000 CO_2/H_2O analyser (figure 3.5) is a non-dispersive, infrared (NDIR) gas analyser that is designed to deal with large quantities of data, with high precision. Infrared radiation that is filtered through two sampling cells gets absorbed. The difference in the absorption between the two cells, allows for the concentrations of CO_2 and H_2O to be measured. This instrument measures the concentrations of CO_2 and H_2O simultaneously, with or without a known concentration of a reference gas (LI-COR, 2000).

Figure 3.5. LI-COR LI-7000 CO_2/H_2O analyser (LI-COR, 2012).

As illustrated in the figure 3.6, concentrations of carbon monoxide were measured by a TEI 48C CO analyser over this same period. This gas filter correlation analyser is one of the models included in the range of instruments developed and manufactured by Thermo Environmental Instruments. This analyser works on the basis that CO has the ability to absorb IR radiation at specific wavelengths of 2.3 and 4.6 µm, within the IR spectrum. This absorption is therefore an indicator of the existence of CO in the sampling air mass and concentrations can then be measured (TEI, 2000).

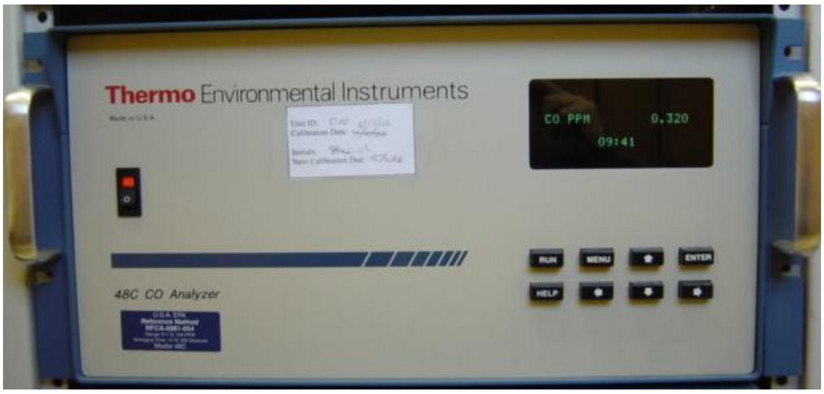

Figure 3.6. TEI 48C CO analyser (APCD, 2003).

With reference to household air pollution and personal exposure, it is necessary and important to examine the emission of CO as it is a good indicator of indoor air pollution when investigating combustion processes. The health impacts associated with the release of CO from the burning of domestic solid fuels, specifically the combustion of wood, are vast. The health impacts associated with the emission of CO is exacerbated in poorly ventilated households that exist in low-income settlements. In attempting to prevent the warm air from escaping from poorly insulted houses, by sealing open gaps, residents tend to not only trap these harmful pollutants in the houses but also do not allow sufficient air flow into the houses. Dimished air flows as well as poor combustion techniques inhibit the complete oxidation for carbon monoxide (Scorgie *et al*. 2004a).

Examining the levels of CO_2 emitted during the combustion of domestic fuels is related to the importance of monitoring concentrations of CO in households. As the concentrations of CO and CO_2 vary in relation to the various stages of a fire, it is therefore crucial that these levels are compared to better understand the processes involved in residential burning and how these processes are influenced by poor burning techniques.

3.5. Dispersion Modelling

Combustion processes, for the purposes of boiling water, cooking and heating, are responsible for the emission of large quantities of a variety of pollutants. The combustion of fuels such as coal, wood, gas and paraffin all contribute to these emissions. When the amounts of fuels burnt during these various activities are multiplied by an emission factor for a specific pollutant that is released, the emission can be calculated or estimated with a degree of uncertainty.

A dispersion modelling system will allow for the patterns of distribution of the emissions to be better understood. Factors including the local climate, atmospheric stability and changes in the mixing depth are key elements in determining the fate and the rate at which these pollutants are transported or dispersed. The CALPUFF air quality modelling system was employed to assess the dispersion of pollutants emitted from the Zenzele and Orange Farm settlements.

3.5.1. Atmospheric Dispersion Potential

The atmospheric dispersion potential of pollutants over the interior of South Africa is governed by the atmospheric conditions associated with the continental high pressure system that is dominant during the winter period. With stable conditions and little to no rainfall, surface and elevated inversions are a common occurrence over Johannesburg at this time of year. These phenomena decrease the depth of the mixing layer, thereby inhibiting the dispersion of pollutants. Wind speeds determine how far the pollutants will be transported and to what extent they will be diluted (Tyson *et al.* 2000).

3.5.2. CALPUFF Dispersion Model

CALPUFF is a non-steady-state Lagrangian Gaussian puff model designed to simulate the dispersion of pollutants in the atmosphere. This multi-dimensional dispersion model has the ability to replicate the transport, transformation and removal of pollutants under a range of meteorological conditions, as these conditions vary with space and time. Its applicability is extensive as it is able to simulate the transport of pollutants from a variety of sources and the extent of modelling domain can range from tens of metres to hundreds of kilometres. An additional important advantage of using CALPUFF, in preference to a Gaussian plume model, is that CALPUFF has the capacity to predict the transport of pollutants under calm conditions (Barna *et al.* 2002).

Puff models differ from traditional plume models in the way that the polluting substances are represented. Puff models use separate parcels of the pollutants instead of a continuous plume and are designed to estimate the concentration of these pollutants at certain time intervals, as the puffs reach a pre-determined receptor (figure 3.7). The concentrations that are measured at the various time intervals are represented by the numerous circles (puffs) in figure 3.7. At each subsequent sampling time step, the puff develops as it moves, changing in size (Scire *et al.* 2000).

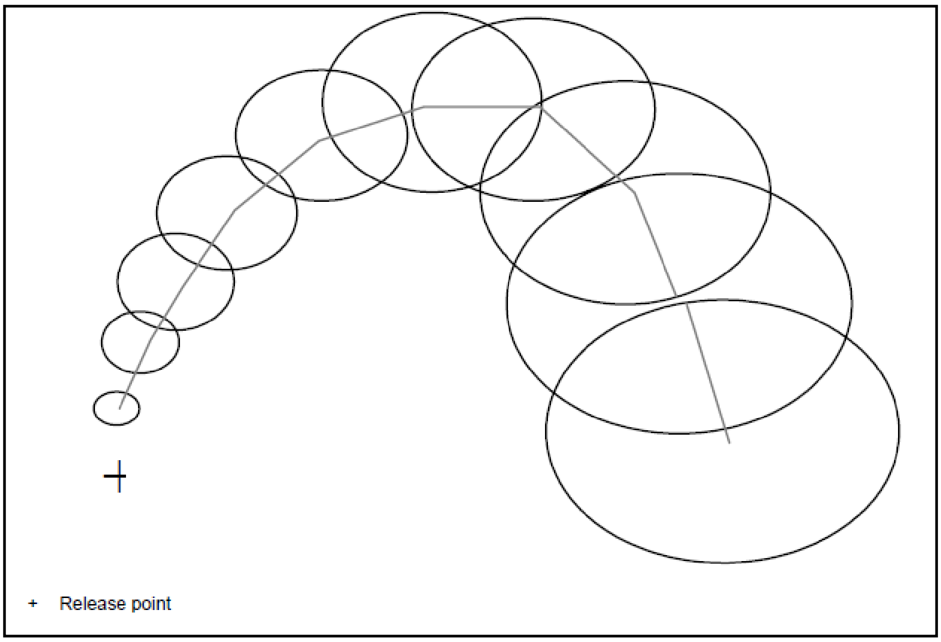

Figure 3.7. Graphical representation of the puff modelling approach (Bluett *et al.* 2004).

This air quality modelling system consists of three major components and includes pre-processing and post-processing capabilities. CALMET is the meteorological model, CALPUFF is the Gaussian puff dispersion model and CALPOST is the post-processing program. A number of other processing tools can be used to prepare additional datasets, to be used alongside these components of the model. The operational processes of this air quality modelling system are highlighted in figure 3.8 (Scire *et al.* 2000).

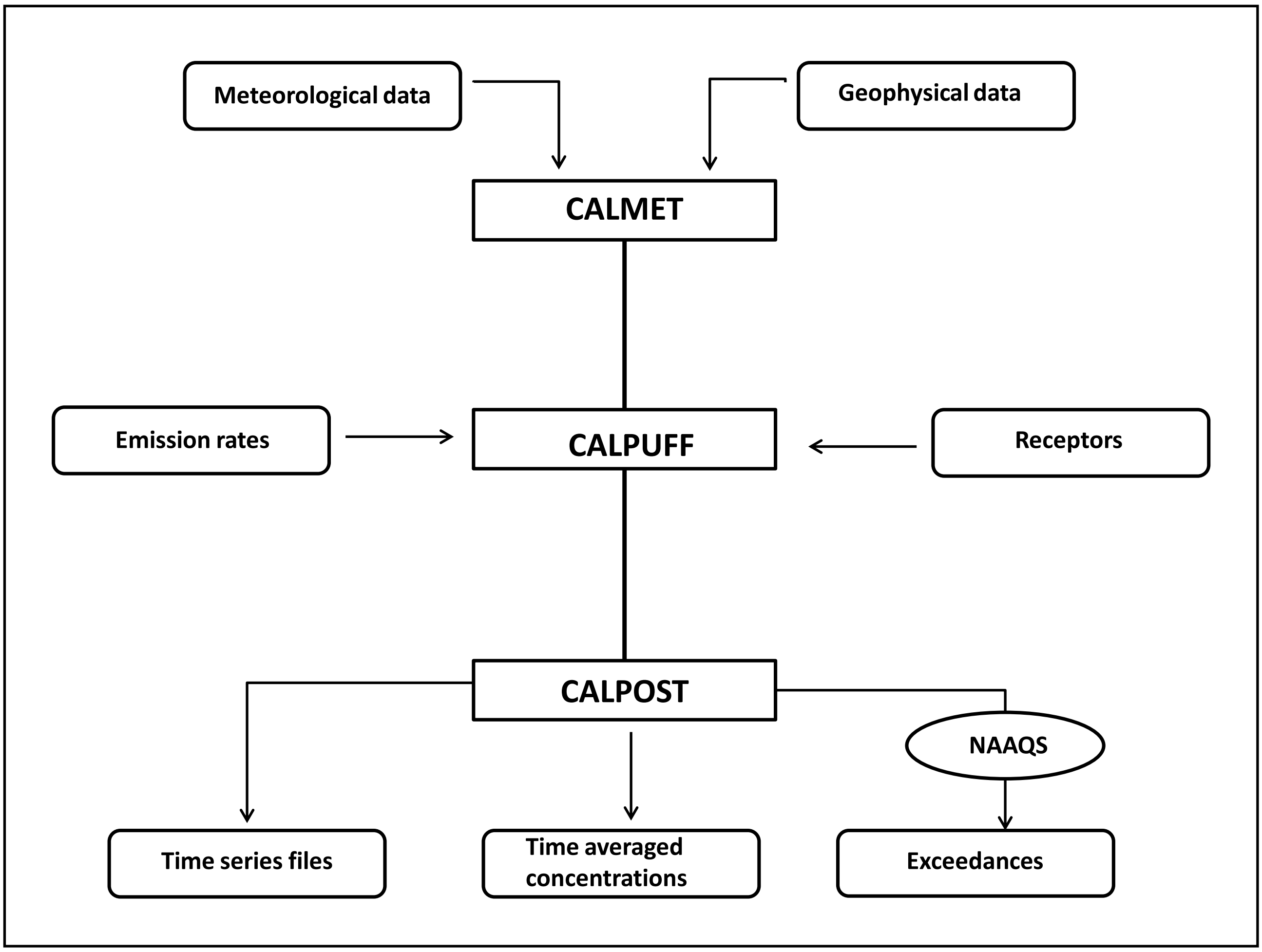

Figure 3.8. Process flow diagram of the CALPUFF Modelling System (adapted from Scire *et al.* 2000)

CALMET produces hourly wind and temperature files that are represented on a three-dimensional grid, used in the modelling domain. Related files for characteristics such as mixing height, terrain elevations, land use properties and other dispersion characteristics are included as two-dimensional fields as these elements are correlated with the wind fields. The CALMET.DAT file consists of both the meteorological and geophysical data which is then used as an input file for the CALPUFF component of the modelling system.

CALPUFF simulates the dispersion and transport of the pollutants released in puffs from the various sources. Emissions data for point, line, volume or area sources are used as input files and are modelled based on a range of temporal parameters. Using this data, CALPUFF is then used to predict the hourly surface level concentrations of various pollutants at specific receptor locations, where impacts occur.

CALPOST is used to process the hourly concentrations or deposition fluxes that are generated by CALPUFF for a specific receptor. CALPOST produces outputs that either come in the form of time series files or as time-averaged concentration files. Exceedence files are an additional output of this post processing tool, using the national ambient air quality standards during the computing process.

3.5.3. Calculation of Emissions Data for Model Inputs

For this research project, the households represented in the two low-income settlements were modelled as volume sources. Emissions data that were used as model inputs for CALPUFF were calculated for the settlements of Zenzele and Orange Farm based on the quantification of emissions from 15 households and 10 households in these settlements respectively.

To evaluate the contribution of emissions that these settlements have on the air quality, it was important to determine the size of each settlement and the number of households that exist in each. Zenzele is 1.58 kilometres in length and 0.5 kilometres wide. Orange Farm is far larger, with a length of 7.5 kilometres and a width of 2.2 kilometres. Zenzele and Orange Farm were divided into 9 and 11 separate smaller areas respectively (figure 3.9). Thereafter, using google earth, the houses in each of these areas were counted. From the questionnaires, it was established that coal is seldom burnt on its own during this period and is usually burnt simultaneously with wood. For this reason it was necessary to establish a ratio of the number of households that only burnt wood only to those that burnt both wood and coal to provide for their energy needs. This was done using the information gathered from the questionnaires that were answered by the residents of Zenzele.

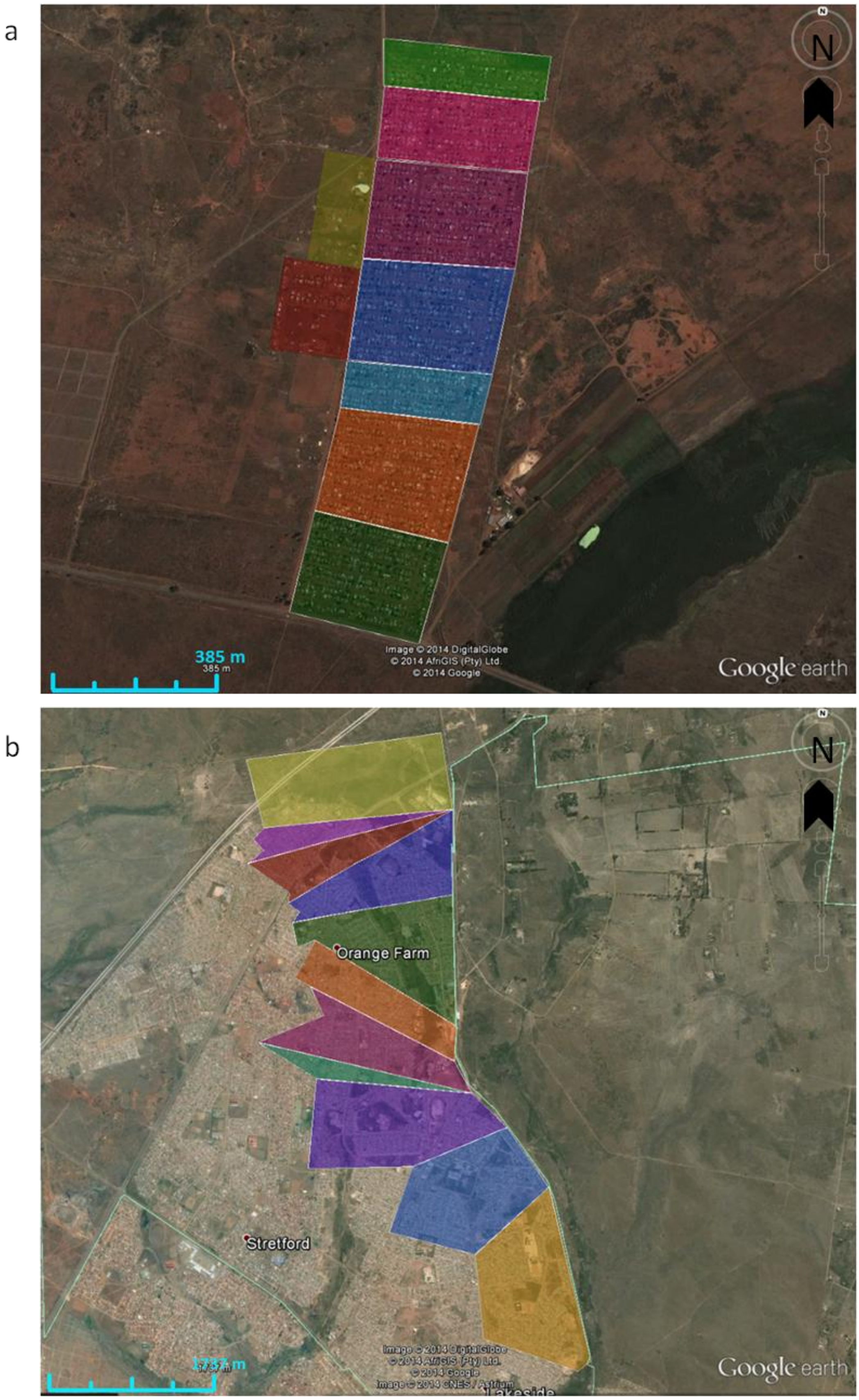

Figure 3.9. Area divisions of (a) Zenzele and (b) Orange Farm used to determine the total number of households in each settlement and the ratio of households that burn wood only to those that burn and coal simultaneously.

Fifteen households in Zenzele were selected to weigh the quantity of coal and wood consumed during the morning and evening burning sessions, over a 5 month period. The amounts of wood and coal consumed were then totalled for each household per month and thereafter multiplied by an emission factor for a specific pollutant to get an emission in grams. These emissions were then divided by the number of days in each respective month to get the average emissions per day in a certain month. The emission rates were then calculated based on the assumption that the morning burning period lasts for three hours and the evening burning period lasts for four. Emission rates in grams per second were calculated by dividing the emissions generated in each burning period by the respective number of seconds in that burning period. These emission rates were then averaged for all the households, to produce one average emission rate for each month from May to September.

Once the average emission rates for both wood and coal were calculated, it was multiplied by the number of households that burn either wood or wood and coal together, based on the ratios that were established from the questionnaires. These scaled emission rates were then used as inputs for the model.

The same process was followed to obtain the average emission rates for wood and coal for Orange Farm, with a slight variation. The Orange Farm settlement was only included in the pilot study and did not form part of the field study and for this reason, no measurements on the consumption of quantities of wood and/or coal were collected from residents. Instead, the only information gathered from households in Orange Farm was from the questionnaires, pertaining to their burning behaviours. Using this information, together with the information gathered from questionnaires answered by residents in Zenzele, similar households that existed in both these settlements were found. The similarities observed between the households from the two settlements included the number of inhabitants that resided in a household and whether households burnt only wood or wood and coal simultaneously. Once the similar households were selected from the two settlements, the consumption and emissions data from the household in Zenzele were then applied to the corresponding household in Orange Farm.

Average monthly emission rates for SO_2, PM_{10}, CO_2 and CO were calculated for wood and coal from May to September 2011 for both the morning and evening burning sessions in Zenzele and Orange Farm. These emission rates, together with a pre-existing meso-scale meteorological dataset, at a resolution of 3km, from the WRF model, were used as the data inputs for CALPUFF and were modelled to produce time-averaged concentration files for these four pollutants. The computing was based on whether households in the respective settlements burnt wood only, wood and coal simultaneously and finally a combination of these two, to represent all the households in a specific area.

3.5.4. Mapping of the Modelled Outputs

It has been suggested that when evaluating model results and comparing them with specific criteria, such as thresholds or limits, its best practice to present these model results as a percentile of the maximum predicted concentrations (Bluett *et al.* 2004). For the purpose of this study, the model results were assimilated and presented in the 99th percentile, removing the highest 1% of the maximum ground-level concentrations from the modelled outputs. Model outputs are typically presented in hourly maximum concentrations, located where two lines intersect in a model grid. Each grid cell represents the highest hourly concentration of a specific pollutant; where two adjacent grid cells will both show the highest concentration of that pollutant but occurring at different times. A map showing modelled outputs will therefore be a composite of the highest concentrations for each hour. The maximum average hourly and daily concentrations of SO_2, the maximum average daily concentrations of PM_{10}, the maximum average hourly and daily concentrations of CO_2 and the maximum average hourly and 8 hourly concentrations of CO for Zenzele and Orange Farm were then mapped using ArcGIS to visually represent the spatial extent of these emissions.

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This research project was conducted in three different parts, with elements of the desktop study and field study taking place in three different low-income settlements, namely Zenzele, Orange Farm and Soweto. A combination of the desktop study, field study and dispersion modelling allowed for an overall understanding of domestic burning in low-income settlements in Johannesburg to be established.

CHAPTER 4: DOMESTIC FUEL USE IN LOW-INCOME SETTLEMENTS

Overview

This chapter will focus on the results generated from two of the three components of this research project. It will highlight the results generated from both the desktop analysis, as well as certain components of the field study that identified the most common fuel types consumed in Zenzele, Orange Farm and Soweto. Chapter 4 will deal specifically with the burning behaviours surrounding coal and wood combustion in the study settlement.

4.1. Study Site Selection

This research project was initially envisioned as a seasonal comparison of wood and coal use by residents living in a low-income settlement in Gauteng. As mentioned in the previous chapter, after consulting the literature, a few inaccurate assumptions were made regarding domestic burning in townships. These assumptions are listed below:

- Coal and wood are common fuel types, which are burnt throughout the year.
- Domestic burning in a residential area or township is restricted to combustion for residential use.
- All formal and informal settlements are structured similarly, in that they are comprised of mainly residential land. Commercial activities are only rife on the outskirts of the settlement.
- Most sub-sections and extensions of a settlement are un-electrified.

As it was assumed that coal and wood are two common fuels that are burnt throughout the year, it was decided that a comparison of their seasonal burning trends would be an interesting topic to examine. After distributing questionnaires to residents in Orange Farm and Soweto, it was discovered that coal and wood are burnt very infrequently during summer. The questionnaires from the pilot study also highlighted that within most electrified households, where household income is somewhat higher than that in un-electrified households, electricity is the preferred source of energy. Although electricity is relatively more expensive than some of the other fuel types, some people opted for the convenience that comes with using electricity.

Participants explained, however, that the case is a little different for electrified households, in which elderly women reside or those that are run by an elderly head. Families that own coal stoves that are usually passed down from one generation to the next; prefer to use these stoves during winter when there is a great need for solid fuels that provide more heat. The reasons for this are two-fold: the most obvious one being the multi-functional capabilities of this appliance. Coal stoves are generally used for cooking but also provide adequate heating in the process. The second reason is one that is not widely found in the literature as it involves the cultural aspects linked to the combustion of domestic fuels. Mdluli (2007) has carried out extensive research in this field of study, specifically focusing on the cultural aspects associated with the combustion of coal in informal townships. Similarly to what was discovered during the discussions had in answering the questionnaires, Mdluli explained that within townships, coal burning instils a sense of family and community amongst residents.

It was further explained, that in un-electrified households, gas or paraffin is sufficient to provide for residents' cooking, heating and lighting needs. It was noted that in these homes, people live from one day to the next and will only purchase what they can afford and what is absolutely essential at that time. For this reason, it is a common practice that in situations such as these, that more than one fuel type can be used for one specific energy requirement. This highlighted once again, agreement with the work done by Mdluli (2007). Other solid fuels such as coal and wood are considered to be suitable fuels during winter as these fuels provide the largest amounts of heat during the combustion process.

Many settlements in South Africa are diverse, in that they are not made up entirely of residential households. This diversity is also observed in the variety of activities requiring combustion. Burning of domestic fuels is not restricted to each individual household's energy needs. These fuels are also consumed for a range of commercial purposes in these areas.

For this specific study, a settlement or at least a portion of a settlement that is completely un-electrified was required. The study also focused on the combustion of domestic fuels required specifically for domestic day-to-day living needs. Orange Farm and Soweto, although selected for the pilot study, allowed for different burning behaviours to be realised but did not satisfy these two prerequisites. Even though the section of Orange Farm that was surveyed was un-electrified; this portion of the settlement was not large enough to carry out this study. Orange Farm and Soweto are also larger settlements where combustion processes do not only occur for domestic energy needs, but also for commercial purposes. Zenzele, however, fulfilled all the requirements necessary for this study to be conducted. The most important consideration was that it was completely un-electrified. The main objectives of this study required that the most commonly burnt fuel types be identified and that the emissions generated from some of these fuels are quantified using the fuel weight approach. It was therefore important to examine the combustion of the solid fuels coal and wood, as it was assumed that these fuels were consumed throughout the year. Once the analysis of the responses to the questionnaires proved differently, it was decided that this study should be conducted during the winter period in order to account for the combustion of these two fuels.

4.2. Pilot Study

There are very few similarities that exist between the burning behaviours of households in Orange Farm and households in Soweto. The simultaneous combustion of wood and coal for heating purposes occurs within most households in both Orange Farm and Soweto but during the colder winter months, wood is a common fuel type used in Orange Farm whereas coal is favoured in Soweto. An analysis of the questionnaires answered during the pilot study, highlighted the following results, in figures 4.1 and 4.2. Questionnaires distributed to inhabitants of randomly selected households in Orange Farm and Soweto highlighted outcomes that proved to be different to the assumptions made.

