

Exploring thermal insulation and energy use in low-income households on the South African Highveld

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ABSTRACT

A significant proportion of households in South Africa are classified as low-income households and often reside in dwellings that are inadequately insulated which threaten indoor thermal environments for occupants. This study was conducted in three low-income settlements on the South African Highveld namely: KwaDela, Jouberton, and KwaZamokuhle-settlements known to have a high proportion of poorly insulated residential dwellings. The purpose of this study was to explore the link between thermal insulation, indoor thermal environments and domestic energy use in low-income households. Indoor and ambient temperature monitoring were done over winter and summer seasons using Thermochron iButton loggers while aerial thermography was done in winter using a FLIR Vue Pro R. Questionnaires were used to gather data to explore the link between thermal insulation and domestic energy use. In winter, the study found that the majority of sampled dwellings' average indoor temperatures fell below 18 °C, the WHO indoor minimum temperature guideline. In some instances, however, day time winter indoor temperatures also dropped below 18 °C, although this was less frequent. Also, during summer season median indoor temperatures regularly exceeded the WHO indoor maximum temperature guideline of 24 °C for both the living room and bedrooms. Furthermore, in winter, the study established that ambient temperatures influence indoor temperatures moreso, at night time showing a night time positive Pearson r which ranged from $r=0.39$ (KwaDela), $r=0.77$ (Jouberton 2016) to $r=0.91$ (Jouberton 2017) in bedrooms and living rooms respectively, and was always stronger than day time. Besides during winter, in KwaZamokuhle, non-insulated dwellings showed the most significant association between ambient and indoor temperatures during day time ($r = 0.68$) while partially insulated dwellings showed a moderate relationship of $r = 0.40$, while insulated dwellings yielded $r = 0.29$. In summer, non-insulated dwellings showed the most significant relationship between ambient and indoor temperatures during night time as well ($r = 0.61$) with partially insulated dwellings showing a weak link during night time ($r = -0.25$), while insulated dwellings yielded almost no link. Furthermore, the study also established that thermal variability between dwellings with different levels of insulation was observable through aerial TIR with non-insulated dwellings exhibiting significant variability and were distinguishable from partially and fully insulated dwellings. Further analysis of aerial thermal infrared (TIR) imagery also showed that non-insulated dwellings had higher temperature variability than partially or fully insulated dwellings. Findings from the study additionally indicated that the difference between TIR imagery obtained during midnight and TIR imagery gathered during the early evening were the most feasible way of identifying non-insulated dwellings with the study estimating that 18% and 10% of 3555 dwellings in the settlement had a very high and high probability, respectively, of being non-insulated. On domestic energy use, some link between thermal insulation status of dwellings and domestic energy use was established with more energy consumption for space heating in non-insulated dwellings

compared to partially or fully insulated dwellings in winter. Furthermore, the study ascertained that low-income households rely on a mixture of energy carriers to meet their domestic needs including electricity, LPG, coal, and wood. This affirms that the insulation status of dwellings has a definite effect on the indoor thermal environments experienced by low-income households and stresses the importance of adequate thermal insulation materials for low-income residential dwellings. The low-quality thermal insulation in low-income residential dwellings means that these households are often exposed to extreme indoor temperatures for prolonged periods. Such exposure could lead to physical health-related ailments that are either directly associated with heat or cold exposure, or indirectly associated with the air pollution that results from indoor burning (for space heating). To improve indoor thermal environments of low-income households thermal insulation retrofits can be used for existing housing stock.

Keywords: *Thermal insulation, indoor temperature, low-income residential dwellings, indoor thermal environment, domestic energy use, aerial thermography*

PREFACE

This thesis is an original work by Newton Matandirotya. The purpose of the thesis was to investigate the link between thermal insulation, indoor temperatures and domestic energy use in low-income households on the South African Highveld. Low-income households are often exposed to living conditions that are characterised by very low indoor temperatures in winter, and very high indoor temperatures in summer. A substantial number of households in South Africa can be classified as low-income households, many of which live in dwellings that are poorly insulated and exposed to the aforementioned conditions regularly. Exposure to such conditions poses a variety of direct and indirect risks to these households. This study contributes towards a better understanding of the indoor living conditions to which low-income households are exposed, and the manner and extent to which insulation influences these conditions. The study further contributes by proposing a screening approach for the identification of non-insulated dwellings. This study would not have been possible without the guidance, assistance and support of the following individuals:

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Some of the work presented in this thesis have already been shared at both local and international conferences, while one peer-reviewed article has also been published in the *Clean Air Journal*.

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TABLE OF CONTENTS

ABSTRACT	I
PREFACE	III
ABBREVIATIONS AND ACRONYMS	XV
CHAPTER 1: INTRODUCTION & BACKGROUND	1
1.1 Introduction	1
1.2 Problem statement	3
1.3 Research aim	4
1.4 Research objectives	4
1.5 Contribution of the study	4
1.6 Research design	5
1.7 Structure of the document	7
1.8 Summary	8
CHAPTER 2: LITERATURE REVIEW	9
2.1 Introduction	9
2.2 Low-income housing	9
2.3 Determinants of indoor thermal environments	14
2.4 Domestic energy use	18
2.5 Health impacts related to poor indoor thermal environments	22
2.6 Summary	26

CHAPTER 3: DATA & METHODOLOGY	27
3.1 Introduction	27
3.2 Study area	27
3.3 Methodological design	29
3.4 Summary	50
CHAPTER 4: CHARACTERISATION OF INDOOR TEMPERATURES	51
4.1 Introduction	51
4.2 Winter indoor temperature characteristics: Bedrooms	51
4.3 Winter indoor temperature characteristics: Living rooms.....	59
4.4 Summer indoor temperature characteristics: Bedrooms	68
4.5 Summer indoor temperature characteristics: Livingrooms	76
4.6 Summary and discussion	84
CHAPTER 5: CHARACTERISATION OF THERMAL INSULATION USING INDOOR TEMPERATURE MEASUREMENTS	87
5.1 Introduction	87
5.2 Winter livingroom indoor temperature variations	87
5.3 Summer	96
5.4 Summary and discussion	103
CHAPTER 6: DETERMINE THE EXTENT TO WHICH AERIAL THERMOGRAPHY CAN BE USED TO EVALUATE THERMAL INSULATION	105
6.1 Introduction	105
6.2 Analysis of flights.....	105
6.3 Summary and discussion	118

CHAPTER 7: CHARACTERISE THE LINK BETWEEN THERMAL INSULATION & DOMESTIC ENERGY USE	119
7.1 Introduction	119
7.2 Energy sources.....	119
7.3 Energy uses	125
7.4 The link between energy use and thermal insulation	133
7.5 Summary and discussion	134
CHAPTER 8: CONCLUSIONS.....	136
8.1 Introduction	136
8.2 Indoor temperatures in low-income households (Objective 1)	136
8.3 Thermal insulation in low-income households (Objective 2)	138
8.4 Characterising thermal insulation through aerial thermography (Objective 3).....	138
8.5 The link between thermal insulation and domestic energy use (Objective 4).....	139
8.6 Limitations of the study	140
8.7 Final remarks	140
8.8 Recommendations for future studies.....	141
REFERENCE LIST	142
ANNEXURES.....	164
Annexure 1 – Consent form.....	164
Annexure 2 – Questionnaire	167
Annexure 3 – TIR images [a] Flight 1, [b] Flight 2, [c] Flight 3	170
Annexure 4 – Examples of sampled structures	173

LIST OF TABLES

Table 2.1:	Factors increasing susceptibility to health impacts associated with extreme indoor heat	23
Table 2.2:	Factors increasing susceptibility to health impacts associated with extreme indoor cold.....	24
Table 3.1:	Number of dwellings selected for indoor temperature measurements and aerial surveys.....	32
Table 3.2:	Number of dwellings selected for the domestic energy use survey.....	32
Table 3.3:	Thermal insulation descriptors	33
Table 3.4:	Technical specifications of FLIR Vue Pro R	40
Table 3.5:	Flight schedule for Campaigns 1 and 2	42
Table 3.6:	Indoor space and non-space heating dwellings during Flight 1	43
Table 3.7:	HEAT Score descriptors.....	49
Table 5.1:	Grouped mean winter day time and night time temperatures in living rooms.....	89
Table 5.2:	Grouped mean summer day time and night time temperature in summer in living rooms	97
Table 6.1:	Roof and property boundary HEAT scores.....	107

LIST OF FIGURES

Figure 1.1:	Flow chart showing a brief outline of the study research design	5
Figure 1.2:	Flow chart representing the structure of the thesis	7
Figure 2.1:	Image showing typical low-income settlement in South Africa mainly composed of RDP dwellings (Matandirotya, 2019)	12
Figure 2.2:	Percentage of households reporting weak walls and roofs in RDP houses by province (Source: Stats SA, 2012)	12
Figure 2.3:	Images showing a typical shack (Source: Matandirotya 2019)	13
Figure 2.4	Physical dwelling characteristics that determine heat gain and retention: (Source: Kenny <i>et al.</i> 2019).....	15
Figure 3.1:	Study area and study sites	28
Figure 3.2:	Conceptual diagram of the methodology	30
Figure 3.3:	Image showing examples of sampled RDP residential dwellings in KwaZamokuhle (Source: Matandirotya 2017).....	34
Figure 3.4:	[a] Data retrieval process from the iButtons.....	36
Figure 3.5:	A FLIR Vue Pro R image (Source: www.flir.eu/home)	39
Figure 3.6:	FLIR Vue Pro R fixed to an aircraft wing for the acquisition of aerial thermal data.....	41
Figure 3.7:	Trigger points across the settlement during flight campaign 1 & 2 (Source, Matandirotya, 2017)	41
Figure 4.1:	Indoor temperature variations within bedrooms in Jouberton 2016:.....	52
Figure 4.2:	Indoor temperature distribution Jouberton 2016: [a] day time, [b] night time	53
Figure 4.3:	Indoor temperature variations within bedrooms in Jouberton 2017: [a] day time, [b] night time	54

Figure 4.4:	Indoor temperature distribution in Jouberton 2017: [a] day time, [b] night time	55
Figure 4.5:	Indoor temperature variations within bedrooms in KwaDela:	57
Figure 4.6:	Indoor temperature distributions in bedrooms kwaDela: [a] day time, [b] night time	58
Figure 4.7:	Association between indoor and ambient temperature association in bedrooms: Jouberton (2016) [a] day time, [b] night time, Jouberton (2017) [c] day time, [d] night time, KwaDela (2014) [e] day time, [f] night time	60
Figure 4.8:	Indoor temperature variations within living rooms in Jouberton 2016: [a] day time, [b] night time	61
Figure 4.9:	Indoor temperature distribution in living rooms winter in Jouberton 2016: [a] day time, [b] night time	62
Figure 4.10:	Indoor temperature variations in winter for living rooms in Jouberton 2017: [a] day time, [b] night time	63
Figure 4.11:	Indoor temperature distribution within living rooms in Jouberton 2017: [a] day time, [b] night time	64
Figure 4.12:	Indoor temperature variations within living rooms in KwaDela 2014: [a] day time, [b] night time	65
Figure 4.13:	Indoor temperature distribution within living rooms in kwaDela 2014:.....	66
Figure 4.14:	Association between indoor and ambient temperature association in living rooms: Jouberton (2016) [a] day time, [b] night time, Jouberton (2017) [c] day time, [d] night time, kwaDela (2014) [e] day time, [f] night time	67
Figure 4.15:	Indoor temperature variations within bedrooms in Jouberton 2016:.....	69
Figure 4.16:	Indoor temperature distribution within bedrooms in Jouberton 2016: [a] day time, [b] night time	70
Figure 4.17:	Indoor temperature variations within bedrooms in Jouberton 2017:.....	71

Figure 4.18:	Indoor temperature distribution within bedrooms in Jouberton 2017: [a] day time, [b] night time	72
Figure 4.19:	Indoor temperature variation within bedrooms in kwaDela 2014:.....	73
Figure 4.20:	Indoor temperature distribution within bedrooms in KwaDela 2014:	74
Figure 4.21:	Association between indoor and ambient temperatures in bedrooms: Jouberton (2016) [a] day time [b] night time; Jouberton (2017) [c] day time [d] night time; KwaDela (2014) [e] day time, [f] night time	75
Figure 4.22:	Indoor temperature variations within living rooms in Jouberton 2016: [a] day time, [b] night time	77
Figure 4.23:	Indoor temperature distribution within living rooms in Jouberton 2016: [a] day time, [b] night time	78
Figure 4.24:	Indoor temperature variations within living rooms in Jouberton 2017: [a] day time, [b] night time	79
Figure 4.25:	Indoor temperature distribution within living rooms Jouberton 2017: [a] day time, [b] night time	80
Figure 4.26:	Indoor temperature variations within living rooms in KwaDela 2014: [a] day time, [b] night time	81
Figure 4.27:	Indoor temperature distribution within living rooms in kwaDela 2014: [a] day time, [b] night time	82
Figure 4.28:	Association between indoor and ambient temperatures within living rooms: Jouberton 2016 [a] day time, [b] night time; Jouberton 2017 [c] day time, [d] night time; kwaDela 2014 [e] day time, [f] night time	83
Figure 5.1:	Indoor temperature variations within livingrooms during winter	88
Figure 5.2:	Day time indoor temperature density distribution: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings.....	91
Figure 5.3:	Night time indoor temperature density distribution: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings.....	93

Figure 5.4:	Regression analysis results for living rooms for day time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings	94
Figure 5.5:	Regression analysis results for living rooms at night time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings	95
Figure 5.6:	Summer indoor temperature variations in living rooms according to insulation type	96
Figure 5.7:	Day time indoor temperature density distributions: [a] non insulated, [b] partially insulated, [c] fully insulated dwellings.....	99
Figure 5.8:	Night time indoor temperature density distributions: [a] non- insulated, [b] partially insulated, [c] fully insulated dwellings.....	101
Figure 5.9:	Regression analysis results for day time indoor and ambient temperatures: [a] none-insulated, [b] partially insulated, [c] fully insulated dwellings	102
Figure 5.10:	Regression analysis results for night time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, and [c] fully insulated dwellings	103
Figure 6.1:	Scatter plot of iButton surface measurements against TIR image radiometric values	106
Figure 6.2:	Kitchen indoor temperature and radiometric values association during Flight 1: [a] non-insulated [b] partially insulated [c] fully insulated & Kitchen indoor temperature and HEAT scores association during Flight 1 [a] non-insulated, [b] partially insulated, [c] fully insulated	110
Figure 6.3:	Living room indoor temperature and radiometric values association during Flight 1 performance: [a] non-insulated, [b] partially insulated, [c] fully insulated & Living room indoor temperature and HEAT scores association during Flight 1 performance [a] non-insulated, [b] partially insulated, [c] fully insulated	111

Figure 6.4:	Living room indoor temperature in heating houses and HEAT score association during Flight 1 performance: [a] non-insulated, [b] partially insulated, [c] fully insulated (not shown - insufficient data points)	112
Figure 6.5:	Box-plots showing radiometric values for properties with known insulation status in the study area during Flight 2 and 3: [a] minimum values, [b] maximum values, [c] range, [d] standard deviation, [e] mean.....	113
Figure 6.6:	Box-plots showing the differences in radiometric values between flights for properties with known insulation status in the study area: [a] minimum values, [b] maximum values, [c] range, [d] standard deviation, [e] mean.....	115
Figure 6.7:	Estimated insulation status of dwellings in KwaZamokuhle	117
Figure 7.1:	Energy sources used by low-income households (expressed as a percentage of households).....	120
Figure 7.2:	Mean monthly coal expenditure by insulation type and season	121
Figure 7.3:	Coal and LPG procured across different dwelling types: [a] coal, [b] LPG..	122
Figure 7.4:	Coal and LPG consumption across different dwelling types: [a] coal, [b] LPG	124
Figure 7.5:	Primary energy sources used for space heating across different dwelling types	125
Figure 7.6:	Coal and LPG used for space heating across different dwelling types: [a] coal, [b] LPG	126
Figure 7.7:	Primary energy sources used for cooking	127
Figure 7.8:	Coal and LPG used for cooking across different dwelling types: [a] coal, [b] LPG.....	128
Figure 7.9:	Slow-cooking activities per week across different dwelling types: [a] coal, [b] LPG.....	129

Figure 7.10:	Coal and LPG used for heating bath water across different dwelling types: [a] coal, [b] LPG	131
Figure 7.11:	Coal and LPG used for doing dishes across different dwelling types: [a] coal, [b] LPG	132
Figure 7.12:	Coal and LPG used for ironing across different dwelling types: [a] coal, [b] LPG.....	133

ABBREVIATIONS AND ACRONYMS

°C	Degree Celsius
µm	Micro-metre
BC	Black carbon
CDHB	Canterbury District Health Board
CH	Methane
cm	Centimetre
CO₂	Carbon Dioxide
CO₃	Carbon Monoxide
g	Gramme
GCP	Ground control points
GHGs	Green House Gases
GPS	Global Position System
HEAT	Home Energy Assessment Technologies
Hz	Hertz
IOM	Institute of Medicine
IPCC	Intergovernmental Panel on Climate Change
Km	Kilometre
LPG	Liquefied Petroleum Gas
m	Metre
NO_x	Nitrogen Oxide
NWU	North-West University
OC	Organic carbon
PHIRST	Prospective Household Observational cohort study of Influenza, Respiratory Syncytial Virus and other respiratory pathogens community burden and Transmission dynamics in South Africa
RDP	Reconstruction Development Programme
SPSS	Statistical Package for the Social Sciences
SEA	Sustainable Energy Africa
SERI	Socio-Economic Rights Institute of South Africa
SLCFs	Short-lived climate forcers
Stats SA	Statistics South Africa
TIASA	Thermal Insulation Association of South Africa
TIFF	Tagged Image File Format
TIR	Thermal Infrared
UN Stats	United Nations Statistics

UNDP	United Nations Development Programme
UNICEF	United Nations International Children Emergency Fund
VOCs	Volatile organic compounds
W	Watts
WB	World Bank
WHO	World Health Organisation
ZAR	South African Rand

CHAPTER 1: INTRODUCTION & BACKGROUND

The chapter provides a detailed background of the study, presents the problem, aim and objectives of the study as well as the ethical considerations of the study.

1.1 Introduction

Africa is struggling with a plethora of socio-economic challenges such as extreme poverty, high unemployment levels, increasing inequality gaps, rapid urbanisation and rapid population growth. These challenges are making access to decent housing for low-income earners difficult. Furthermore, Africa's accelerated population growth is happening under sharp disparities, such as socio-economic and spatial exclusion (Bello-Schünemann & Aucoin, 2016). Adding to this are the external pressures resulting from climate change (Bello-Schünemann & Aucoin, 2016) as well as increases in extreme weather events, which pose further threats to low-income residential dwellings especially and increase the overall vulnerability of low-income households. The combination of the factors mentioned above sketches a scenario where residential dwellings in low-income settlements fail to protect residents adequately from environmental factors, one of which is extreme ambient temperatures (Collins, 1993).

The sub-Saharan African region ranks amongst one of the unequal societies in the world with 20 % of the population earning approximately 5.3 % of the total income generated in the region (Handley *et al.*, 2009). Bello-Schünemann and Aucoin (2016) observed a relationship between this extreme poverty and the housing choices that households make, that is low-income earners generally have been found to occupy older, non-insulated dwellings (Santamouris, 2007). This relationship is especially evident in South Africa where almost all informal settlements bear the hallmarks of extreme poverty and where access to formal housing is beyond the reach of most residents Socio-Economic Rights Institute of South Africa (SERI, 2018). David *et al.* (2018) estimate that 55 % of South Africans are regarded as poor, which concurs with findings from the World Bank (WB, 2018) that estimated that nearly half of the South African population is chronically poor and earns an average of only ZAR 992.00 per month (based on 2015 figures).

Furthermore, in the South African context, rapid population growth impedes the provision of decent housing as urban populations balloon with the main driving factors being natural population growth, in-country migration (rural-urban) as well as inter-country migration (from the whole of Africa) towards the main urban centres. This has placed substantial pressure on the ability of national government, local government and other entities to deliver affordable housing as informal settlements are growing beyond the coping capacity of available infrastructure

(Govender *et al.*, 2011). According to Statistics South Africa (Stats SA, 2013), the total population grew from 44 819 777 in 2001 to 51 770 560 in 2011. This rapid population growth has put an unanticipated strain on the existing housing stock that has led to the proliferation of sub-standard structures, informal structures and shacks in low-income areas. As a result, many of the dwellings occupied by residents in low-income areas are regarded as sub-standard as they are characterised by poor thermal insulation, inadequate heating systems, ill-fitting windows and overall poor thermal environments (WHO, 2004). In South Africa, the housing situation is further complicated by the country's socio-political history. After 1994, South Africa saw a massive boom in Government housing provision through the implementation of the Reconstruction and Development Programme (RDP), a programme that focussed on all areas of transformation including the improvement of living conditions and housing (Moola *et al.*, 2011).