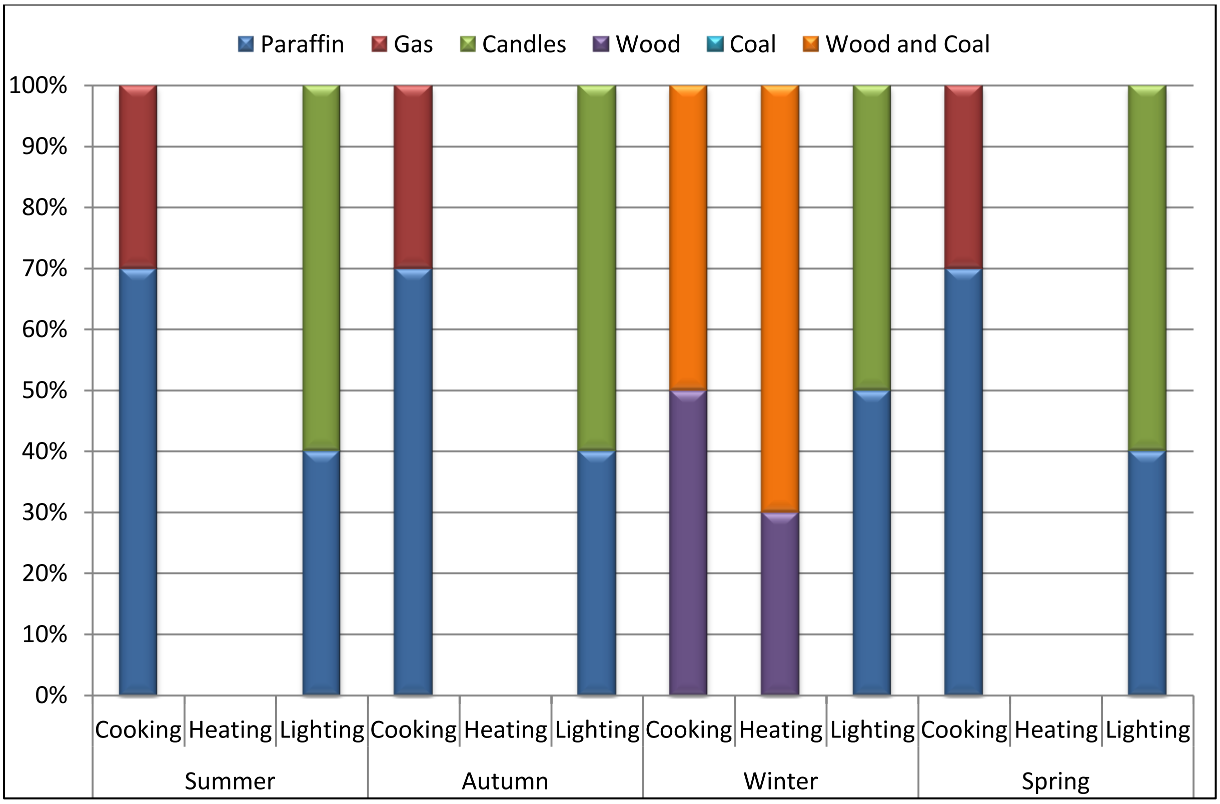

Figure 4.1. Percentages of the different fuels consumed by households in Orange Farm as highlighted in the pilot study questionnaires.

(Note: The sub-section of Orange Farm in which questionnaires were distributed was not electrified.)

Inhabitants living in households that are partially or completely electrified prefer to use electricity during summer, to provide for their energy needs as it is the most convenient source of energy. Informal homes, however, that do not have access to this basic service, as represented by the households in Orange farm, choose gas or paraffin as their preferred fuels for cooking and lighting during summer. The amount of fuel required for heating during this summer period is not significant enough to warrant a mention as the residual heat produced from cooking is sufficient to keeps homes warm during summer.

Most households, however, will change to other solid fuels, such as coal and wood during winter as larger quantities of energy are required for heating purposes. Reasons relating to both temperature and cost will prompt people to shift to these fuel types. These fuels tend to be relatively inexpensive when compared to the cost of electricity and, with the large quantities required mainly for heating purposes in winter; coal and wood become the more feasible options (Mdluli and Vogel, 2010). Low temperatures, during winter, require the most efficient means of heating, so, coal and wood burnt in stoves allows for widespread heating that lasts far longer. If coal stoves are available, people choose to provide for both their cooking and heating needs by this means, otherwise imbaulas will also be used. As imbaulas are not fitted with chimneys, they are generally only used for heating purposes and not for cooking as fires created in these devices have to be done so outside so as to limit the amount of smoke circulating within households. It is, however, important to note that even fine particulates generated from fuels burnt outside the home, still have the ability to infiltrate the house (Brauer *et al.* 1996).

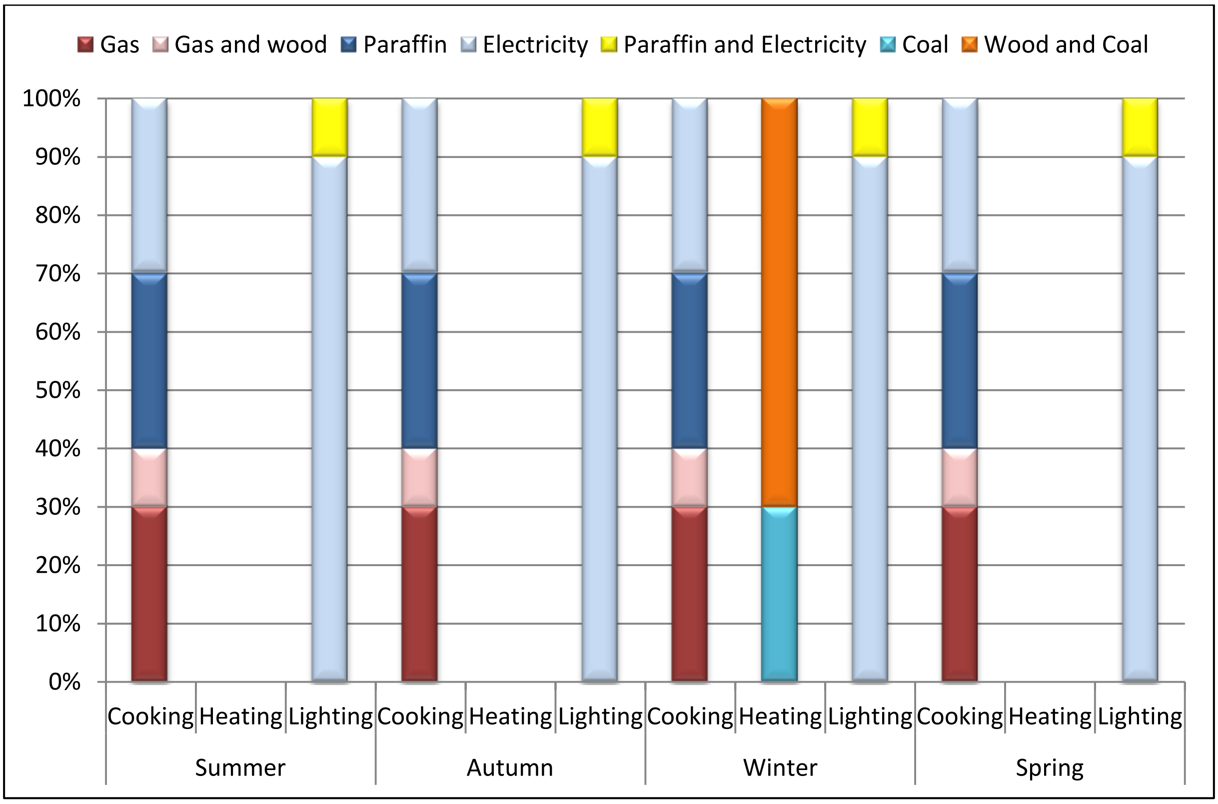

Figure 4.2. Percentages of the different fuels consumed by households in Soweto as highlighted in the pilot study questionnaires.

Electrified households continue to use electricity for lighting purposes and, occasionally for cooking, if a more convenient fuel is required. In un-electrified informal homes, where household income is often lower than those of inhabitants residing in the more formal households, coal is sometimes unaffordable. Wood that is gathered from surrounding areas is usually the preferred fuel type in these homes to provide for their cooking and heating needs. Paraffin, burnt in lanterns, is used for lighting in these households.

Providing low income communities with the access to electricity, does not necessarily mean that they will make use of this service. Often the affordability of electricity can outweigh the convenience of its use. Supplying residents of a household with electricity has no bearing on what they can afford with their monthly income (Mdluli, 2007). Often, although equipped with the tools to utilise a more convenient fuel type, most people cannot afford it. During the warmer months though, when less heating is required, residents of electrified informal homes prefer to use electricity. Still considered expensive in relation to other solid fuels, electricity being the most convenient source of energy does sometimes outweigh the cost of using electricity during summer as smaller quantities are required.

4.3. Analysis of Census Data

An analysis of the 2001 census data for Zenzele was done in an attempt to get an overall understanding of the dynamics of this settlement as well as the burning behaviours of residents, before undertaking the field study. Datasets pertaining to population, informal housing and fuels used for domestic needs were all examined and the results are presented below. The population statistics presented in the Census 2001 data shows that the total number of people residing in Zenzele at this time was 7212.

Table 4.1. Percentages of informal and un-electrified households in Zenzele (Census, 2001)

	Total Number of Households	Total number of Informal Households	Total number of Un-electrified Households
Zenzele	2379	2330 (97.95%)	2362 (99.29%)

According to the census data, in 2001, there were 2379 houses in Zenzele. The Randfontein Local Municipality’s Integrated Development Plan recorded 2462 in 2009 (RLM, 2010) and according to the count at the time this research project was conducted, in 2011; the number of households had increased to 2502. Table 4.1 highlights the number of informal houses and un-electrified houses in Zenzele, relative to the total number of households recorded in 2001. 97.95% of all the houses in Zenzele are classified as informal and 99.29% of the households do not have access to electricity.

Three specific activities in low-income settlements require either electricity or other fuels as an energy source. These activities are: cooking, heating and lighting. There are a range of fuel types that can be utilised in any one of these activities but these will vary according to the season, availability and affordability. Figures 4.3, 4.4 and 4.5 represent the percentages of a range of fuel types utilised for these three activities.

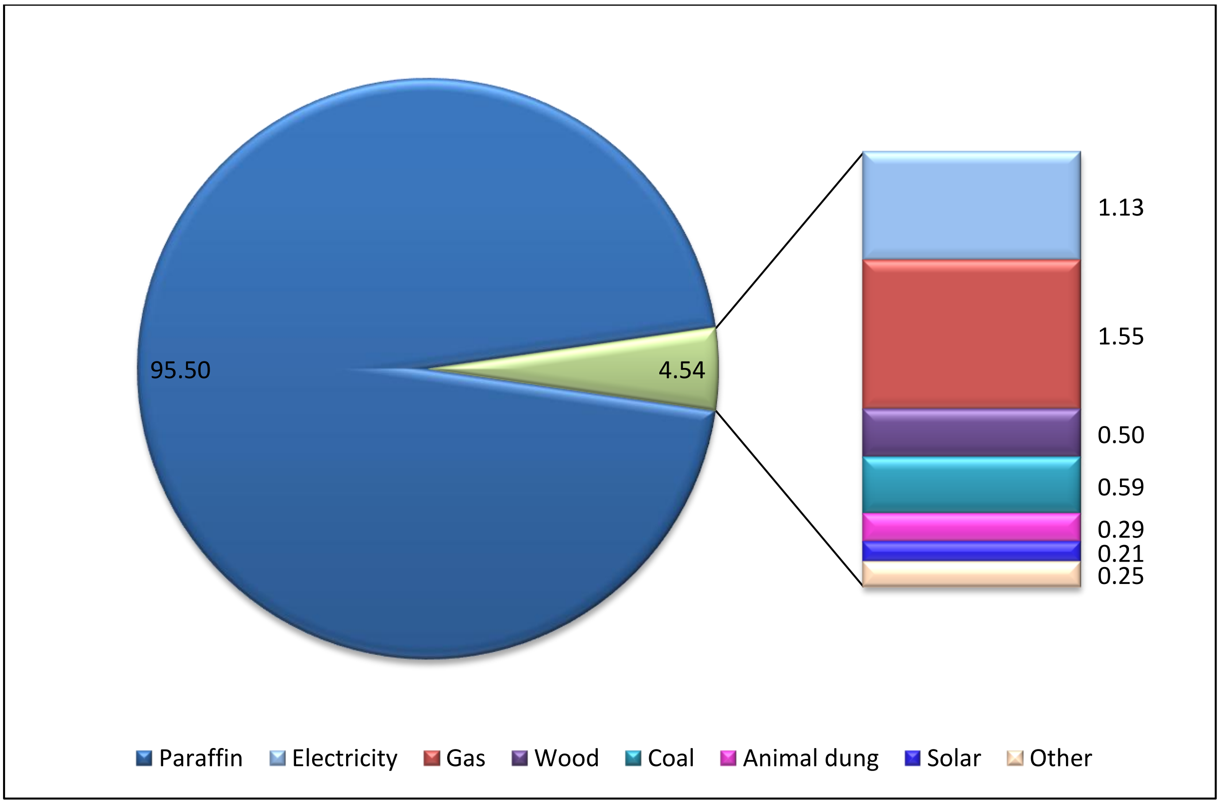

Figure 4.3. Percentage fuel use for cooking in Zenzele (Census 2001).

For cooking purposes, the fuel types examined were electricity, gas, paraffin, wood, coal, animal dung, solar power and any other fuel that was utilised, which did not fall into one of the specified categories. Once again, this information was recorded relative to the number of households. It is evident in figure 4.3, that the most common fuel used by many households within this settlement, for cooking purposes, is paraffin. At 95.5%, it constitutes the bulk of the total amount. Far fewer, but a noticeable number of households also make use of gas, electricity, coal and wood for cooking.

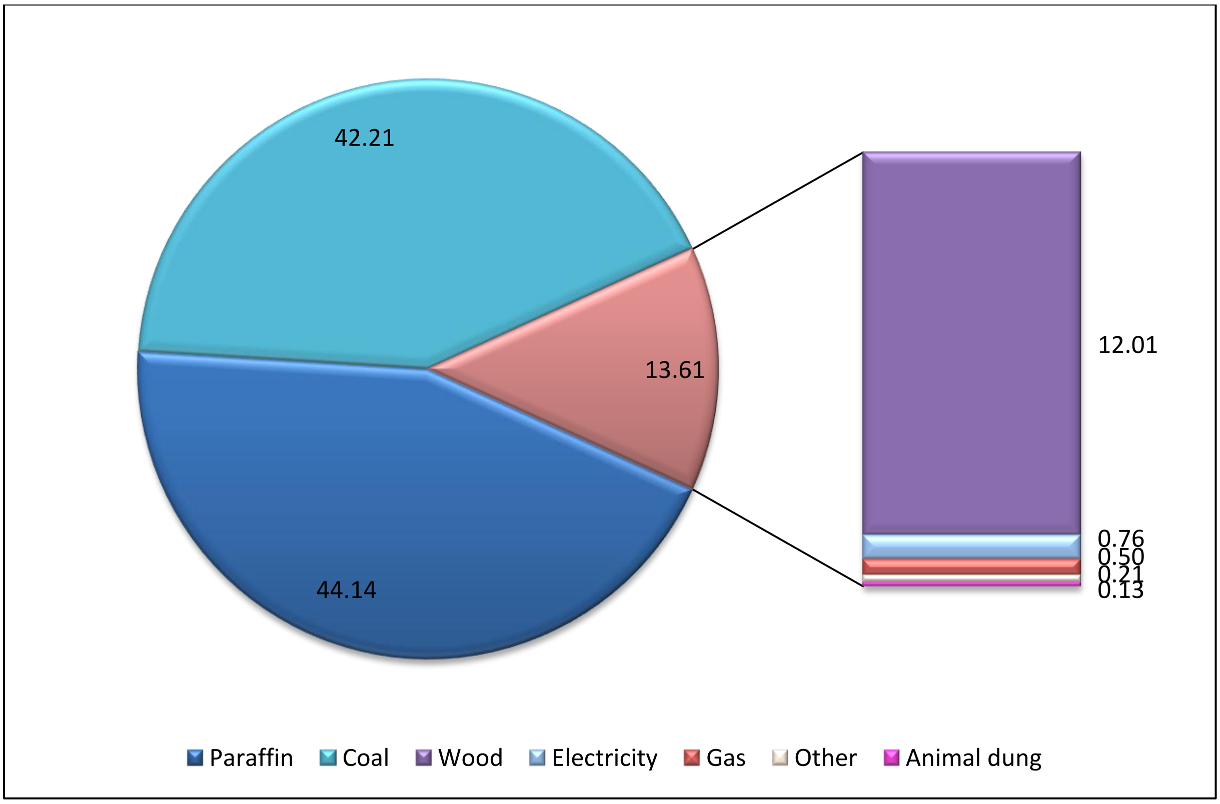

Figure 4.4. Percentage fuel use for heating in Zenzele (Census 2001).

The heating of households in this settlement will vary at different times of the year as it is highly dependable on the same factors, which include season, availability and affordability. As mentioned previously, a very small percentage of annual fuel use is attributable to heating in summer. Figure 4.4 illustrates that paraffin; coal and wood are the most common fuels used for heating purposes.

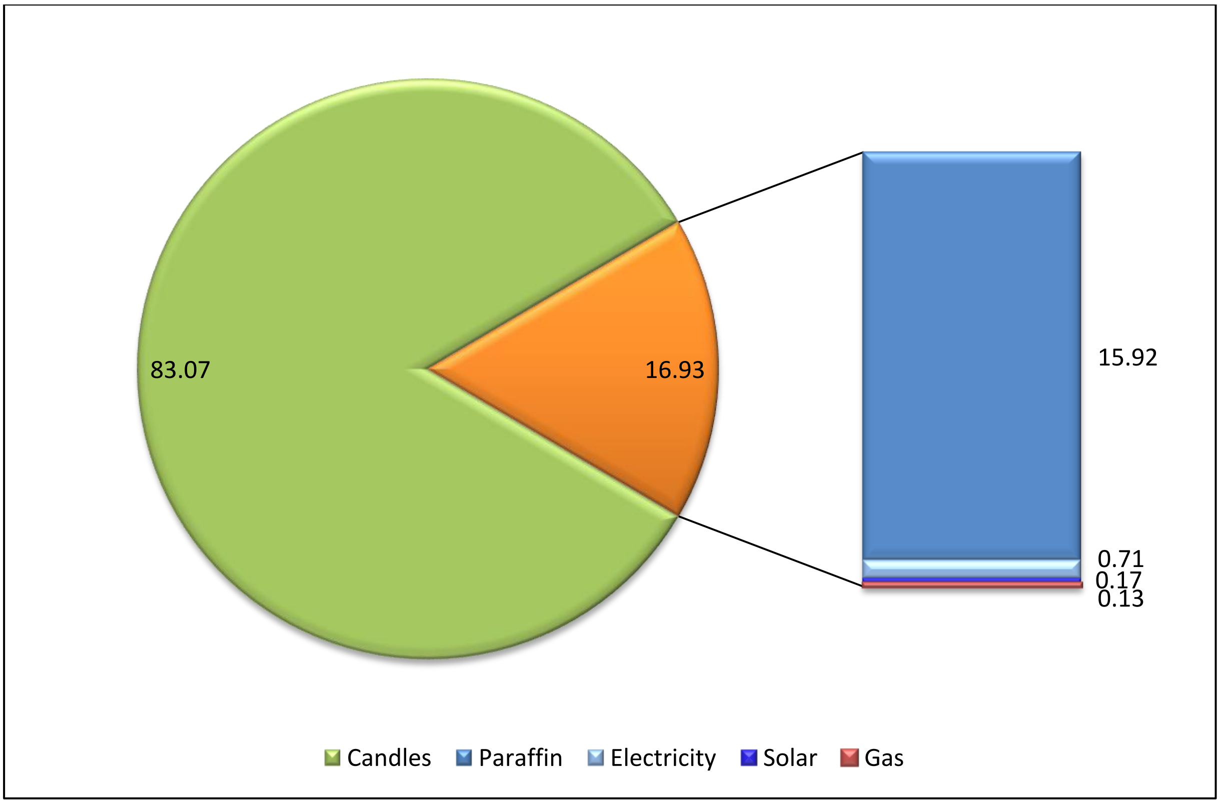

Figure 4.5. Percentage fuel use for lighting in Zenzele (Census 2001).

Often solid fuels used for cooking and heating purposes in completely un-electrified homes do not provide sufficient lighting. Lighting therefore needs to be provided for by other means. According to the 2001 Census study, the most frequently used fuels by households in Zenzele are candles and paraffin (figure 4.5). Although candles are seldom used as a fuel of choice for cooking and heating, over 80% of households utilise candles to supply their lighting needs.

Table 4.1 can confirm that Zenzele is a settlement that can be classified as almost completely informal and un-electrified. Although these data did not specifically look at the seasonal choices of fuels, it is clear in figures 4.3, 4.4 and 4.5 above, that all the fuels, consumed over the different seasons, are well represented.

Following the analysis of the census data, it is evident that Zenzele displays similar characteristics to Orange Farm in terms of fuel consumption. Zenzele and the sub-section of Orange Farm, in which residents answered questionnaires, are un-electrified and, therefore exhibit similar fuel choices and burning behaviours. In both areas, paraffin, gas and candles are predominantly used in the warmer months and a combination or wood and coal are used during the colder winter months.

4.4. Domestic Energy Use

A combination of results gained from the questionnaires and the scale measurements was used to identify some of the most common domestic fuels used in Zenzele. Data gathered from the scale measurements were used to further validate the results obtained from the questionnaires and to give additional insight into the seasonal burning behaviours of residents of this low-income settlement.

4.4.1. Questionnaires

Questionnaires were distributed to two different groups of people in Zenzele, those that participated in the field study as well as 20 other randomly selected residents. The responses to these questionnaires gave valuable insight into some of the burning behaviours that exist within Zenzele. Results gathered from the census data and the pilot study provided some background as to what was to be expected with regard to the use of domestic fuels. The information gathered from this short list of questions allowed for the seasonal consumption trends to be recognised.

Table 4.2. Number of people residing in each of the 15 households in Zenzele.

	Household Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
May	3	5	1	4	4	2	6	3	5	7	4	8	3	5	5
June	3	5	1	4	4	2	6	3	3	7	4	8	3	x	5
July	3	5	1	4	4	2	6	3	3	x	4	7	4	x	5
August	3	5	1	4	4	2	6	3	3	x	4	7	4	8	5
September	5	5	1	4	4	2	6	3	3	x	4	8	4	8	5

Note: "x" denotes month in which house was vacant

The number of inhabitants per household, for the 15 households that participated in the study, ranged from 1 person to 8 people during the 5 month study period, as shown in table 4.2. The number of people residing in each household, however, did not stay constant for some of the households over this period. This variation can be explained by a number of reasons, such as illness, death and ceremonial rituals. An "x" indicated in table 4.2 represents those households that were left vacant for that specific month. Residents of household 10 were relocated to an RDP house (Reconstruction and Development Programme, ANC 1994) and a death in the family of residents of household 14 forced these residents to move to their village over the months of June and July. The ages of residents were not recorded but did range from very young to elderly in almost all of the households. The type of stove used was another parameter that was recorded in each household, as displayed in table 4.3. Of the households in Zenzele, participating in the field study, 53% utilised the smaller hand-made stoves and 47% used the bigger coal stoves.

Table 4.3. Type of stove used in each study household in Zenzele.

Household number	Type of stove
ZEN 1	Small hand-built stove
ZEN 2	Small hand-built stove
ZEN 3	Small hand-built stove
ZEN 4	Small hand-built stove
ZEN 5	Small hand-built stove
ZEN 6	Big coal stove
ZEN 7	Big coal stove
ZEN 8	Small hand-built stove
ZEN 9	Big coal stove
ZEN 10	Big coal stove
ZEN 11	Small hand-built stove
ZEN 12	Big coal stove
ZEN 13	Big coal stove
ZEN 14	Small hand-built stove
ZEN 15	Big coal stove

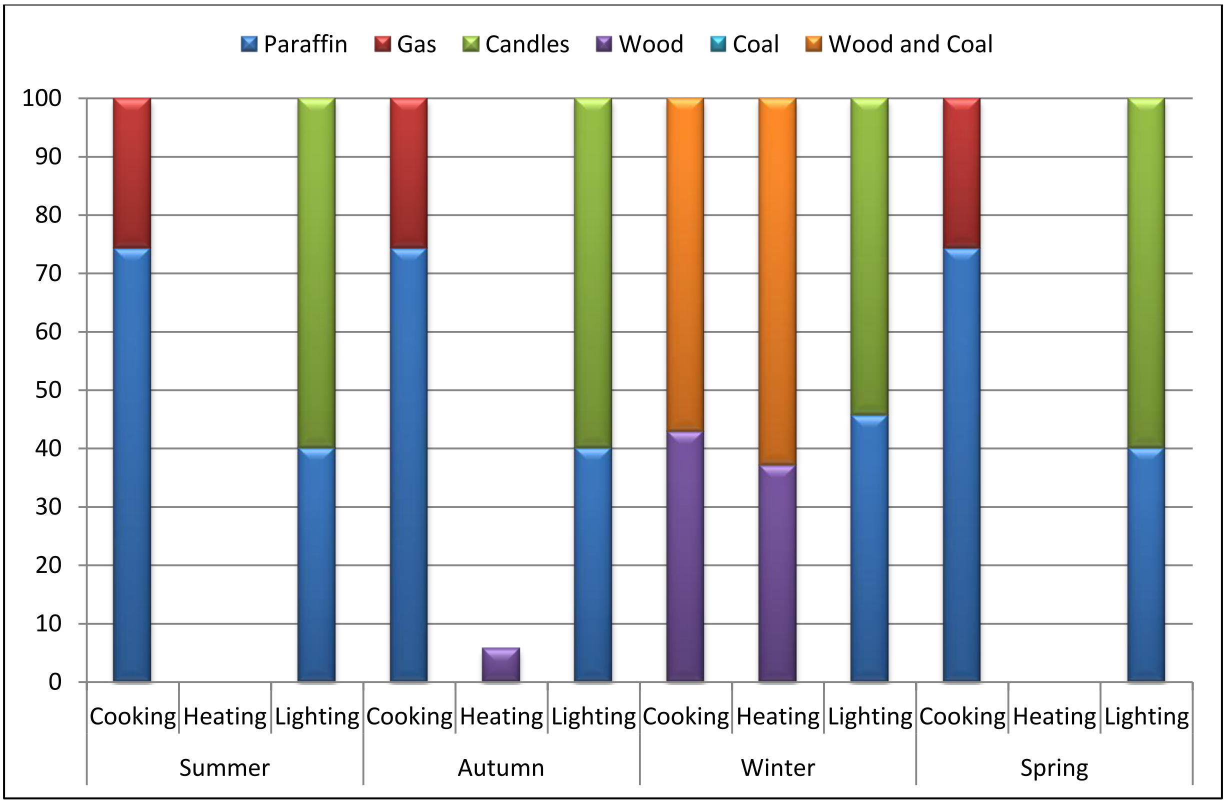

Figure 4.6. Percentages of the different fuel types consumed by households in Zenzele as highlighted in the field study questionnaires.

Figure 4.6 represents the percentage fuel use of a range of recorded fuels over the various seasons. The results shown in this figure are representative of the questionnaires distributed to both groups of people in Zenzele, totalling a sample of 35 people. When presented with options to choose from in the questionnaire, residents often chose more than one fuel as their fuels of choice during the colder winter months. When asked if the different fuels were burnt at different times of the day or in combination with other fuels, a common response was often "*yes*", indicating that often different fuels were used simultaneously. Mdluli (2007) explains that this practice does not correspond with that seen in the literature but is, in fact, something that is often widespread amongst the poorer communities in South Africa.

There are a large portion of un-electrified households that do not always use vast quantities of coal and/or wood to provide for their energy needs. Even at the height of winter, when temperatures are at their lowest, households will have to get by with what they have remaining from the previous season, supplemented with a small stock of solid fuels. The price and availability of these fuels play a key role in determining what fuels are consumed in winter. These factors, in addition to temperature, have a major influence on the seasonal as well as the diurnal burning habits of residents of low-income settlements. An examination of the responses to the questionnaires highlighted that wood and coal are not the only common fuels utilised in this low-income settlement. Large quantities of paraffin, gas and candles too, are common fuels made use of in summer.

4.4.1.1. Comparison of Zenzele Questionnaires to Census Data

Many similarities have been identified between the information gathered from the questionnaires distributed in Zenzele and the analysis of the 2001 census data. The census data, however, examined fuel types that were not considered in this study as they were not mentioned when participants answered the questionnaires. Fuel types such as solar and animal dung are examples of these. Electricity too, although an option specified in the questionnaire, was not a fuel type selected by residents as all the households that participated in the study were un-electrified. The 2001 census data examined the use of a range of fuel types individually but the questionnaires, however, gave the option for more than one fuel type to be chosen. The simultaneous use of wood and coal was highlighted as a frequent combination in the Zenzele questionnaires.

As is evident in the census data, gas and candles are commonly used fuels for cooking and lighting respectively (figures 4.3 and 4.5), in the warmer months. Paraffin has also been identified as a major fuel, utilised for both these activities. The same fuel choices and seasonal burning patterns are highlighted in the questionnaires, as illustrated in figure 4.6. In both the responses to the questionnaires and the census data it is evident that wood and coal, be it individually or simultaneously, are burnt most frequently during winter and in some of the colder months leading up to it. This is used particularly for cooking and heating purposes. Similarities also emerge in the major fuels used for lighting during winter. Paraffin and candles have been identified by both sets of information as the most commonly used fuels.

4.4.2. Scale Measurements

Larger volumes of solid fuel combustion occur at lower temperatures. For almost all households that participated in this study, there is a gradual increase in the amount of wood burnt from May to June and a further, often very slight increase from June to July. After peaking around June and July, the amount burned slowly starts to decrease into August and September.

The results gathered from the scale measurements of each household participating in this field study, are presented below. The weights of both coal and wood consumed by each of the fifteen households were measured and then totalled, once the measurement data were collected. The values presented in tables 4.4 and 4.5 correspond with the total consumption of the 15 households and figures 4.7 and 4.8 highlight the total consumption of wood and coal for one specific household over the 5 months. Figures 4.9 to 4.12 represent the average usage of these two fuel types over the same period.

For various personal reasons, there were some households that could not complete the study. In certain instances measurements could not be taken every day and, on occasion, for specific households, over extended periods of time. For this reason, there are a small number of gaps in the dataset. Some of these reasons include family illnesses, family deaths, amongst some others.

Table 4.4. Mean, total and maximum amounts of wood burnt in the mornings and evenings by all 15 households in Zenzele from May 2011 to September 2011.

Wood	Morning		Evening	
	Mean kg/day (Total) kg/month	Max kg/day	Mean kg/day (Total) kg/month	Max kg/day
May	30.9 (958.8)	20.8	76.5 (2370.1)	44.6
June	49.9 (1498.3)	37.2	96.8 (2904.6)	74.2
July	36 (1117.2)	29.2	92.9 (2878.4)	47.2
August	42.2 (1306.7)	49	80.6 (2497.4)	45
September	28.5 (854.5)	39	16.6 (497.3)	14

Table 4.4 shows the mean and total amounts of wood consumed by all of the 15 households, during the morning and evening burning sessions, in each respective month. The mean values refer to the amounts of wood that all 15 households burn collectively, during either the morning or evening burning period in one day of that specific month. The maximum amounts of wood burnt by one specific household out of the total of 15 households, in each respective

month, have also been identified and are displayed in table 4.4. The minimum amounts of wood burnt are not displayed in this table as the values were zero for each month. During the morning burning session, there is a considerable increase in the amount of wood consumed from May to June, with an average increase of 19kg per day. The same pattern is observed during the evening burning session, where the difference in the mean consumption rate is 20.3kg per day. After peaking in June, the average and total consumption of wood during both the morning and evening burning sessions declines slightly in July; and further in August and September. The lowest mean and total amounts of wood consumed during the morning and evening burning sessions occurs during September.

Table 4.5. Mean, total and maximum amounts of coal burnt in the mornings and evenings by all 15 households in Zenzele from May 2011 to September 2011.

Coal	Morning		Evening	
	Mean kg/day (Total) kg/month	Max kg/day	Mean kg/day (Total) kg/month	Max kg/day
May	4.2 (129.4)	16.8	22 (681.4)	44.6
June	6.7 (199.8)	28.7	27.9 (835.7)	11.4
July	0.6 (17.2)	9.4	22.8 (706.3)	12.2
August	4 (122.6)	10.2	15.6 (483.2)	19
September	3.6 (107.6)	16.2	2.5 (74.8)	14.2

The mean and total amounts of coal consumed by all of the 15 households, during the morning and evening burning sessions, in each respective month is shown in table 4.5. The mean values refer to the amounts of coal that all 15 households burn collectively, during either the morning or evening period in one day of that specific month. The maximum amounts of coal burnt by one specific household, in each respective month have also been presented in this table. The minimum amounts of coal burnt are not displayed in table 4.5 as the values were zero for each month. As is the case with wood, there is an increase in the amount of coal consumed between May and June. Although not as substantial, the mean and total amounts of coal burnt during the morning and evening burning sessions are at their highest during June. After peaking in June, the average and total consumption of coal during the evening burning session starts to decline progressively from July, to August and into

September. This pattern of consumption is different to that observed during the morning burning session, as the lowest mean consumption rate for the combustion of coal in the mornings was recorded during July.

It is evident in tables 4.4 and 4.5 that the consumption of wood occurs on a larger scale to that of coal. Although, with that said, both wood and coal are consumed more frequently during the evening burning session than in the mornings with the exception of September, where the consumption of both wood and coal are higher in the mornings.

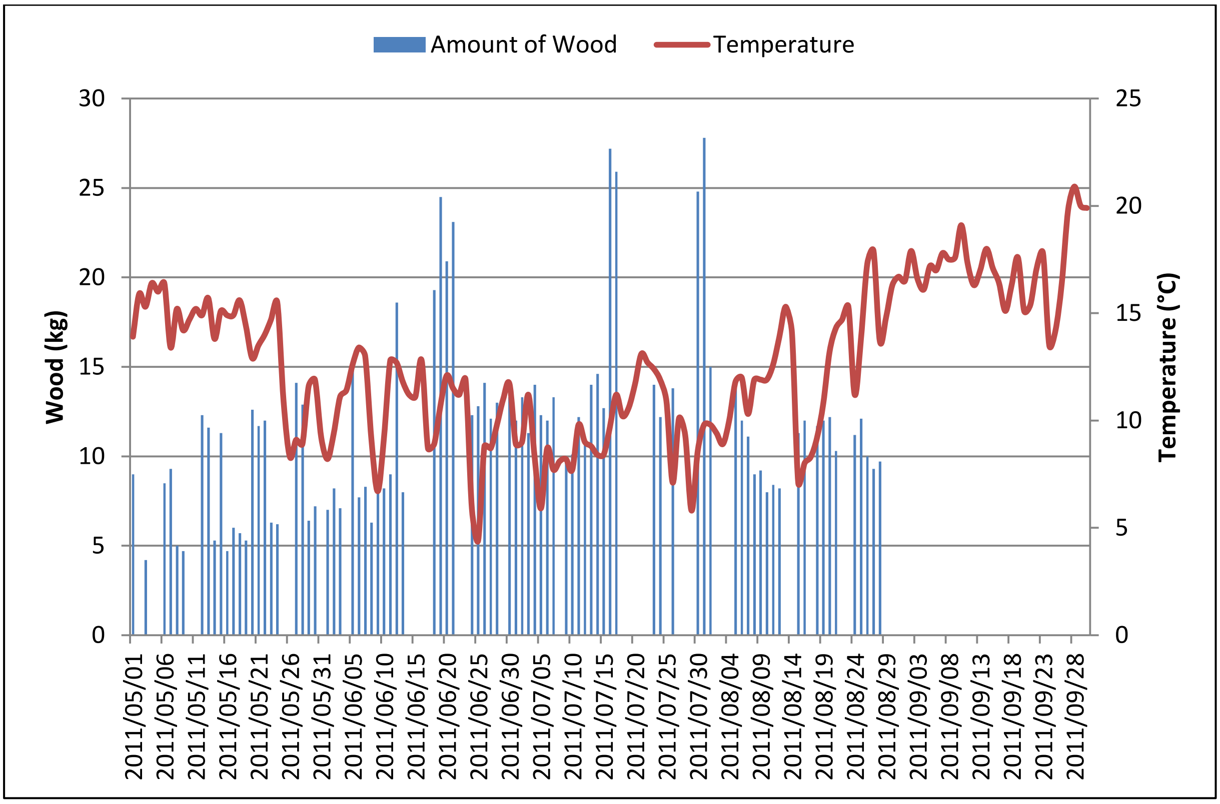

Figure 4.7. Total amount of wood burnt each day by Household 2 in Zenzele compared with the daily average temperature from May 2011 to September 2011.

Figure 4.7 illustrates the total amount of wood burnt each day by Household 2. This total consumption represents a combination of the morning wood and evening wood consumed. As mentioned in the methodology, this study was done over a 5 month period in order to analyse the seasonal trends that might have arisen over the winter months. Figure 4.7 demonstrates that the amount of wood consumed by the residents of household 2 gradually starts to increase from May, into June and further in July, before decreasing in August and no consumption was recorded in September. This figure further illustrates that there is an inverse relationship that exists between the consumption of wood by household 2 and temperature. A large proportion of these households exhibit similar burning behaviours, being larger fuel combustion at lower temperatures. For almost all households, there is a gradual increase in the amount of wood burnt from May to June and a further, often very slight increase from June to July. After peaking around June and July, the amount burned slowly starts to decrease into August and September.

In certain instances, where this trend was not followed, several explanations can be provided from information gathered from the questionnaires, as well as from conversations carried out with residents during regular visits to the study site. A common explanation for the deviation from this trend was a variation in the number of people residing in a household from one month to the next, over the 5 month period. Family deaths, cultural gatherings and school holidays, were amongst some of the most common reasons for this variation. It is also interesting to note that the greatest peaks in fuel use occur the day after an unusually large decline in the temperature. When temperatures decrease drastically, people tend to expect similar temperatures the following day and therefore tend to burn more fuel irrespective of whether the temperature decreases or not.

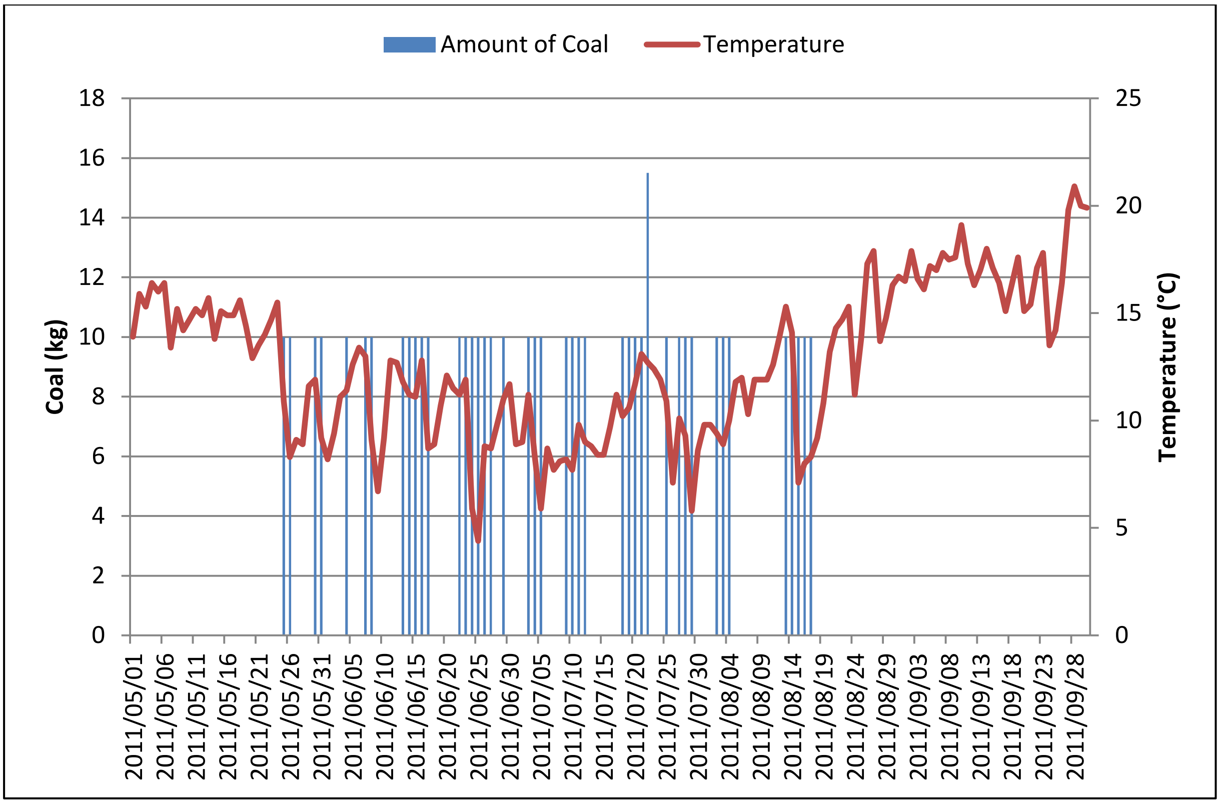

Figure 4.8. Total amount of coal burnt each day by Household 2 in Zenzele compared with the average daily temperature from May 2011 to September 2011.

Figure 4.8 illustrates the total amount of coal burnt each day by Household 2. A comparison of figures 4.7 and 4.8 highlights the total amount of coal burnt over this period is far less than that of wood. It was expected that the combustion of coal would follow the same seasonal trend as that of wood, but this is not the case. Coal is seldom burnt during May and September as these months are generally warmer than the winter months. During the months of June, July and August, however, the combustion of coal shows a very uniform pattern with the total consumption on all days, except one, being recorded at 10 kg. This suggests that residents will probably limit their usage of coal to one 10kg bag per burning period if the household burns coal during both the morning and evening burning session or per evening. An analysis of the information provided in figures 4.7 and 4.8 shows that given no variation in the number of people residing in one household, the amount of coal consumed in a fire stays constant and is supplemented by wood as the temperature decreases over the winter period.

As mentioned previously, when residents of Zenzele were presented with various options of fuel types to choose from, in the questionnaire, there were instances where people chose more than one fuel. Residents explained that both coal and wood are commonly used fuels during winter, especially if a coal stove is owned. Both these fuels are burnt in larger coal stoves, in hand built stoves and even in imbaulas. When asked about which fuels were consumed at different times of the day, it was made clear that wood is generally burnt in the mornings if the need arises and, in the evening, coal and wood simultaneously, together in the same fire (Davis, 1998).

In order to gauge the average daily consumption of these two fuels, an average was then calculated for both the morning and evening burning periods for each of the 5 months. The following four figures represent the average amounts of wood and coal burnt by residents during their respective morning and evening burning periods.

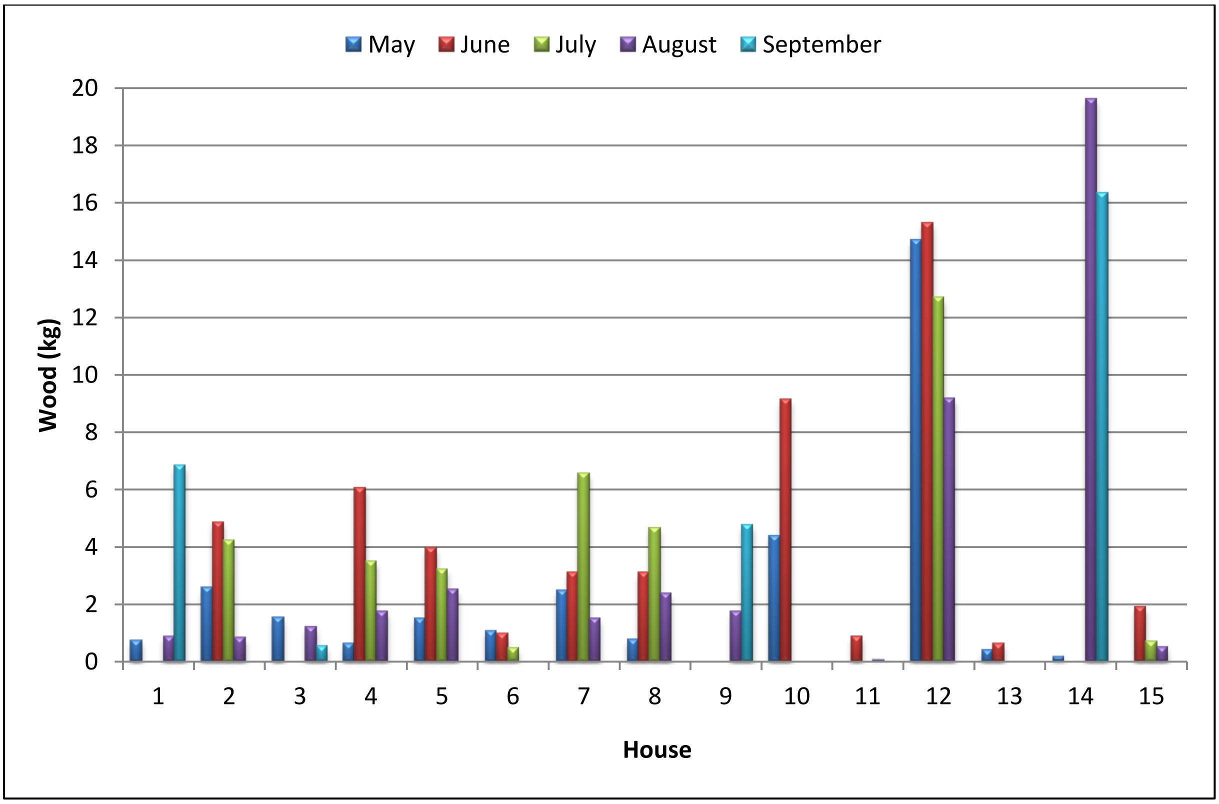

Figure 4.9. Average amount of wood burnt in the morning by each household in Zenzele from May 2011 to September 2011.

Figure 4.9 illustrates the average amount of wood burnt every morning by each of the 15 households. There is a gradual increase in the amounts of fuel consumed from May to July and then a decrease in the quantities in August and an even further reduction in September. In May, when temperatures started to drop, households started to make use of fuelwood. As the temperatures declined even further, larger quantities of wood were consumed. By September, some households were not consuming any wood at all. There are, however, some households that did not follow this trend and for these isolated cases, other factors come into play. These factors include monthly income, accessibility to wood and various personal reasons.

Specifically in the cases of “House 9” and “House 14”, a variation in the number of inhabitants residing in each of these houses over the 5 month period, explains the deviation from the common trend and amount of wood used from one month to the next. The number of people living in Household 9 decreased from 5 people in May, to 3 people for the rest of the 5 month period, after a marriage was celebrated by this family. After a death in their extended family, the family residing in household 14 had 3 family members move in with them. The number of people living in household 14 then increased from 5 people to 8 people. In both of these instances, the change in the number of people living in each household would have an impact on the quantity of fuel used for cooking and heating purposes as well as the period over which these fuels are burnt.

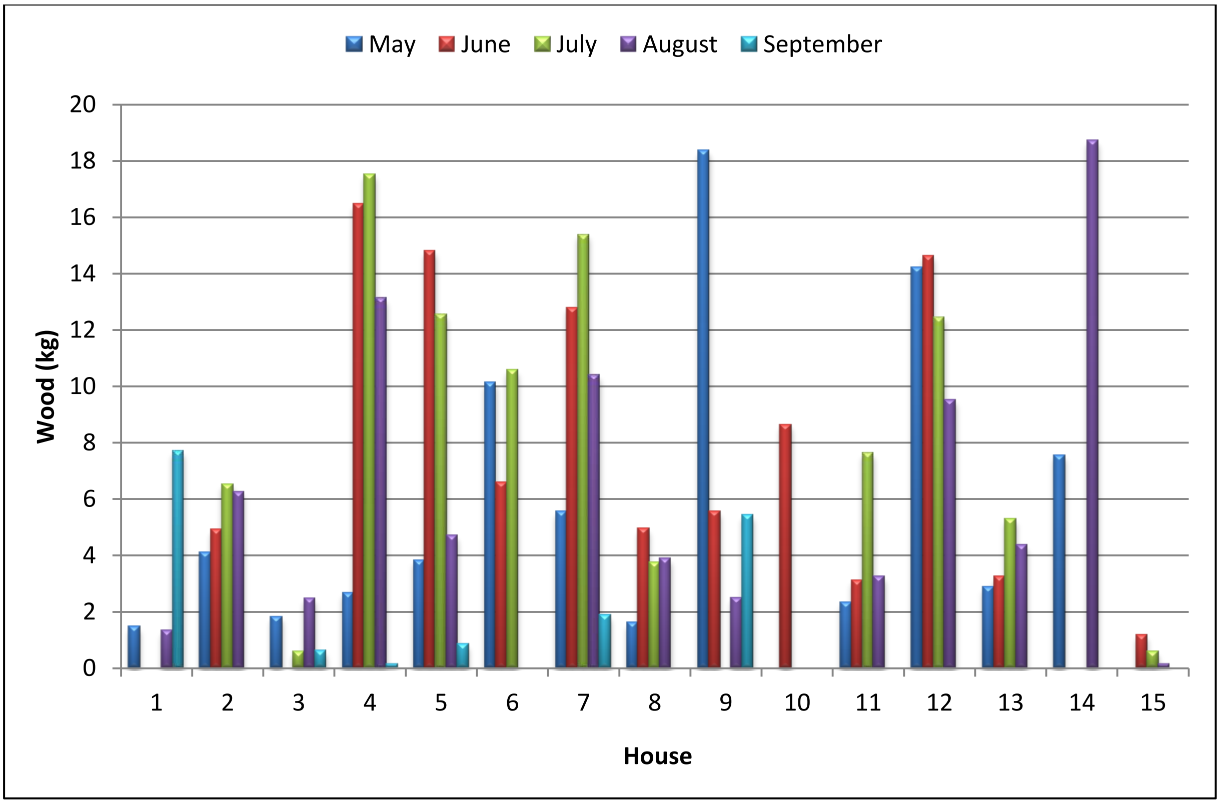

Figure 4.10. Average amount of wood burnt in the evening by each household in Zenzele from May 2011 to September 2011.

The average amount of wood burnt in the evening by each household (figure 4.10) was also examined over the same 5 month period. It is evident that a far larger amount of wood is burnt in the evenings as opposed to the mornings. The main reasons for this include convenience and temperature. As most residents spend a limited amount of time in their homes in the morning before leaving for either school or work, the heat generated from a coal and/or wood fire would be wasted. For this reason, residents opt for other fuels that are more convenient to provide for their heating and cooking needs in the mornings. Paraffin or gas is the commonly used fuels for boiling water in the mornings. The heat produced from these wood fires can generally warm a home for hours after the fire has been lit. Thus, wood becomes a more worthwhile fuel when utilised in the evenings.

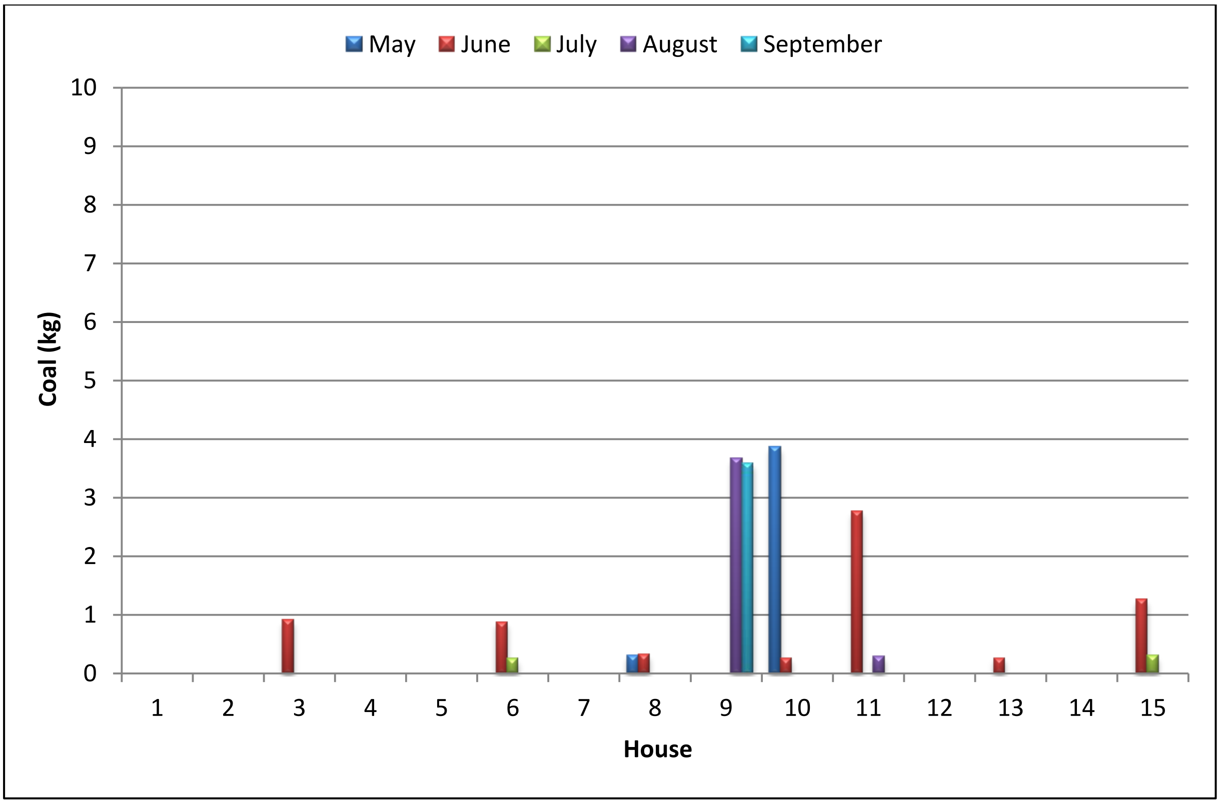

Figure 4.11. Average amount of coal burnt in the morning by each household in Zenzele from May 2011 to September 2011.

The combustion of coal occurs on a far smaller scale to wood burning, for both the morning and evening burning periods. Although the gathering of wood is not as easily done in urban townships as it is in rural settlements, it is still cheaper than coal, if residents were to purchase fuelwood. Relative to electricity, however, coal is cheaper and for this reason remains a common fuel type even in electrified households. Figure 4.11 illustrates the average amount of coal burnt in the morning by each of the 15 households. As very small quantities of coal were burnt by the households under examination over this period, there is not sufficient data to view any noticeable seasonal trends. However, amongst the few houses that did consume coal in the mornings, during this period, almost all of these households burnt coal in June.