The RDP programme was meant to deliver housing units on a large scale and increase housing access for the low-income population group. Although an estimated 2.1 million houses were delivered through the programme, anecdotal evidence suggests that due to, amongst other things, the short timeframes in which construction took place, many of these so-called RDP houses were not built to acceptable standards (Linstra, 2016). Some quality issues that have been identified in RDP housing units include cracks, mouldy interiors, lack of plaster, leaky roofs, and poor insulation (Govender *et al.*, 2011). The same authors found further that 38 % to 48 % of inhabitants reported two or three structural problems on the primary dwellings, with 90 % indicating that they could not afford resources to effect repairs. In terms of indoor environments, Makaka and Meyer (2005) established that traditional huts had better indoor thermal environments than RDP structures while, Naicker *et al.* (2017), further found that RDP houses were sensitive to ambient temperature fluctuations because most of these houses are single-walled with very little or no insulation.

Poor indoor thermal environments – resulting in poor indoor conditions – have further been linked to specific health issues (Krieger & Higgins, 2002; WHO, 2018a) as prolonged exposure to extreme indoor temperatures (low or high) can compromise the human body's thermo-regulation ability (Anderson *et al.*, 2013). Furthermore, dwellings with low indoor temperatures have specifically been associated with higher risks of cardiovascular disease and respiratory infections (WHO, 2004; Hamilton *et al.*, 2017). In England, exposure to low indoor temperatures has been associated with higher rates of winter mortality, contributing to an estimated 27,000 deaths per annum (Lewis, 2015; Hamilton *et al.*, 2017). However, in South Africa, no literature could be found that directly links extreme indoor temperatures to increased incidences of physical health ailments.

Apart from the physical health threats to occupants, low winter indoor temperatures result in high energy demand for space heating, which low-income households often cannot afford, leading to a dependency on solid fuels like coal and wood (Makonese *et al.*, 2017; Mgwambani *et al.*, 2018; Nkosi *et al.*, 2018). The burning of these solid fuels for indoor heating purposes leads to ambient and indoor air quality degradation that further threatens human health (Smith *et al.*, 2013; Nkosi *et al.*, 2018). According to the American Institute of Medicine (IOM, 2011), indoor thermal environments for the poor are projected to worsen in the face of climate change as human exposure to extreme indoor temperatures is expected to vary regionally among different segments of the population with the elderly, children and the economically disadvantaged being the most vulnerable (Fisk, 2015).

1.2 Problem statement

According to Stats SA (2018), of all formal housing in South Africa, 13.6 % is classified as RDP houses. Also, an estimated 10.2 % of those living in RDP houses in South Africa reported weak walls, while 9.9 % reported weak roofs (Stats SA, 2018). In some areas these numbers are significantly higher, such as in the Amathole District of the Eastern Cape Province, where Manomano and Tanga (2018), found that 91.2 % of households reported poor quality roofs and 93.6 % reported weak, collapsing and cracking walls. In 2013 the Public Protector received a total of 5 000 complaints from occupants of RDP dwellings (IOL, 2013) claiming in many cases that houses had no foundations, no insulation or toilets (Southern African Catholic Bishops' Conference, 2017). These reported structural weaknesses hurt the thermal performance of houses which essentially exposes occupants to physical health risks as mentioned earlier. The above is partly confirmed in a study by Wright *et al.* (2019) conducted in the city of Johannesburg that found that people residing in poor quality government subsidised housing often experienced heat-related health issues such as headaches and nausea. Findings from studies by Kapwata *et al.* (2018), Naicker *et al.* (2017) and Makaka and Meyer (2005), confirm that low-income households, and specifically those residing in RDP houses, often experience extremely high indoor temperatures in summer and extremely low indoor temperatures in winter which is most likely due to the poor thermal efficiency of houses. The main reason for this is that RDP houses often lack adequate thermal insulation and ceilings (Makaka & Meyer, 2005). A comprehensive characterisation of indoor temperatures across winter and summer periods, the link between the insulation and indoor temperatures, and the subsequent link to energy use have, however, not yet been fully explored.

The study sought to understand this link as it severely affects low-income households who have limited access to resources, i.e. limited ability to improve their living conditions. Studies by Mdluli and Vogel (2010), Nkosi *et al.* (2017); Makonese *et al.* (2017) and Mgwambani *et al.* (2018) have

established prevalent dependency on solid fuels for indoor heating in low-income settlements which further degrades indoor and ambient air quality leading to increased health risk. The study sought to investigate and characterise the problem of poor thermal insulation in RDP structures on the South African Highveld. To help in the investigation of the complex causal relationships between quality of housing (thermal insulation), indoor temperatures and domestic energy use the study performed indoor measurements, aerial thermography and domestic energy surveys in three low-income settlements.

1.3 Research aim

This study aims to investigate the link between indoor temperatures, thermal insulation, and domestic energy use in low-income households on the South African Highveld.

1.4 Research objectives

The following objectives informed the aim of the study:

1. Characterise indoor temperatures in low-income residential dwellings on the South African Highveld.
2. Characterise thermal insulation in low-income residential dwellings on the South African Highveld.
3. Determine the extent to which thermal insulation can be characterised through aerial thermography.
4. Characterise the link between thermal insulation and domestic energy use.

1.5 Contribution of the study

This study contributes to the body of knowledge by providing a comprehensive analysis and characterisation of indoor temperatures in low-income dwellings on the South African highveld. This is done across winter and summer periods and for settlements in different geographical regions. This characterisation provides additional insight into the extent to which inhabitants of low-income houses are exposed to extreme indoor temperatures. The study further makes a methodological contribution by proposing and testing a novel approach for the identification of poorly insulated houses in a settlement through remote sensing techniques. This is the first study to test such an aerial thermography approach in the South Africa context. The study further highlights the effects that poorly insulated dwellings can have on residents as a result of exposure to extreme indoor temperatures.

1.6 Research design

The study adopted a mixed-method approach to achieve the aim and objectives and therefore employed both quantitative and qualitative methods. Quantitative methods were used to inform Objectives 1 to 3, while qualitative methods were used to inform Objective 4. Figure 1.1 illustrates the research design, which was applied in the study, while a detailed description is provided in Chapter 3. The study was conducted over three settlements in the Highveld: KwaZamokuhle, KwaDela and Jouberton. Ethical factors considered in the study are discussed in the following section.

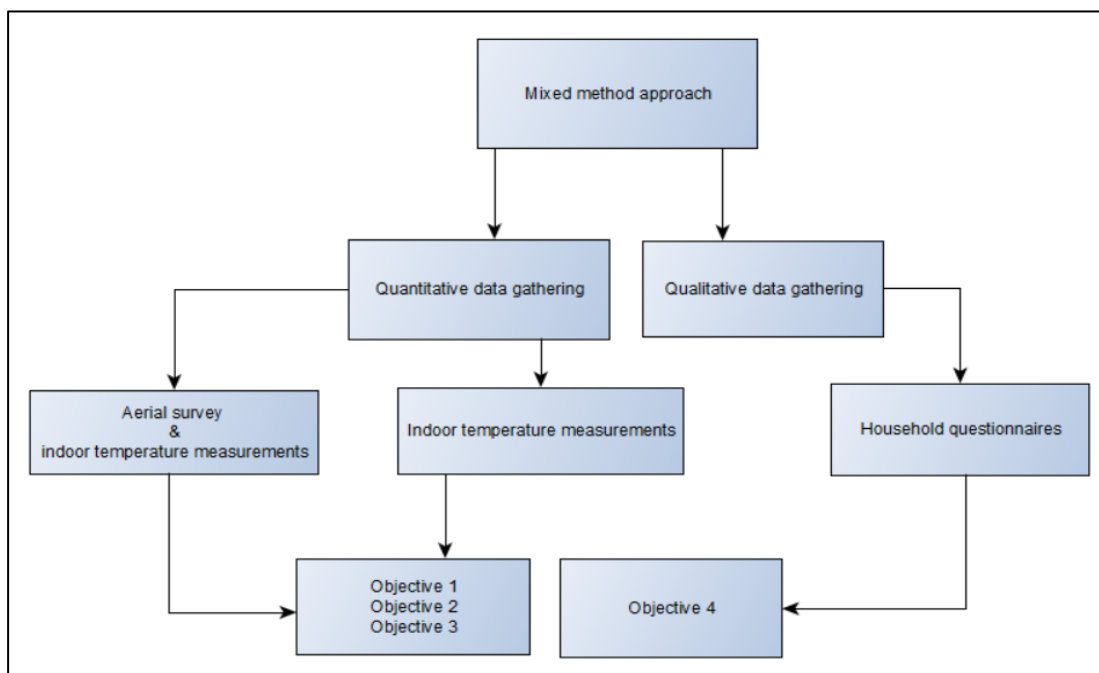


Figure 1.1: Flow chart showing a brief outline of the study research design

1.6.1 Ethical considerations in the study

It is necessary for studies that involve human contact to adhere to ethical standards, and the study was, therefore, subject to ethical review. Ethical clearances were obtained from the North-West University Health Research Ethics Committee for KwaDela (ethics number **NWU-00066-13-A3**) and KwaZamokuhle (ethics number **NWU-00191-14-A3**). Clearance for the Jouberton survey was obtained under the PHIRST (Prospective Household Observational cohort study of Influenza, Respiratory Syncytial Virus and other respiratory pathogens community burden and Transmission dynamics in South Africa) from the University of Witwatersrand, Johannesburg (ethics number **HREC 150808**). The following key ethical considerations are highlighted.

Informed consent

To safeguard participants, written informed consent was obtained from all potential contributors (across all three study areas) before the commencement of the study. An effort was made to explain the purpose of the study as well as the risks involved in the study to all participants in their native language. Following the explanation, the participants were asked to decide whether they would be willing to participate in the study. The right of participants to opt-out at any stage of the study if they so choose (Cohen *et al.*, 2011; Blanche *et al.*, 2016) was respected and exercised throughout the study.

Privacy and confidentiality

The study took steps to ensure that it was not too intrusive on the privacy of households, and this was maintained throughout the study (Polit & Beck, 2010). Furthermore, the study ensured that the participants' identities were not linked in any way to the dwellings being studied using codes as identifiers of sampled dwellings instead of using actual house numbers (Polit & Beck, 2010; Fouka & Mantzourou, 2011). Anonymity revolves around the idea that information gathered from participants should not in any way link them to their true identity (Cohen *et al.*, 2011). Furthermore, consent forms had no real names of participants but instead used codes as identifiers throughout the study. It was important that the study-maintained confidentiality of the data gathered. This was done through non-disclosure of thermal dwelling performance data to third parties, save for the study thesis and publications (Babbie, 2013).

Beneficence - Do no harm

During the surveys contributors were not subjected to any risk, harm or discomfort resulting from the study activities (Polit & Beck, 2010), thus minimising any potential harm to participants (Fouka & Mantzourou, 2011, Babbie, 2013) as well as maximising possible benefits that accrue to contributors (Newman & Kaloupek, 2009). Throughout the study, no harm or accident befell any participant.

1.6.2 Reliability and validity of the study

Reliability refers to the ability of a research technique to yield accurate and consistent data repeatedly (Polit & Beck, 2010; Babbie, 2013), including the dependability, consistency and replicability of instruments and techniques to reproduce similar results under the same conditions (Cohen *et al.*, 2011). The study addressed the issue of reliability by ensuring the calibration of instruments, standardising the placement of instruments and the manner of measurement. Sampling across diverse study sites and over different periods also contributed to the reliability of the results.

Validity refers to the extent to which an empirical measure reflects meaning in a subject under study (Babbie, 2013) while, Blanche *et al.* (2016), refers to validity as a measure to which an instrument does what it is intended to do. Additionally, another element that concerns the quality of evidence that the researcher yields is the link between independent and dependent variables (Polit & Beck, 2010). The study used two instruments, indoor temperature sensors and aerial infrared thermal sensors. In the study, the independent variable for Objectives 1 and 2 was regarded as ambient temperature with the dependent variable being indoor temperature. For Objective 3, the independent variable was regarded as indoor temperature with the dependent variable the being rooftop temperatures. “Validity” in this study was further cemented by selecting the right instrumentation for both indoor temperature measurements and aerial survey thermography with all the instruments going through a calibration process before deployment to take measurements.

1.7 Structure of the document

This section highlights the structure of the document, as outlined in Figure 1.2. The study is composed of eight chapters. Chapter 2 deals with the Literature Review while Chapter 3 presents the Methodology. Results and Discussions are presented from Chapter 4 to Chapter 7, while Chapter 8 gives the conclusions from the study.

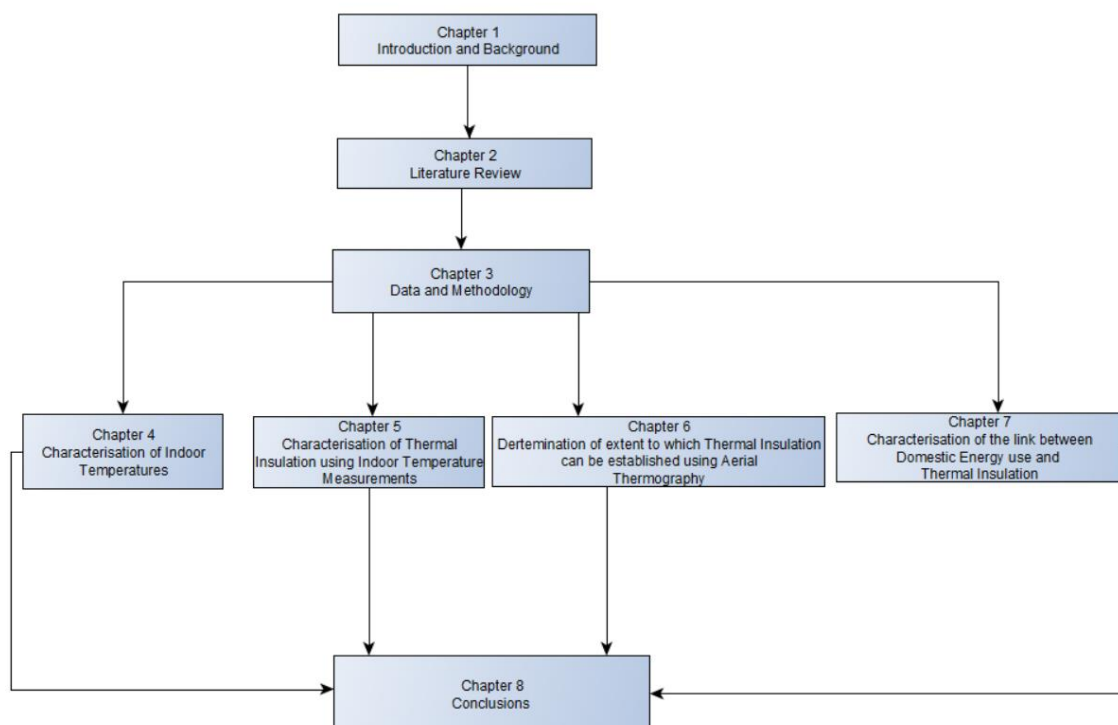


Figure 1.2: Flow chart representing the structure of the thesis

1.8 Summary

Chapter 1 provided a background to the study by highlighting and contextualising the research aim, objectives as well as giving a brief overview of the methodological approach that was followed. A literature review is presented in Chapter 2, while the detailed methodological design followed in the study will be discussed in Chapter 3. Results are presented and discussed in Chapters 4 to 7 and conclusions are presented in Chapter 8.

CHAPTER 2: LITERATURE REVIEW

This chapter provides an overview on the low-income housing sector, determinants of indoor thermal environments, physical health effects of extreme temperature exposure and domestic energy use as well as the potential health effects of solid fuel use in low-income households.

2.1 Introduction

Residential dwellings play a fundamental role in protecting occupants against extreme temperatures and weather conditions, thus making dwelling quality (thermal insulation) a profound determinant of indoor living conditions. Low-income households generally face a challenge in obtaining decent quality housing. Furthermore, the low-income housing sector is relevant because households in this category are more prone to extreme poverty and vulnerable to the effects of climate change. As a result, these households often have a higher dependency on solid fuels for cooking and heating purposes which pose possible health risks. Hence, this study explored the link between thermal insulation, indoor temperature and domestic energy use. This chapter provides an overview of the low-income housing sector, determinants of indoor thermal environments, domestic energy use, as well as the probable health effects of poor indoor environments. The low-income housing sector is discussed first.

2.2 Low-income housing

Low-income housing is a class of residential dwellings that is affordable to low-income earners. In South Africa, to be considered for the government-subsidised housing programme (which focus on low-income households), a household must have a monthly income of less than ZAR 3,500 (SERI, 2018). Throughout the writeup, the terms “low-income housing” and “low-cost housing” are used interchangeably.

2.2.1 Global status of low-income housing

According to United Nations Statistics (UN Stats, 2019), an estimated one billion people worldwide reside in sub-standard housing which includes slums/shacks, low-income dwellings, and informal dwellings. Approximately 80 % of these people come from just three regions: Eastern and South-Eastern Asia (370 million), sub-Saharan Africa (238 million) and Central and Southern Asia (227 million) (Bello-Schünemann & Aucoin, 2016). In India the shortage of housing for low-income households increased from 10.4 million in 1991 to 15.5 million in 2001 (Sivam &

Karuppannan, 2002) while in Malawi over 70 % of the urban population is estimated to still live in informal settlements (Adams, 2016). Furthermore, Ormandy and Ezratty (2016) indicated that people of low socioeconomic status generally have little disposable income resulting in them often occupying thermally inefficient dwellings. It is estimated that more than 60 % of Africa's population reside in informal dwellings and that the urban population will increase to around 1.2 billion shortly (UN Habitat, 2015). This expected growth will place significant pressure on the housing sector in Africa and its ability to provide residents with good quality housing. In the next section, the status of the low-income housing sector in South Africa is expounded.

2.2.2 Status of low-income housing in South Africa

Low-income government subsidised housing in South Africa is mainly provided through the Department of Human Settlements RDP programme and caters to households with a monthly income of less than ZAR 3,500 (SERI, 2018). A new bill, proposing an expansion of the criteria against which households are evaluated has, however, recently been tabled. Proposed changes include, amongst others, a criterion through which child-headed households and households headed by individuals older than 60 years, could also qualify for a subsidy (DHS, 2016). Although the South African government was able to provide an estimated 3.7 million housing units in the period between 1994 and 2014 (Eglin and Kenyon, 2017), the housing backlog has still risen from 1.5 million to 2.1 million since 1994 (IRR, 2015). Low-income housing in South Africa is, however, not just developed through subsidy programmes, as is evident from the rising backlog of subsidy housing. In many cases, low-income households must revert to building their housing structures, which can range from informal structures to formal structures. Low-income housing is a common feature in the South African landscape, and will, in all likelihood, become more and more relevant in the future. For purposes of this study, a low-income household was regarded as one whose monthly income is equal to or lower than ZAR 3, 500. The following section outlines the different classes of low-income dwellings in South Africa mainly divided into formal and informal.

2.2.3 Classes of low-income dwellings in South Africa

Low-income residential dwellings in South Africa can be classified as either informal low-income housing or formalised low-income housing. Formalised low-income housing refers to dwellings that were developed through legally prescribed township establishment processes while informal low-income housing refers to dwellings that were erected without the necessary approval from authorities. In this study, the focus fell on formalised low-income housing in the form of government-subsidised housing (often referred to as RDP housing). However, to provide a thorough overview of low-income housing in South Africa, informal housing will also be discussed.

2.2.3.1 Government-subsidised RDP housing

According to Stats SA (2017), approximately 80 % of households were living in formalised dwellings in 2017. The provinces with the highest percentage of households living in formalised dwellings were Limpopo (91.7%), Mpumalanga (86.9 %) and the Northern Cape (86.0 %) (Stats SA, 2017). These statistics represent a variety of formalised housing types, such as townhouses and apartment buildings, but also RDP houses. A typical house built under the RDP, i.e. an RDP house, has an approximate floor area of 36 m² and is typically located on a property of roughly 250 m² (Moola *et al.*, 2011). In most cases, an RDP house will consist of an open-plan bedroom, living room and a kitchen (Also refer to Annexure 4 for a floor plan of RDP structures). These homes are mostly built from brick and mortar with galvanised iron roofs with little or no insulation (Wentzel, 2006; Moola *et al.*, 2011) however in some instances roofing was from asbestos material (Mathee *et al.*, 2000). Both roofing types present possible challenges for indoor environments as asbestos has been found to contribute to respiratory ailments such as asbestosis, while corrugated iron sheets can lead to high indoor temperatures. According to Govender *et al.* (2011), many RDP houses are of inferior quality as a result of being built in large numbers and in short timeframes. These quality issues include non-plastered walls, leaking roofs, as well as cracked walls (Govender *et al.*, 2011).

According to a national survey conducted by Stats SA (2012), 16.3 % of households reported that their RDP dwellings had weak walls while 16.4 % reported weak roofs. In the North West Province, 15.4 % reported weak walls while 15.9 % reported weak roofs, while in Mpumalanga Province 12.1 % and 13.7 % were reported respectively (these are the two provinces in which the study was conducted). Weak walls and weak roofs imply structural defects which could result in dwellings becoming energy-inefficient and occupants being exposed to poor indoor thermal environments. Besides the structural issues often associated with RDP houses, informal shack structures are often also erected against and around them (Govender *et al.*, 2011). Section 2.2.3.2 provides an overview of informal dwellings with specific reference to shacks.