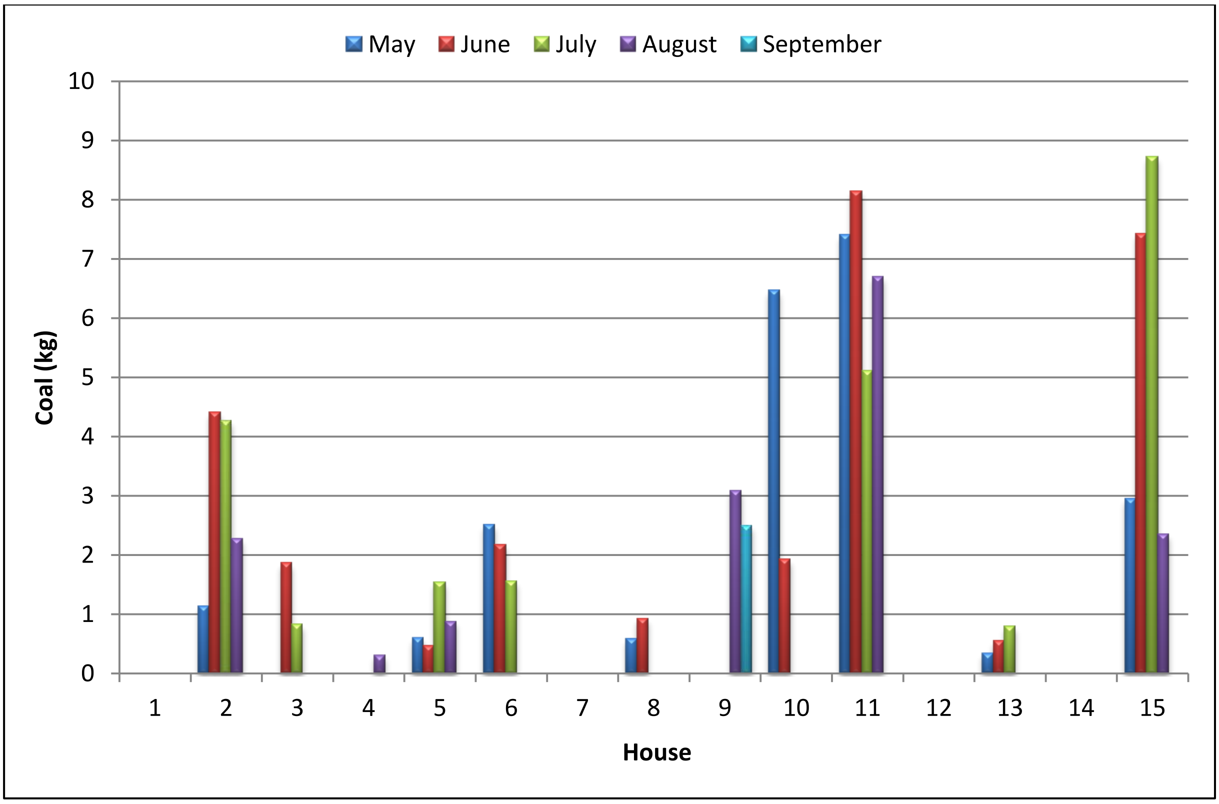

Figure 4.12. Average amount of coal burnt in the evening by each household in Zenzele from May 2011 to September 2011.

When comparing the average amount of coal burnt in the evenings by each household (figure 4.12) to that burnt in the morning, it is evident that combustion occurs more frequently and on a larger scale in the evenings. The average amount of coal burnt in the evenings by each household is presented above. For the same reasons, listed above, coal, like wood, provides large amounts of heat when combusted; so it is commonly used in the evenings. A similar seasonal trend to the one seen in wood burning is also witnessed in coal burning. The amount of coal consumed increases from May to June and even further in July and then gradually starts to decrease in August, with a further decline in September.

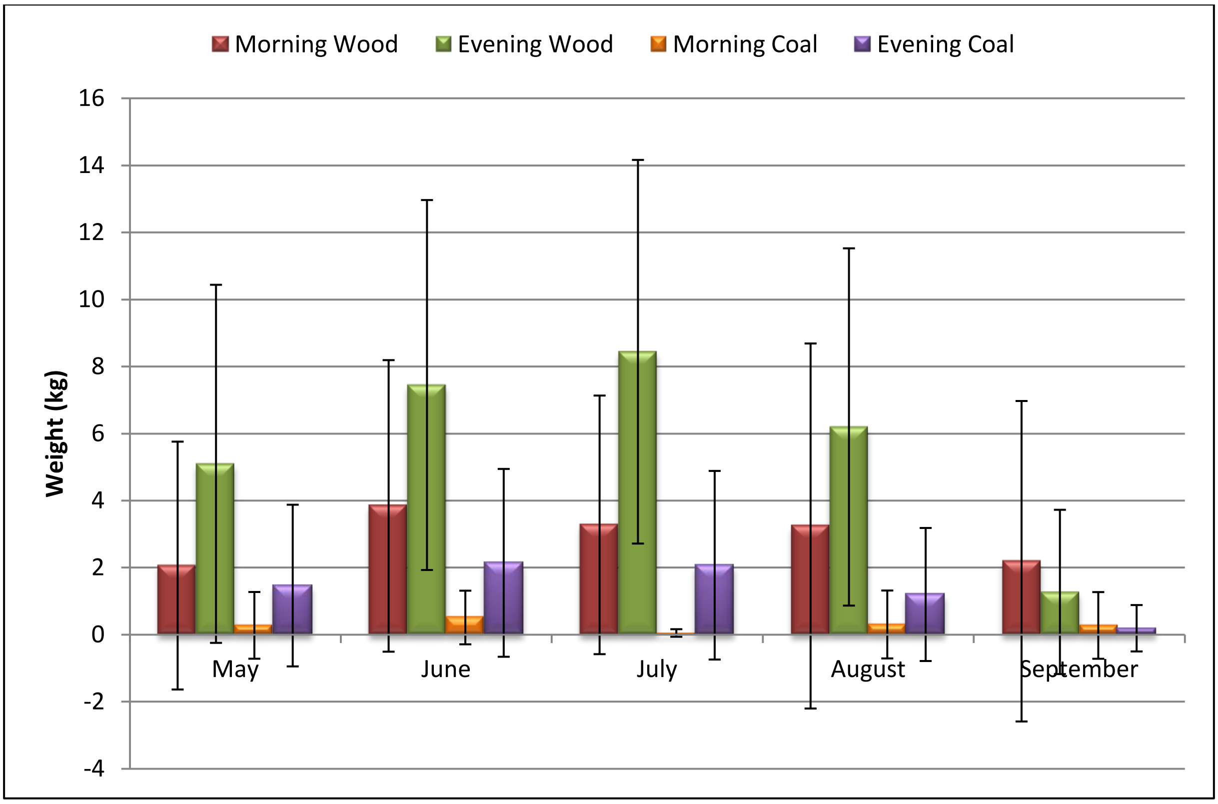

Figure 4.13. Average quantities of wood and coal consumed per days by all 15 households in Zenzele from May 2011 to September 2011.

The average amounts of wood and coal consumed per day during the morning and evening burning periods by the 15 households are illustrated in figure 4.13. The bottom and top caps of the error bars represent the standard deviation from the averages during each burning period, over that specific month. In most cases, an increase in the average consumption rates of both solid combustion fuels are seen during the colder months.

If there is only a limited supply of either fuel type, wood or coal, residents would prefer to utilise these stocks during the evening burning sessions. Once the cooking has been done and the fire has progressed through all the combustion stages, evening fires are generally rekindled to provide additional heat for warmth throughout the night.

4.4.3. Emission Estimates

There is often a degree of uncertainty that arises when using emission factors that are not calculated within the study as they do not relate directly to the dataset being examined. For this reason, amongst some others, there is some uncertainty that, therefore, also exists within the emission estimates. Specifically, as was the case in this study, the most significant uncertainties in the emission estimates arose on account human error. In comparing their study to another study, Bhattacharya *et al.* (2000), highlight an array of uncertainties that can arise with regard to the approach taken in conducting the study as well as with the emission factors and datasets used. They have explained that if the dataset used was collected and analysed for another study, it may be unreliable as it does not pertain to the specific needs of that current study. They have further explained that fuel specific emission factors as opposed to emission factors based on the end-use seldom takes into account the device used during combustion (Bhattacharya *et al* 2000; Zhang *et al.* 2000). For the purpose and scope of this study, fuel specific emission factors are sufficient.

Using a set of emission factors adapted from the 2004 FRIDGE (Funds for Research into Industrial Development, Growth and Equity) Report, the data collected from the scale measurements were converted into emission estimates. The set of emission factors made use of in calculating the emission estimates are as follows: SO_2 for wood and coal, PM_{10} for wood and coal, CO_2 for wood and coal, and finally, CO for wood and coal. The emission factors associated with this set of pollutants are recorded on different scales and for this reason, although all the figures below apply the same base data, one graph will differ from the next. The emission factors used for the combustion of wood are as follows: 0.18 grams of SO_2, 15.7 grams of PM_{10}, 1542.2 grams of CO_2 and 114.6 grams of CO, for every kilogram of wood burnt. The emission factors used for the combustion of coal are as follows: 19 grams of SO_2, 4.1 grams of PM_{10}, 2997.6 grams of CO_2 and 187.4 grams of CO, for every kilogram of coal burnt. These emission estimates were calculated using a total burning period of 7 hours. It was assumed that the morning burning period lasts for 3 hours and the evening burning period lasts for 4 hours.

The average emission rates, from May 2011 to September 2011, for each pollutant under investigation are illustrated in figures 4.14, 4.15, 4.16 and 4.17. These average emission rates are representative of all 15 households in Zenzele and have been calculated for both fuel types over the two different burning periods.

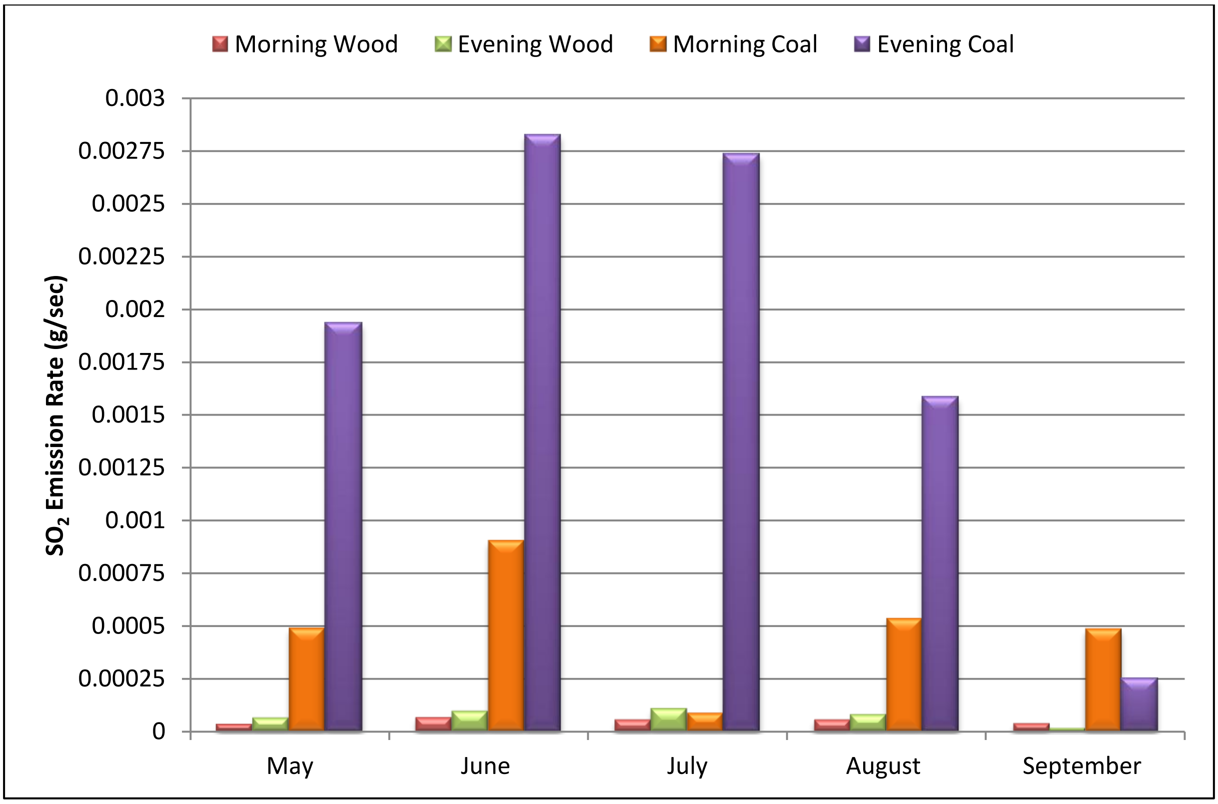

Figure 4.14. Average SO_2 emission rates per household in Zenzele from May 2011 to September 2011.

The average SO_2 emission rates that are associated with the 15 households are presented in figure 4.14. At 0.0028g/sec, the combustion of coal in the evening over the month of June has the highest emission rate for SO_2. The lowest SO_2 emission rate of 0.000016g/sec occurs in September during the evening combustion of wood. It has already been established and is evident in the consumption data that on average wood is consumed more frequently during both the morning and evening burning sessions. Figure 4.14, however, illustrates SO_2 emission rates for coal that are far higher than that of wood. This is attributed to the high emission factor associated with coal and SO_2; and therefore the greater amount of sulphur dioxide released when coal is burnt as opposed to wood.

In figures 4.15, 4.16 and 4.17, where the emission rates from wood combustion are more pronounced, the seasonal trends associated with this type of combustion are evident. Generally the emission rates for both wood and coal are higher during the colder months.

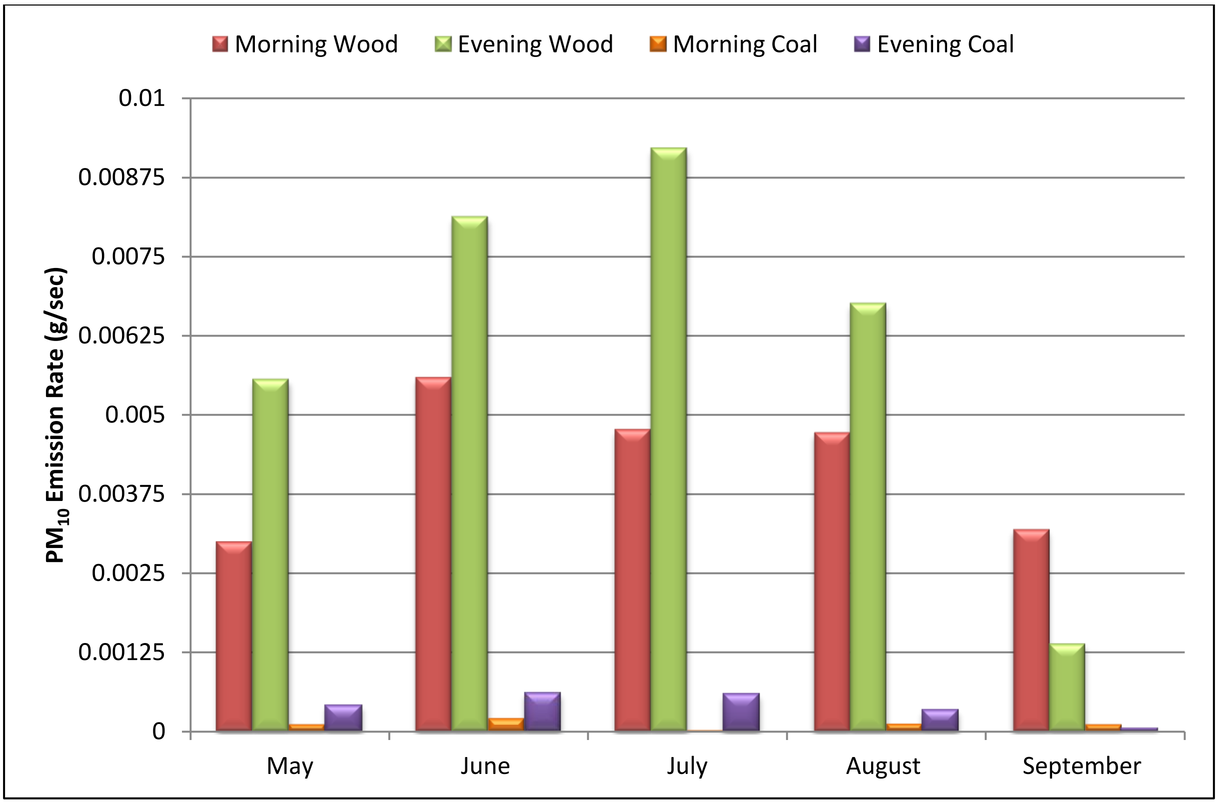

Figure 4.15. Average PM_{10} emission rates per household in Zenzele from May 2011 to September 2011.

The average emission rates for PM_{10} are illustrated in figure 4.15. The highest emission rates occur during the evening combustion of wood from May to August but in September, however, the highest rate occurs during the morning combustion of wood. The emission rates for the evening combustion of wood peaks in July at 0.0092g/sec. As temperatures start to gradually increase, less fuel is required for space heating in the evenings and can therefore be used for other activities such as boiling water and cooking in the mornings. The highest PM_{10} emission rates that correspond with both the morning and evening burning sessions over this 5 month period are for wood. Coal burnt in the mornings has the lowest emission rate, with a value of 0.000019g/sec being recorded in July. This is in line with the expected trend as the consumption of coal during the morning burning sessions is far less than that consumed during the evening burning session. Residents opt for creating labour and fuel intensive fires in the evenings so as to gain the maximum benefit of the heat generated. In addition, coal is utilised more in the evenings in a bid to save already limited funds, as the demand for this commodity drives prices up (Mdluli and Vogel, 2010). As a consequence of this increased demand, the supply and availability of both coal and wood can often also become a problem.

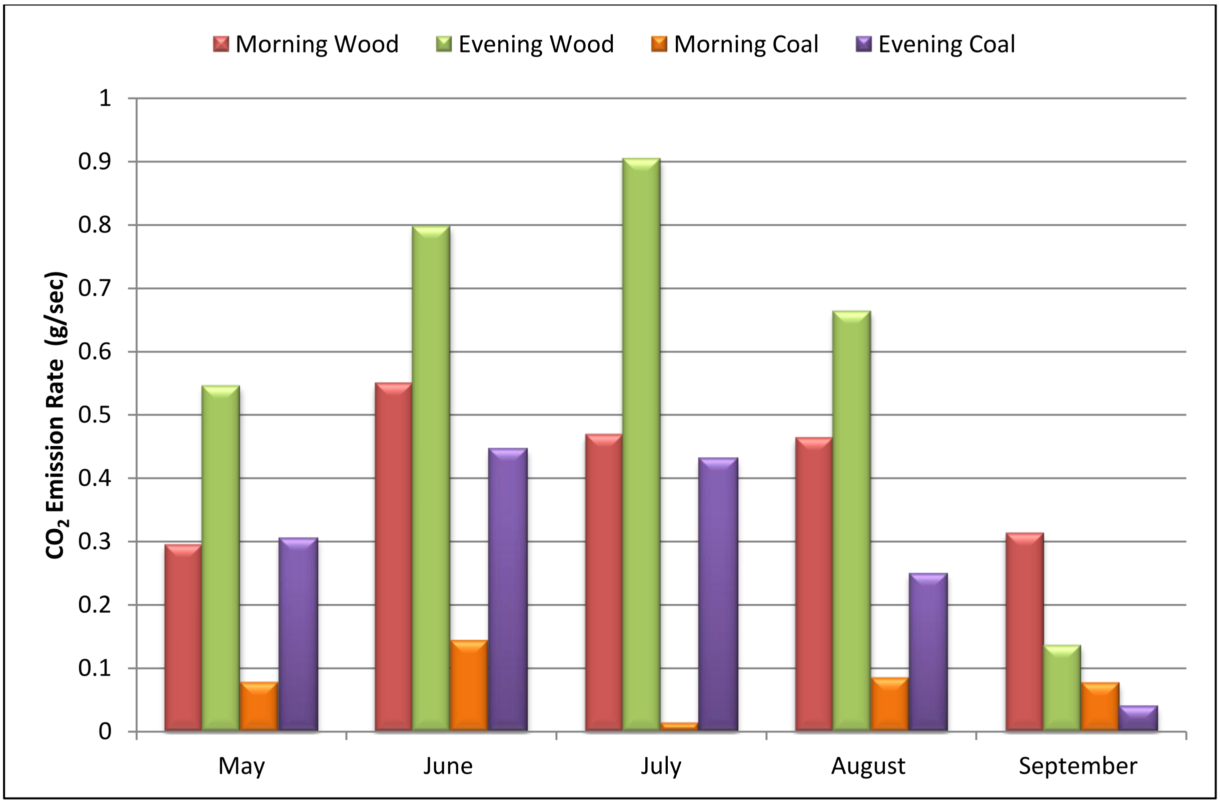

Figure 4.16. Average CO_2 emission rates per household in Zenzele from May 2011 to September 2011.

Figure 4.16 displays the average CO_2 emission rates that correspond with the morning and evening combustion of wood and coal. The general pattern shows a gradual increase of the evening emission rates from May to July, with the emission rates starting to decrease from July to September. On the other hand, the morning emission rates for both wood and coal increase from May to June and then decreases in July. As discussed previously, the combustion of both wood and coal occurs on a smaller scale in the mornings. A deviation from this pattern is seen during the morning combustion of wood and coal. As the supply of coal lessens in the colder months, so too will the supply for good quality wood, as its demand increases (Matsika *et al.* 2013). The highest average emission rate of 0.904 g/sec still corresponds to the combustion of wood in the evenings of July but there is a substantial increase in the quantity of coal consumed in the evenings as opposed to the mornings. The lowest average emission rate for CO_2 was recorded at 0.014 g/sec for July, during the morning combustion of coal.

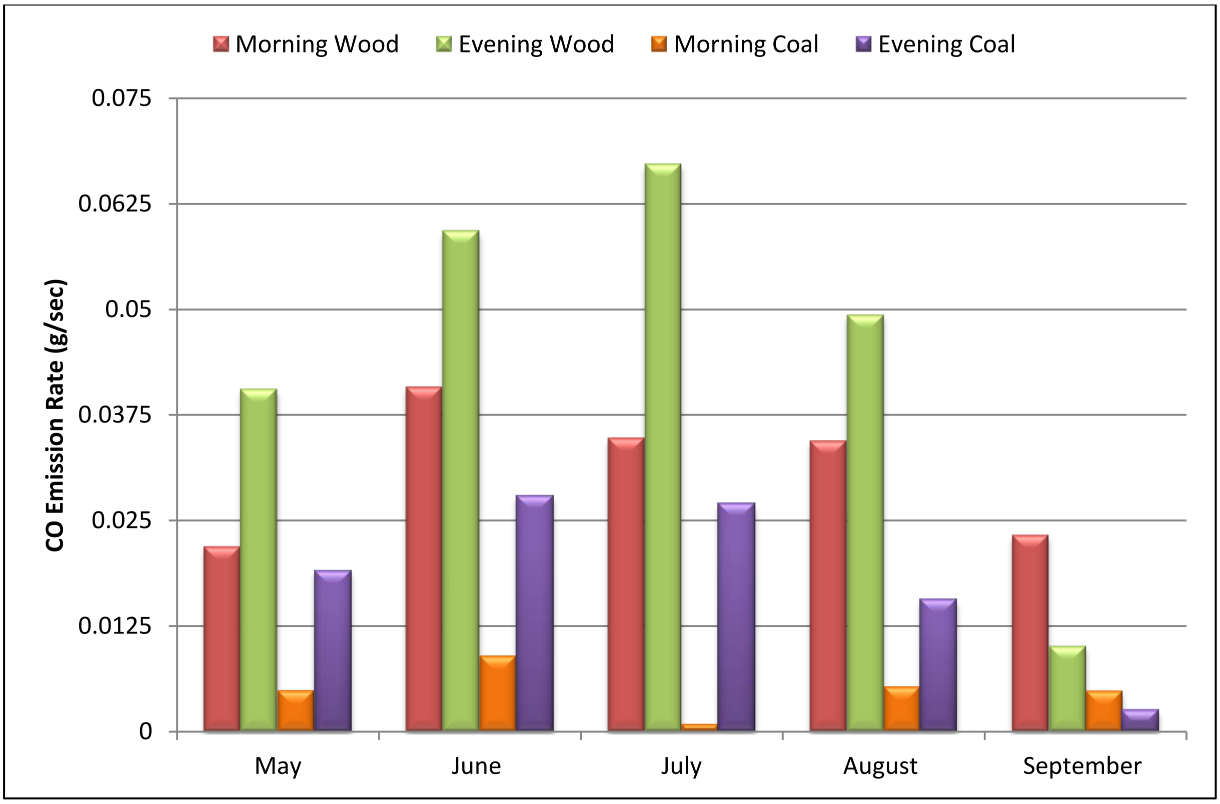

Figure 4.17. Average CO emission rates per household in Zenzele from May 2011 to September 2011.

The average emission rates for CO are shown in figure 4.17. The highest average emission rate for CO was recorded at 0.067 g/sec for the evening combustion of wood during July. The morning combustion of coal in July shows the lowest average emission rate for CO, at 0.00089 g/sec. It is expected that the CO emission rates for the morning combustion of coal would be relatively low during May and September as temperatures are higher but should be the highest in July, at the height of winter. This, however, is not the case as this pattern is consistent with the increase in the price of coal during the colder months, as the demand for coal increases (Daioglou *et al.* 2012).

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In un-electrified households, paraffin and liquid petroleum gas, used specifically for cooking and lighting, are the most commonly used fuel types during the warmer months. During the colder months, however, residents of households in low-income settlements prefer to use solid fuels such as wood and coal. Factors such as seasonality, the availability and the price of these fuels as well as cultural aspects all have a bearing on residents' fuel choices and the quantity consumed. As the temperature declines, the rate at which these solid fuels are consumed increases.

CHAPTER 5: AMBIENT MEASUREMENTS AND DISPERSION MODELLING

Overview

Chapter 5 provides further results on an additional component of the field study, as well as the final component of this research project, the dispersion modelling. Ambient measurements of CO_2 and CO associated with domestic burning activities are observed in this chapter to gain a better understanding of the impact of household air pollution (HAP). These findings are accompanied by an application of the results obtained in Chapter 4, using CALPUFF to determine the fate of emissions generated from domestic combustion.

5.1. Indoor Measurements

As part of this field study, ambient monitoring instruments were set up concurrently for a period of 24 hours on the 30th of August 2011, measuring concentrations of CO_2 and CO during the various burning periods. Equipment, including analysers, a generator and a data logger were temporarily installed at one of the 15 study households, chosen from those that participated in the scale measurements.

Table 5.1. Indoor measurements of CO_2 and CO taken at different stages of combustion on the 30th of August 2011.

Time	CO_2 (ppm)	CO (ppm)
04h45	986.345	6.710909
05h30	810.4926	3.232991
06h15	753.2042	3.683721
07h00	823.3872	4.890253
11h00	696.8401	2.066934
14h05	655.4453	1.852
17h00	760.0872	2.445753
17h45	691.3505	2.090417
16h30	728.8917	3.960726
19h15	739.9084	4.801413

Ten measurements for both CO_2 and CO were taken at specific times during the course of the day, corresponding with the morning and evening burning periods. Table 5.1 highlights the values of CO_2 and CO measured at precise times during a fire. The first four readings were taken during the morning burning period and the last four were taken during the evening burning period. The readings in between, were taken at two random times between the morning and burning sessions to get an idea of the indoor concentrations when fuels were not being burnt.