Figure 2.1: Image showing typical low-income settlement in South Africa mainly composed of RDP dwellings (Matandirotya, 2019)

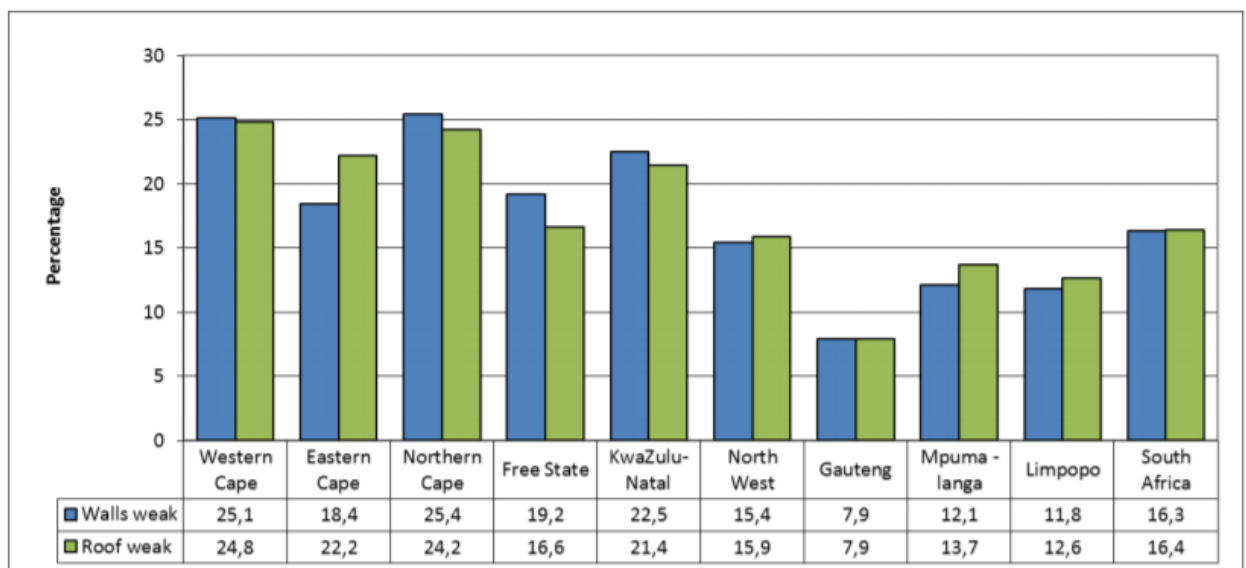


Figure 2.2: Percentage of households reporting weak walls and roofs in RDP houses by province (Source: Stats SA, 2012)

2.2.3.2 Informal dwellings and shacks

An informal dwelling is defined as a makeshift structure whose construction has not been approved by the relevant authorities. Examples of these are backyard shacks, which are often connected to formal structures, or freestanding shacks located on undesignated land (Stats SA, 2017). In South Africa, an estimated 13.5 % of all households live in squatter housing which is usually concentrated on the periphery of towns and cities (Stats SA, 2017). This amounts to between 1.1 and 1.4 million households in South Africa, living in informal housing (Del-Mistro & Hensher, 2009; SERI, 2018). Although the number of shacks and informal dwellings in South Africa decreased in the period between 2001 and 2011 (Stats SA, 2013), the number of households living in shacks, and more specifically backyard shacks, increased over the same period, and it is estimated that approximately 150 000 new households house themselves in this way every year (Stats SA, 2017). The two provinces with the highest number of households residing in shacks are the North West (19.9 %) and Gauteng (19.8 %) provinces (Stats SA, 2017). Residents of informal dwellings, such as shacks, are often faced by challenges such as poor living conditions and lack of services such as electricity, water supply and waste management (Chikoto, 2009; SERI, 2018). In addition to these challenges, residents are also exposed to living conditions characterised by often extreme temperatures. Figure 2.3 shows a typical shack constructed from corrugated iron sheets, which is a material that offers very little insulation from ambient temperatures. Section 2.3 explores the factors that affect indoor thermal environments.



Figure 2.3: Images showing a typical shack (Source: Matandirotya 2019)

2.3 Determinants of indoor thermal environments

This section outlines the factors that influence indoor thermal environments in residential dwellings. These factors include the physical characteristics of a dwelling, outdoor meteorological conditions, occupant behaviour and, to a lesser extent, the urban heat island.

2.3.1 Thermal insulation

Thermal insulation can be defined as the layer in the housing envelope that is responsible for regulating the thermal environment inside a house (Hong *et al.*, 2008; TIASA, 2010; German, 2010; Nienhuys, 2012; Salih, 2015). In the context of the study, housing envelope refers to the superstructure of the residential dwelling. The thermal capacity and conductivity of construction material, type and number of windows in a house, orientation of the dwelling, as well as the dwelling's size, all affect a structure's ability to gain, retain and emit heat (IOM, 2011; Kenny *et al.*, 2019). The thermal performance of a dwelling is, therefore, determined by the thermal properties of the material used for construction (Al-Homoud, 2005), and without a properly functional insulation, approximately 42 % of heat escapes through the roof, 10 % through the floor and 24 % through the walls (TIASA, 2010; Canterbury District Health Board (CDHB), 2012). Dwellings that lack adequate thermal insulation can be expected to offer poor indoor thermal environments (Loughnan *et al.*, 2015; Naicker *et al.*, 2017) as has been observed in many RDP dwellings in South Africa which were found to be highly sensitive to outdoor temperature fluctuations, suggesting that these types of dwellings are generally poorly insulated (Makaka & Meyer, 2005). Furthermore, a study by French *et al.* (2007) found that older dwellings with old insulation are likely to show reduced thermal performance when compared to newer dwellings, suggesting that more modern houses would generally be more comfortable throughout the year (French *et al.*, 2007; TIASA, 2010; Grimes *et al.*, 2011; Nienhuys, 2012; Ormandy & Ezratty, 2014; European Union Parliament, 2016; Bouzarovski *et al.*, 2016). In addition to the improvement of indoor thermal conditions during winter (CDBH, 2012), insulated houses in New Zealand were found to contribute to a reduction in respiratory-related illnesses, associated hospitalisation, pharmaceutical costs and mortality rates (Grimes *et al.*, 2011). Similarly, in South Africa, a study concluded that health co-benefits could accrue from insulation retrofits while household expenditure on energy could be reduced (WHO, 2018a). This also concurs with a study in Ireland which concluded that housing retrofitting programmes would result in energy savings, health benefits and avoidable mortality (Chapman *et al.*, 2009). These studies indicate that without adequate insulation a building cannot adequately regulate its indoor environment, suggesting that the thermal insulation component of a structure, therefore, play a very critical role in limiting

occupant's exposure to extreme temperatures. Apart from thermal insulation, other factors that influence indoor temperatures, as outlined in the following section.

2.3.2 Other physical factors

In addition to thermal insulation, indoor thermal environmental conditions are also influenced by the interrelationship between a structure's foundation, floor, roof, size, and heating and ventilation system (IOM, 2011). Low-cost housing units in South Africa, for example, have been characterised by un-plastered single brick walls, that get very cold when exposed to cold weather and very hot when exposed to hot weather for prolonged periods (Naicker *et al.*, 2017). In terms of dwelling size, Yohanis *et al.* (2008) found a positive association between dwelling size and level of energy consumption which suggests that larger dwellings are more difficult to heat, therefore affecting the indoor thermal environment. Figure 2.4 provides an overview of factors that influence indoor thermal environments, including physical characteristics, occupant's behaviour, the material used for construction as well as the ventilation systems of a dwelling. Regarding RDP structures, Wright *et al.* (2019) noted that they are normally small in size and constructed from low-quality materials, making them vulnerable to extreme weather effects. In the next section, the effects of meteorological conditions on such structures are discussed.

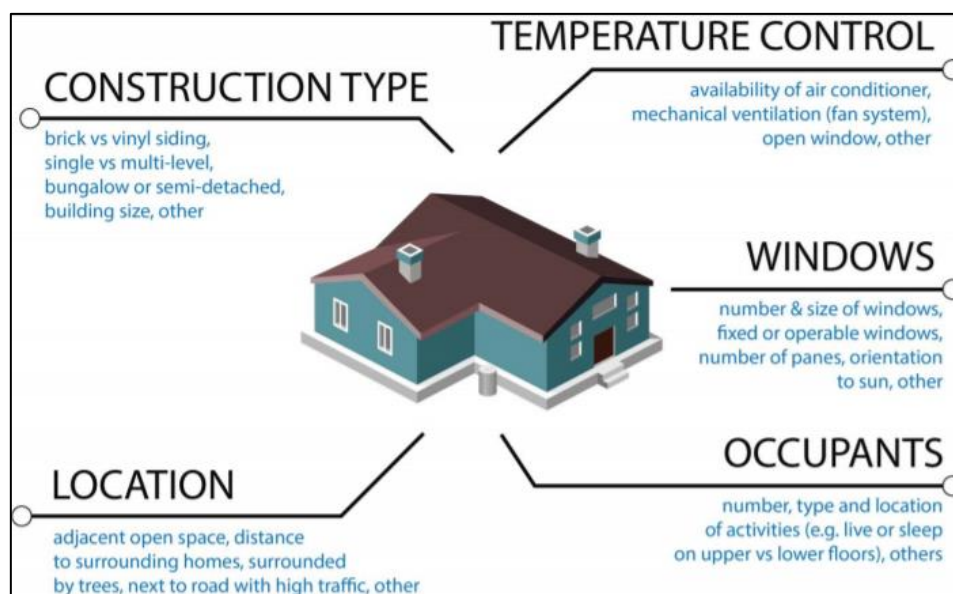


Figure 2.4 Physical dwelling characteristics that determine heat gain and retention: (Source: Kenny *et al.* 2019)

2.3.3 Meteorological conditions

Seasonal variations typically determine indoor temperatures meaning that indoor temperature is a function of ambient temperature changes, which includes the amount of solar energy reaching

a dwelling (IOM, 2011; Tamerius *et al.*, 2013; Nguyen *et al.*, 2014; Kenny *et al.*, 2019). The relationship between indoor and ambient temperatures is most significant at temperatures higher than 20 °C (Tamerius *et al.*, 2013; WHO, 2018a) and subsequently, high ambient temperatures result in high indoor temperatures in poorly insulated dwellings (Kowanacki *et al.*, 2019). Inside of dwellings, internal variations exist as a result of horizontal and vertical temperature gradients which are mainly influenced by external meteorological conditions (Oreszczyn *et al.*, 2006; Ormandy & Ezratty, 2014). This means that different temperatures could be observed in a room if measurements are taken at different heights and distances from walls and windows. Apart from meteorological conditions, climate change and extreme weather events also influence indoor thermal environments.

Climate change projections are estimating a 1.5 °C to 2 °C ambient global mean temperature rise above pre-industrial times (IPCC, 2007; Ebi *et al.*, 2018; Kapwata *et al.*, 2018). Additionally, Southern Africa has been identified as a climate change hot spot with the region expected to experience a 2 °C mean temperature rise compared to the global mean of 1.5 °C (IPCC, 2012; van Wilgen, 2016). Climate change affects human health through increased exposure to episodes of extreme heat (Hoegh-Guldberg, 2018), for example, heat-waves. Incidences, frequency and intensity of extreme weather events, such as heat-waves, are generally on the rise and are especially relevant in urban environments (IPCC, 2007; Mavrogianni *et al.*, 2010; White-Newsome *et al.*, 2012; Anderson *et al.*, 2013). In Africa, in particular, the frequency of extreme heat-waves has increased from 12.3 per year to 24.5 per year between 2006 and 2015 (WHO, 2018a). During extreme heat events, night-time outdoor temperatures are often elevated, resulting in indoor temperatures also remaining high (Kenny *et al.*, 2019). This increase in heatwave occurrence is expected to especially affect low-income residential dwellings which in most cases are not sufficiently insulated and ventilated.

Heat-waves have also been observed in other parts of the world such as Northern Europe where notable heat-waves were observed in 2003 and 2005 which contributed to an estimated 15, 000 premature deaths in France and an estimated 70, 000 across 16 other European countries (Vandentorren *et al.*, 2006; Lomas & Porrit, 2017; Kowanacki *et al.*, 2019). Furthermore, between 2001 and 2012, heat stroke in India was estimated to account for 4 % of all deaths resulting from natural calamities (Tasgaonkar *et al.*, 2018), while during a 2010 heat-wave an estimated 4,462 deaths were attributed to extreme heat exposure (WHO, 2018a). Groups of people at high risk of heat-related illnesses include the elderly, young children and people with existing underlying chronic physical health conditions (Hoegh-Guldberg *et al.*, 2018). Studies have found that as people get old, their ability to deal with external environmental stressors decreases due to a

reduction in organ functionality (IOM, 2011) as affirmed by Kenny *et al.* (2014), Flynn *et al.* (2005), Keatinge (2003) and Vanhems *et al.* (2003).

2.3.4 Household socio-economic status and human behaviour

The ability of a household to regulate indoor thermal environments can often be linked to its socio-economic status. According to Kenny *et al.* (2019), indoor thermal environments of low-income households, in particular, are closely associated with ambient meteorological conditions, which concurs with Harlan *et al.* (2014), who found a relationship between socio-economic status and risk to heat exposure. Most low-income households reside in free-running residential dwellings, which can be defined as structures whose indoor thermal environment is naturally controlled and non-mechanical. This implies that human behaviour, such as the opening of doors and windows, also plays a significant role in determining indoor thermal environments (Ormandy & Ezratty, 2016). However, people living in low-income areas are often exposed to high crime rates, and hence might be afraid to open doors and windows during the night for fear of being victimised (IOM, 2011), which in turn might lead to higher indoor temperatures. Occupant behaviour has been estimated to account for 51 % of the variance in heat loss across different types of dwellings (Kelly *et al.*, 2013). Within the dwelling, there are also several other indoor sources of radiant heat such as cooking appliances and space heating appliances that release heat into the immediate indoor environment contributing to increasing temperatures (Ormandy & Ezratty, 2016). Furthermore, the human body is estimated to emit 65 to 80 watts of energy per hour per person, which also contributes to the increase in indoor temperatures (Ormandy & Ezratty, 2016), especially in households comprising of a large number of people. These studies illustrate the complexity of challenges often faced by low-income households who are mostly limited to natural ventilation approaches. Besides human behaviour, the physical properties of a town or city can also affect indoor temperatures, as highlighted in the next section.

2.3.5 Physical properties of the city

The physical properties of a town or city (such as roads and buildings) can influence the meteorological conditions experienced in and around the urban area. Heat islands form when large urban surfaces (buildings, roads, pavements) absorb solar radiation during the day and transfer the energy to the immediate environment during the night (Kenny *et al.*, 2019) and is mostly observable over larger the urban areas (Voogt & Oke, 2002). This generally results in higher ambient temperatures symbolised by the reduction of daytime vs night time temperature

differences (Santamourious *et al.*, 2001; Kenny *et al.*, 2019). The urban heat island leads to night time temperatures that could be as much as 4 °C higher than adjacent rural areas (Ormandy & Ezratty, 2016). This increase in temperature within the settlement, i.e. higher ambient temperatures, leads to a rise in indoor temperatures which are often closely related to ambient temperatures (Ashtiani *et al.*, 2014), especially in low-income dwellings. Low-income households in urban areas are therefore more likely to be affected by the effect of the urban heat island phenomena than their rural counterparts.

2.4 Domestic energy use

A link exists between the type of residential dwellings and the type of energy used by people residing in low-income settlements. Previous studies have shown a close association between low-income households, energy poverty and reliance on solid fuels. This section presents an overview of energy use in low-income households, with specific reference made to the use of solid fuels. The study used the terms of energy and fuel interchangeably.

2.4.1 Solid fuel use for domestic purposes

Almost three billion people worldwide depend on solid fuels – biomass (wood, dung, agricultural residues) and coal – for at least some of their cooking and space heating requirements (WHO, 2016; Makonese *et al.*, 2017). It is estimated that the use of these fuels contributed to an estimated 3.5 million premature deaths in 2010 alone, mainly as a result of indoor air pollution (WHO, 2016). In Africa, an estimated 600 million people have no access to electricity and still rely on solid fuels to satisfy their domestic energy needs (WHO, 2000; Makonese *et al.*, 2017). Furthermore, it is expected that by 2030, 2.7 billion people will be dependent on biomass as their main energy source (Mekonnen & Kohlin, 2009). Lim *et al.* (2013) estimated that a single household consumes two tonnes of biomass per year resulting in a total of 730 million tonnes of biomass burned and one billion tonnes of carbon dioxide released into the atmosphere each year.

In South Africa, it is estimated that half of the population depend on a mixture of coal and wood for cooking, water heating and space heating (Masekameni *et al.*, 2017). According to Stats SA (2016), 38 % of non-electrified households in South Africa use firewood to meet their energy needs, while 16 % use paraffin and another 13 % use paraffin and wood as energy sources. Furthermore, it is estimated that 80 % of residents of electrified dwellings also still rely on solid fuels for uses such as space heating and cooking (Nkosi *et al.*, 2017; Mdluli & Vogel, 2010). This was confirmed in a study by Nkosi *et al.* (2017), who determined that 90 % of households with

access to electricity still use solid fuels for space heating, cooking and boiling water. This trait could be ascribed to the costs associated with electricity and the fact that electricity in developing countries is mainly utilised for lighting rather than cooking (Malla & Timilsina, 2014). It is estimated that households consume approximately one million tonnes of coal annually in South Africa, most of which are burnt during winter for space heating (Winkler *et al.*, 2000; Wagner *et al.*, 2005). The majority of these households are located in the Gauteng and Mpumalanga provinces where coal is widely available with 15 % of households in Mpumalanga province utilising coal for space heating purposes which can be attributed to its close proximity to the major coalfields. Dependency on solid fuels to satisfy domestic energy requirements is still a global challenge, more so for low-income households whose limited resources reduces their access to clean modern energy sources such as electricity.

2.4.2 Determinants of domestic fuel choices

Several factors influence the choices made by households when decisions on fuel to use for heating and cooking purposes are taken. Many of these are socio-economic related factors such as disposable income, household size, and level of education. It has been observed, for example, that households will switch to cleaner, more modern fuels, as disposable income increases (Bansal *et al.*, 2013; Nlom & Karimov, 2015; Heltberg, 2005). However, this does not mean that households will stop using solid fuels altogether, but rather diversify their energy mix by also making use of cleaner fuels (Mekonnen & Kohlin, 2008; Akpalu *et al.*, 2011). Another factor that influences household fuel choices is fuel price which concurs with findings by Jain (2010) and Schlag and Zuzarte (2008) who also established that solid fuels continued to be favoured in many parts of the world, mainly due to the low costs in accessing such fuels. Additionally, household size also influences fuel choices, as the household size affects energy needs (Malla & Timilsina, 2014, Makonese *et al.*, 2017). Nlom and Karimov (2015) further found that the level of education of the household head also plays a role, as they found that households with educated household heads were less likely to use firewood for cooking and more likely to use substitutions such as LPG or Kerosene. These studies highlight the challenges on domestic energy use as choices are hinged on several factors ranging from the socio-economic status of the individual household to the available sources in a region.

2.4.3 Energy poverty and low-income households

According to Boardman (1991), an 'energy poor household' is one that spends more than 10 % of its income on energy to heat its home to acceptable indoor thermal standards. Energy poverty is quantified by determining the energy burden of households based on the notion that poor

households spend a higher proportion of their income on energy than their wealthier counterparts (Ismail, 2015). It is mainly driven by three factors, which are income, cost of energy, and the energy efficiency of the dwelling (Brounen et al., 2012). Additionally, a dwellings size, age and the type of heating system used, also contribute to energy poverty. In Africa, recent estimates are that as many as 620 million people are facing energy poverty (Mbewe, 2016). In the South African context, energy poverty has often been viewed as a lack of access to modern, clean fuels such as electricity. Although South African rates of energy poverty are lower than neighbouring countries, it remains a country where a large proportion of the population is struggling to extract itself from energy poverty (Sylvia et al., 2015) with 52 % and 34 % of households reported to be energy poor in 2008 and 2014/2015, respectively (Mbewe, 2016). Energy poverty in South Africa is further exacerbated by the poor quality of housing (Howden-Chapman et al., 2011) as poor households generally have to spend a large proportion of their income to heat thermally insufficient dwellings (Klunne, 2002). In cases where households can't afford to attain fuel, they are often depended on natural ventilation to manage indoor temperatures, i.e. opening windows and doors. The above studies highlight the close relationship between energy poverty and low-income households. Low-income households are likely to also be energy poor.

2.4.4 The link between energy poverty and thermal regulation

Exposure to low winter indoor temperatures is closely related to energy poverty, and poverty in general (Hamilton et al., 2017). As mentioned earlier, poor households spend a more significant percentage of their income on energy than their wealthier counterparts (Barnes et al., 2010). With little disposable income, low-income households may only be able to afford to live in energy-inefficient dwellings and may often not be able to afford enough energy to heat these dwellings (Ormandy & Ezratty, 2014). Energy poverty and poverty in general, are interlinked and exacerbate each other as low-income households are, in addition to being poor, are burdened with a high share of the energy-related costs to meet basic energy needs. As a result, households often resort to traditional forms of energy, such as wood and paraffin, to fulfil their basic energy needs. Being energy-poor implies the failure of households to regulate indoor environments.

2.4.5 Gender link to energy poverty

In many developing countries, the sourcing of solid fuels such as wood and coal for heating and cooking is primarily the responsibility of women (UNDP, 2013). While energy poverty is a burden of most poor populations, it can be argued that women are disproportionately impacted. The effects of energy poverty on women and girls are harsh and include travelling long distances to gather fuel, prolonged exposure to indoor air pollution, and decreased school attendance (UNDP,

2013). According to Brunner *et al.* (2012), single women are generally more susceptible to poverty, and subsequently energy poverty, and are often compelled to use cheaper and hazardous fuels such as wood and coal (SEA, 2017). There seems to be a close relationship between women and the phenomena of energy poverty as in most societies' women are the custodians of energy choices. The previous is especially true in developing countries. Section 2.4.6 presents the link between domestic energy use and climate change.

2.4.6 Domestic energy use link to climate change

Globally, household emissions of carbon dioxide (CO₂) account for approximately 17.8 % of direct CO₂ emissions from domestic combustion sources. Of that total, 11.3 % are indirect emissions resulting from electricity generation, while 6.5 % of emissions are generated at the household level, i.e. through the burning of solid fuels (WHO, 2011). Most solid fuel users in developing countries rely on simple technologies such as metal stoves, that often have no chimneys, resulting in incomplete and inefficient combustion and leading to the emission of potentially harmful compounds into the atmosphere (Bailis *et al.*, 2003). These compounds include well-mixed GHGs such as CO₂, Methane (CH₄), short-lived climate forcers (SLCFs) which include black and organic carbon (BC and OC), aerosols, as well as volatile organic compounds (VOCs) (Bailis *et al.*, 2015). After CO₂, black carbon is considered to be the second-largest contributor to climate change. Besides global warming effects, black carbon also has more regional effects such as the melting of glaciers caused by solar absorption by blackened ice and snow (Foell *et al.*, 2011). Methane (CH₄) is another potent greenhouse gas which stays in the atmosphere for decades, causing unbearable harm and contributing to climate change (WHO, 2006). According to Bailis *et al.* (2003), the net GHG emissions from residential energy use in Sub-Saharan Africa in 2000 were estimated to be 79 million tonnes of carbon (with 61 %, 35 %, 3% and 1 % coming from wood, charcoal, kerosene and LPG respectively). This total has probably increased significantly over the last 20 years. Studies have found strong linkages between domestic energy and global warming as particulate matter emitted into the atmosphere trap incoming solar radiation, thereby increasing atmospheric temperature as asserted by Zhang *et al.* (2010) who established a rising trend in the levels of carbon emissions from energy combustion in rural China from 8.89 x 10⁸ tonnes in 1979 to 28.74 x 10⁸ in 2007 mostly being derived from a dependency on coal. A similar situation prevails in South Africa where a study by Nkosi *et al.* (2017) established that households in KwaDela (a settlement on the South African Highveld) consumes an estimated 512 tonnes of solid fuels (wood, coal) per year thus contributing towards carbon emissions. Studies have linked carbonic emissions to global warming a phenomenon contributing to the anthropogenic driver to climate change.

2.5 Health impacts related to poor indoor thermal environments

Residents of dwellings characterised by poor indoor thermal environments are considered to be vulnerable to a variety of physical health-related impacts. These impacts relate to both the exposure to extreme temperatures and exposure to indoor air pollution. Thermal comfort guidelines for residential dwellings is first discussed, followed by the discussion on potential health impacts.

Indoor thermal comfort guidelines for residential dwellings

The WHO guidelines set a standard of 18 °C to 24 °C for healthy indoor environments (WHO, 1984; Critchley *et al.*, 2007; Santamouris *et al.*, 2014; Miller *et al.*, 2017; Kenny *et al.*, 2019). The temperature range is based on the WHO's guidance on home environments and means that dwellings should not be subject to indoor temperatures below 18 °C or above 24 °C (Ormandy & Ezratty, 2016). Although only guidelines, they are widely accepted, frequently applied in scientific studies, and has not been successfully challenged to date (Kenny *et al.*, 2019).

Physical health effects associated with exposure to extremely high indoor temperatures

Normal body temperature is maintained at approximately 37 °C by the anterior hypothalamus through the process of thermoregulation (Cheshire Jr, 2016; Hifumi, 2018). In circumstances where the atmospheric conditions limit the body's ability to effectively regulate itself (for example, during heat waves), the core temperature will begin to rise, and health problems might commence. This might result in heat stress which, in extreme cases, could lead to death (Robnson, 2000; Szekely *et al.*, 2015). Loss of salts and water through sweat can induce dehydration and salt depletion which in turn can lead to heat exhaustion, weakness, muscle cramps, nausea, mild confusion (Yamamoto *et al.*, 2007; Kovats & Hajat, 2008; Cheshire, 2016; Hifumi, 2018) and in extreme cases culminate into seizures or comas (Cheshire, 2016). Additionally, prolonged exposure to extremely high indoor temperatures increase incidences of heart attacks, heat exhaustion, heat rashes, bronchitis, pneumonia, respiratory diseases, as well as cardiovascular mortality (Santamouris, 2007; WHO, 2018a). Furthermore, heat stress can even exacerbate underlying medical conditions such as heart and lung diseases (Pantavou *et al.*, 2011; Sakka *et al.*, 2012; Kenny *et al.*, 2018) when temperatures rise above 40 °C (Hifumi, 2018). The ability of the body to regulate its core temperature depends on such factors as age, sex, fitness, as well as an adaptation from previous exposure (Robnson, 2000). Children under the age of five are particularly at risk because their thermoregulatory system is still immature (Kovats & Hajat, 2008; Ormandy & Ezratty, 2014) while individuals above 60 are at increased risk of suffering heat-

related health ailments because of physiological impairments in regulating core temperature (Wright et al., 2019) with heat associated physical health risk being severe heightened in the first 0 to 3 days after heat exposure (Gronlund *et al.*, 2016). In the United States, there is good evidence to suggest that people of lower socioeconomic status are at increased risk of death resulting from heat exposure during heat waves (Basu, 2009). Table 2.1 summarises the factors that increase susceptibility to health impacts associated with extreme indoor heat. These identified studies highlight the consequences of exposure to extreme high indoor temperatures; however, the most affected populations are the young and the elderly.

Table 2.1: Factors increasing susceptibility to health impacts associated with extreme indoor heat

Human factors	Vulnerability trait
Age	-The elderly particularly those above 75 -Very young children, toddlers and babies
Health status	-People with underlying physical health chronic conditions, for example, cardiovascular, diabetes, respiratory, renal conditions and epilepsy
Socio-economic	-People of low socio-economic status
Dwelling characteristics	-No means of external shading -Inadequate, ineffective structural insulation on the walls, windows and roof -Dampness in the structure reducing the effectiveness of thermal insulation
Ventilation	-Inefficient, ineffective, excessive and inappropriate ventilation -Lack of adequate means of controlling ventilation -Disrepair means of ventilation -None existence of air conditioning

(Source: Ormandy & Ezratty, 2016)

Physical health effects associated with exposure to extremely cold indoor temperatures

Prolonged exposure to indoor temperatures of less than 18 °C is associated with a variety of health risks such as worsening cardiovascular conditions, respiratory diseases, and other minor illness such colds and flu (Curriero *et al.*, 2001; San Miguel-Bellod *et al.*, 2018). Studies have found that although temperatures below 18 °C present a threat to physical human health (Ormandy & Ezratty, 2014), temperatures below 16 °C can result in respiratory or cardiovascular

injury (Collins, 1993; Omandy & Ezratty, 2014). Prolonged exposure to temperatures below 16 °C could further result in hypothermia (Omandy & Ezratty, 2014), which is when the core body temperature falls below 35 °C (Cheshire, 2016). Furthermore, indoor temperatures below 16 °C, particularly in the presence of high humidity, pose an exceptionally high risk to vulnerable groups such as the elderly and young children (WHO, 2011). Inhaling cold air inflames lungs and inhibits circulation, increasing the risk of respiratory conditions such as asthma attacks, pneumonia, worsening of chronic obstructive pulmonary disease, and infection (Anderson *et al.*, 2012; Santamouris *et al.*, 2014; Magalhaes *et al.*, 2016; Grey *et al.*, 2017; WHO, 2018a). All these studies provide some association between extreme low-indoor temperatures and physical health risks especially for those residing in poor quality housing.

Table 2.2: Factors increasing susceptibility to health impacts associated with extreme indoor cold

Human factors	Vulnerability characteristics
Age	-The elderly especially those above 75 -The very young, babies and toddlers
Health	-Those with underlying chronic physical health conditions -Chronic cardiovascular/respiratory/diabetes and arthritis
Socio-economic	-Those of low socioeconomic status
Gender	-Pregnant women
Dwelling factors	
Thermal insulation	-Inadequate structural thermal insulation on walls, windows and roof -Dampness that reduces the effectiveness of thermal insulation
Provision for heating	-Inappropriate, inefficient heating appliances
Ventilation	-Inefficient, ineffective, excessive ventilation Inadequate ventilation -Ill-fitting doors, windows and uncontrollable draughts

(Source Ormandy & Ezratty, 2016)

The elderly and young children are at increased risk as they are less able to generate heat by shivering or preserve heat by vasoconstriction (Cheshire, 2016). The elderly, who often possess weak biological mechanisms of temperature regulation, are more likely to fall into hypothermia (Tanaka & Takudome, 1991) and are more susceptible to temperature extremes, especially cold temperatures (Nguyen *et al.*, 2014; Anderson & Bell, 2009; Hajat *et al.*, 2007). In the USA, Curriero *et al.* (2001) estimated that mortality associations with colder temperatures were more significant for cities with higher proportions of elderly people. Low temperatures during winter cause an

estimated 40, 000 excess winter deaths in the UK (Santamouris, 2007) while excess winter deaths due to cold housing conditions have been estimated at 38, 200 per year across 11 European countries (WHO, 2018a). In South Africa, no literature linking extreme indoor cold temperatures to mortality could be found. Table 2.2 summarises the factors that increase susceptibility to extreme indoor cold.

Indoor air pollution and associated physical health impacts

As mentioned earlier, the incomplete combustion of biomass fuels leads to the release of harmful emissions that can potentially impact on human health (Heltberg, 2005; IOM, 2011; Akpalu, 2011, Masekameni *et al.*, 2017). Indoor air pollution is a daily reality for an estimated 3 billion people worldwide and is especially relevant in low-income regions where biomass fuels and coal are commonly burned for cooking and space heating (Klunne, 2002; WHO, 2004; WHO, 2014; Gordon *et al.*, 2014; Perera, 2017). It is estimated that indoor air pollution contributed to approximately 3.8 million premature deaths worldwide in 2016 (WHO, 2016) while an estimated 500, 000 premature deaths were attributed to solid fuel use in Asia and sub-Saharan Africa in 2010 (Lim *et al.*, 2012; Malla & Timilsina, 2014).

Indoor air pollution is the degradation of indoor air quality by harmful chemicals and other harmful substances. Contained spaces, such as houses, enables potential pollutants to concentrate and build up more than in open spaces (Kankaria *et al.*, 2014). As discussed earlier, low-income households in South Africa often burn solid fuels, and especially coal, for cooking and heating purposes (Buthelezi *et al.*, 2019). Domestic coal burning result in excessive concentrations of air pollutants that have a measurable negative impact on health (Wagner *et al.*, 2005). These include carbon monoxide, methane, non-methane hydrocarbons, as well as particulate matter (Bailis *et al.*, 2003). These pollutants, and especially the finer particles, can penetrate deep into the lungs causing severe health problems and it is estimated that ambient air pollution in South Africa has been responsible for approximately 2, 489 deaths per annum (Fried, 2010; Buthelezi *et al.*, 2019).

Studies further estimate that health-related effects associated with poor indoor air quality are higher than malaria and tuberculosis combined, with more than 4, 000 lives estimated to be lost per day worldwide (Masekameni *et al.*, 2017). Exposure to household air pollution is estimated to be among one of the most important causes of ill health in developing countries (Bonjour *et al.*, 2013) with the WHO estimating that more than 1.5 million people prematurely die each year due to exposure to smoke and other air pollutants from burning solid fuels (Jetter & Kariher, 2008; Morrissey, 2017). As a result, the WHO lists indoor air pollution amongst one of its top 10 health risks (WHO, 2018b). These studies highlight the association between domestic solid fuel use and

air pollution and suggesting that low-income households are more at risk of air-related ailments as solid fuel use remains extensive.

2.6 Summary

This chapter provided an overview of low-income housing both globally and locally. Determinants of indoor thermal environments were outlined, which included the physical characteristics of dwellings, outdoor meteorological conditions, household socioeconomic status, and the urban heat island. Climate change is considered to pose a threat to indoor thermal environments, especially for low-income households which often reside in inadequately insulated dwellings. Prolonged exposure to extreme indoor temperatures is believed to contribute to numerous health issues, especially amongst vulnerable groups such as children and the elderly. The indoor burning of solid fuel exacerbates these health impacts. The burden of disease is likely to increase as a result of confluence between climate change, poor housing and reliance on solid fuels within low-income settlements. Developing countries are likely to be more at risk as they lack adaptation capacity. Chapter 3 outlines the data and methodology used in the study.

CHAPTER 3: DATA & METHODOLOGY

This chapter presents a detailed account of the research design and methodology used for the study. The study objectives were achieved through the application of a mixed-methods research approach. The sections covered in this chapter include the study area, overview of methodology, data gathering, and the data analysis plans.

3.1 Introduction

The study was conducted on the South Africa Highveld in three low-income settlements that share similar climatic conditions and socio-economic characteristics. Data were gathered using *in situ* temperature measurements, aerial thermography and questionnaires that is, a mixed-methods approach. The study area is discussed first, followed by a detailed discussion of the methodological design of the study, which includes data capturing and analysis.

3.2 Study area

The three settlements, or study sites, were located on the South African Highveld and represented low-income settlements. The South African Highveld is a portion of the inland plateau of South Africa located at an altitude above 1,500 m but below 2,100 m (Balashov *et al.*, 2014) covering parts of the Free State, Gauteng, Eastern Cape, Northern Cape, North West, Limpopo and Mpumalanga. Summer in the region is normally in the period between October and February, while winter is between May and August. The three settlements allowed for the characterisation of indoor environments of low-income dwellings. The sites further provided the opportunity to explore the effects of different climatic conditions across the Highveld on indoor environments.

KwaDela

KwaDela (-26.463; 29.664) is a low-income settlement situated in the Msukaligwa Local Municipality which forms part of the Gert Sibande District in the Mpumalanga Province. The settlement is within the so-called Highveld Priority Area, an area characterised by high GHGs emissions from both domestic and industrial sources. According to Wernecke *et al.* (2015), approximately 97 % of the township has access to electricity although roughly 76 % of households still rely on solid fuels for either cooking or heating, or both. KwaDela covers an estimated area of 0.8 km² and has a total population of 3, 781 people, disaggregated as 1, 846 males and 1, 935 females (Stats SA, 2011). The settlement is dominated by government-subsidised Reconstruction and Development Programme (RDP) dwellings which made it a suitable study site. Stats SA (2011) estimated that 15.2 % of households had no source of income while the highest group of

earners was in the group of ZAR 19, 601 to ZAR 38, 200 per annum at 24.8 %, meaning that the highest group of households earned an estimated income of only ZAR 3,183 per month in 2011.

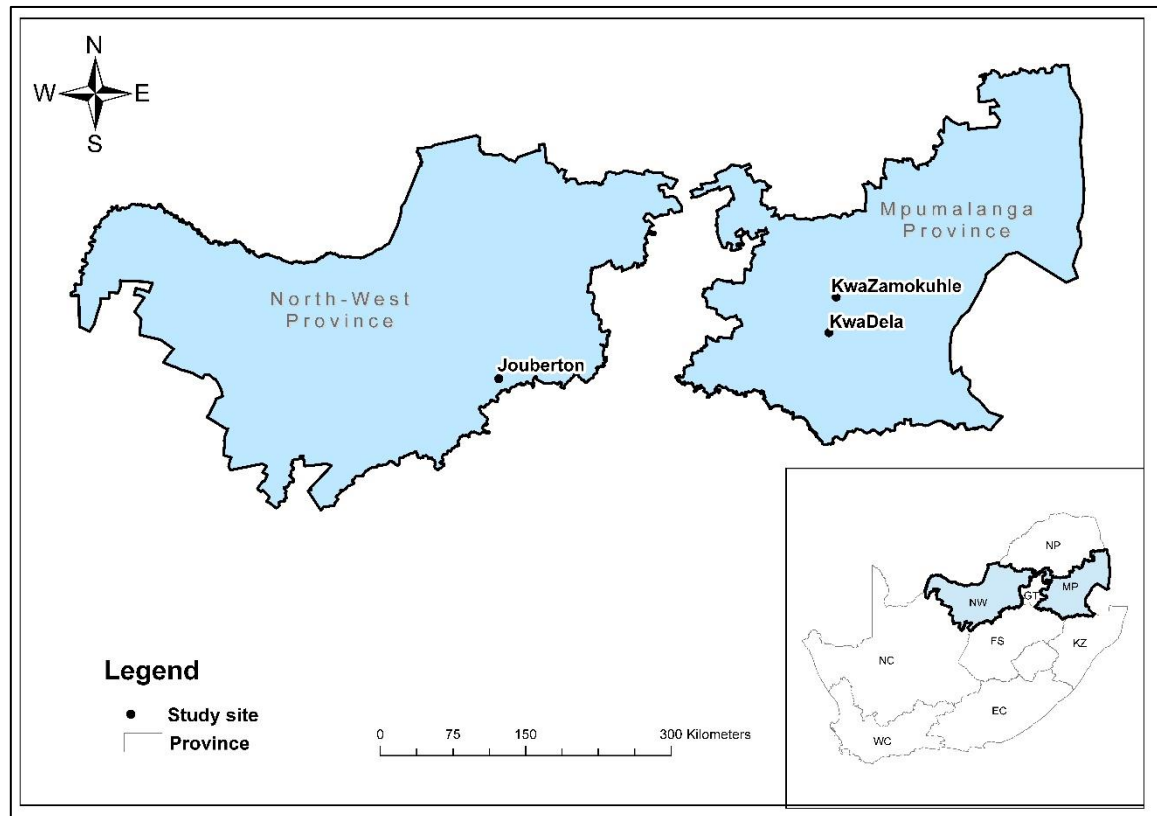


Figure 3.1: Study area and study sites

KwaZamokuhle

KwaZamokuhle (-26.134; 29.734) is a low-income settlement located in the Steve Tshwete Local Municipality that forms part of the Nkangala District in the Mpumalanga Province. KwaZamokuhle covers an area of approximately 3.8 km² and has a total resident population of 20, 500 disaggregated as 10, 50 males and 10, 000 females (Stats SA, 2011). The settlement is also characterised by government-subsidised RDP structures making it suitable as a study site. According to Stats SA (2011), 13.2 % of households earned no income, while the highest group of earners was in the group ZAR 38, 201 to ZAR 76, 400 at 21.2 %.

Jouberton

Jouberton (-26.893; 26.604) is a low-income settlement located in the City of Matlosana Municipality, which falls within the in the Dr Kenneth Kaunda District in the North West Province. The settlement covers an area of approximately 23.04 km² (Stats SA, 2011) with a total population of 2, 000 and 32,000 households disaggregated as 57,000 females and 54, 000 males (Stats SA, 2011). Most residential dwellings in the settlement are classified as RDP houses. According to the 2011 national census, 15.9 % of households had no source of income while the largest group of earners were in the group of income ZAR 19, 601 to ZAR 38, 200 per annum at 18.3 % (Stats SA, 2011). Figure 3.1 shows the location of the three sites in South Africa.

Amongst the three settlements, a similar socio-economic characteristic noted was that more than 10 % of households surveyed during the 2011 census had no source of income, while the majority of other households had a relatively low income. This would imply that the majority of households in the three settlements would have limited resources to spend towards regulating indoor thermal environments. Of the three settlements, KwaZamokuhle had the highest-earning households, earning between ZAR 38, 201 and ZAR 76, 400, while in comparison the highest earners in the settlements of KwaDela and Jouberton were earning between ZAR 19, 601 and ZAR 38, 200 at (Stats SA, 2011). According to the data, KwaDela was the most impoverished settlement followed by Jouberton and KwaZamokuhle. The crucial shared characteristic among the sites was that all are located on the Highveld with little variations in the climatic conditions.

3.3 Methodological design

The study employed a mixed-methods research approach, enabling a more in-depth enquiry as well as increasing the reliability and validity of the study (Kabir, 2016). Mixed-methods research is the class of research where the researcher combines quantitative and qualitative research techniques into one study. Researchers collect multiple datasets using different strategies, approaches and methods in such a way that is likely to result in complementary strengths (Johnson & Onwuegbuzie, 2004). Mixed method studies might involve concurrent triangulation of data collection, separate data analysis and the integration of datasets (Creswell, 2013). A conceptual framework illustrating the methodological design is shown in Figure 3.2.