At 04h45, the first measurements of CO_2 and CO were taken, signalling the beginning of the morning burning session. Thereafter, a further three measurements were recorded at 45 minute intervals, concluding the measurements taken for the morning session at 07h10. Measurements for the evening burning period were obtained between 17h00 and 19h15, allowing for the readings to be taken during the different phases of the lit fire. Morning and evening burning periods will vary from one household to the next depending on the activities of residents in that specific household. The concentrations of CO_2 and CO obtained are illustrated in figure 5.1.

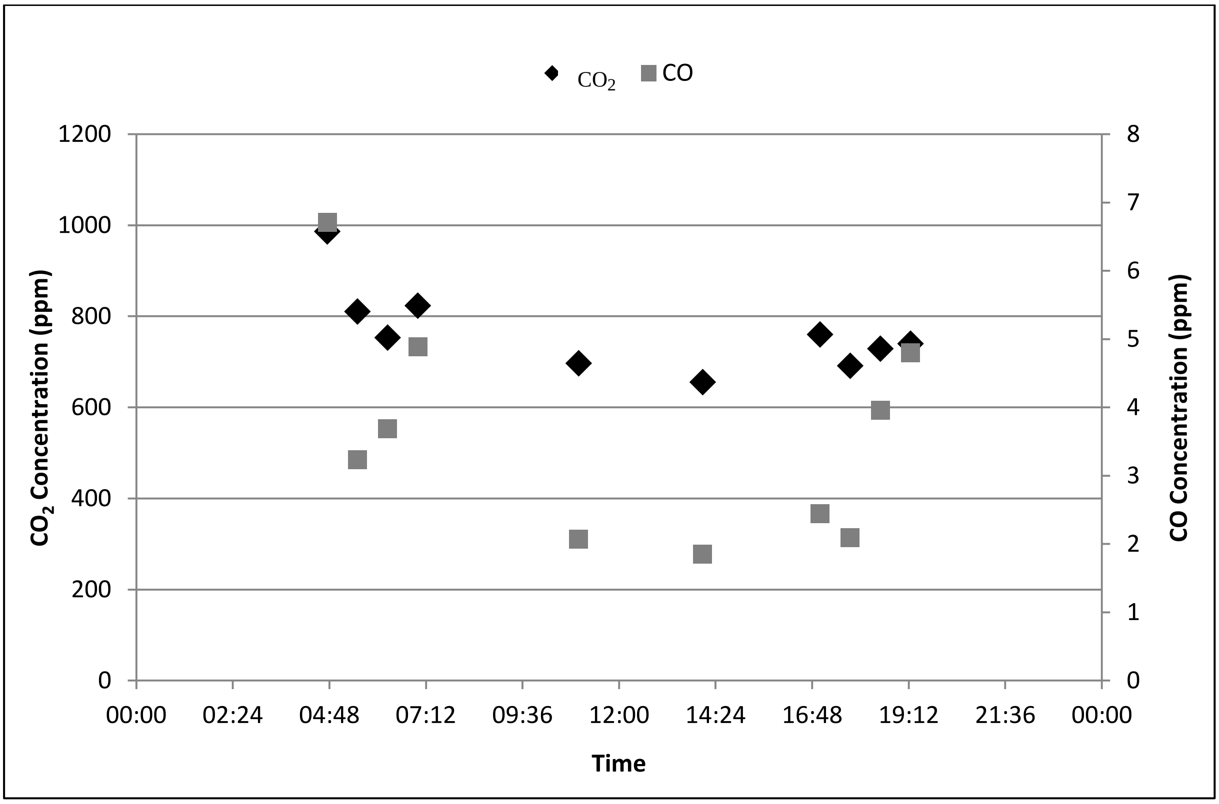

Figure 5.1. Indoor concentrations of CO_2 and CO taken at different stages of combustion on the 30th of August 2011.

Although presented at different magnitudes, the concentrations of CO_2 and CO follow the expected trend, showing distinct peaks at times corresponding with that of the morning and evening burning periods. There are noticeable increases in concentrations of CO_2 during the flaming stages of the fire. These measurements correspond with the measurements taken at 04h45 for the morning burning session and at 17h00 for the evening burning period. Concentrations of CO_2, a by-product of a complete combustion process, are usually highest during the flaming phase of a fire, when temperatures are at their highest. There are also clear peaks evident within the CO measurements at 06h15 for the morning fire and at 16h30 for the evening fire. These readings highlight increased concentrations of CO during the final stages of combustion. With conventional fires, the largest amounts of smoke are emitted during the final stages of combustion, resulting in increased levels of CO.

In order to ensure the continued function of the analysers on the 30th of August 2011, the generator and analysers had to run for a few days prior to the day that the measurements of CO_2 and CO were taken. Data corresponding to this period were also collected and analysed. The results obtained from this analysis are illustrated in figures 5.2 and 5.3. Hourly averages for CO_2 and CO were calculated using these datasets to allow for the examination of the diurnal trends.

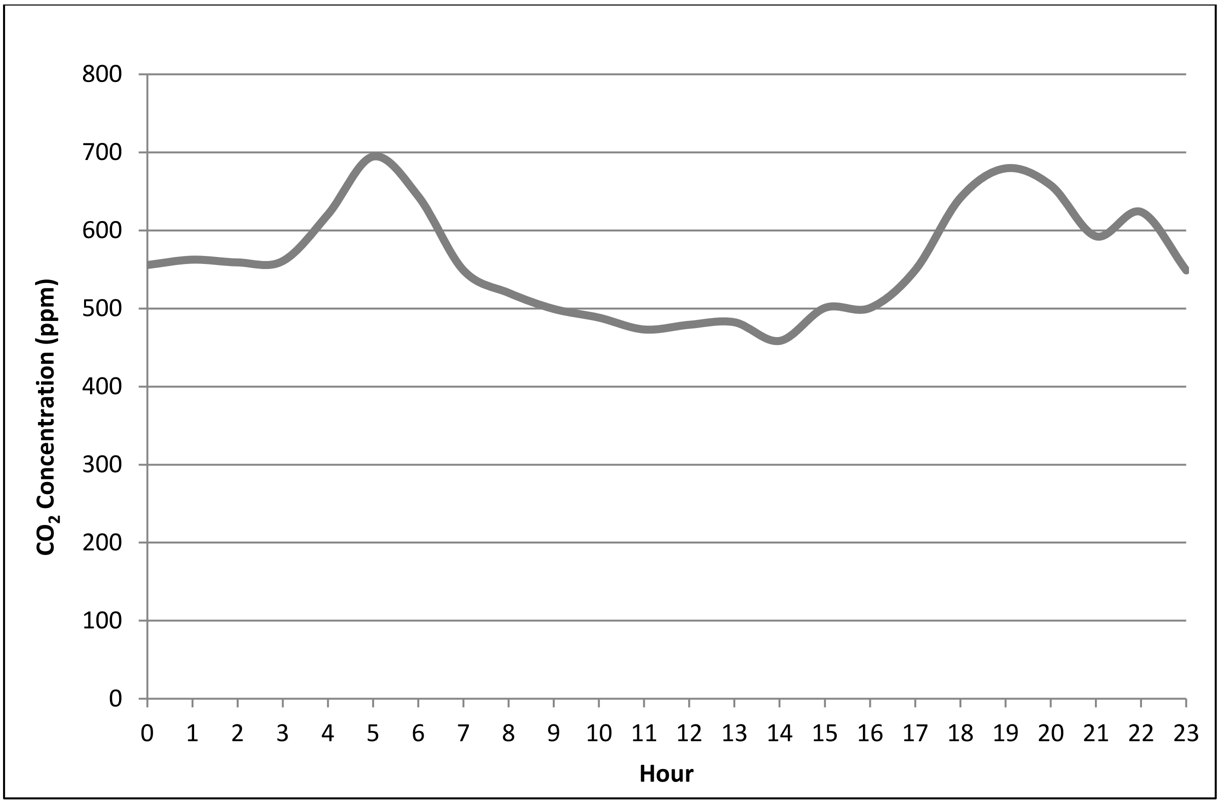

Figure 5.2. Indoor hourly average concentrations of CO_2 from 23 August 2011 to 30 August 2011.

Figure 5.2 illustrates the hourly averages for CO_2 from the 23rd of August 2011 to the 30th of August 2011. This figure highlights distinct peaks starting in the early mornings and early evenings which are consistent with the morning and evening combustion of domestic fuels. The morning peak reaches a maximum of 694.74 ppm at approximately 05h00 and the concentration of CO_2 peaks in the evening at around 19h00 at 679.58 ppm. A further peak, although not as high, but still fairly distinct, occurs at approximately 22h00. This corresponds with the re-lighting of the pre-existing evening fire that will provide heating for the rest of the night and into the early hours of the following morning.

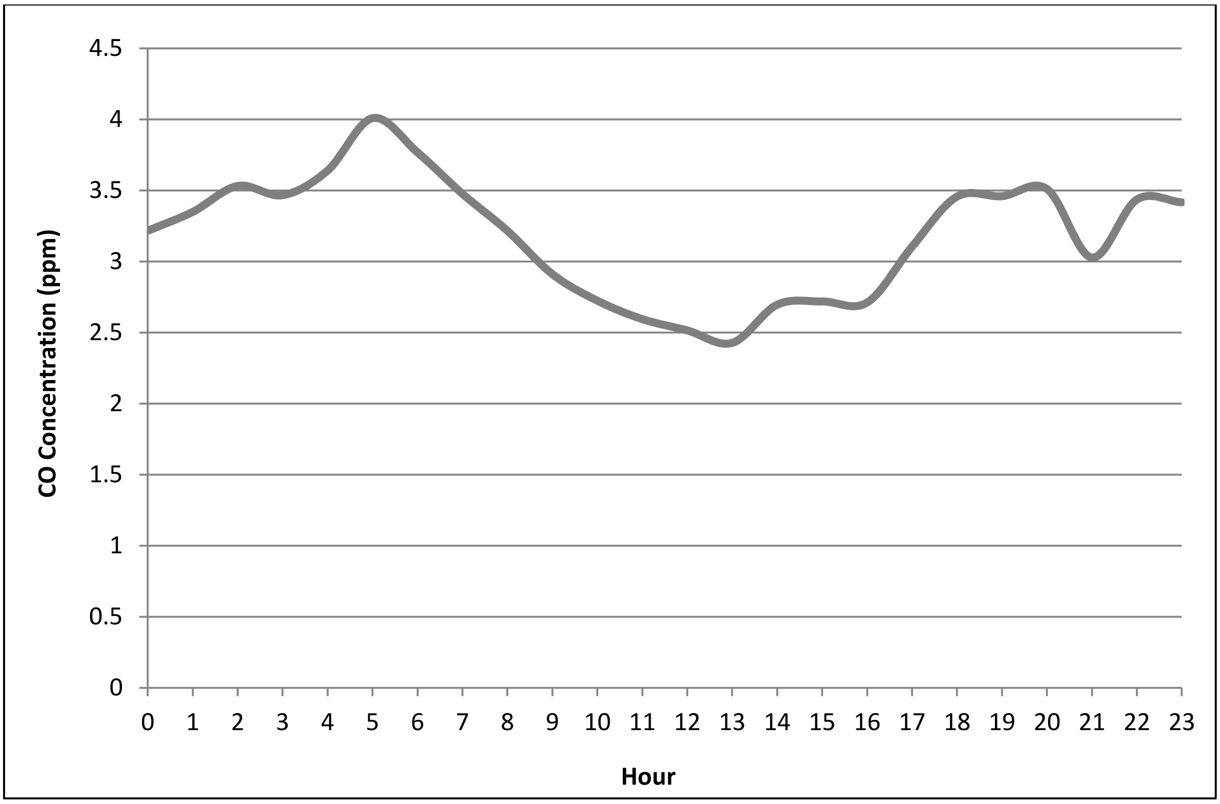

Figure 5.3. Indoor hourly average concentrations of CO from 23 August 2011 to 30 August 2011.

Similar peaks as those observed in the previous figure are also seen in figure 5.3. Like CO_2, the increases in CO also correspond to the morning and evening combustion periods. Maximum values of 4.01 ppm and 3.51 ppm have been averaged for the morning and evening periods respectively. Concentrations of CO are at their lowest close to midday, with values of around 2.43 ppm. In this figure, the highest peak is associated with the morning combustion period and a lower peak with the evening burning period. This pattern is different from that followed by the CO concentrations discussed in section 4.4.3 on emission estimates in the previous chapter, as the larger concentrations were observed in the evening burning period when the largest amounts of fuel were consumed. This difference could possibly be accounted for by a difference in the morning and evening combustion techniques, where the process of igniting the fire in the evening is altered so that the fire can be sustained for longer periods. Poorer combustion techniques could yield larger quantities of products of incomplete combustion and increased concentrations of CO. This variation could also be explained by the limited supply of air filtering into and through the house in the early hours of the morning if residents seal gaps in poorly insulated houses overnight. This is an interesting finding that requires further research.

5.2. Dispersion Modelling

There are a range of pollutants that are generated from the various processes associated with domestic combustion. Air pollution emissions generated within low-income settlements are often localised and therefore affect the air quality within the immediate area. With the numerous environmental and health concerns associated with these pollutants, it is therefore important to establish their fate.

The concentrations of pollutants, where they are transported to and where they are eventually deposited can be predicted by an air pollution dispersion model. Model predictions can be validated using observed data from air quality monitoring instruments that are stationed nearby.

5.2.1. Predictions from CALPUFF

The movement of air has a major impact on the distribution of pollutants in the atmosphere. For this reason it is important to have an understanding of the wind movements around the two modelled areas, Zenzele and Orange Farm, during May to September 2011, before examining the model outputs. The wind speed will determine how far from the polluting source the emissions will be transported as well as how this will influence the extent to which dilution occurs. Calmer winds often do not allow for sufficient mixing, thereby inhibiting the dilution of pollutants. Wind direction will determine what path the pollutants will take.

A full wind dataset for the study period was not available from the Randfontein Local Municipality and for this reason, wind data from the South African Weather Service’s Potchefstroom station were used to create a wind rose for Zenzele. The Air Quality Management Plan, compiled for the West Rand District Municipality in 2010 confirmed that the surface wind flows over much of the area that the West Rand District Municipality covers as well as the neighbouring Potchefstroom area, are influenced by the same large scale circulation. The prominence of the continental high pressure during that winter months allows for calm winds and very limited mechanical turbulence (WRDM, 2010).

There was also an incomplete wind dataset from the City of Johannesburg's air quality monitoring station in Orange Farm for this 5 month period. Data from the South African Weather Service's Vereeniging station were therefore used to create a wind rose for Orange Farm. With reference to the Vaal Triangle Airshed Priority Area Air Quality Management Plan, compiled in 2009, it has been noted that the winds at Orange Farm are usually moderate to strong and flow predominantly from a north-west to west-south westerly direction (DEAT, 2009). The medium term review of the 2009 Air Quality Management Plan for the Vaal Triangle Airshed Priority Area (VTAPA) identifies the presence of the anti-cyclonic circulation over this priority area. Orange Farm and Vereeniging both exist within the central parts of the area delineated as the VTAPA, where the regional topography of this area can be described as fairly flat (DEA, 2013).

The wind roses for Potchefstroom and Vereeniging are presented in figures 5.4 (a) and (b) respectively.

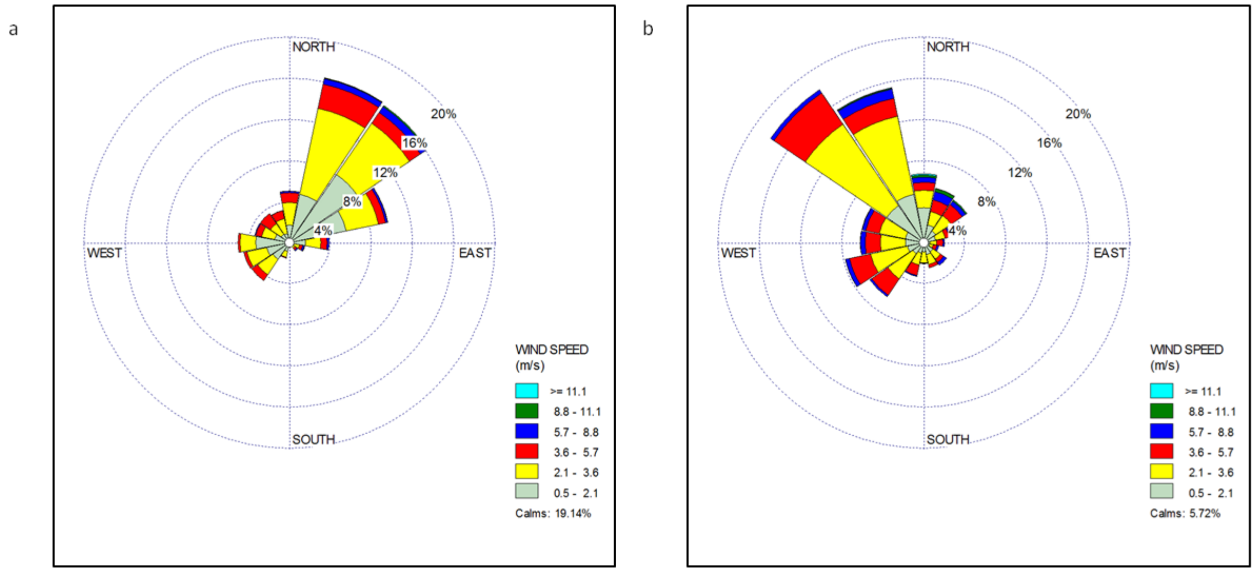

Figure 5.4. Wind roses for (a) Potchefstroom and (b) Vereeniging from May 2011 to September 2011 (SAWS, 2011).

In the Potchefstroom area, it is evident that the dominant winds as well as the strongest winds were blowing from a north to north-easterly direction over this study period (figure 5.4a). In Vereeniging, the dominant wind direction from May to September 2011 was north to north-westerly, with the strongest winds originating in a north to north-east (figure 5.4 b).

The time-averaged concentrations of SO_2, PM_{10}, CO_2 and CO as predicted by CALPUFF are presented in figure 5.5 to 5.18. The predicted maximum average hourly and daily concentrations of SO_2, maximum average daily concentrations of PM_{10}, the maximum average hourly and daily concentrations of CO_2 and the maximum average hourly and 8 hourly concentrations of CO for Zenzele and Orange Farm will be examined in this section.

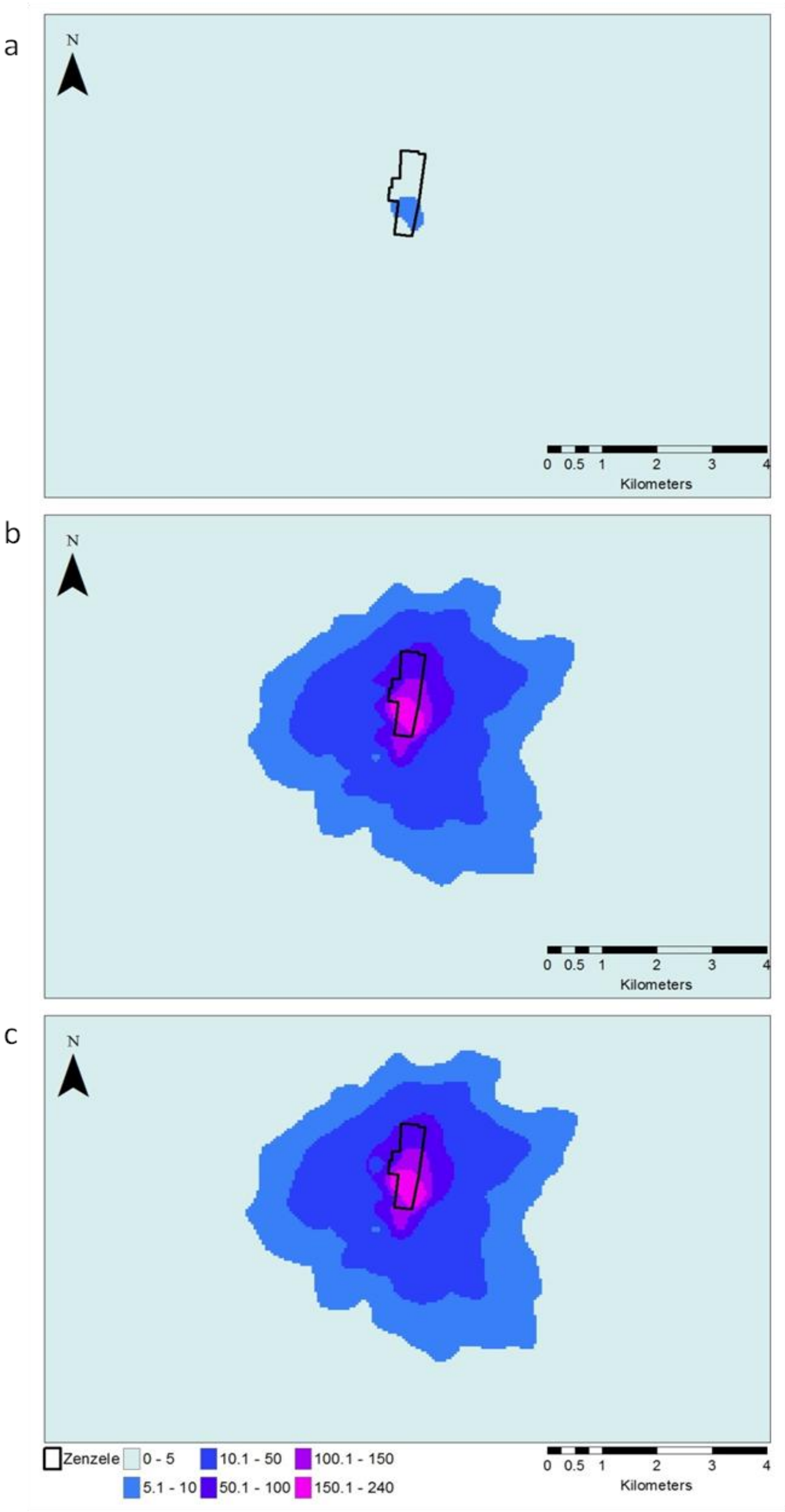

Figure 5.5. Maximum average hourly SO_2 concentrations in µg/m³ from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

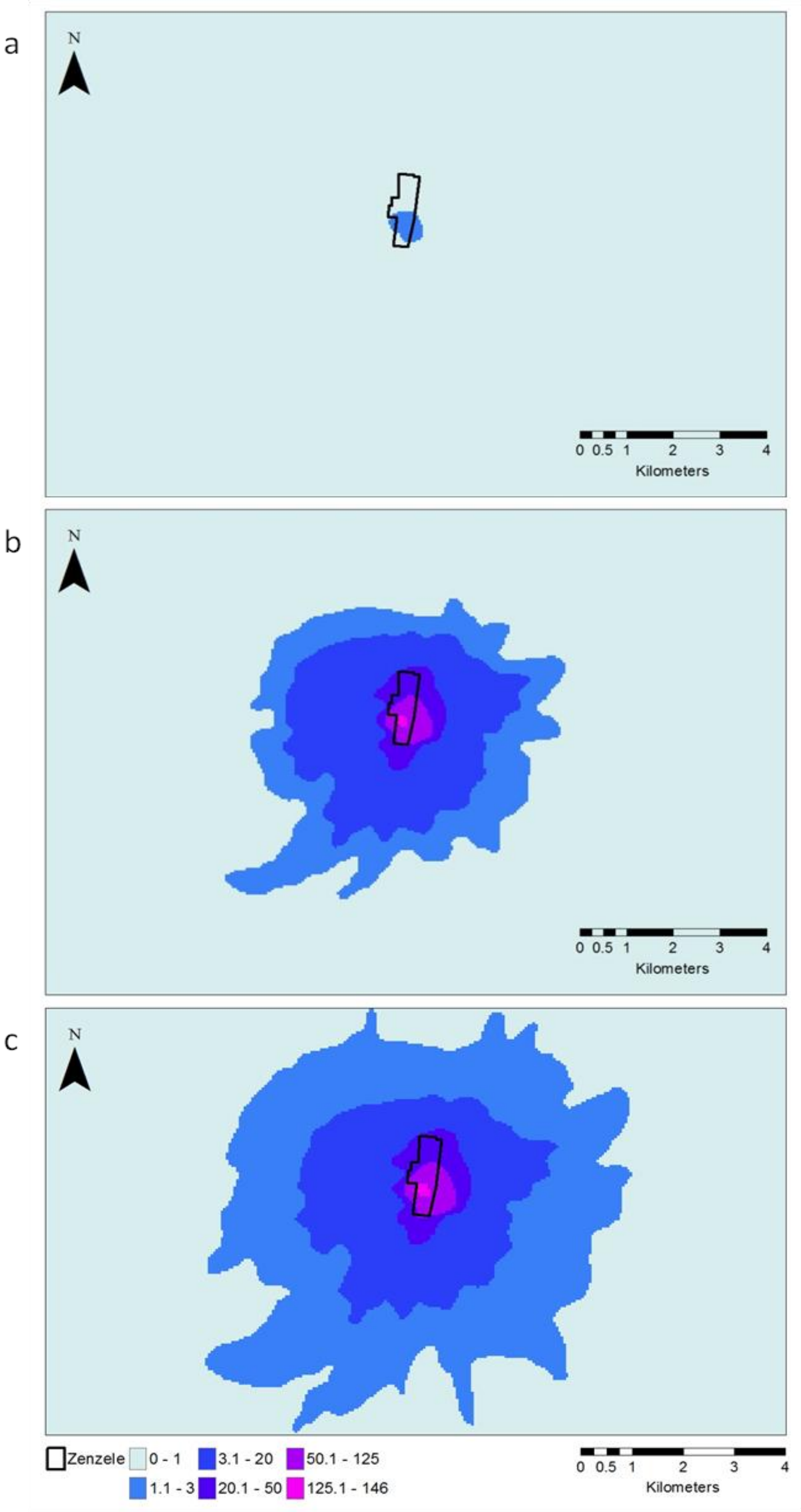

Figure 5.6. Maximum average daily SO_2 concentrations in µg/m³ from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