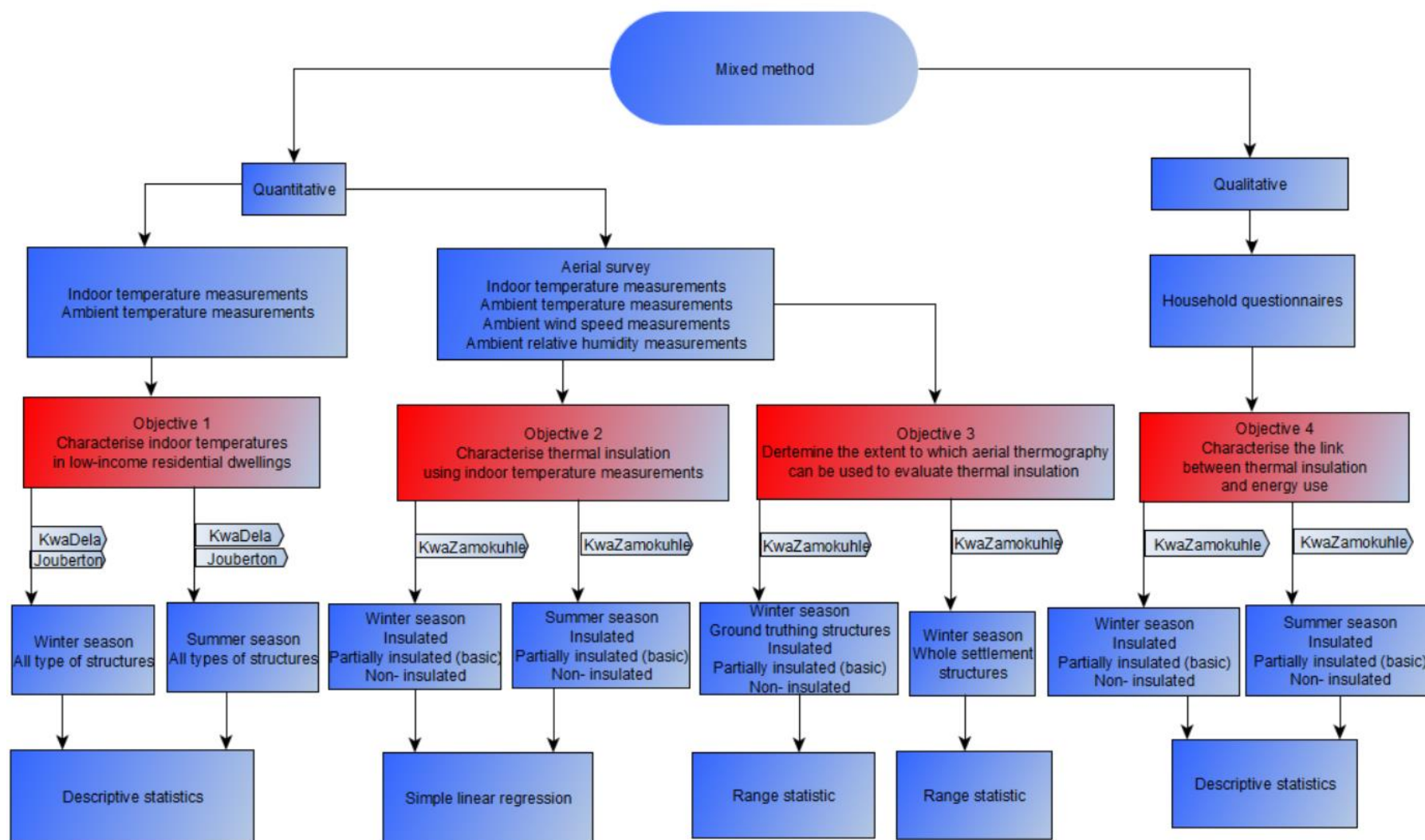


Figure 3.2: Conceptual diagram of the methodology

3.3.1 Data gathering

The protocols and steps that were followed during data acquisition are discussed in this section. Indoor temperature monitoring surveys were conducted on a seasonal basis (winter and summer), while the aerial survey was restricted to the winter season only. The reason for the aforementioned is because the surveys dealt with different study objectives which were conducted at different sites. The indoor seasonal- based monitoring allowed comparison of extreme heat/cold exposure over time and scale and across seasons, while the aerial survey aimed to determine the extent to which poorly insulated houses could be characterised through the use of aerial thermography. The study assumed that household indoor space heating would be high during the winter (night time) and, therefore, heat signatures of poorly insulated houses could be identified. Also, aerial thermography data gathering was only done during night time to minimise the effects of solar radiation on the targeted roofs (Hay *et al.*, 2011; Bitelli *et al.*, 2015). Night time gathering of the thermogram also meant that solar heat absorbed during day time would have disappeared from targeted surfaces, subsequently improving the quality of data gathered.

3.3.1.1 Dwelling unit selection (Objectives 1 to 4)

Only RDP dwellings were considered for selection in the study and were the only criterion applied for selection of dwellings in KwaDela and Jouberton (Objective 1). However, for KwaZamokuhle (Objectives 2 to 4), the insulation status of houses was also considered based on a thermal insulation retrofitting intervention done in the settlement. In addition to the selection of houses for long-term indoor temperature measurements, additional houses were selected in KwaZamokuhle to act as ground-truthing references. The total number of dwellings that were selected for participation in the study is summarised in Table 3.1 (indoor temperature monitoring, aerial survey – quantitative data) and Table 3.2 (domestic energy use – qualitative data). A total of 502 dwellings were sampled in the study. The study did, however, encounter challenges concerning some households choosing to withdraw from the survey midway through the study. In some instances, the study was able to replace some of those households that had withdrawn.

Table 3.1: Number of dwellings selected for indoor temperature measurements and aerial surveys

Site	Number of dwellings in winter	Winter - number of indoor monitoring days	Number of dwellings in summer	Summer - number of indoor monitoring days
Jouberton (2016) -Indoor temperature monitoring) <i>Objective 1</i>	32	16 July 2016 to 22 August 2016	32	23 April 2016 to 30 April 2016
Jouberton (2017)-Indoor temperature monitoring) <i>Objective 1</i>	48	2 June 2017 to 04 July 2016	48	2 February 2017 to 6 March 2017
KwaDela (2014)-Indoor temperature monitoring) <i>Objective 1</i>	26	11 July 2014 to 30 July 2014	26	11 February 2014 to 5 March 2014
KwaZamokuhle (2017 – Characterisation of thermal insulation) <i>Objective 2</i>	35	19 July 2017 to 21 August 2017	15	1 September 2017 to 22 October 2017
KwaZamokuhle (2017 - Aerial survey; ground-truthing) <i>Objective 3</i>	17	17 June 2017 to 17 June 2017	N/A	N/A
KwaZamokuhle (2017- Aerial survey, known insulation) <i>Objective 3</i>	110	17 June 2017 to 17 June 2017	NA	N/A
Total dwellings	268		121	

Table 3.2: Number of dwellings selected for the domestic energy use survey

Site	Winter/Summer
kwaZamokuhle (2016) <i>Objective 4</i>	• 49 Fully insulated houses • 54 Partially insulated • 10 Non-insulated
Total dwellings	113

Brief description of dwellings

All sampled structures were naturally ventilated, detached RDP dwellings with the majority of the structures being constructed from cement blocks, sand and hollow bricks erected on strip foundations and roofed with corrugated iron sheets with no ceilings. RDP structures consist mainly of a single-walled, two-room brick structure of approximately 36 m² (Moola *et al.*, 2011),

although some newer houses have up to five rooms (Greyling, 2009). The study selected a mixture of the old version RDP structures and newer version RDP structures across the three settlements. Figure 3.3. shows examples of some of these dwellings (Also refer to Figure 2.1 and Annexure 4), while Table 3.3 further expands on the materials that were used to insulate different types of dwellings, i.e. partially insulated, fully insulated and non-insulated.

Table 3.3: Thermal insulation descriptors

Level of insulation	Material used
Non-insulated	• No wall insulation • No roof insulation • No ceiling • Un-plastered walls
Partially insulated	• Roof insulation • Ceilings installed using expanded polystyrene material (EPS) • Draught proofing installed
Fully insulated	• Roof insulation • Ceiling installed using expanded polystyrene material (EPS) • Draught proofing installed • Wall insulation installed

Table 3.3 highlights the differences in insulation levels for the different dwellings types (non-insulated, partially insulated and fully insulated) selected for sampling in the settlement of KwaZamokuhle. Roof insulations (partially and fully insulated houses) were generally done using expanded polystyrene material (EPS) while fully insulated dwellings had an additional layer of wall insulation installed. Annexure 4 also shows different dwellings with different levels of insulation. Furthermore, fully insulated dwellings were painted black on the Northern walls to absorb more solar radiation during the day with the intention that it would further improve the thermal indoor environment during night time.



Figure 3.3: Image showing examples of sampled RDP residential dwellings in KwaZamokuhle (Source: Matandirotya 2017)

3.3.1.2 Indoor temperature monitoring survey (Objectives 1 and 2)

This section describes the instrumentation and data-gathering process that was followed during indoor temperature measurement surveys. Table 3.3 shows the purpose for which houses were selected. Due to the limited number of sensors, loggers were deployed in only a select number of bedrooms and living rooms. Different sites were selected to fulfil different objectives. For example, the indoor monitoring datasets for Jouberton and KwaDela were used to satisfy Objective 1 because the two sites did not have dwellings with well-known insulation levels, unlike KwaZamokuhle where there was a thermal insulation retrofitting intervention and insulation statuses were known. Therefore, KwaZamokuhle datasets were used to achieve objective 2, 3 and 4.

Table 3.3: Dwellings selected for the survey of indoor temperature measurements

Site and purpose	Winter (bedroom)	Summer (bedroom)	Winter (living room)	Summer (living room)
Jouberton (2016) <i>Objective 1</i>	5	5	25	25
Jouberton (2017) <i>Objective 1</i>	41	41	7	7
KwaDela (2014) <i>Objective 1</i>	12	12	14	14
KwaZamokuhle (2017) <i>Objective 2</i>	0	0	35	15
Total	60	60	81	61

Instrument description for indoor and ambient temperature measurements

Indoor air temperature measurements were made using Thermochron (DS1922L) *iButtons* manufactured by Maxim Integrated Products (formerly Dallas Semiconductor). The *iButtons* have a diameter of 17.35 mm and a thickness of 6 mm (Johnson *et al.*, 2005) with an ability to measure a temperature range of -40 °C to 85 °C. Thermochron loggers are rugged, water-resistant and self-sufficient sensors that measure temperature and record the result internally in a protected memory section of the instrument (Hubbart *et al.*, 2005). Temperature recording can be performed at user-defined rates with a possibility to record a total of 8, 192 recordings for an 8 bit and 4, 096 recordings for a 16-bit *iButton*. Thermochron *iButtons* have an 8, 192-byte temperature log with accuracy correctable to ± 0.5 °C from -10 °C to 65 °C. All loggers were programmed individually and programmed to take readings at a temporal resolution of 30 minutes continually for 24 hours. Figure 3.4b shows an image of the Thermochron *iButton*.

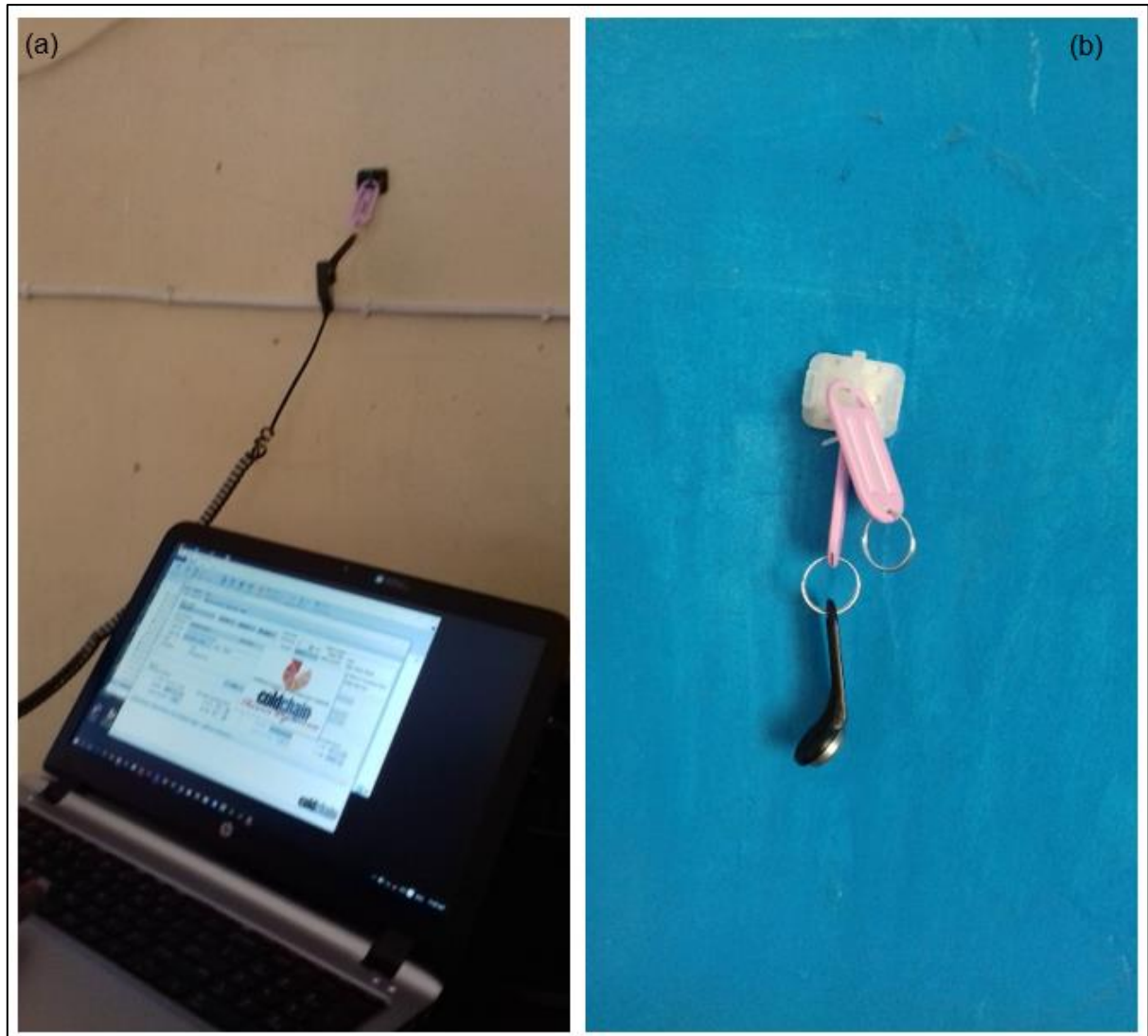


Figure 3.4: [a] Data retrieval process from the *iButtons*
[b] *iButton* affixed to an indoor wall (Source: Matandirotya, 2019)

These sensors were selected based on the following considerations:

- They are easy to install in indoor environments;
- They are portable;
- They have relatively high accuracy and reliability ($\pm 0.5^{\circ}\text{C}$);
- They are non-obstructive and do not interference with occupants' daily activities;
- They can collect high-resolution data at a fraction of the cost of other loggers on the market (Johnson *et al.*, 2005; Ibrahim *et al.*, 2009); and
- They are water-resistant, thus permitting deployment in highly humid indoor environments.

In the following section, the way indoor temperature measurements were taken is discussed.

Indoor air temperature measurements

Sensors were placed in bedrooms and living rooms as per Table 3.3. Sensors were placed at a standard height of between 1.5 m and 1.6 m above the floor surface, similar to the placement in numerous other studies (White-Newsome *et al.*, 2012; Healy & Clinch, 2002; Lee & Lee, 2015; Yohanis & Mondol, 2010). This is also in line with the World Meteorological Organisation (WMO, 2010) recommendation that a height range of 1.5 m to 2 m should be used for air temperature measurements (Chakraborty *et al.*, 2014). This height allows the instruments (indoor sensors) 'breathing space' and also avoids the recording of floor room temperatures. All indoor sensors were placed against the southern wall of all rooms to avoid excess solar radiation which northern walls receive in the Southern Hemisphere, and which can likely lead to sensor errors. Precautions were taken to ensure that loggers were not obstructed by furniture and were not exposed to direct solar radiation, heat or any other source of radiant heat (Malama & Sharples, 1996; Mavrogianni *et al.*, 2010; Loughnan *et al.*, 2014; Lee & Lee, 2015; San Miguel-Bellod *et al.*, 2018). Indoor measurements were taken continually over a 24-hour cycle at a temporal resolution of 30 minutes. The sensors were calibrated and checked for accuracy by the manufacturer before deployment in the dwellings.

For Objective 1, which was characterising indoor temperatures, two iButtons were deployed in each selected dwelling and placed in the living- room and bedrooms in the settlements of KwaDela (summer and winter, 2014) and Jouberton (summer and winter, 2016 & 2017). The living room was chosen as this is the space in which inhabitants spend considerable time during the day and early evenings (Jiang *et al.*, 2015). Therefore, the temperature in this space acted as a proxy indicator of indoor extreme temperature exposure during the day time. Furthermore, the living-room sensor was also used to monitor space heating activities in the living room during winter when indoor temperatures were low. The second sensor was placed in one of the bedrooms. The study assumed the occupation of this space at night. The bedroom sensor, therefore, became a proxy representative of indoor night extreme temperature exposure.

For Objective 2, which was to characterising thermal insulation, single sensors were placed in the living rooms of dwellings in KwaZamokuhle (winter and summer, 2017 – see Table 3.3). Deployment of iButtons was done according to each dwelling's thermal insulation status (fully insulated, partially insulated and non-insulated).

Ambient air temperature measurements

Ambient air temperature measurements were taken for comparison with indoor measurements and were also made using the ThermoChron *iButtons*. The *iButtons* were placed outside a select number of dwellings and programmed to take measurements at 30-minute intervals over a 24-hour cycle. Ambient sensors were placed on the Southern elevation of dwellings, thus avoiding the Northern elevations which receive much of the solar radiation on the South African Highveld during day time. Exposure to too much solar radiation can cause the sensors to record wrong erroneous measurements. Supplementary ambient air data were obtained from the South African Weather Service (SAWS) for all the three sites using the nearest weather station (Klerksdorp station for Jouberton, and Ermelo station for KwaDela and KwaZamokuhle).

Quality control iButton data

Data from most loggers were usable except for a few uncharacteristic spikes and drops from certain *iButtons*. Sensors in which data were missing were excluded from the study. Other factors used as exclusion criteria were, continuously repeated temperature values and unrealistic indoor temperature measurements of $<-10\text{ }^{\circ}\text{C}$ and $>45\text{ }^{\circ}\text{C}$. Graphs for each room in each house were plotted to check for further anomalies in the data. Rooms that showed unusual spikes and anomalies were excluded from further analysis (San Miguel-Bellod *et al.*, 2018). Also, measurements were consolidated in a database which was used during analysis. The aerial thermography survey is discussed next.

3.3.1.3 Aerial thermography survey (Objective 3)

Objective 3 which was to characterise thermal insulation using aerial thermography, was achieved through a combination of aerial thermography and *in situ* temperature measurements. The survey was done in KwaZamokuhle, which was chosen because the insulation status of many houses was known, and ongoing indoor measurements were being done in the settlement. The insulation status of individual dwellings was known as a result of an energy intervention programme on thermal insulation retrofitting conducted by the NOVA Institute. Aerial thermography is a remote sensing technique through which temperatures of objects are measured through the use of a thermal sensor or camera affixed to an aircraft or satellite. The sensor measures radiation emitted within the thermal infrared band by targeted objects on the ground (Holst, 2000). The thermal infrared band is a portion in the electromagnetic spectrum from $0.7\text{ }\mu\text{m}$ to $1,000\text{ }\mu\text{m}$ while, for remote sensing purposes, the best atmospheric window lies between $8\text{ }\mu\text{m}$ and $14\text{ }\mu\text{m}$ (Prakash, 2000). When fixed to an airborne platform, thermal sensors can be used to map residential heat loss through the identification of hot spots on rooftops through which heat is escaping (Hay *et al.*, 2011). The advantage of this approach is that housing defects, and possibly poorly insulated

houses, can be identified without physically accessing the buildings and intruding on residents' privacy (Fox *et al.*, 2014). The sensor that was used in the study is the FLIR Vue Pro R.

Radiation concept

Any object with a temperature above 0 degrees (absolute zero or -273.15C) radiates energy in the infrared electromagnetic spectrum (Hemachandran, 2013). Thermal remote sensors observe the spatial patterns of upwelling thermal radiance received by the remote sensor (Voogt & Oke, 2002). Real surfaces are not black-bodies and their radioactive behaviour are controlled by emissivity (ϵ), which in general is a function of wavelength and observing angle (Bitelli *et al.*, 2015). Emissivity is a measure of a material's ability to radiate absorbed energy (Hay *et al.*, 2011). During an aerial thermography survey, the thermal sensor attached to the aircraft detects some radiances emitted by the roof and some of the incident radiation reflected from the roof. Additionally, the column of air between the roof and the sensor, while having relatively high transmissivity in the 8 μ m to 14 μ m wavelength band, still absorbs some of the radiation originating at the roof and emits some radiation as a function of its temperature that is detected by the sensor (Alison, 2007). Aerial thermal cameras detect the amount of infrared coming from an object and translate them into thermograms (Thomas, 2018), therefore thermal sensors can detect radiation coming from objects in the invisible infrared spectra (Keyan *et al.* 2018).

Instrument description for aerial thermography survey: FLIR Vue Pro R

Aerial thermal imagery was acquired using a 16-bit FLIR Vue Pro R radiometric thermal camera manufactured by FLIR Systems, Inc. (Wilsonville, OR, USA). It is an off-the-shelf radiometric sensor with an ability to gather non-contact temperature measurements from an aerial perspective. The FLIR camera has a spectral band of 7.5 μ m to 13.5 μ m and thermal sensitivity of 0.05 °C. Figure 3.5 shows the FLIR Vue Pro R image while Further technical specifications for the FLIR Vue Pro R camera are highlighted in Table 3.4



Figure 3.5: A FLIR Vue Pro R image (Source: www.flir.eu/home)

Table 3.4: Technical specifications of FLIR Vue Pro R

Characteristic	Description
Weight	92 to 113g
Sensor resolution	640 x 512
Field of view	19 mm: 32°x 26°
Spectral band	7.5 µm to 13.5 µm
Operating temperature range	-20 °C to +50 °C
Operational altitude	12 192 metres
Thermal sensitivity	0.05 °C
Frame rate	30 Hz
Power Dissipation (peak)	2.1 W (3.9W)
Input voltage	4.8-6.0 VDC
Pixel pitch	17 µm

(Source: www.flir.eu/suas/vupror)

Aerial thermal image acquisition

The FLIR Vue Pro R was affixed to a wing of a Maule M5-235 light aircraft, as shown in Figure 3.6. The aircraft was flown at an altitude of 665 metres above ground, a height allowable in the built environment, at an average speed of 130 km/h. These were the standard flight protocols used across the two air campaigns as detailed in Table 3.5. Flight guidance was done with an AG-NAV-GUIA loaded with LiNav software (www.agnav.com) supported by a Novatel DGPS for precision direction guidance. Images were taken as per pre-flight programmed trigger points across the whole settlement guided by a Global Position System (GPS) as shown in Figure 3.7. All thermal images captured during the flights were saved onboard onto a micro-SD card with a tablet backup and stored as 8bit *.tiff files. The thermal image acquisition was conducted in two campaigns, which will be referred to as Campaign 1 (Flight 1) and Campaign 2 (Flight 2 and Flight 3) (see Table 3.5). Data were captured only during the night time to avoid the interference of solar radiation.



Figure 3.6: FLIR Vue Pro R fixed to an aircraft wing for the acquisition of aerial thermal data

The study followed the standard meteorological protocols used in the acquisition of aerial thermal images as applied in previous similar studies. Conditions that were considered were:

- Clear skies prevented unpredictable variations in sky temperature (Habaibeh *et al.*, 2003, Biteli *et al.*, 2015);
- Good visibility to reduce atmospheric attenuation (Haigh & Pritchard, 1980);
- Low ambient air temperature to maximise the temperature differences between the inside and outside of the building (Jack & Bowman, 1979);
- Low humidity and roof surface temperatures above the dew point to avoid condensation (Syder & Schott, 1994);
- Calm winds to reduce heat loss from the roofs and prevent thermal shadows in built-up areas (Brown *et al.*, 1981); and
- No precipitation during the survey (Fox *et al.*, 2014).



Figure 3.7: Trigger points across the settlement during flight campaign 1 & 2 (Source, Matandirotya, 2017)

Table 3.5: Flight schedule for Campaigns 1 and 2

Campaign 1	Date	From	To
Flight 1	14 June 2017	18:05 SAT	20:25 SAT
Campaign 2	Date	From	To
Flight 2	14 August 2017	18:05 SAT	20:25 SAT
Flight 3	14 August 2017	00:00 SAT	02:00 SAT

The aerial surveys were performed in two campaigns, as shown in Table 3.5. The first campaign consisted of the acquisition of aerial thermal imagery on 4 June 2017 (hereinafter referred to as Flight 1) accompanied by indoor temperature measurements in 17 dwellings (Table 3.1) selected based on their insulation status (non-insulated, partially insulated and fully insulated). One *iButton* was deployed in the kitchen (chimney – to verify if burning took place) and one in the living rooms of the 17 dwellings. Amongst these 17 dwellings, 9 were space heating and 8 were not space heating during Flight 1 as detailed in Table 3.6. The second campaign entailed only an aerial survey without ground measurements on 14 August 2017 and consisted of two flights. An early evening flight – referred to as the Flight 2 – and a midnight flight – referred to as the Flight 3 (Table 3.5). The study was able to conduct two aerial campaigns which were sufficient to make comparisons of datasets collected at different times of the night.

To acquire good quality TIR images certain meteorological conditions, as discussed earlier, had to be met. Both nights were regarded as cold winter nights and weather conditions were regarded as ideal as they maximised the temperature differences between housing unit roofs and ambient temperatures. Flight 1 was undertaken on 14 June 2017 early evening from 18:05 to 20:25 (SAT) at an altitude of 665 m. The average ambient temperature during the flight period was 12 °C with a wind speed of 0.8 m/s and with no precipitation observed. Early evenings were targeted as space heating is most prevalent in the settlement and, therefore, the study anticipated waste heat to be captured through the aerial imagery. Flight 2 occurred on the 14 August 2017 in the early evening from 18:00 to 20:25 (SAT) using the same flight altitude as the Flight 1. The average ambient temperature was 11 °C, with an average wind speed of 1.2 m/s and no precipitation. Flight 3 occurred on 14 August 2017 but after midnight from 00:00 to 02:00 (SAT). This time was chosen as it allowed for housing structures to reach thermal equilibrium (Hemachandran, 2013). The flight applied similar flight parameters, and similar meteorological conditions prevailed. For Flight 3, the average ambient temperature was 5 °C, with an average wind speed of 0.3 m/s and no precipitation.

Table 3.6: Indoor space and non-space heating dwellings during Flight 1

House code	Heating status	Insulation status
H02	Non-space heating	Full
H05	Space heating	Full
H07	Space heating	Full
H08	Non-space heating	Full
H11	Non-space heating	Full
H03	Space heating	Partially insulated
H04	Non-space heating	Partially insulated
H09	Non-space heating	Partially- insulated
H12	Non-space heating	Partially insulated
H13	Space heating	Partially insulated
H14	Space heating	Partially insulated
H17	Space heating	Partially insulated
H01	Non-space heating	Non-insulated
H06	Non-space heating	Non-insulated
H10	Space heating	Non-insulated
H15	Space heating	Non-insulated
H16	Space heating	Non-insulated

Ground-truthing

To assess and determine the accuracy of TIR images for use in the study, ground surface measurements were done simultaneously during Flight 1 using Thermochron *iButtons*. Seven *iButtons* were placed on various homogenous surfaces with the study choosing pavements and a water body, similar to the approach used by Bitelli *et al.* (2015). Six of the seven sensors were placed on pavements while the seventh one was placed on a water body however, readings from only four of these sensors were useable as the other sensors reported errors. These surfaces were selected because they would easily be recognised on the thermal images (Bitelli *et al.*, 2015). The readings from the four sensors were plotted against the measurements extracted from the TIR image and an r^2 score calculated.

3.3.1.4 Domestic energy use survey: household questionnaires (Objective 4)

To fulfil Objective 4, data were obtained through the use of questionnaires. Questionnaires are research instruments containing a series of questions to gather information from respondents (Kabir, 2016). Households residing in RDP dwellings were selected from the settlement of KwaZamokuhle with the main selection criterion being the thermal insulation characteristics of dwellings (Table 3.2), i.e. non-insulated, partially insulated and fully insulated. These dwellings were not the same as those which participated in the indoor temperature monitoring survey for Objective 2, however, a key component in the study was to investigate the link between the levels of thermal insulation and domestic energy use. Data were gathered through a face-to-face questionnaire administration format in collaboration with the NOVA Institute (a developmental organisation that is active in KwaZamokuhle and spearheaded the thermal insulation retrofits in the settlement). A total of 113 questionnaires were completed and analysed. Questions were a mixture of open-ended and closed (dichotomous) questions. The questionnaires were structured in nature and the interviews took 30-45 minutes per household. Responses from households were recorded by research assistants. Furthermore, to assist the enumerators there was also audio recorders to corroborate each household responses. Before being fully administered 10 questionnaires were pilot tested in the settlement and the feedback from households were used to improve on the structure of questions. The survey questions focused on four main themes, namely:

- Energy carriers used in the settlement;
- Energy consumption levels according to dwelling types;
- Energy expenditure patterns according to dwelling insulation levels; and
- The primary energy carriers used for space heating.

These four main themes were selected as they provide detailed insight into the energy use patterns in low-income households on the South African Highveld, as well as on whether or not thermal insulation influences energy consumption quantities and patterns.

Sampling

The questionnaires were administered over winter and summer seasons using stratified random sampling (Babbie, 2013). Households were categorised into groups (strata's) based on their insulation status and the primary energy carrier used, and the following selection made: coal users (10 non-insulated, 37 partially insulated, 34 fully insulated) and LPG users (17 partially insulated and 15 fully insulated) (see Table 3.2). Households sampled for participation in the domestic survey were selected from the overall study.

3.3.2 Data analysis

This section gives a detailed account of the data analysis procedures that were followed for Objectives 1 to 4. A total of six datasets were collected from the three study sites to achieve the four objectives. Indoor temperature datasets gathered from Jouberton (2016), Jouberton (2017) and KwaDela were used to fulfil Objective 1, while indoor temperature datasets gathered from KwaZamokuhle were used to fulfil Objective 2. Furthermore, aerial and indoor datasets gathered from KwaZamokuhle were used to achieve Objective 3, while the domestic energy use dataset obtained from KwaZamokuhle was used to fulfil Objective 4.

3.3.2.1 Characterisation of indoor temperatures (Objective 1)

Indoor temperature measurements were performed in winter and summer seasons. Data were checked, verified and stored in Microsoft Excel Version 2016. After anomalies and erroneous data were excluded from the rest of the data set, data were uploaded into the SPSS (Statistical Software for Social Sciences) version 25 for further analysis to fulfil Objective 1. The collected data (indoor and ambient recordings) were transformed into hourly means for each room and each dwelling over both the winter and summer monitoring periods to enable further analysis. Day time was staggered as being from 08:00 to 20:00, as these are the times that people are generally active indoors, thus catering for living rooms occupation. For each room, day time hourly mean temperatures were calculated for summer and winter across all settlements using Equation 1. Mean values were used to describe the internal dynamics in each dwelling throughout the day as proposed by Oreszczy *et al.* (2006). Night time was defined as the period from 21:00 to 07:00. For each room, night time hourly mean temperatures were also calculated for summer and winter across all settlements. There are no local indoor thermal guidelines, so the study resorted to the use of WHO guidelines discussed in Chapter 2, i.e. a minimum of 18 °C and a maximum of 24 °C. Using SPSS software, descriptive statistics were calculated and presented in tabular and graphical format.

$$\bar{x} = \frac{\sum x}{N}$$

(Equation 1)

$\sum$ represents the summation

x represent scores

N represents the number of scores

Percentage frequency distribution of indoor temperatures per room

Indoor temperature exposure can be determined by the frequency of exposure to extreme temperatures. Exposure levels can, therefore, be inferred through the analysis of indoor temperature distribution. Frequency distribution was further used to highlight the indoor fluctuations through the passage of time of day. The frequency distribution of indoor temperature recordings was also used as a proxy for the effectiveness of thermal insulation as reflected by the response of indoor temperatures to ambient temperature changes.

$$\% = (\text{frequency} / \text{total number of values}) \times 100$$

3.3.2.2 Characterisation of thermal insulation using indoor temperature measurements (Objective 2)

To characterise thermal insulation status in different dwelling types, indoor temperature variations first had to be calculated. This was achieved by calculating the hourly mean for indoor and ambient temperatures through the monitoring period, disaggregated according to day time and night time. Results were presented graphically and through descriptive statistics such as mean, median, standard deviations, 10th quartiles and 90th quartiles. These descriptive statistics were used to infer and show the variations in non-insulated, partially insulated, and fully insulated dwellings.

Indoor and ambient temperature association through the Pearson coefficient of correlation

The Pearson (*r*) coefficient is the ratio of covariance of two variables, i.e. is the degree of relationship between two variables (Hall, 2015). Correlation models denote an association between two or more quantitative variables (Gogtay & Thatte, 2017), showing their strength (Aggarwal & Ranganathan, 2016). Besides measures of association for binary variables, correlation coefficient measures the strength and extent of an association between the variables as well as its direction (Gogtay & Thatte, 2017). The degree of correlation can be expressed numerically as a linear correlation with a coefficient of correlation (Spriestersbach *et al.*, 2009). Thermal insulation functionality of dwellings, as well as the relationship between indoor and outdoor temperatures, were explored by plotting indoor temperatures against ambient temperatures and calculating correlation coefficients. This was done for all houses using hourly means.

3.3.2.3 Determine the extent to which thermal insulation can be evaluated using aerial thermography (Objective 3)

This section details the process that was followed to characterise thermal insulation through aerial thermography. Data management is discussed first, followed by the analysis processes that were applied.

Geo-rectification and digitising aerial images (Geometric correction)

A 2018, 50 cm colour (RGB) orthophoto and an October 2017 Google Earth Pro image were used to geo-reference all 768 TIR images. The images were provided in TIFF format, so there was no need for conversion of the file format. The procedure involved:

- **Stage 1:** Selecting 16 ground control points (GCP) per image, linking and plotting them on the thermal image.
- **Stage 2:** Visually checking the TIR image for accuracy and correcting in ArcGIS 10.3 software.
- **Stage 3:** All individual geo-rectified TIR images were uploaded into PIX 4 D mapper Pro Version 4.2.25 which was able to ortho-mosaic them into a single image (representing whole settlement) for further statistical analysis starting with the extraction of raw digital values for individual dwellings as identified by GPS coordinates and the Surveyor-General cadastre. PIX 4 D is a professional photogrammetry software which can ortho-mosaic, noise filter, and smooth thermal images.

Radiometric distortions from atmospheric influences are negligible for low flight altitudes (Campbell & Wyne, 2011; Sagan *et al.*, 2019) and hence no atmospheric corrections were applied during the study (Hay *et al.*, 2011). Furthermore, the study used raw digital values as recorded by TIR sensors.

Extraction of digital radiometric values from the thermal images

Two approaches were used to extract radiometric values from the thermal image, namely, the rooftop boundary and the property boundary. Each house was identified using GPS coordinates as obtained during ground survey exercise.

Using ArcGIS Version 10.3, the first step was to digitise the rooftops of each of the 17 selected dwellings whose insulation statuses were known (the same dwellings where indoor temperature measurements were taken during Flight 1), i.e. individual rooftop polygons were created for each property roof. Through activating the zonal statistics tool in ArcMap 10.3, descriptive statistics (maximum, minimum, mean, range and standard deviation) were extracted for each property roof. This was done for all 17 structures used in Flight 1.

The second approach was the use of property boundaries as obtained from the Surveyor General cadastre. Using ArcGIS 10.3 software, the property boundaries were superimposed on the georeferenced image to calculate statistics for all the properties in the settlement. The zonal statistics tool was again used to calculate descriptive statistics. Negative values were removed from the data set, as these indicated a sensor error. Values were extracted for all 3,555 residential properties in the study area.

HEAT Score calculation

To explore the amount of heat escaping from individual dwellings, the study applied the HEAT (Home Energy Assessment Technologies) score approach as adopted from a study by Hay *et al.* (2011). HEAT Scores (waste heat metrics) are ranked numbers that range from 0 to 100 (cold to hot) and is a representation of the amount of waste heat leaving a dwelling. A dwelling with a HEAT Score of 1 represents very low waste heat while a dwelling with a HEAT score of 100 represents very high waste heat (Hemachandran, 2013). HEAT scores were developed based on the z-score or standardised score (Equation 2). A standard score indicates how many standard deviations an observed value (rooftop or property average score) are above the population mean.

$$Z - score = (x - u) / \sigma$$

(Equation 2)

To calculate the z-core, x is the average temperature to be standardised, u is the average of all temperatures measured in the settlement, and σ is the standard deviation of the average temperatures in the settlement (Hay *et al.*, 2011). Heat scores were derived using Equation 3

$$HEAT\ Score = (z - score + 3.5) / 7 * 100$$

(Equation 3)

HEAT scores were classified into six classes (Table 3.6) after Hay *et al.* (2011) and allowed for the comparison of the thermal performance of dwellings. HEAT scores were calculated in two phases, as discussed below:

- HEAT scores were first calculated for the 17 sampled dwellings (dwellings whose insulation status was known and in which temperature measurements were taken during Flight 1) mentioned earlier and using the values obtained from the TIR imagery for Flight 1. The HEAT scores were calculated twice, once using the rooftop boundaries and once

using the property boundaries. Upon classification, the results were compared and found to be similar.

- Based on the analysis as mentioned above, property boundaries were then used to calculate HEAT scores for the rest of the settlement. HEAT scores were calculated for all 3,555 residential properties and across all the three flights.

Table 3.7: HEAT Score descriptors

HEAT Score	Relative description
90-100	Very high
75 – 89	High
50 – 74	Moderately high
25 – 49	Moderately low
10 – 24	Low
0 – 9	Very low

Relationship between radiometric mean values, HEAT scores and indoor temperatures

The 17 selected dwellings for which indoor measurements were taken during Flight 1, were grouped according to their insulation status. To establish if any relationship existed between indoor and the radiometric values across dwellings with different insulation levels, mean radiometric scores and HEAT scores (both calculated for property boundaries and using data obtained from Flight 1) were plotted against indoor temperature measurements, and coefficients of determination (r^2) calculated. Simple linear regression analysis was used to analyse possible relationships.

Evaluating thermal insulation status across multiple flights

The statistics (min, max, mean, standard deviation and range) extracted for Flight 2 and Flight 3, as well as the HEAT scores that were calculated, were used to explore how the thermal insulation status of houses could be characterised using TIR data.

Table 3.7: Probability classes

Class	Value
Very high probability	< -146.060
High probability	-146.060 to -114.220
Low probability	-114.221 to -70.390
Very low probability	> -70.390

The values for 127 properties with known insulation statuses were used to generate boxplots which were further analysed for variability. Two-sample, unpaired T-tests (at the 95% confidence interval) were also conducted to test for significant differences in the means of variables (radiometric values) used to identify houses with high-probability of being non-insulated. ArcMap 10.3 was used to classify the difference in the range statistic across the two flights into four classes of the probability of being non-insulated, as shown in Table 3.7. This was done for all the 3, 555 houses in KwaZamokuhle.

3.3.2.4 *Characterise the link between thermal insulation and domestic energy use* **(Objective 4)**

The responses obtained from the questionnaires were categorised into themes and coded for further analysis (Bryman, 2012). The coded data were saved into spreadsheets and under relevant themes. Data coding was performed in Microsoft Excel with the coded sheets exported to SPSS for further analysis. The main themes of the survey were the household source of energy, leading energy carriers, the purpose of energy carriers, cost of energy, energy carriers for space heating, cooking and the overall dominant energy carriers in the settlement. The study used descriptive statistics, graphs and tables to facilitate the interpretation of the data.

3.4 Summary

The chapter gave a detailed description of the study sites, followed by an overview of the study methodology. Different data gathering instruments were used in the study that included ThermoChron iButtons, FLIR Vue Pro R camera and household questionnaires. All these tools converged on connecting the quality of housing to indoor thermal conditions and domestic energy use. The chapter also presented data analysis plans for different data frames to meet the four study objectives. In the following chapter, results on the characterisation of indoor temperatures in low-income residential dwellings are presented.

CHAPTER 4: CHARACTERISATION OF INDOOR TEMPERATURES

This chapter characterises indoor temperatures in low-income settlements in winter and summer seasons. Living rooms and bedrooms were chosen as the occupied spaces of the dwellings for daytime and night time, respectively, thus providing insights into indoor temperature variations.

4.1 Introduction

To gauge the seasonal indoor temperature characteristics in low-income residential dwellings, indoor diurnal temperature measurements were taken in the two settlements of KwaDela and Jouberton as detailed in Chapter 3. Temperatures were analysed for winter and summer and compared with the WHO minimum indoor thermal comfort guidelines of 18 °C minimum and 24 °C maximum. The results for the winter season will be discussed first, followed by the results for the summer season.

4.2 Winter indoor temperature characteristics: Bedrooms

This section presents the results of bedroom indoor temperatures measured during the winters of 2014, 2016 and 2017. The study assumed bedrooms would be occupied mostly during night time, between 21:00 and 07:00, although it is acknowledged that daytime occupation – 08:00 to 20:00 – was possible for a distinct group of people (for example children, the chronically ill and other sedentary people). Indoor temperatures were analysed through the use of descriptive statistics and graphs, while the association between indoor and ambient temperatures was investigated through the use of Pearson's correlation.