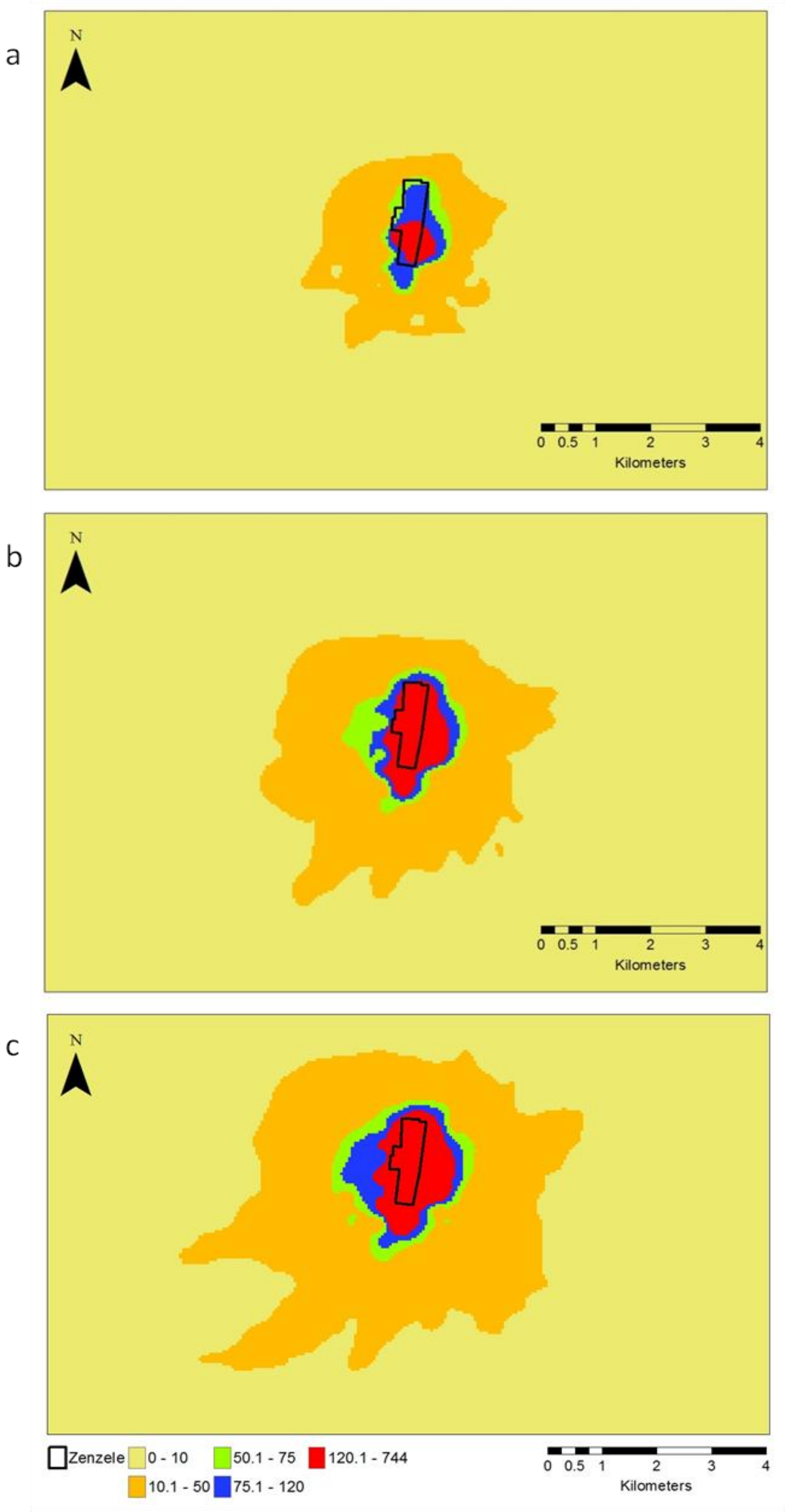

Figure 5.7. Maximum average daily PM_{10} concentrations in µg/m^3 from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

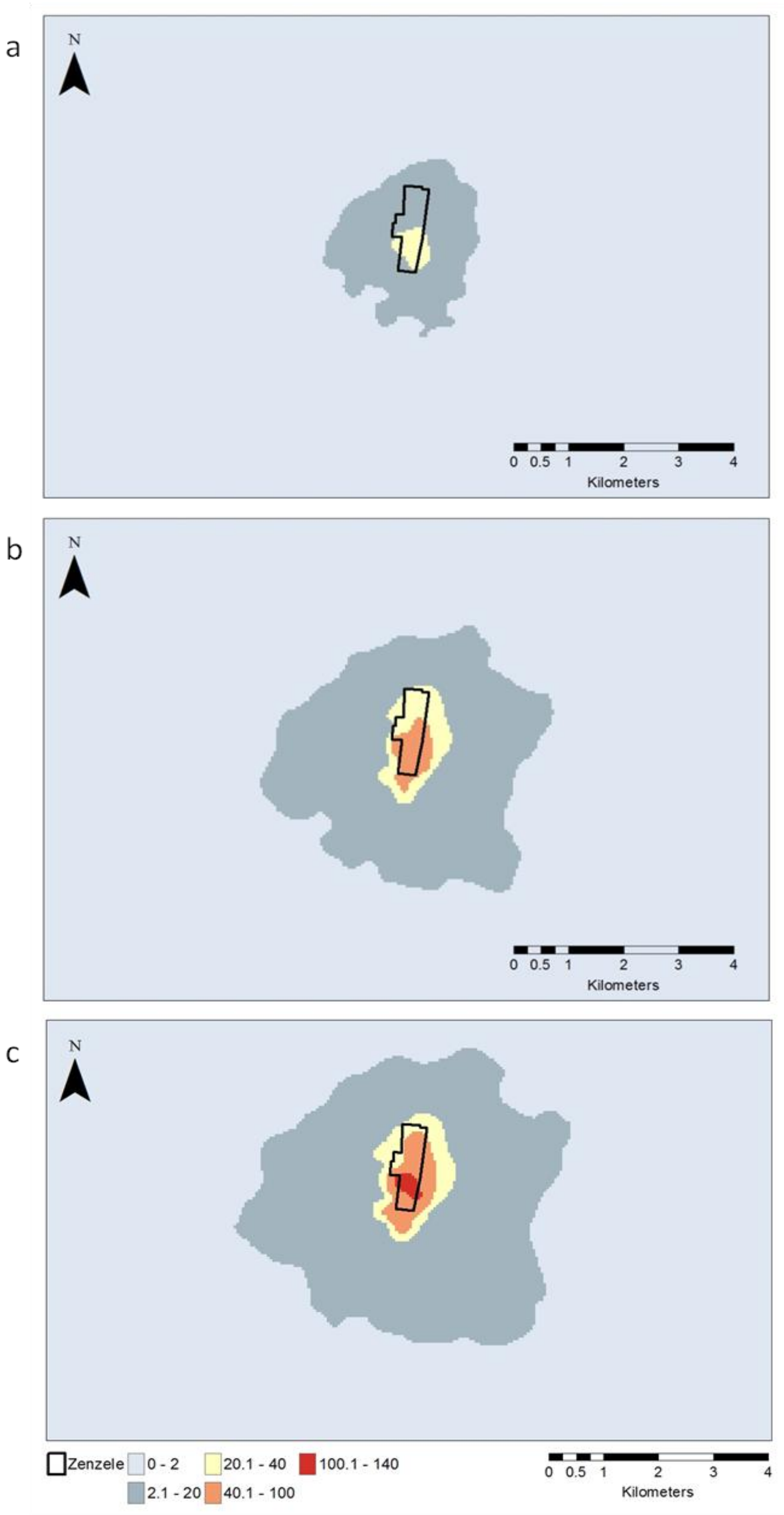

Figure 5.8. Maximum average hourly CO_2 concentrations in ppm from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

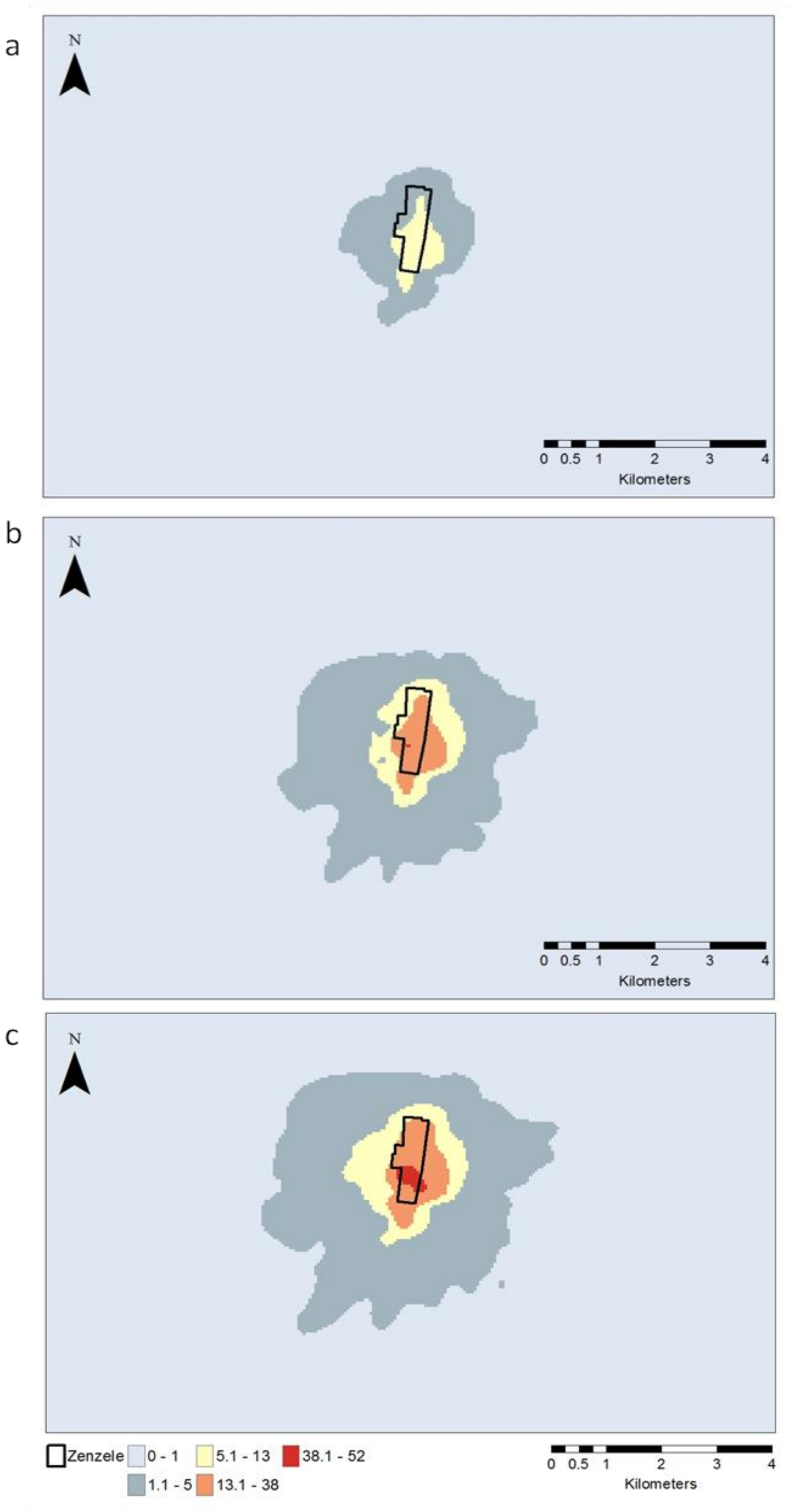

Figure 5.9. Maximum average daily CO_2 concentrations in ppm from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

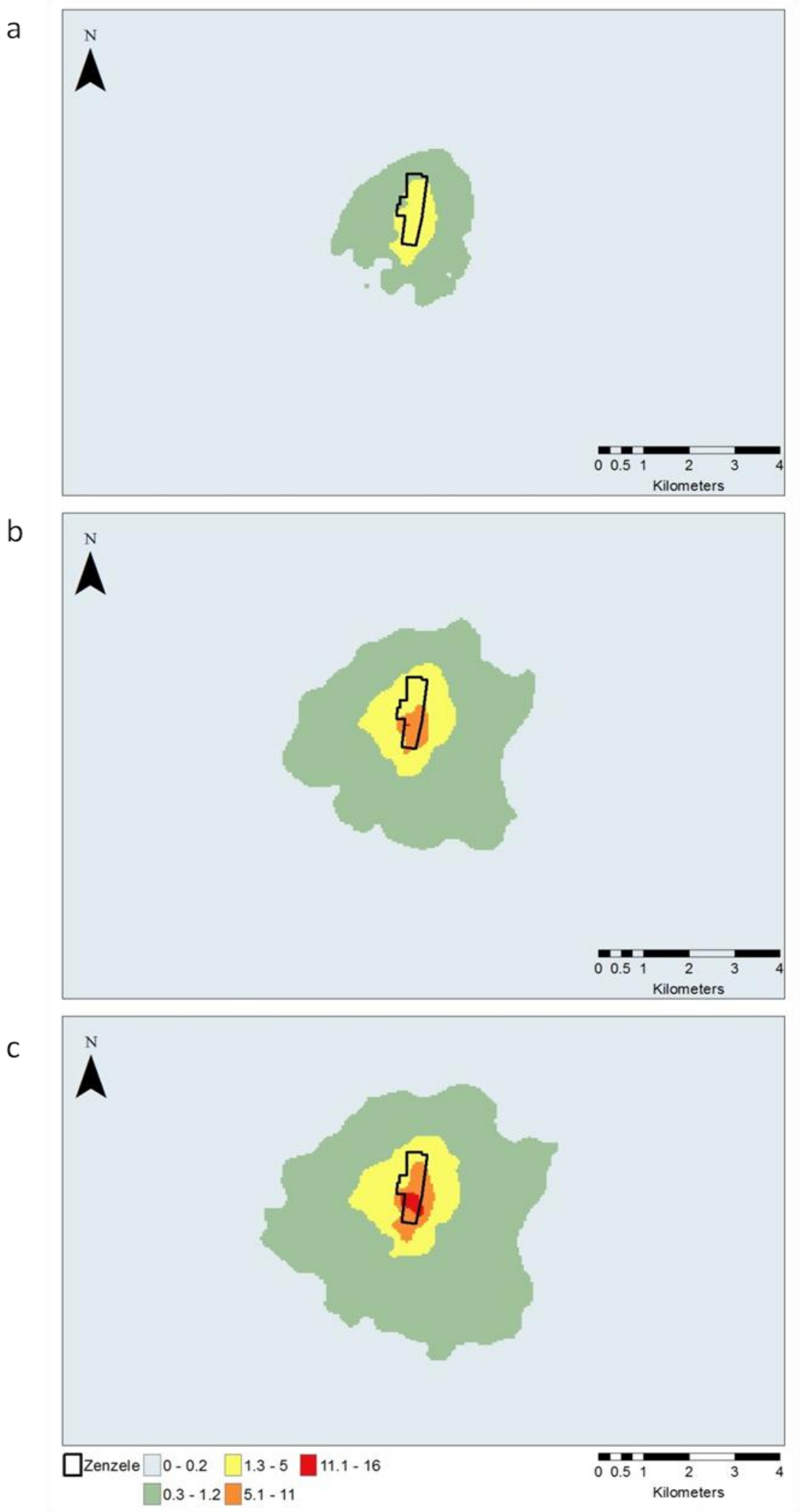

Figure 5.10. Maximum average hourly CO concentrations in ppm from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

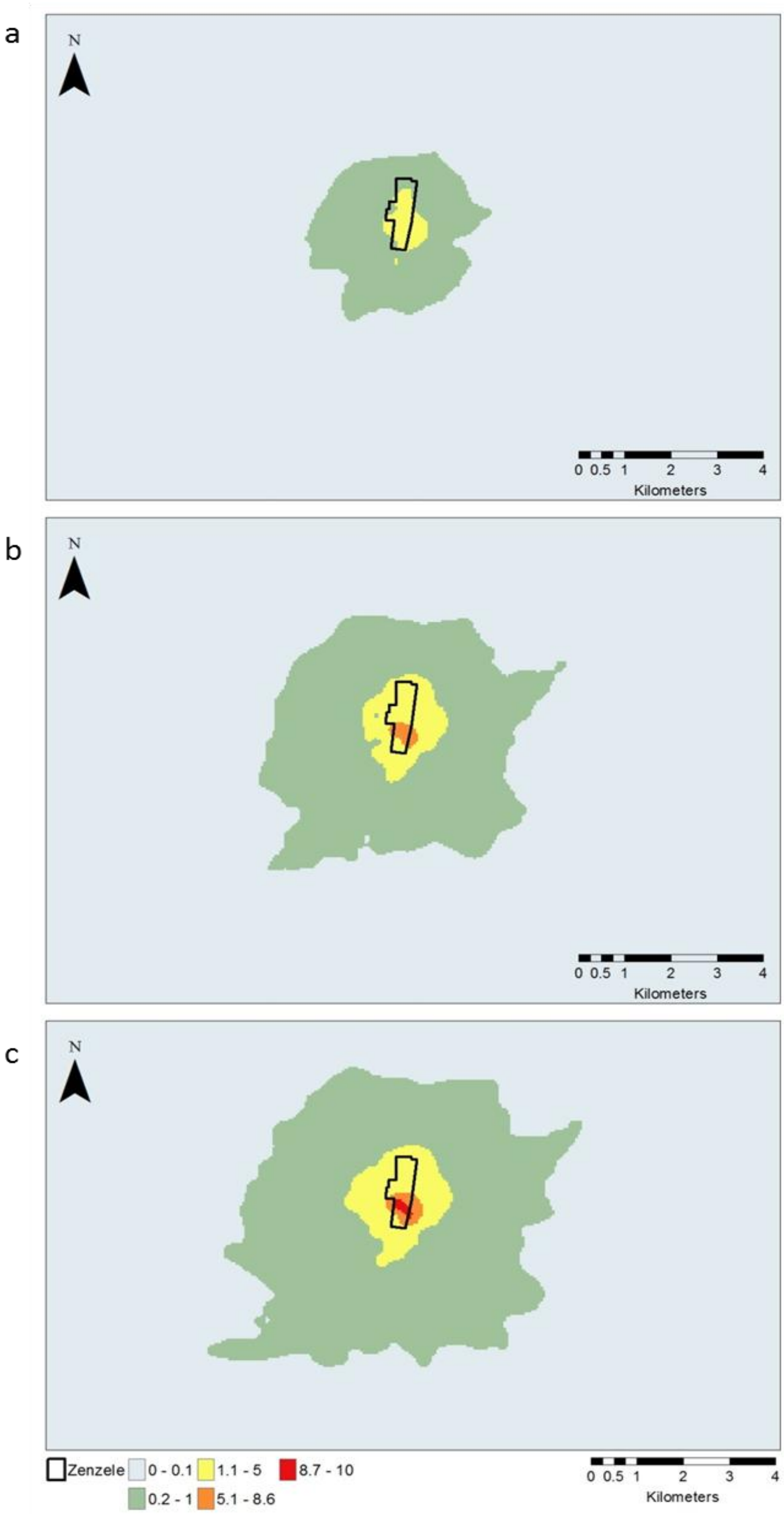

Figure 5.11. Maximum average 8 hour CO concentrations in ppm from May 2011 to September 2011 for (a) the households in Zenzele that burn wood only, (b) the households in Zenzele that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Zenzele.

Figures 5.5 to 5.11 illustrate the extent to which the emissions associated with the domestic combustion of wood and coal in Zenzele are dispersed. Figures 5.5 and 5.6 explore the concentrations associated with emission of SO_2, where the modelled maximum average hourly and maximum average daily concentrations are examined respectively. Figure 5.7 examines the modelled maximum daily concentrations of PM_{10}. Figures 5.8 and 5.9 deal with the concentrations associated with the emission of CO_2, where the modelled maximum average hourly and maximum average daily concentrations are examined respectively. Figures 5.10 and 5.11 explore the concentrations associated with the emission of CO, where the modelled maximum average hourly and maximum average 8 hourly concentrations are examined respectively. With respect to all the figures mentioned above, panel (a) illustrates the concentrations associated with the households in Zenzele that burn wood only, panel (b) illustrates the concentrations associated with the households in Zenzele that burn wood and coal simultaneously and panel (c) is a combination of these two modelled sources, representing all the households in Zenzele.

With reference to the maximum average hourly and maximum average daily concentrations of SO_2, figures 5.5 and 5.6 confirm that a significant portion of these SO_2 emissions are associated with the combustion of coal. This is in line with the calculated average emission rates for SO_2, discussed in section 4.2.3 of the previous chapter. The average SO_2 emission rates associated with coal were the most prominent because of the high emission factors, even though larger quantities of wood were consumed over the study period.

The current South African national ambient air quality standard (NAAQS) for the hourly and daily concentrations of SO_2 specifies limit values of 350µg/m³ and 125µg/m³ respectively. Maximum average hourly concentrations do not exceed this limit value but areas that are situated within the outline of the settlement and highlighted in bright pink (figure 5.6) are in exceedence of the daily limit value and have the potential to be in non-compliance with the South African NAAQS if this limit is exceeded more than the allowable frequency of exceedence. The predicted maximum average hourly and the maximum average daily concentrations of SO_2 do not account for background concentrations of SO_2.

The World Health Organisation stipulates a value of 20µg/m³ as the air quality guideline for daily concentrations of SO_2. The maximum average daily SO_2 concentrations that fall within the three highest classes, indicated by the purple, magenta and bright pink, all exceed this air quality guideline.

The current and future South African national ambient air quality standards (NAAQS) associated with the daily concentrations of PM_{10} specifies limit values of 120µg/m³ and 75µg/m³ respectively. It is evident in panels (a), (b) and (c) of figure 5.7 that these limit values are being exceeded. In fact, in panels (b) and (c), the impact of the maximum average daily PM_{10} concentrations is noticeable over the entire outline of the settlement, where this whole area exceeds the current NAAQ limit value. Once again, the potential for exceedence of both the current and future NAAQS is high.

The air quality guideline specified by the World Health Organisation (WHO) for daily concentrations of PM_{10} is 50µg/m³. Once again, this air quality guideline is exceeded in all three panels of figure 5.7. Although this guideline is lower than both of South Africa's national standards, it is of great importance as it specifies the limit at which daily concentrations of PM_{10} become harmful to human health. With concentrations in all three panels of figure 5.7 significantly exceeding the WHO standard, the health impact on residents' of Zenzele is of great concern.

Although there are no national ambient air quality standards or WHO air quality guidelines associated with CO_2 concentrations there are suggested thresholds to limit its emission and for this reason, it is still important to examine these concentrations. The current South African national ambient air quality standard (NAAQS) for the hourly and 8 hourly concentrations of CO specifies limit values of 26 ppm and 8.7 ppm respectively. The indoor concentrations of CO_2 and CO (figure 5.1) associated with one of the study households in Zenzele are higher than the ambient concentrations of CO_2 and CO predicted by CALPUFF. This is to be expected as concentrations of pollutants are higher closer to the fire, where the inlet for the monitoring instruments was placed. An additional variation in CO_2 and CO concentrations can further be explained by the fact that the model does not account for background concentrations of these substances. The Intergovernmental Panel on Climate Change Fifth Assessment Report cited a value of 390.5 ppm for the global concentrations of CO_2 in 2011 (IPCC, 2013). Background levels of CO exist at approximately 0.2 ppm to 0.25 ppm (DEAT, 2009).

It is evident in figures 5.5 to 5.11 that there are hotspots, showing increased concentrations of all the pollutants, situated over the same part of this settlement. There is a larger volume of households situated in the south end of Zenzele and for this reason; increased concentrations of pollutants can be observed in this location.

It is apparent in figures 5.5 to 5.11 that the winds do play a key role in the dispersion field patterns seen over Zenzele. In almost all of the mapped model outputs, there are clear extensions in the dispersion fields that occur in a south-westerly direction. This corresponds with the dominant winds around Zenzele over this period that was blowing from a north-easterly direction.

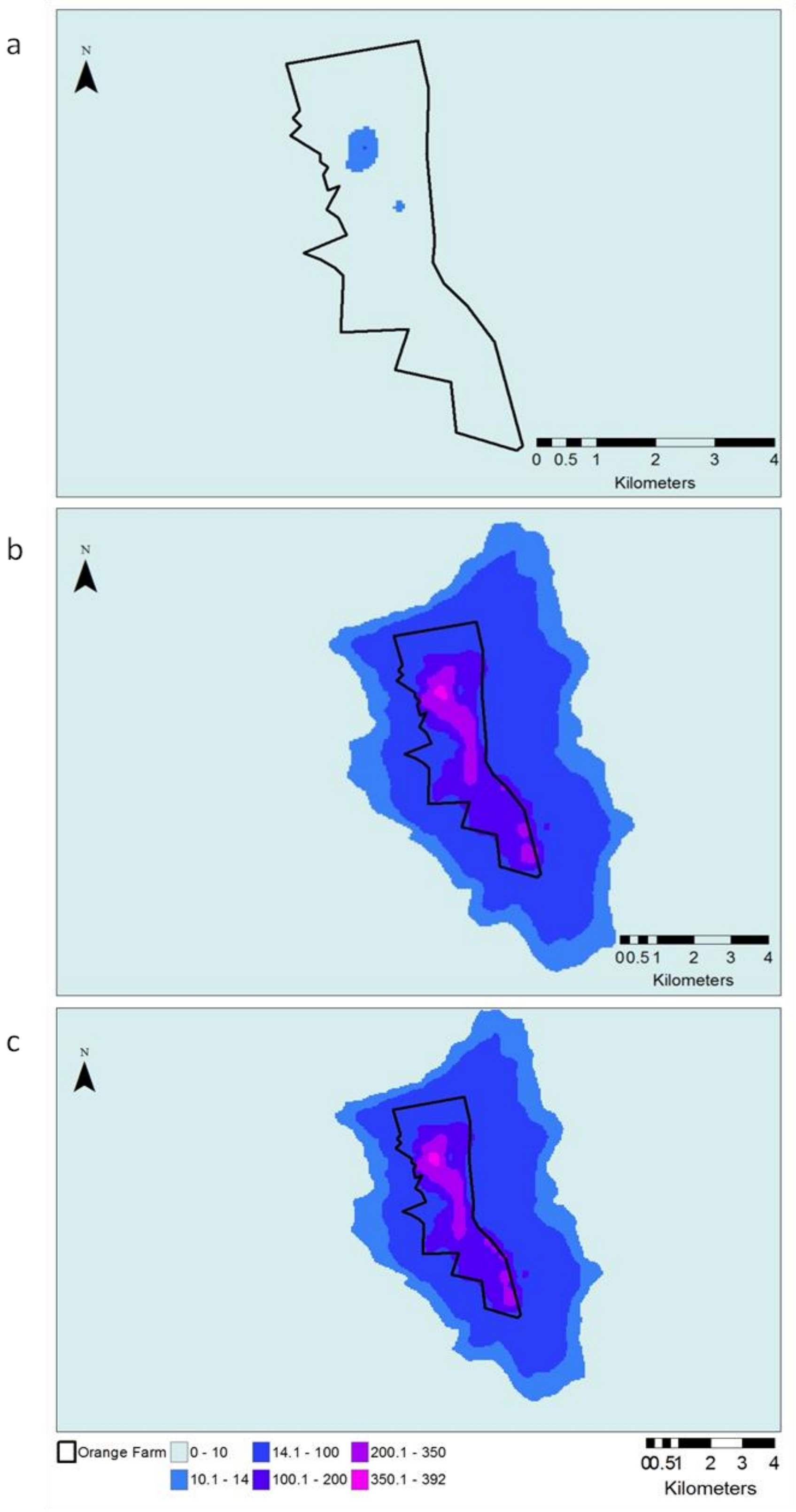

Figure 5.12. Maximum average hourly SO_2 concentrations in µg/m³ from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