4.2.1 Day time and night time indoor variations: Jouberton 2016

This section presents indoor temperature variations in bedrooms during the winter of 2016 with Figure 4.1 showing measurements during day time and night periods.

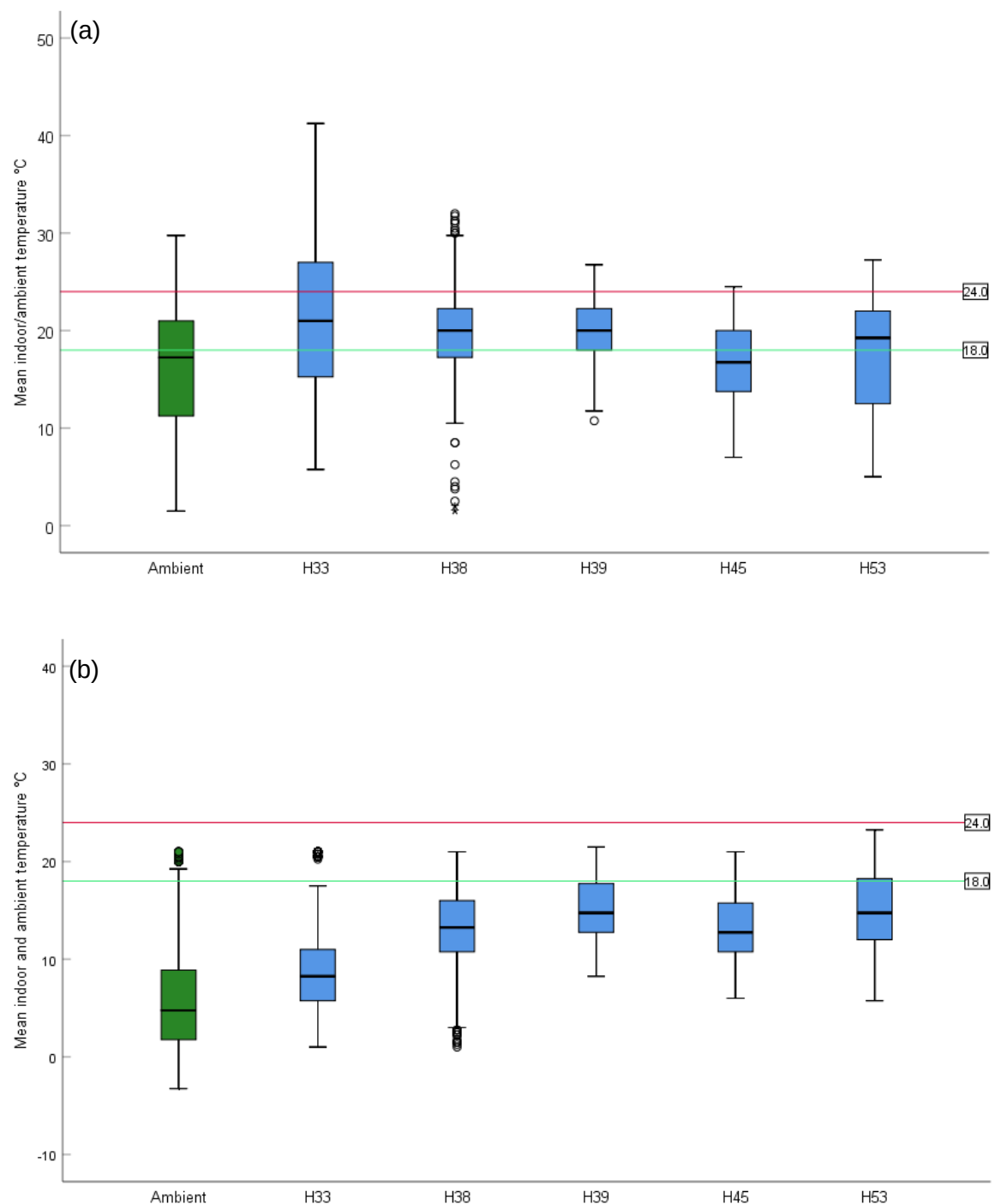


Figure 4.1: Indoor temperature variations within bedrooms in Jouberton 2016: [a] day time, [b] night time

As illustrated in Figure 4.1 the median day time temperatures for bedrooms in Jouberton (2016) never rose above 24 °C, although some of the houses did experience episodes were temperatures higher than 24 °C were measured. Although the median day time ambient temperature during the sampling period was below 18 °C, only one house registered a median day time temperature of below 18 °C. During night time, however, all houses sampled showed a

median temperature of below 18 °C. Most night time measurements taken were below the 18 °C threshold with the lowest indoor temperature registered being 1 °C in house H33. These results suggest that bedrooms, which are assumed to be occupied during night time, were subject to extremely cold temperatures, far below the WHO guideline of 18 °C, in Jouberton during the winter of 2016.

4.2.2 Indoor temperature distribution: Jouberton 2016

To illustrate the distribution of indoor temperatures, two houses were selected for further investigation – the house in which the lowest temperature was measured (H33), and the house in which the highest temperature was measured (H39).

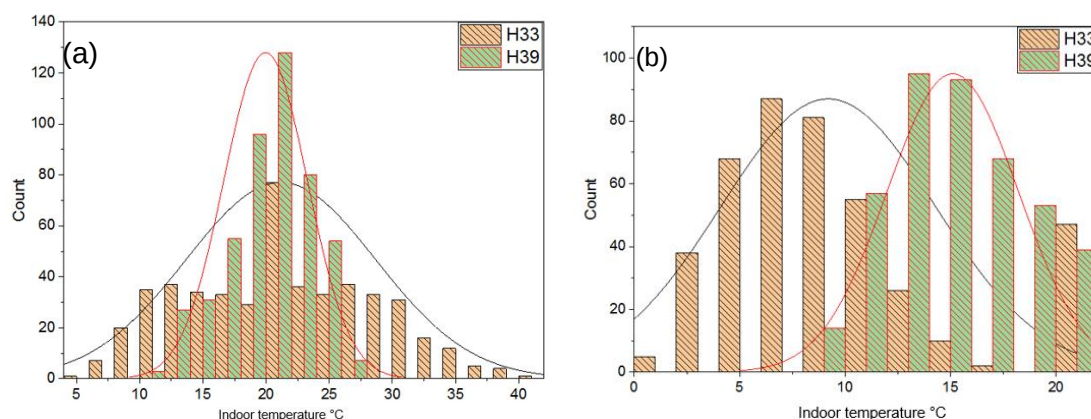


Figure 4.2: Indoor temperature distribution Jouberton 2016: [a] day time, [b] night time

Figure 4.2 represents the indoor temperature distribution in these two dwellings. Clear differences could be observed between the two dwellings, especially in terms of night time measurements. In H33, in which the coldest temperature was measured, the majority of night time measurements were between 3 °C and 11 °C while in H39 they were roughly between 12 °C and 20 °C. For H33, 90% of indoor temperatures recorded at night time were below 18 °C, while this percentage was significantly smaller for H39. Although the distributions were more similar during the day time, this shows that houses respond differently to ambient temperatures, especially at night (during winter and summer). The reasons for this are further explored in Section 5.2.6 and 5.3.6 of Chapter 5.

4.2.3 Day time and night time indoor variations: Jouberton 2017

This section presents indoor temperature variations in bedrooms during the winter of 2017 with Figure 4.3 showing measurements during day time and night time periods.

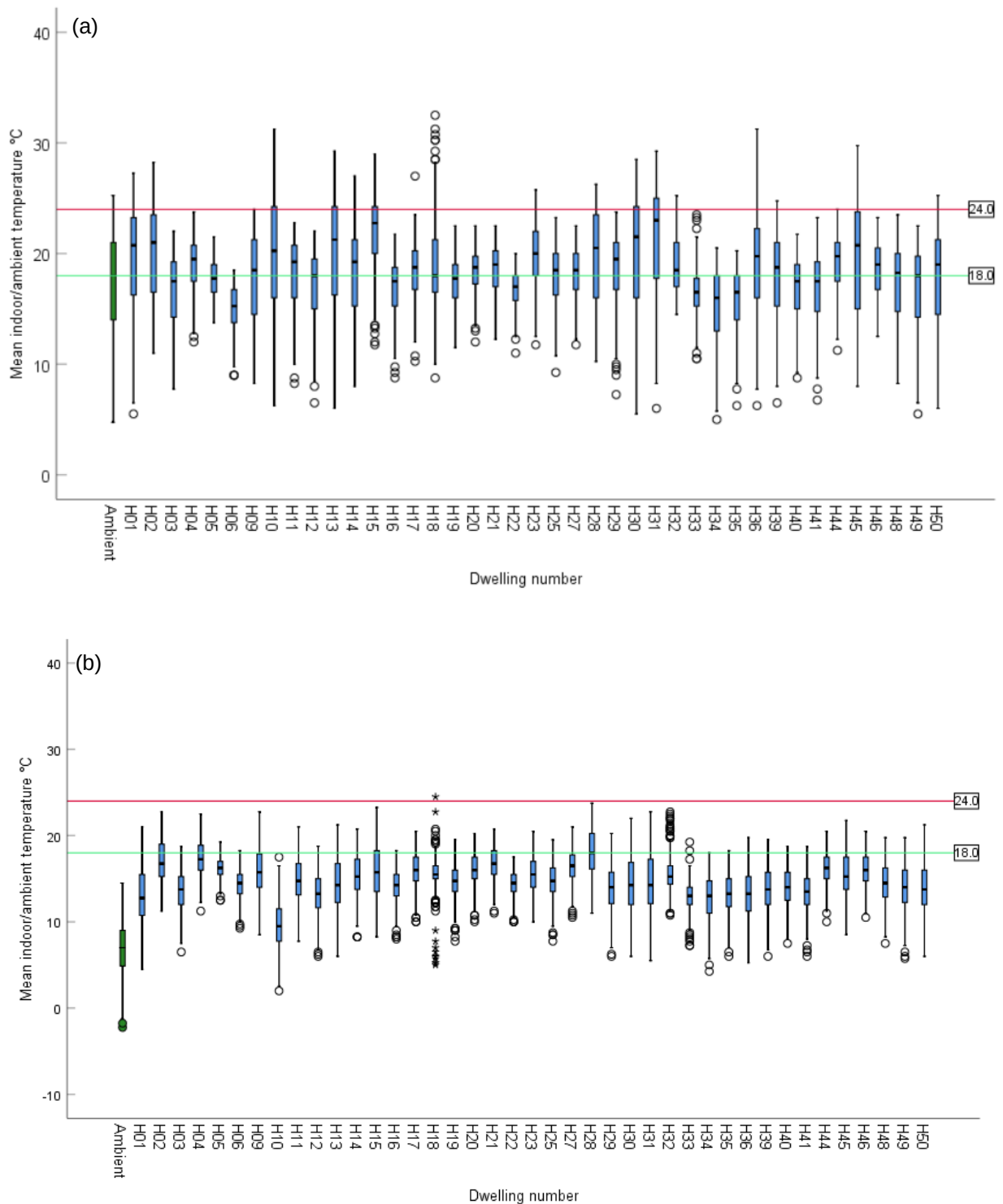


Figure 4.3: Indoor temperature variations within bedrooms in Jouberton 2017: [a] day time, [b] night time

As illustrated in Figure 4.3, similar to the 2016 Jouberton campaign, the median day time temperatures for bedrooms in Jouberton (2017) never rose above 24 °C, with only a few houses experiencing episodes where temperatures rose above 24 °C. Although the median day time ambient temperature during the sampling period was 18 °C, only a few houses registered a

median day time bedroom temperature of below 18 °C. However, 98 % of dwellings sampled had a median temperature of below 18 °C during night time. Similar to the 2016 campaign, most night time measurements taken were below the 18°C threshold with the lowest indoor temperature registered being 2 °C in dwelling H10. These results further suggest that bedrooms, which are assumed to be occupied during night time, were subject to extremely cold temperatures, far below the WHO guideline of 18 °C, in Jouberton during the winter of 2017 as well.

4.2.4 Indoor temperature distribution: Jouberton 2017

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation – the dwelling in which the lowest temperature was measured (H10), and the dwelling in which the highest temperature was measured (H27).

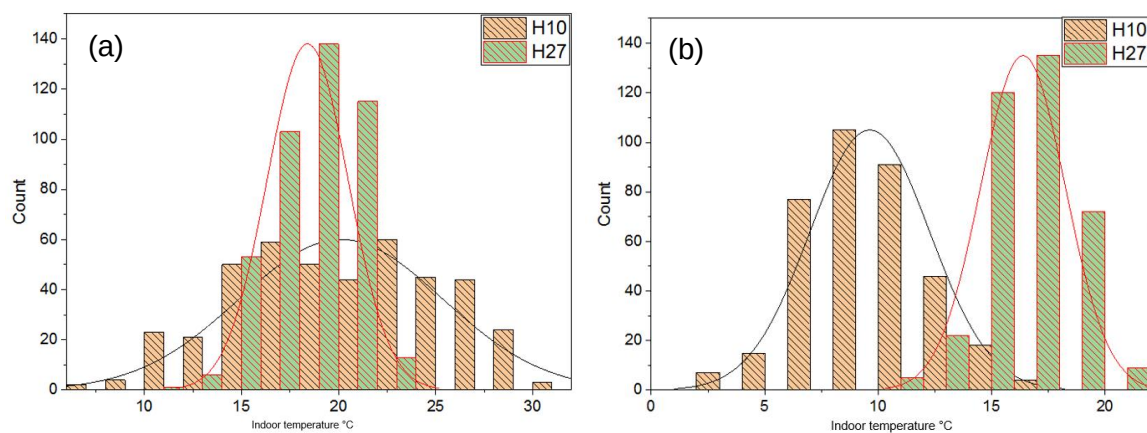


Figure 4.4: Indoor temperature distribution in Jouberton 2017: [a] day time, [b] night time

Figure 4.4 represents the indoor temperature distribution in these two dwellings. Similar to the two dwellings in the Jouberton 2016 campaign, apparent differences could be observed, especially in terms of night time measurements. In H10, in which the coldest temperature was measured, the majority of night time measurements were between 7 °C and 13 °C while in H27 they were roughly between 12 °C and 20 °C. For H10 all measurements taken at night time were below 18 °C. The distributions for the two houses also differed significantly during the day time with H10 registering a wide range of temperatures ranging from 0 °C to 30 °C while H27 mostly registered temperatures between 13 °C and 23 °C. This further shows that houses respond differently to ambient temperatures, especially at night.

4.2.5 Day time and night time indoor variations: KwaDela 2014

This section presents indoor temperature variations in bedrooms in KwaDela during the winter of 2014 with Figure 4.5 showing measurements during day time and night time periods. As illustrated, the median day time temperatures for bedrooms in KwaDela (2014) never rose above 24 °C, although some of the houses did experience episodes where temperatures higher than 24 °C were recorded. In contrast with the houses in Jouberton, half of the houses in KwaDela experienced day time median temperatures below 18 °C, which is probably because the ambient temperature was lower than for the two Jouberton campaigns. During night time all houses sampled, except for one, recorded median temperatures of below 18 °C. Like Jouberton, most night time measurements taken were below the 18 °C threshold. The lowest indoor temperature registered was 4.75 °C in house H04, which is somewhat higher than that recorded in Jouberton. These results further support the notion that bedrooms, which are assumed to be occupied during night time, are generally subject to extremely cold temperatures, far below the WHO guideline of 18 °C, during the winter.

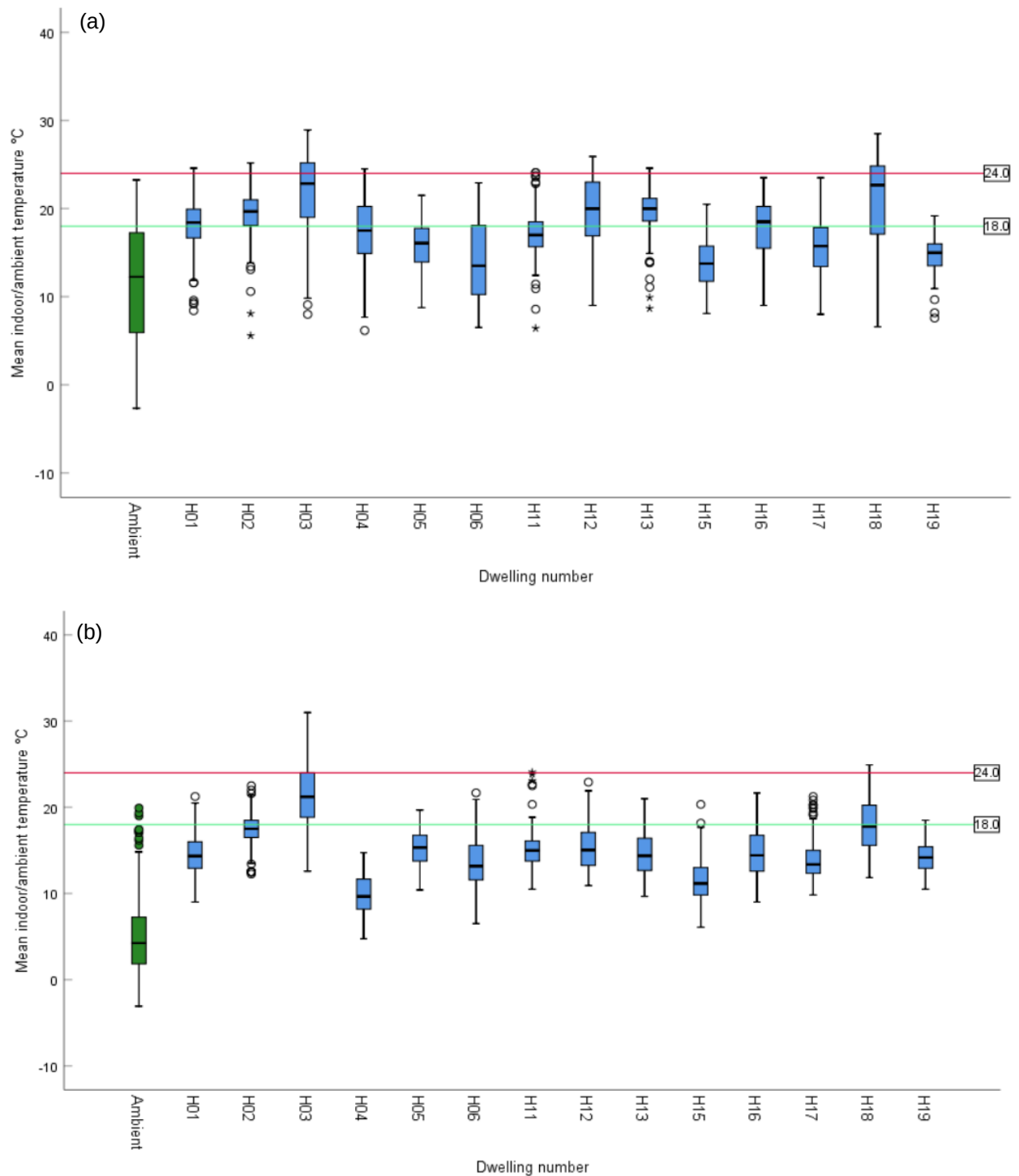


Figure 4.5: Indoor temperature variations within bedrooms in KwaDela: [a] day time, [b] night time

4.2.6 Indoor temperature distribution: KwaDela 2014

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation – the dwelling in which the lowest temperature was measured (H04), and the dwelling in which the highest temperature was measured (H03).

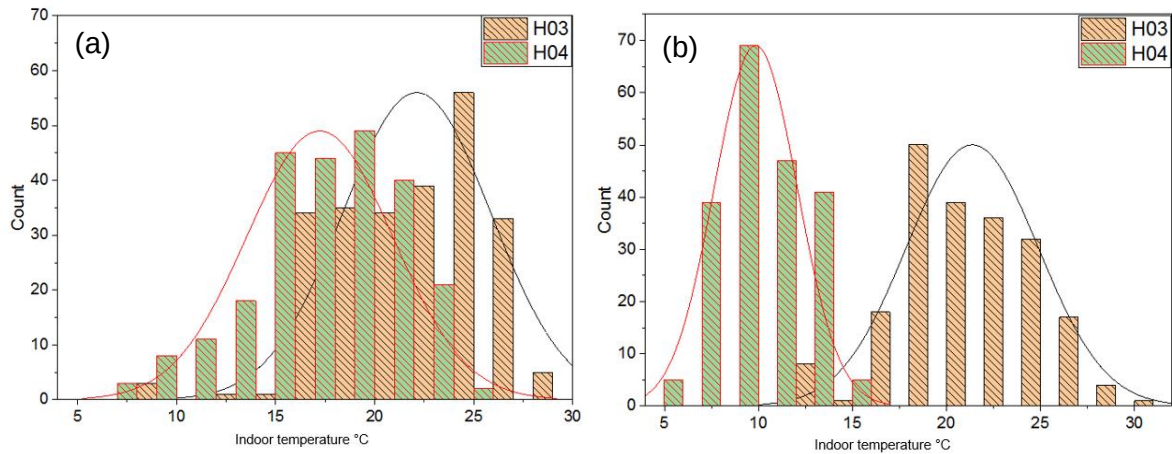


Figure 4.6: Indoor temperature distributions in bedrooms kwaDela: [a] day time, [b] night time

Figure 4.6 illustrates the indoor temperature distribution in these two dwellings. Similar to the dwellings in the two Jouberton campaigns, clear differences could be observed, again especially in terms of night time measurements. In H04, in which the coldest temperature was measured, the majority of night time measurements were between 7 °C and 14 °C while in H03 they were roughly between 17 °C and 27 °C. For H04 all measurements taken at night time were below 18 °C. The distributions for the two houses differed somewhat less during the day time with H04 registering temperatures mostly ranging from 15 °C to 24 °C while H03 registered temperatures mostly between 17 °C and 27 °C. This, however, still supports the observation that houses respond differently to ambient temperatures, especially at night.