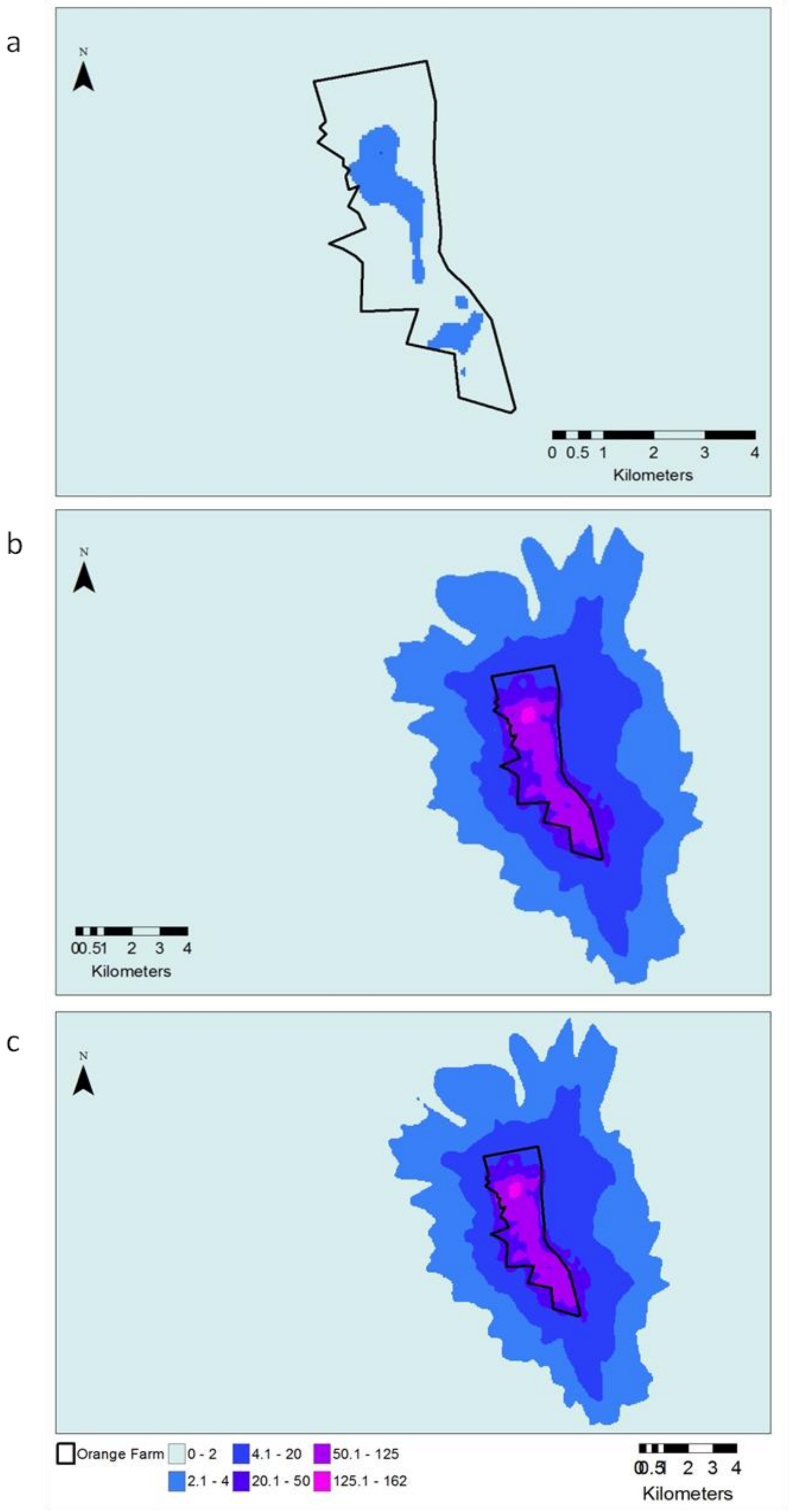

Figure 5.13. Maximum average daily SO_2 concentrations in $\mu g/m^3$ from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

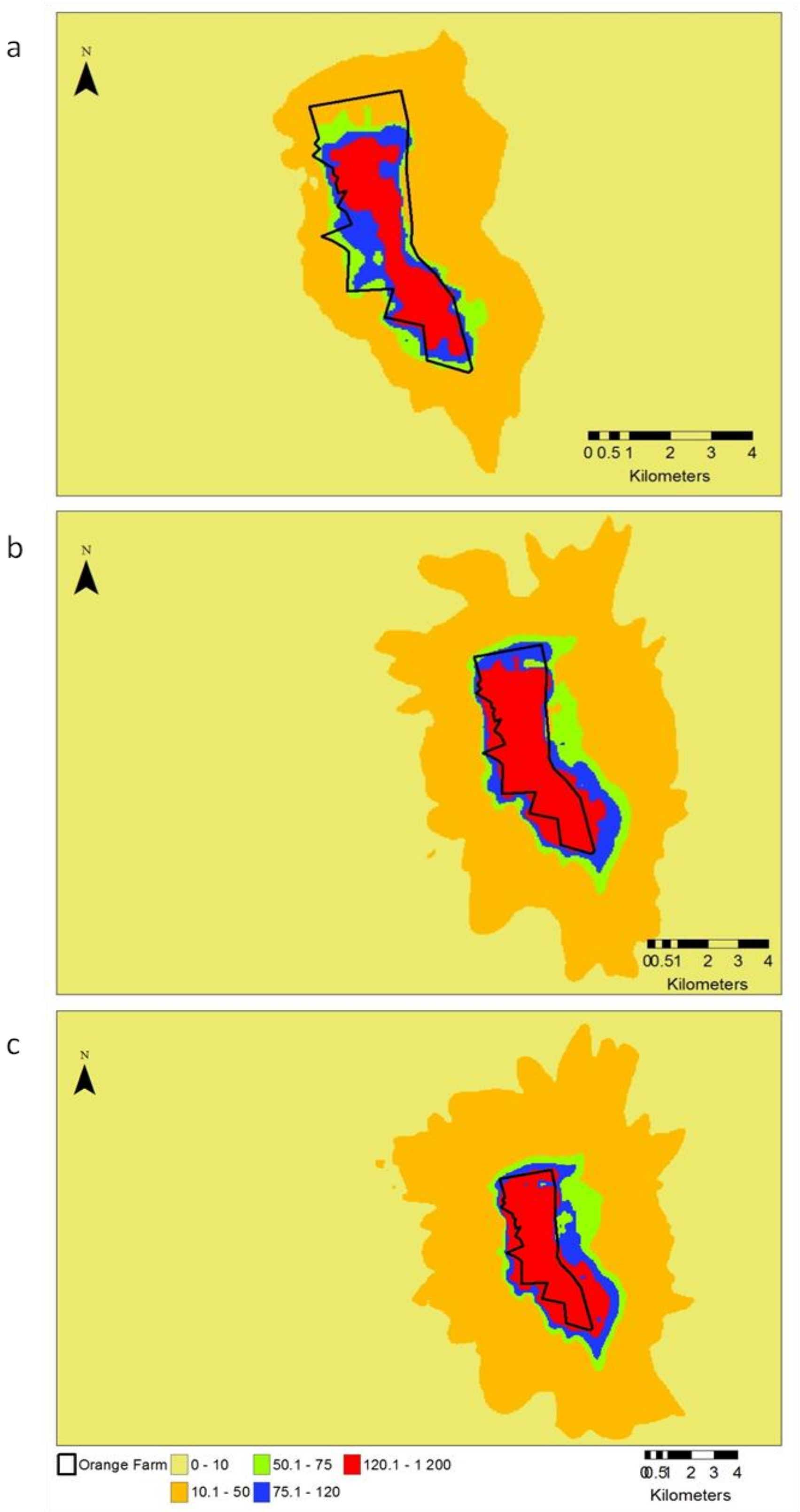

Figure 5.14. Maximum average daily PM_{10} concentrations in µg/m^3 from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

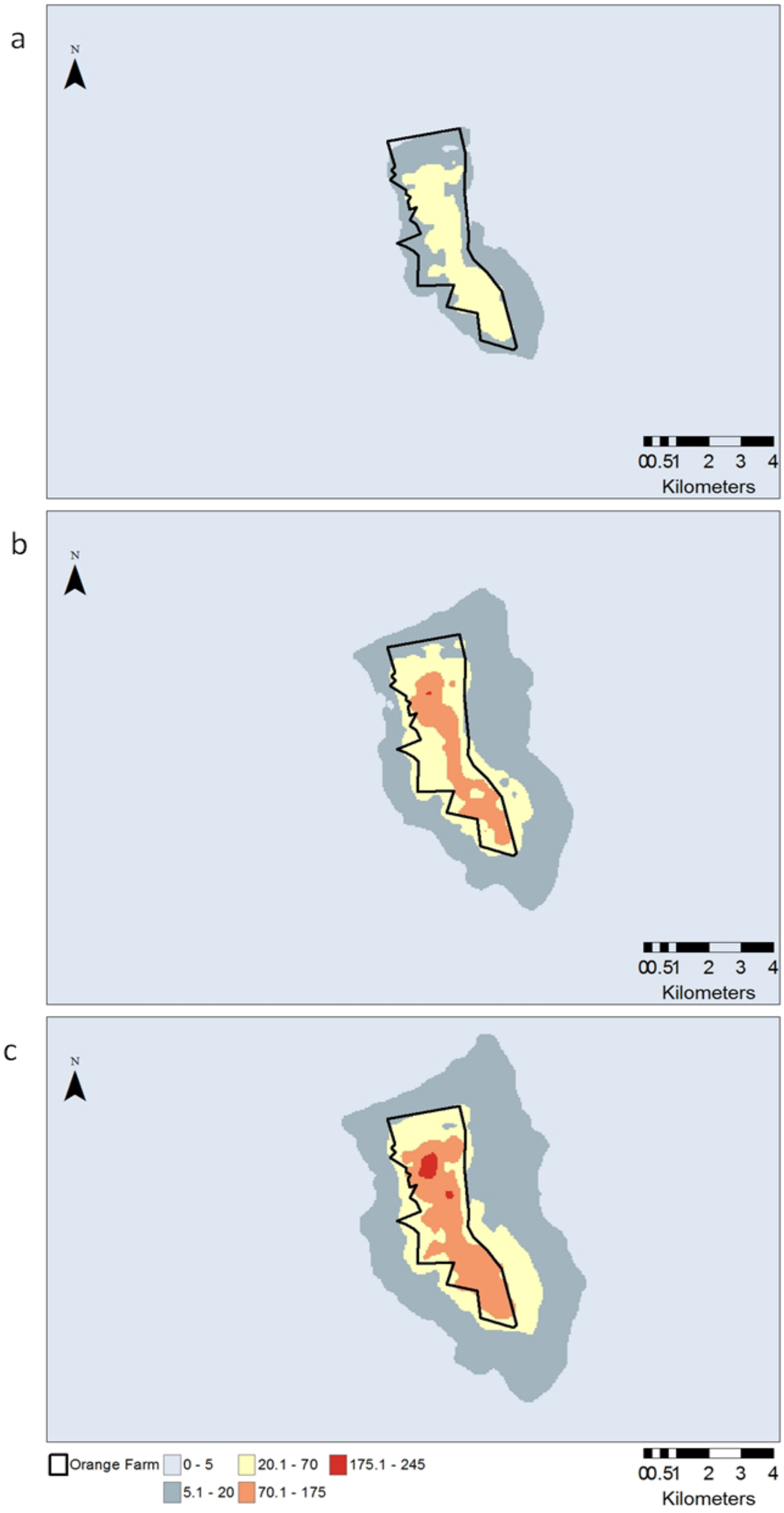

Figure 5.15. Maximum average hourly CO_2 concentrations in ppm from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

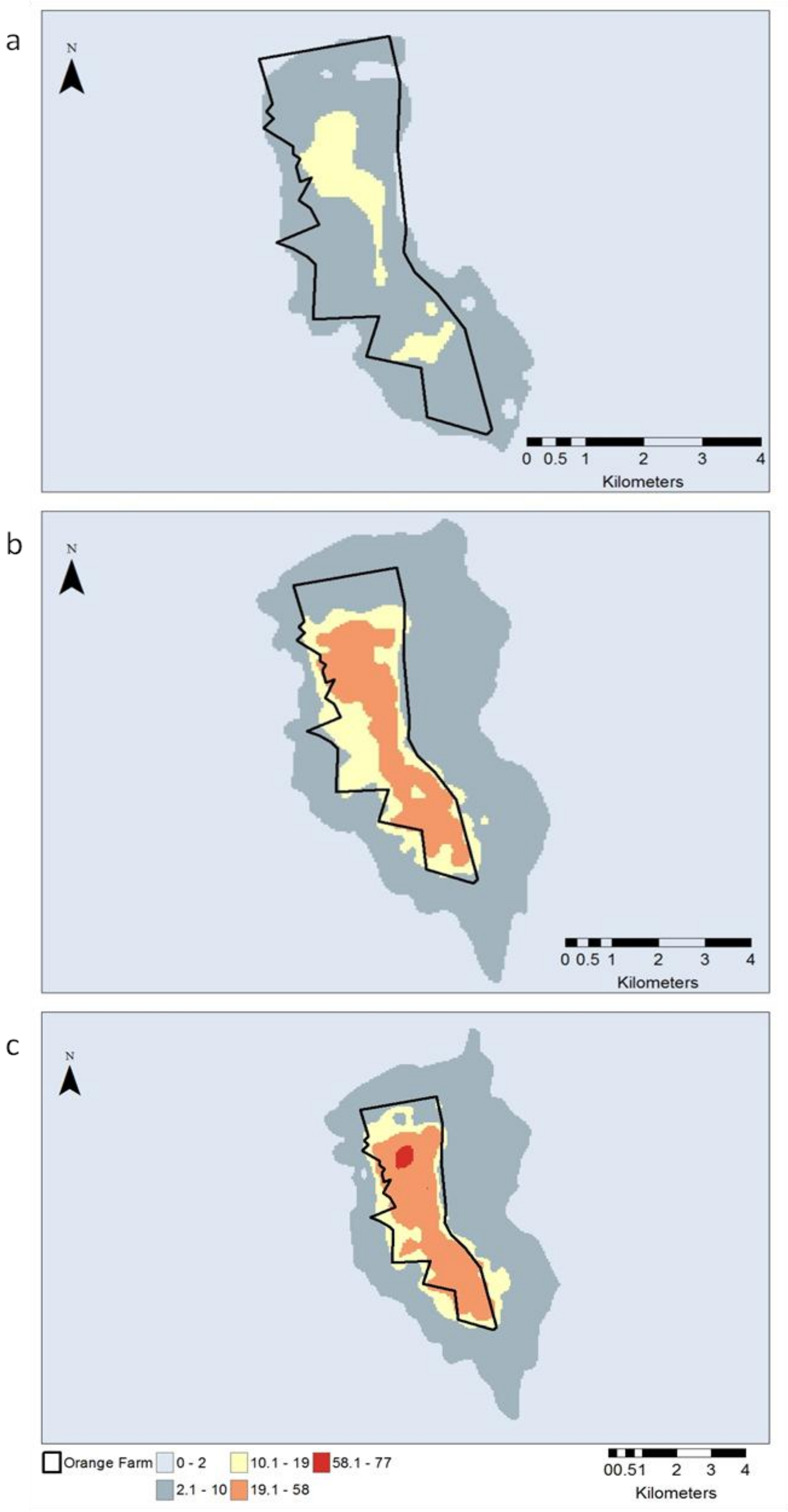

Figure 5.16. Maximum average daily CO_2 concentrations in ppm from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

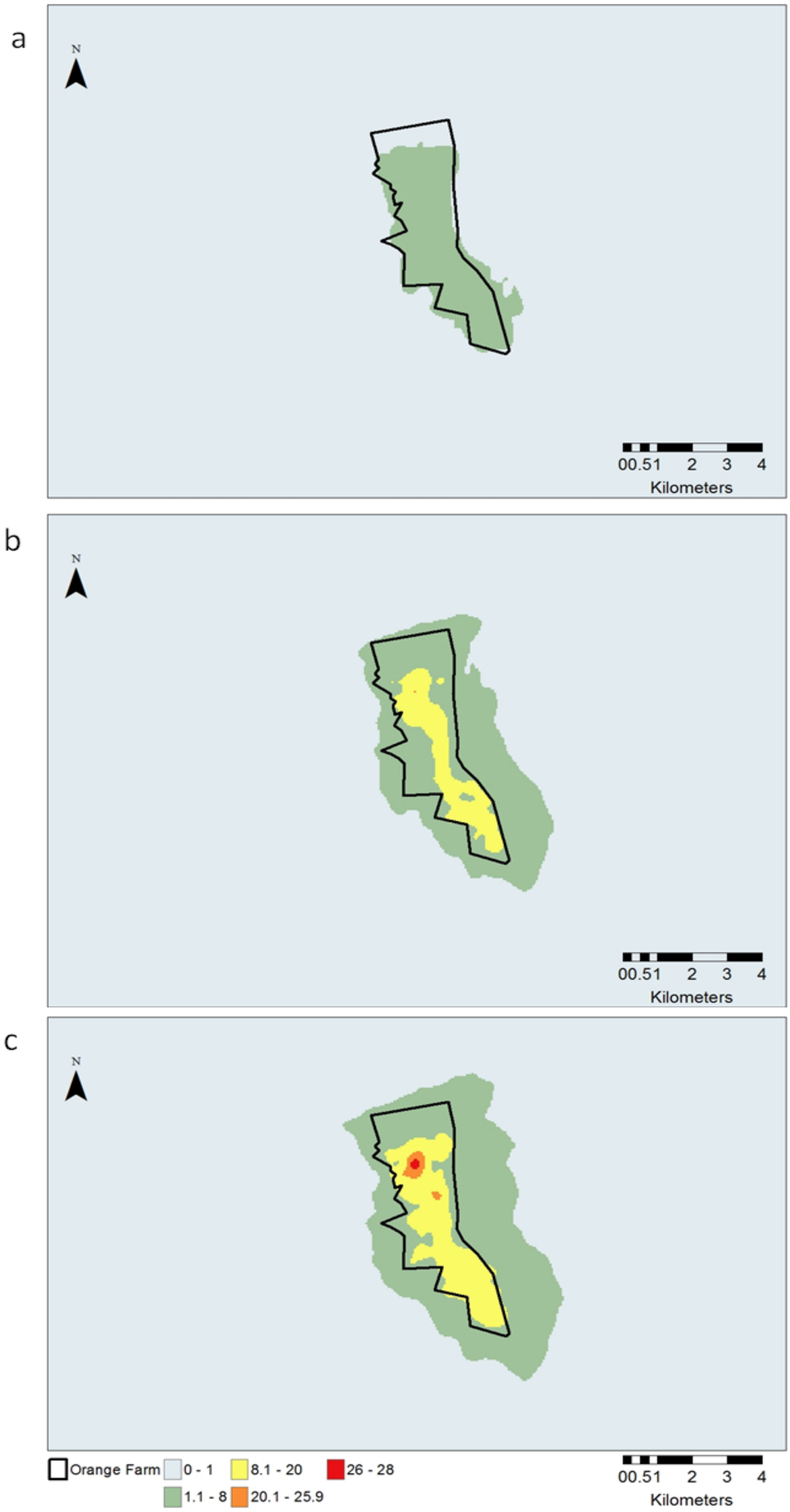

Figure 5.17. Maximum average hourly CO concentrations in ppm from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

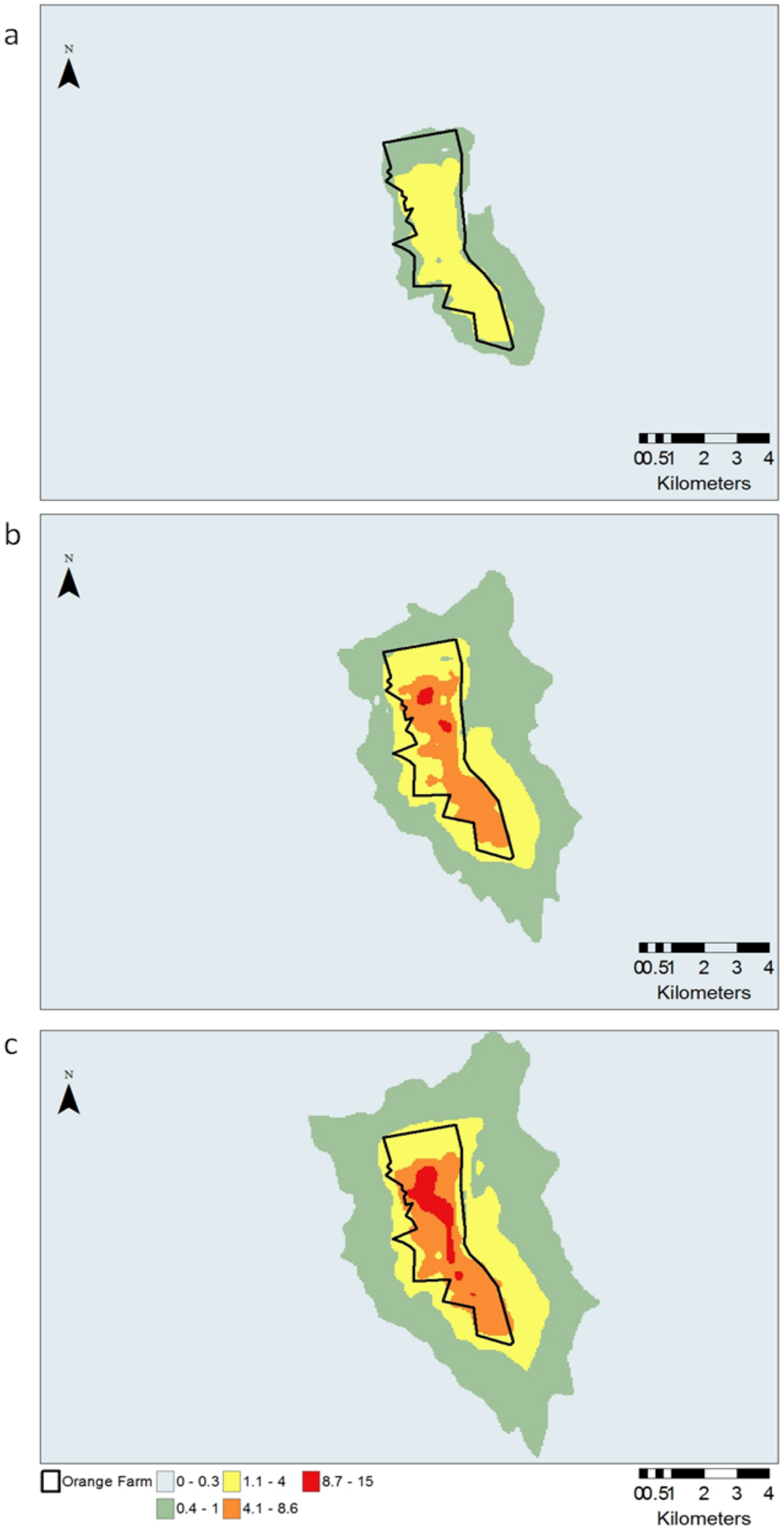

Figure 5.18. Maximum average 8 hour CO concentrations in ppm from May 2011 to September 2011 for (a) the households in Orange Farm that burn wood only, (b) the households in Orange Farm that burn wood and coal simultaneously and (c) a combination of these two sources, representing all the households in Orange Farm.

Figures 5.12 to 5.18 illustrate the extent to which the emissions associated with the domestic combustion of wood and coal in Orange Farm are dispersed. Figures 5.12 and 5.13 explore the concentrations associated with the emission of SO_2, where the modelled maximum average hourly and maximum average daily concentrations are examined respectively. Figure 5.14 examines the modelled maximum daily concentrations of PM_{10}. Figures 5.15 and 5.16 deal with the concentrations associated with the emission of CO_2, where the modelled maximum average hourly and maximum average daily concentrations are examined respectively. Figures 5.17 and 5.18 explore the concentrations associated with the emission of CO, where the modelled maximum average hourly and maximum average 8 hourly concentrations are examined respectively. With respect to all the figures mentioned above, panel (a) illustrates the concentrations associated with the households in Orange Farm that burn wood only, panel (b) illustrates the concentrations associated with the households in Orange Farm that burn wood and coal simultaneously and panel (c) is a combination of these two modelled sources, representing all the households in Orange Farm.

In almost all of these figures, panels (b) and (c) have been presented on a smaller scale to that of panel (a) in order to include as much of the modelled data associated with all the households in Orange Farm as possible. The extent of the dispersion fields associated with the maximum average concentrations that fall within the second classes of panels (b) and (c) are larger than that in panel (a), and for this reason, the outline of the settlement appears smaller. Larger concentrations of pollutants are dispersed and transported further, increasing the range of the dispersion field.

The current South African national ambient air quality standards (NAAQS) for the hourly and daily concentrations of SO_2 specify limit values of 350µg/m^3 and 125µg/m^3 respectively. Maximum average hourly and maximum average daily concentrations exceed this limit value, and are represented by the areas shading in bright pink in figures 5.12 and 5.13. Once again, these concentrations only exceed the NAAQ limit value but have the potential to be in non-compliance with the South African NAAQS if this limit is exceeded more than the allowable frequency of exceedence. The predicted maximum average hourly and the maximum average daily concentrations of SO_2 do not account for background concentrations of SO_2.

The maximum average hourly and maximum average daily concentrations of SO_2 highlighted in figures 5.12 and 5.13 indicate that a large portion of the SO_2 emissions are associated with the combustion of coal. The average SO_2 emission rates associated with coal were the most prominent because of the high emission factors, even though larger quantities of wood were consumed over the study period.

The World Health Organisation stipulates a value of 20µg/m³ as the air quality guideline for daily concentrations of SO_2. The maximum average daily SO_2 concentrations that fall within the three highest classes, indicated by the purple, magenta and bright pink, all exceed this air quality guideline.

The current and future South African national ambient air quality standards (NAAQS) associated with the daily concentrations of PM_{10} specifies limit values of 120µg/m³ and 75µg/m³ respectively. It is evident in panels (a), (b) and (c) of figure 5.14 that these limit values are being exceeded. In fact, in panels (b) and (c), the impact of the maximum average daily PM_{10} concentrations is noticeable over the entire outline of the settlement, where this whole area exceeds the current NAAQ limit value. Once again, the potential for exceedence of both the current and future NAAQS is high.

The air quality guideline specified by the World Health Organisation (WHO) for daily concentrations of PM_{10} is 50µg/m³. Once again, this air quality guideline is exceeded in panels (a), (b) and (c) of figure 5.14. Although this guideline is lower than both of South Africa's national standards, it is of great importance as it specifies the limit at which daily concentrations of PM_{10} become harmful to human health. With concentrations in all three panels of figure 5.14 well in exceedence of the WHO guideline, the impact on residents' of Orange Farm health is of great concern.

Although there are no national ambient air quality standards or WHO air quality guidelines associated with CO_2 concentrations there are suggested thresholds to limit its emission and for this reason, it is still important to examine these concentrations. The predicted maximum average hourly and daily concentrations of CO_2 from CALPUFF do not account for background global concentrations of CO_2 that existed in the atmosphere at concentrations of 390.5 ppm in 2011 (IPCC, 2013).

The current South African national ambient air quality standards (NAAQS) for the hourly and 8 hourly concentrations of CO specifies limit values of 26 ppm and 8.7 ppm respectively. Maximum average hourly concentrations of CO that fall within the highest class of figure 5.17 present values that just exceed the NAAQ limit value. There are however, many more exceedences of the NAAQ limit value for 8 hourly concentrations of CO and for this reason there is greater chance for the exceedence of the NAAQS. The predicted maximum average hourly and daily concentrations of CO from CALPUFF do not account for background concentrations of CO, which occur in a range of 0.2 ppm to 0.25 ppm (DEAT, 2009).

There is a larger volume of households situated in the north end of Orange Farm. It is also clear in figures 5.12 to 5.18 that there are hotspots of increased concentrations of pollutants situated over the same part of Orange Farm. Once again, larger concentrations of pollutants are often concentrated over areas where there is a substantial volume of households and these zones are usually indicative of pollutant hotspots.

The wind movement around Orange Farm, as discussed at the beginning of this section, is consistent with what is occurring in figures 5.12 to 5.18. An extension in the dispersion fields towards the south end of Orange Farm in a south easterly direction corresponds with a north-westerly dominant wind over this area from May to September 2011.

5.2.2. Time-series Comparison

Elbir (2003) suggests that the performance of the model can be evaluated by comparing the simulation predicted by the model with measured time-series data for a specific pollutant. The 24-hour average concentrations of SO_2 and PM_{10} that were predicted by CALPUFF for Orange Farm were compared with the average daily concentrations for the same two pollutants from data obtained from the City of Johannesburg's air quality monitoring station in Orange Farm. Figures 5.19 and 5.20 illustrate the observed and predicted 24-hour average concentrations of SO_2 and PM_{10} respectively.

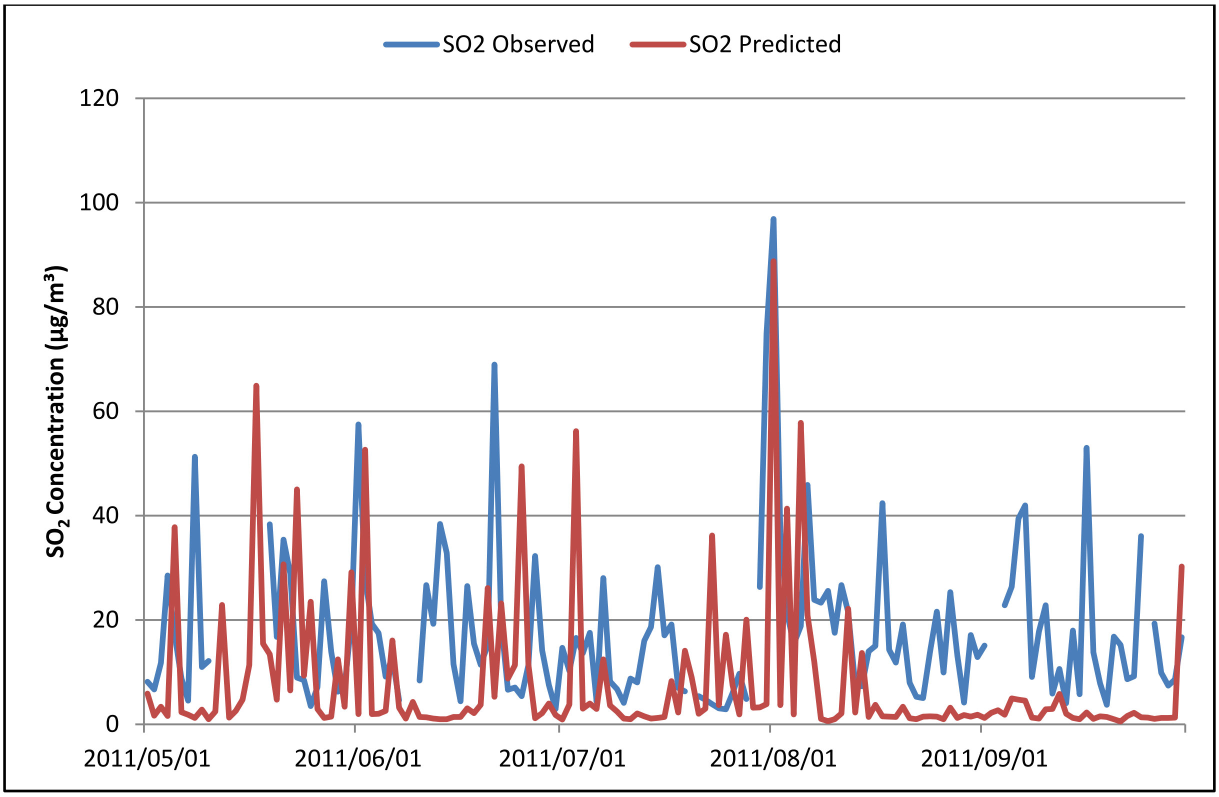

Figure 5.19. Observed and predicted 24-hour average concentrations of SO_2 in Orange Farm from May 2011 to September 2011.

In general, the model results for SO_2 compare well in magnitude with the measured data from the air quality monitoring station in Orange Farm (figure 5.19), indicating that the model setup was reasonable. Similar peaks are observed between the two datasets, the most striking of which, is the highest peak for the study period, occurring at the beginning of August 2011. Generally the base of the observed data tends to be a bit more elevated than that of the predicted data. This is to be expected as the time-series files created by CALPUFF for Orange Farm do not account for background concentrations of SO_2 that are captured at air quality monitoring stations, thereby under predicting the concentrations of SO_2. There are a number of other contributing sources of long-term ground level concentrations of SO_2 prevalent in the Vaal Priority Area that have an influence on the ambient concentrations of SO_2, including those measured at the City of Johannesburg's air quality monitoring station at Orange Farm. These sources include power generation, iron and steel processes as well as petrochemical processes (DEAT, 2009).

CALPUFF also used a daily 7 hour burning period, where positive values were used to represent only the 7 hours of burning in a day and zero values were used to represent the nonburning hours. Ambient concentrations, however, that are measured at the monitoring station are done so throughout the day. These factors provide explanations for the discrepancies between the observed and predicted datasets such as the elevated base of the observed data.

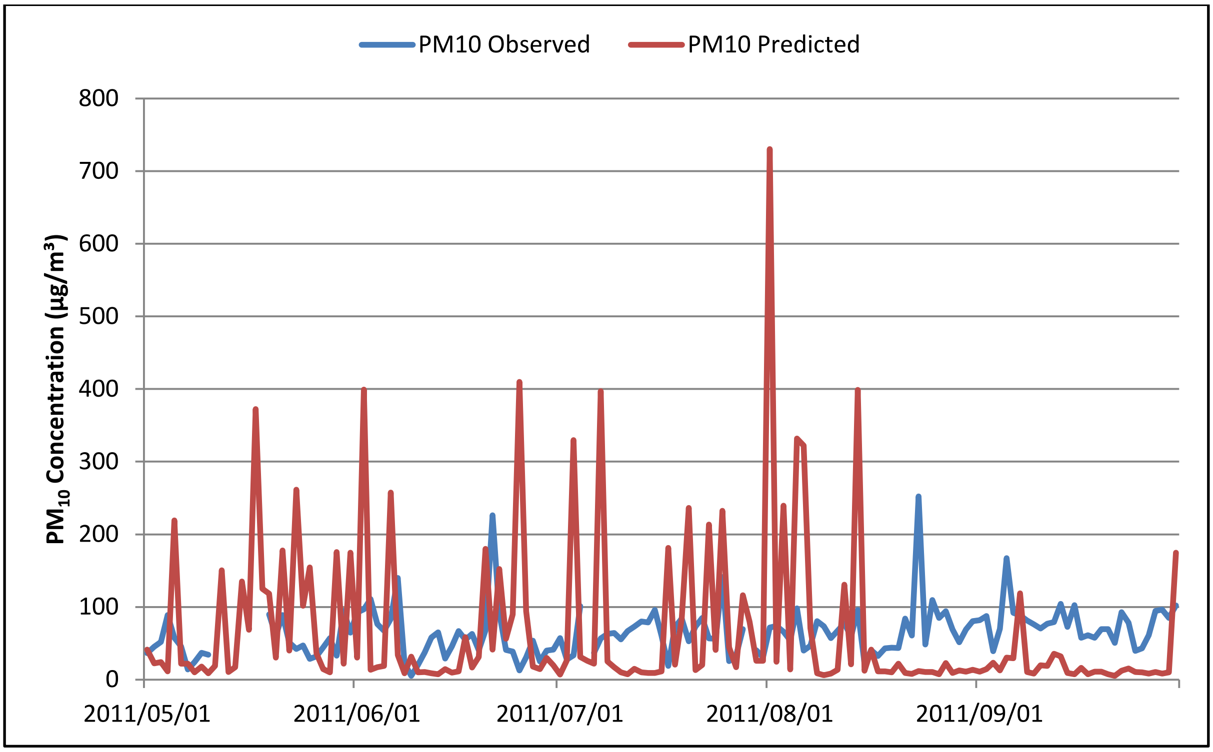

Figure 5.20. Observed and predicted 24-hour average concentrations of PM$_{10}$ in Orange Farm from May 2011 to September 2011.

Once again, in figure 5.20 the base of the observed data is elevated, highlighting the difference in the measurement periods and the presence of background concentrations of PM$_{10}$ between CALPUFF and the Orange Farm air quality monitoring station. Common sources of long-term ground level concentrations of PM$_{10}$ dominant in the Vaal Triangle Priority Area and specifically surrounding Orange Farm include smaller industries, iron and steel processes, power generation, mines, ferroalloy processes and petrochemical processes (DEAT, 2009). Data applied in CALPUFF were associated with a daily 7 hour burning period whereas the observed data cover measurements over a full 24 hour period. With that said, though, peaks in the predicted data tend to be higher than those of the observed data, indicating that the model could be over predicting the concentrations.

The calculated ratio, used to differentiate between the households that burn wood only as opposed to those that burn wood and coal simultaneously, might not be accurately representative of Orange Farm and the emissions therefore overestimated. Although the section of Orange Farm used in the pilot study was un-electrified, large portions of Orange Farm are electrified. As discussed earlier in chapter 4, even if electrified households continue to use solid fuels, the convenience of using electricity can outweigh the savings gained when using solid fuels, thereby reducing the combustion of wood and coal. Large quantities of wood and coal are burnt in Zenzele as this settlement is completely un-electrified and residents do not have the option of using electricity. Model inputs used in CALPUFF for Orange Farm were based on the emissions data associated with Zenzele's solid fuel consumption and for this reason if households in Orange Farm consume less solid fuels, CALPUFF would over predict their emissions. As coal is more readily available to residents of Orange Farm, the settlement as a whole consumes more coal during domestic combustion than wood (CoJ, 2008). This is evident in the lower PM_{10} concentrations present in the observed dataset. Smaller quantities of wood as opposed to coal suggest not only lower concentrations of PM_{10}, but also increased concentrations of SO_2 as highlighted in figure 5.19.

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With regards to indoor air pollution measurements, CO_2 concentrations are at their highest during the initial flaming stages of combustion, and CO concentrations peak during the final stages of combustion, where large amounts of white smoke are created. The section on dispersion modelling highlights a large number of exceedences of the South African NAAQ limit values, and the WHO air quality guidelines for almost all the averaging periods of the criteria pollutants under investigation.

CHAPTER 6: CONCLUSIONS

Overview

The purpose of this study was to identify the major fuels associated with domestic burning activities in low-income settlements in Johannesburg and further quantify them according to the quantities of these fuels that are consumed. An additional objective was to determine the potential of applying one township's emissions to another. Chapter 6 provides a summary of these findings and the conclusions made with regards to the aims of this study. It further provides recommendations based on the study limitations.

6.1. Domestic Energy Use

Information gathered from questionnaires distributed during the pilot studies and the field study provided insight into the common fuel choices used by a portion of the inhabitants in Soweto, Orange Farm and Zenzele. The findings gathered from these questionnaires are as follows:

- People's perceptions and their understanding surrounding the topics of air quality and domestic burning can have a major influence on the information that they divulge.
- Even some people who live in electrified houses still make use of solid fuels. In these households, electricity becomes the preferred fuel type because of its convenience in terms of time.
- Residents of low-income settlements live from one day to the next; if lower temperatures do not call for the use of more expensive solid fuels, residents would rather opt for spending less money at one time on a litre of paraffin, than having to part with a larger sum of money at one go on a 10 kg bag of coal.
- Paraffin and gas are common fuels, made use of in un-electrified or partially electrified households during the warmer summer months for cooking, heating and lighting activities.
- In un-electrified households, wood and coal are generally used during the colder winter months for cooking and heating activities. These fuels, however, are burnt infrequently during the warmer months. During winter, wood is burnt most frequently. Coal is only used if residents are able to afford it; but it is burnt infrequently on its own. Coal is generally burnt simultaneously with wood.

- Paraffin and candles are most commonly used for lighting purposes throughout the year, even during the colder winter months. Paraffin can also be used for cooking activities during winter as it is more convenient than creating a labour and fuel intensive wood and/or coal fire.
- Large coal stoves are generally passed down from one generation to the next, thereby bringing a cultural association to domestic burning. If a coal stove is owned, these devices are made use of often because of their multi-functional nature, providing large amounts of heat during cooking.
- Hand-built stoves, with attached chimneys are also made use of in households to provide for both cooking and heating purposes.
- Imbaulas are widely used in townships that are un-electrified and are generally used for outdoor cooking and heating. Households in low-income settlements are usually poorly ventilated. As a consequence, when imbaulas are placed indoors during a combustion process, there is a danger of smoke inhalation.
- Faced with the options of various fuel types, Zenzele residents chose more than one fuel preference, especially during winter. They further explained that wood was generally burnt in the mornings and both coal and wood were used in the evenings simultaneously. A general observation has been that residents will limit their usage of coal to one 10kg bag per burning period if the household burns coal during both the morning and evening burning session or per evening if coal is only burnt in the evenings.
- Factors such as seasonality, the price and the availability of solid fuels all have a major influence on the fuel type and the quantity consumed. There are a large portion of un-electrified households that do not always use vast quantities of coal and/or wood to provide for their energy needs. Even at the height of winter, when temperatures are at their lowest, households will have to get by with what they have remaining from the previous season, supplemented with a small stock of solid fuels. The price and availability of these fuels play a key role in determining what fuels are consumed in winter. These factors, in addition to temperature, have a major influence on the seasonal as well as the diurnal burning habits of residents of low-income settlements.
- Cultural aspects also have a bearing on the fuel choice of residents in townships. Combustion devices such as the larger coal stoves create an atmosphere, within a home, which is conducive to the gathering of family members.

6.2. Quantification of Emissions

The emissions generated from the combustion of domestic fuels in Zenzele were quantified using the fuel-weight approach. Scale measurements of selected fuels, together with emissions factors allowed for the emissions associated with this combustion to be quantified. The results of this process are as follows:

- Larger volumes of solid fuel combustion occur at lower temperatures. For almost all households that participated in this study, there is a gradual increase in the amount of wood burnt from May to June and a further, often very slight increase from June to July. After peaking around June and July, the amount burned slowly starts to decrease into August and September.
- The same is true for the emissions associated with the combustion of these fuels; in general the emission estimates for all the observed pollutants are higher during the colder winter months. They start to increase towards the end of May, and peak in July, followed by a gradual decrease during August and September. Generally the emission rates for both wood and coal are higher during the colder months.
- The greatest peaks in fuel use occur the day after an unusually larger decline in the temperature. When temperatures decrease dramatically, people tend to expect similar temperatures the following day and therefore tend to burn more fuel irrespective of whether temperature decreases or not.
- Given no variation in the number of people residing in one household, the amount of coal consumed in a fire stays constant and is supplemented by wood as the temperature decreases over the winter period.
- As a result of larger volumes of wood and coal being consumed in the evenings, there are higher emission rates associated with combustion in the evenings, than the morning combustion. With reference to the concentrations of CO from the indoor measurements, however, the highest peak is associated with the morning combustion period and a lower peak with the evening burning period. This variation is a significant finding and requires further investigation.

- Residents opt for labour and fuel intensive fires in the evenings so as to gain the maximum benefit of the heat generated. If there is only a limited supply of fuel, wood or coal, residents would prefer to utilise these stocks during the evening burning sessions. Once the cooking has been done and the fire has progressed through all the combustion stages, evening fires are generally rekindled to provide additional heat for warmth throughout the night.

- Coal is utilised more in the evenings in a bid to save on already limited funds, as the demand for this commodity drives prices up. As a consequence of this increased demand, the supply and availability of both coal and wood can often also become a problem. As the supply of coal lessens in the colder months, so too will the supply for wood, as its demand increases.
- There is often uncertainty over the amounts of various fuels used in these areas, thereby making it difficult to estimate the amounts of fuel being burnt. A large portion of this uncertainty lies in the lack of data surrounding the amount of fuel consumed and consequently the same uncertainty would apply to the emissions. Specifically in the case of this study, the most significant uncertainties in the emission estimates could arise on account of human error, if participants did not divulge the actual amounts of fuel being consumed.
- There is also a degree of uncertainty that arises when using emission factors that are not calculated within the study as they do not relate directly to the dataset being examined, which can influence the emission estimates.

6.3. Dispersion Modelling

The emission rates that were calculated for Zenzele and Orange Farm were modelled using the CALPUFF air quality dispersion modelling system, to better understand the impact of these emissions on the surrounding areas. Gurjar *et al.* (2008), importantly identifies that a good and accurate emissions inventory is a significant requirement for any modelling study (Gurjar *et al.* 2008). This exercise was carried out to determine whether emission rates from one low-income settlement could potentially be used to quantify and further predict the emissions generated as a result of domestic burning activities, from other townships that exhibit similar burning behaviours. The outcomes from this dispersion modelling exercise are listed below:

- The SO_2 concentrations associated with the households that burn wood only are far lower than those of the households that burn wood and coal together, in Zenzele and Orange Farm. This is true for both the maximum average hourly and daily concentrations of SO_2 highlighting that a significant portion of these SO_2 emissions are associated with the combustion of coal. The average SO_2 emission rates associated with coal were the most prominent due to the high emission factors, even though larger quantities of wood were consumed over the study period.

- The extent of the dispersion field is determined by the volume of pollutant presented in the mapped model output as well as how the mapping classes are defined. Larger concentrations of pollutants are dispersed and transported further, increasing the size of the dispersion field.
- The CALPUFF model outputs show exceedences of the South African national ambient air quality standard (NAAQS) limit value and the World Health Organisation (WHO) air quality guideline for the maximum average daily concentrations of SO_2 associated with those households in Zenzele that wood and coal simultaneously as well as in with the combination scenarios, representing all the households in Zenzele. The maximum average daily PM_{10} concentrations are also in exceedence of the current and future South African NAAQ limit value as well as the WHO air quality guideline in Zenzele. The maximum average 8 hourly concentrations of CO, associated with all the households in Zenzele, exceeded the South African NAAQ limit value.
- The current South African national ambient air quality limit values for the maximum average hourly and daily concentrations of SO_2, the maximum average daily concentrations of PM_{10} as well as the maximum average hourly and 8 hourly concentrations of CO are all exceeded in Orange Farm. The future South African NAAQ limit value for the maximum average daily concentrations of PM_{10} and the WHO air quality guidelines for the maximum average daily concentrations of SO_2 and PM_{10} are also in exceedence in Orange Farm.
- All observed cases of exceedence of the NAAQ limit value, only showed the potential for exceedence of the South African national ambient air quality standards as the number of allowable exceedences associated with each standard spans one full year and this study only took place over 5 months.
- The observed average 24-hour concentrations of SO_2 for Orange Farm compare well in magnitude with the average 24-hour concentrations of SO_2 predicted by CALPUFF.
- The base of the observed data for the average 24-hour concentrations of SO_2 and PM_{10} is a bit more elevated than that of the predicted data. This difference can be attributed to the fact that the time-series files created by CALPUFF for Orange Farm

do not account for background concentrations of these two pollutants and only a daily 7 hour burning period was used, whereas the ambient concentrations measured at the monitoring station are done throughout the day.

- The peaks in the average 24-hour PM_{10} concentrations highlighted in the predicted data tend to be higher than those of the observed data, indicating that the model could be over predicting these concentrations. The calculated ratio, used to differentiate between the households that burn wood only as opposed to those that burn wood and coal simultaneously, might not be accurately representative of Orange Farm and the emissions therefore overestimated. There are also large portions of Orange Farm that are electrified and at times, for the sake of convenience, residents will opt to use electricity instead of solid fuels, thereby reducing their consumption of wood and coal. Large quantities of coal are available and therefore burnt in Orange Farm, and to a lesser extent wood, highlighting higher average SO_2 concentrations in the observed data that compares well with the predicted data from CALPUFF.
- The ratio of households that burn wood only to those that burn wood and coal together is based on the burning behaviours of 15 households in Zenzele. This ratio therefore might not be representative of the entire settlement thereby resulting in either an overestimation or an underestimation in the emissions associated with domestic burning in Zenzele.
- Uncertainties associated with outdated emission factors can also have an impact on the estimation of emissions from domestic burning activities.
- An important limitation of this modelling process; in trying to use one township's emission rates to estimate the emissions of another township, is that this process does not account for individual household's social and cultural aspects associated with domestic fuel combustion.

Recommendation 1: A sample size that is more representative of the entire settlement needed to be used. Due to limited resources, this was not possible but it should be taken into account for future studies of this nature.

Recommendation 2: The available emission factors associated with domestic fuel combustion need to be verified and revised to reflect the most updated and current values that can be made use of in future studies.

Recommendation 3: Further research needs to be conducted to establish possible reasons as to why indoor concentrations of CO show a higher peak during the morning combustion period than the evening combustion period, even though larger quantities of solid fuels are consumed during the evening period.

Recommendation 4: Information on additional variables such as household income, specific combustion activities and types of combustion devices need to be taken into account when comparing households in one settlement to those in another.

Recommendation 5: It is important to have an understanding of the social and cultural dynamics surrounding domestic fuel combustion that exists in low-income settlements.

In spite of the uncertainties and limitations associated with the modelling process and the potential for the widespread application of one township's emission rates, the results obtained from this study represent an important assessment of the components necessary in achieving an objective such as this. It is possible to apply the emission rates associated with one low-income settlement to another with a degree of uncertainty but this process will require more than just linking two different households, located in two different settlements, to each other using similarities in burning behaviours and the number of people that reside in a household.

Another important focus of this study was to shed some light on common domestic fuels, consumed in low-income settlements in Johannesburg. With reference to the responses of the questionnaires answered in Zenzele, Orange Farm and Soweto, it was discovered that within both electrified and un-electrified settlements large quantities of solid domestic fuels are still being consumed. Although not as widely used during the warmer months, wood and coal are common fuels burnt frequently in low-income settlements during the colder winter month. In identifying these common fuels and highlighting the patterns in which they are utilised, this study further provides a dataset on the consumption rates of these fuel types, and in so doing, attempts to address in some way the uncertainties associated with their consumption.

CHAPTER 7: REFERENCES

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APPENDIX A: PARTICIPANT INFORMATION SHEET

Title of Research Project

The Quantification of Emissions Generated from Domestic Burning Activities in Townships in Johannesburg.

Purpose of the Project

This research is for my Masters degree in Atmospheric Sciences at the University of the Witwatersrand.

Project Information

This research project will be conducted in order to derive a method to quantify the emissions generated from the various burning activities of households situated within an informal settlement. This study will also investigate how different sources of energy contribute to the total amount of emissions released into the atmosphere.

Your Contribution

If you decide to participate, you will be required to answer a few questions on a questionnaire about your view on the state of the air around you.

Confidentiality

The names of participants are not required. The questionnaires can be answered on a purely anonymous basis.

My use of this Information

The information gained from these questionnaires will be used to gain a better understanding of the most commonly used fuel types in this study area, as well as how these fuel types impact on the quality of the surrounding air.

Further Information

Please contact Seneca Naidoo on 072 389 9015

APPENDIX B: PILOT STUDY QUESTIONNAIRE

Please tick the appropriate box

1. How many people live in your house?

   1 ☐

   2 ☐

   3 ☐

   4 ☐

   5 ☐

   6 – 10 ☐

   10 + ☐

2. Do you understand what air pollution is?

   Yes ☐

   No ☐

3. What is the condition of the sir like around you?

   Good ☐

   Bad ☐

4. If bad, what do you think are some of the problem associated with poor air quality? (you may tick more than one box)

   Respiratory illnesses ☐

   Poor visibility ☐

   Soot or ash deposition in households ☐

   Other ☐

5. Which source causes the greatest amount of air pollution in your area?

   Domestic burning ☐

Vehicles ☐

Dust ☐

6. How do you provide for your energy needs?

6.1. In the summer season (December – February),

6.1.1. Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.1.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.1.3. Which substance do you use most often for light?

- Coal ☐
- Wood ☐
- Candles ☐
- Paraffin ☐
- Domestic waste ☐
- Electricity ☐
- Other ☐

6.1.4. What is the most important reason for using this fuel source/s?

- Temperature ☐
- Price ☐
- Availability ☐

6.1.5. How often do you burn this fuel source/s (frequency)?

- Twice a day (morning and evening) ☐
- Once a day (morning or evening) ☐
- Twice a week ☐
- Once a week ☐
- Once every two weeks ☐
- Once a month ☐

6.2. In the autumn season (March – May),

6.2.1. Which substance do you use most often for cooking?

- Coal ☐
- Wood ☐
- Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.2.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.2.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.2.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

6.2.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐
Once a day (morning or evening) ☐
Twice a week ☐
Once a week ☐
Once every two weeks ☐
Once a month ☐

6.3. In the winter season (June – August),

6.3.1. Which substance do you use most often for cooking?

Coal ☐
Wood ☐
Candles ☐
Paraffin ☐
Domestic waste ☐
Electricity ☐
Other ☐

6.3.2. Which substance do you use most often for warmth?

Coal ☐
Wood ☐
Candles ☐
Paraffin ☐
Domestic waste ☐
Electricity ☐

Other ☐

6.3.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.3.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

6.3.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐

6.4. In the spring season (September – November),

6.4.1. Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.4.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.4.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

6.4.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

6.4.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐

APPENDIX C: FIELD STUDY QUESTIONNAIRE

Please tick the appropriate box

1. How many people live in your house?

   1 ☐

   2 ☐

   3 ☐

   4 ☐

   5 ☐

   6 – 10 ☐

   10 + ☐

2. How do you provide for your energy needs?

2.1. In the summer season (December – February),

2.1.1 Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.1.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.1.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.1.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

2.1.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐

2.2. In the autumn season (March – May),

2.2.1 Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.2.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.2.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.2.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

2.2.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐

2.3. In the winter season (June – August),

2.3.1. Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.3.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.3.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.3.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

2.3.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐

2.4. In the spring season (September – November),

2.4.1. Which substance do you use most often for cooking?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.4.2. Which substance do you use most often for warmth?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.4.3. Which substance do you use most often for light?

Coal ☐

Wood ☐

Candles ☐

Paraffin ☐

Domestic waste ☐

Electricity ☐

Other ☐

2.4.4. What is the most important reason for using this fuel source/s?

Temperature ☐

Price ☐

Availability ☐

2.4.5. How often do you burn this fuel source/s (frequency)?

Twice a day (morning and evening) ☐

Once a day (morning or evening) ☐

Twice a week ☐

Once a week ☐

Once every two weeks ☐

Once a month ☐