4.2.7 Indoor and ambient temperature association for bedrooms: all three campaigns

This section explores the relationship between indoor bedroom temperatures and ambient temperatures during day time and night time. As shown in Figure 4.7 there seems to be a stronger relationship between indoor bedroom temperatures and ambient temperatures during night time as is evident in all three cases. For Jouberton (2016) the r-score for night time was 0.77 while, for the day time, it was 0.44. A similar trend is observed for Jouberton (2017) with scores of 0.91 and 0.59 for night time and day time, respectively. Although the relationships between indoor and ambient temperatures in KwaDela were much weaker, the same trend was observed with scores of 0.39 and 0.26.

4.3 Winter indoor temperature characteristics: Living rooms

This section presents the results of living rooms indoor temperatures recorded during the winters of 2014, 2016 and 2017. The study assumed that living rooms would mostly be occupied during the daytime, between 08:00 to 20:00, although, in some instances, these rooms were also used by households for sleeping purposes. Indoor temperatures were analysed through the use of descriptive statistics and graphs, while the association between indoor and ambient temperatures was investigated through the use of Pearson's correlation.

4.3.1 Day time and night time indoor variations: Jouberton 2016

This section presents indoor temperature variations in bedrooms in Jouberton during the winter of 2016. Figure 4.8 illustrates the measurements for day time and night time periods. The median daytime temperatures for living rooms in Jouberton (2016) never rose above 24 °C, although in some instances temperatures higher than 24 °C were recorded (Figure 4.9). The median daytime ambient temperature during the sampling period was below 18 °C, and it was observed that 10 of the 25 houses (40 %) registered median living room temperatures of below 18 °C. During night time, however, all houses sampled showed a median temperature below 18 °C. The majority of night time measurements taken were below the 18 °C threshold with the lowest indoor temperature registered being -1 °C in house H46. The same house also registered the lowest day time temperature of 4 °C. These results suggest that living rooms, which are assumed to be occupied during day time, were in some cases subject to relatively cold conditions during the day time in Jouberton during the winter of 2016

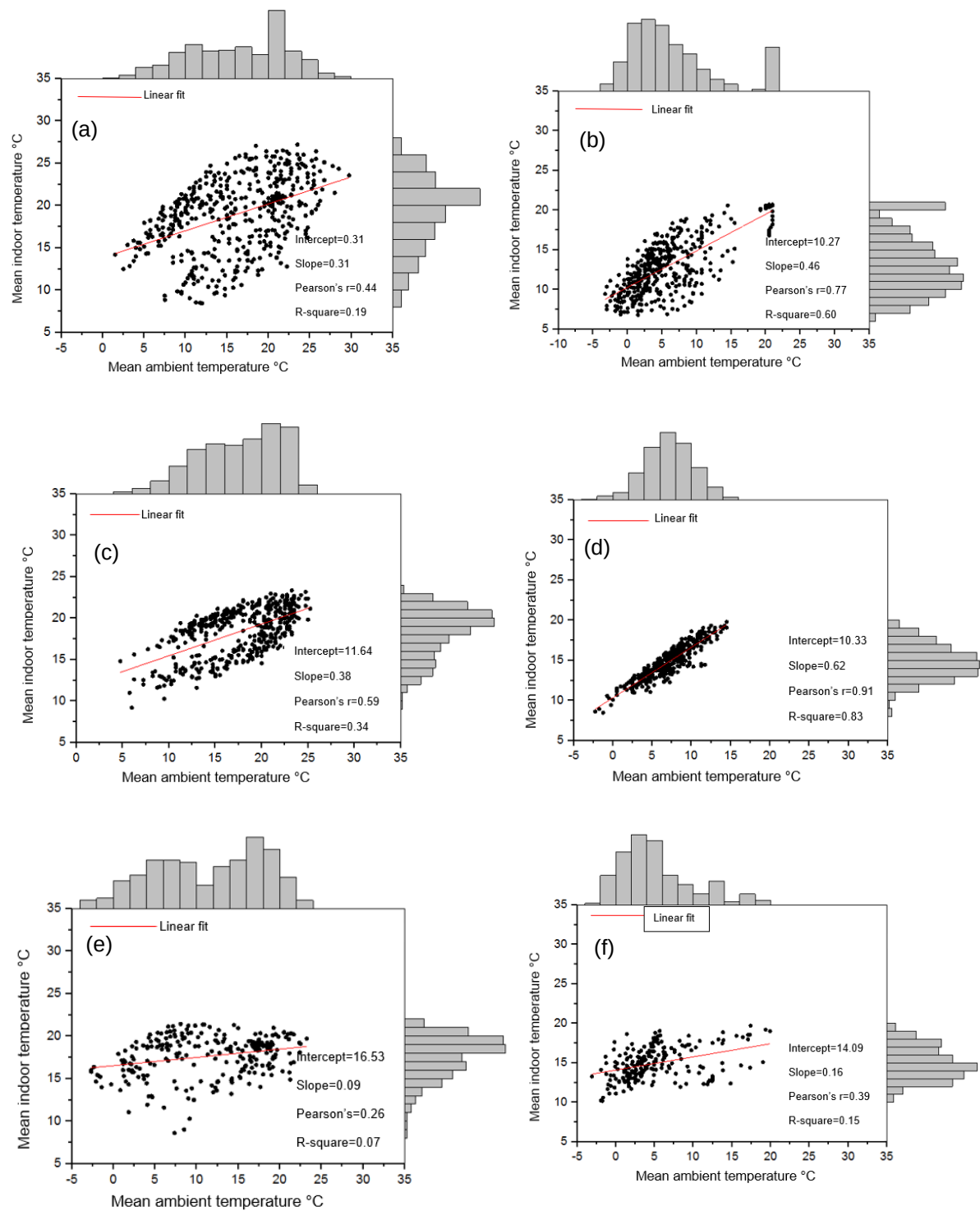


Figure 4.7: Association between indoor and ambient temperature association in bedrooms: Jouberton (2016) [a] day time, [b] night time, Jouberton (2017) [c] day time, [d] night time, KwaDela (2014) [e] day time, [f] night time

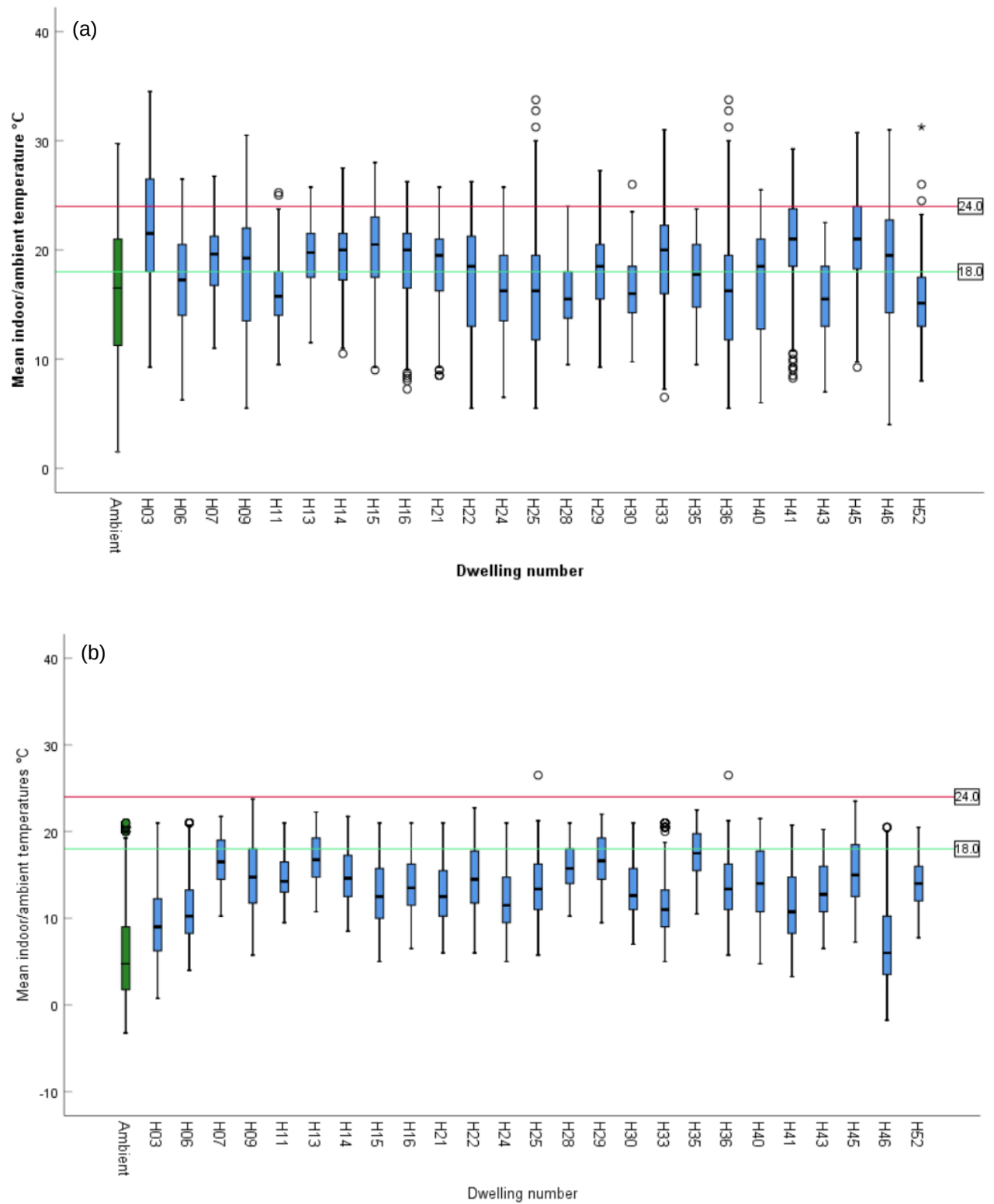


Figure 4.8: Indoor temperature variations within living rooms in Jouberton 2016: [a] day time, [b] night time

4.3.2 Indoor temperature distribution: Jouberton 2016

To illustrate the distribution of indoor living room temperatures, two dwellings were selected for further investigation, H46 and H35 as represented in Figure 4.9.

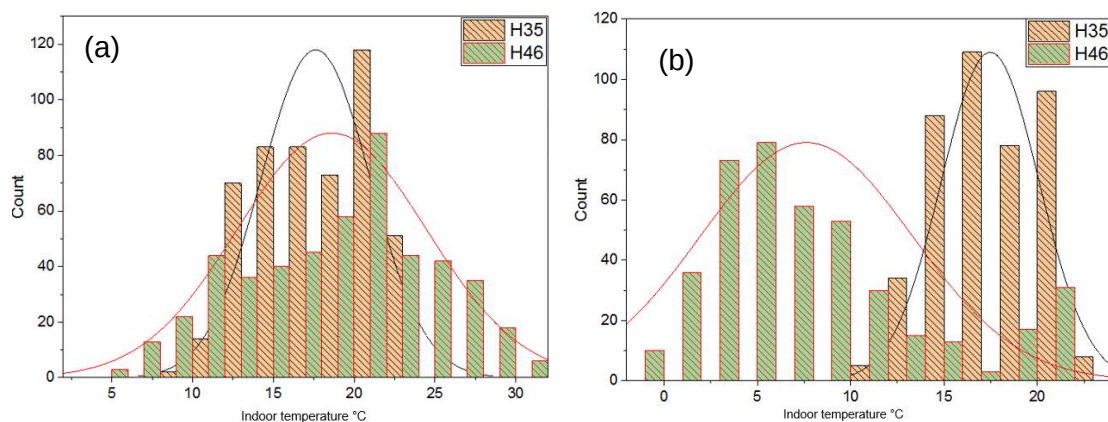


Figure 4.9: Indoor temperature distribution in living rooms winter in Jouberton 2016: [a] day time, [b] night time

Figure 4.9 represents the indoor temperature distribution in these two dwellings. Apparent differences could be observed between the two dwellings, especially in terms of night time measurements. In H46, in which the coldest temperature was measured, the majority of night time measurements were between 0 °C and 12 °C while, in H35, they were roughly between 10 °C and 23 °C. For H46 the majority of indoor temperatures recorded at night time were below 18°C, while this was the case for less than 50% of the measurements in H35. Although the distributions were more similar during the day time, H46 registered a more extensive range of temperatures. This further supports the notion that houses respond differently to ambient temperatures.

4.3.3 Day time and night time indoor variations: Jouberton 2017

This section presents indoor temperature variations in living rooms during the winter of 2017 in Jouberton with Figure 4.10 showing measurements during day time and night time periods. As illustrated in Figure 4.10, the median day time temperatures for living rooms in Jouberton (2017) never rose above 24 °C, although, in some instances, temperatures higher than 24 °C were recorded in living rooms. Although the median day time ambient temperature during the sampling period was 18 °C, only one house registered a median living-room temperature of below 18 °C. During night time, however, all houses recorded a median temperature of below 18°C. The majority of night time measurements taken were below the 18°C threshold with the lowest indoor temperature recorded being 1 °C in house H24. The same house also registered the lowest daytime temperature of 6 °C. These results, similar to the 2016 campaign, suggest that living rooms, which are assumed to be occupied during day time were, in some cases, also subject to relatively cold conditions during the daytime in Jouberton during the winter of 2017.

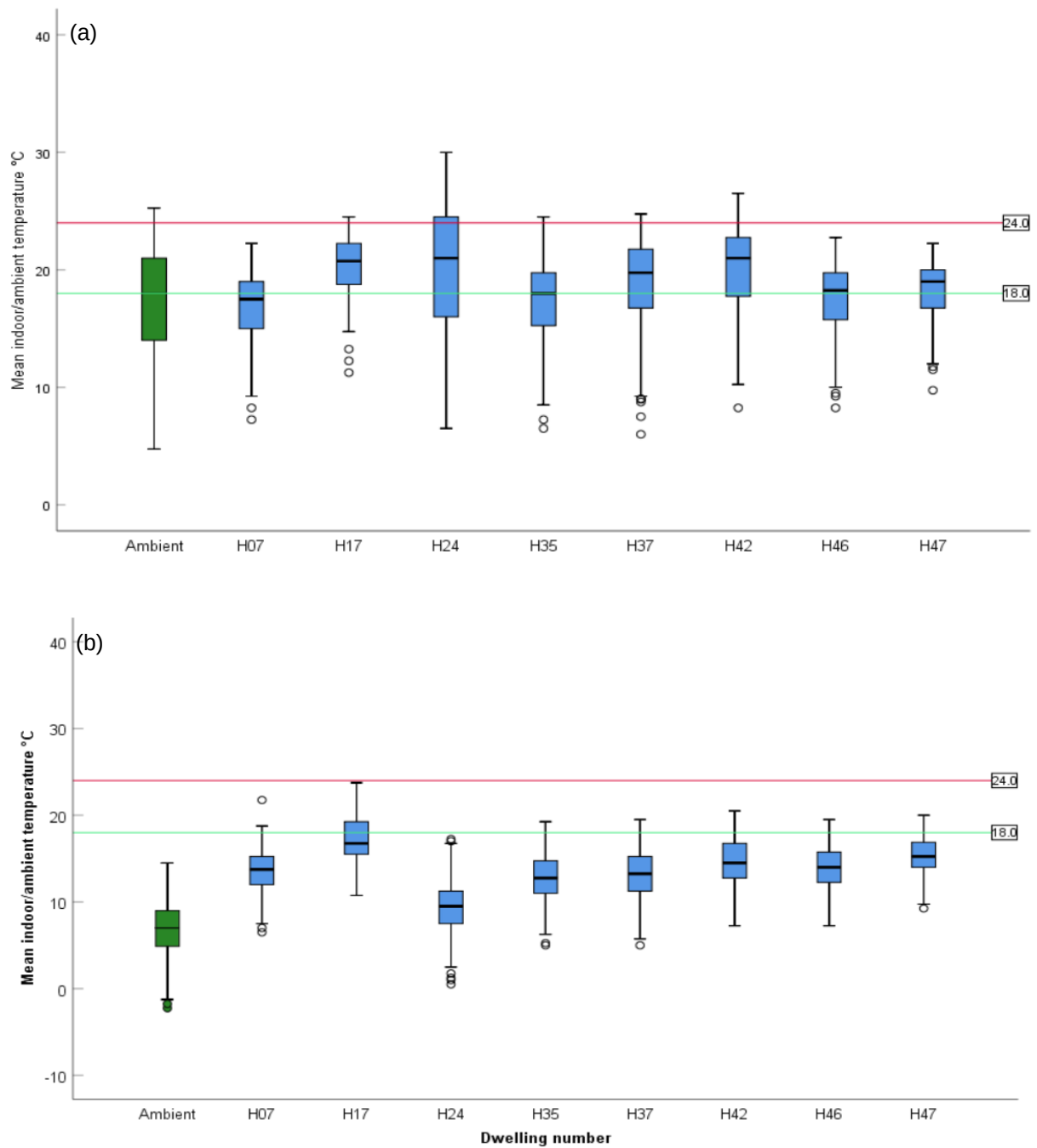


Figure 4.10: Indoor temperature variations in winter for living rooms in Jouberton 2017: [a] day time, [b] night time

4.3.4 Indoor temperature distribution: Jouberton 2017

Figure 4.11 shows the indoor temperature distribution for two dwellings- H24 and H17.

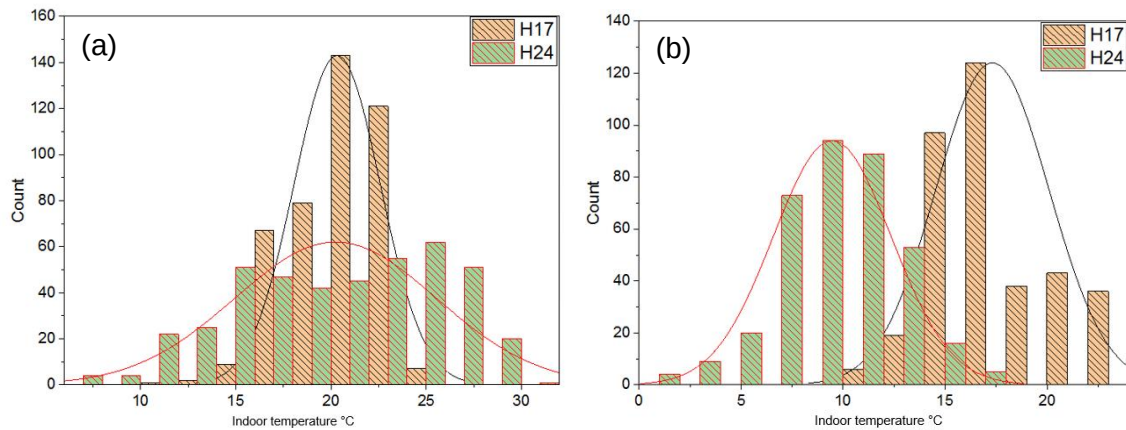


Figure 4.11: Indoor temperature distribution within living rooms in Jouberton 2017: [a] day time, [b] night time

Figure 4.11 represents the indoor temperature distribution in these two dwellings. Apparent differences could again be observed between the two dwellings for both night-time and day time measurements. In H24, in which the coldest temperature was measured, the majority of night time measurements were between 5 °C and 13 °C while in H17 they were roughly between 14 °C and 17 °C. For H24 all of the indoor temperatures recorded at night time were below 18 °C, while this was the case for less than 70 % of the measurements in H24. Apparent differences were also observed during day time with H24 registering a more extensive range of temperatures. This further supports the notion that houses respond differently to ambient temperatures. The reasons for this are also explored in Chapter 5

4.3.5 Daytime and night time indoor variations: KwaDela 2014

This section presents indoor temperature variations in bedrooms during the winter of 2014 for KwaDela. Measurements for day time and night time periods are shown in Figure 4.12. The median day time temperatures for living rooms in KwaDela (2014) never rose above 24 °C, although, in some instances, it came very close. The median day time ambient temperature during the sampling period was below 18 °C, and it was observed that 6 of the 14 houses (43 %) registered median living room temperatures of below 18 °C. During night time the majority of houses sampled (86 %) showed a median temperature of below 18 °C. The lowest night time indoor temperature registered was 4 °C in house H04 while house H06 registered the lowest day time temperature of 6 °C. These results suggest that living rooms, which are assumed to be occupied during day time, were in some cases and similar to Jouberton (2016 and 2017), subject to relatively cold conditions during the daytime in KwaDela (2014).

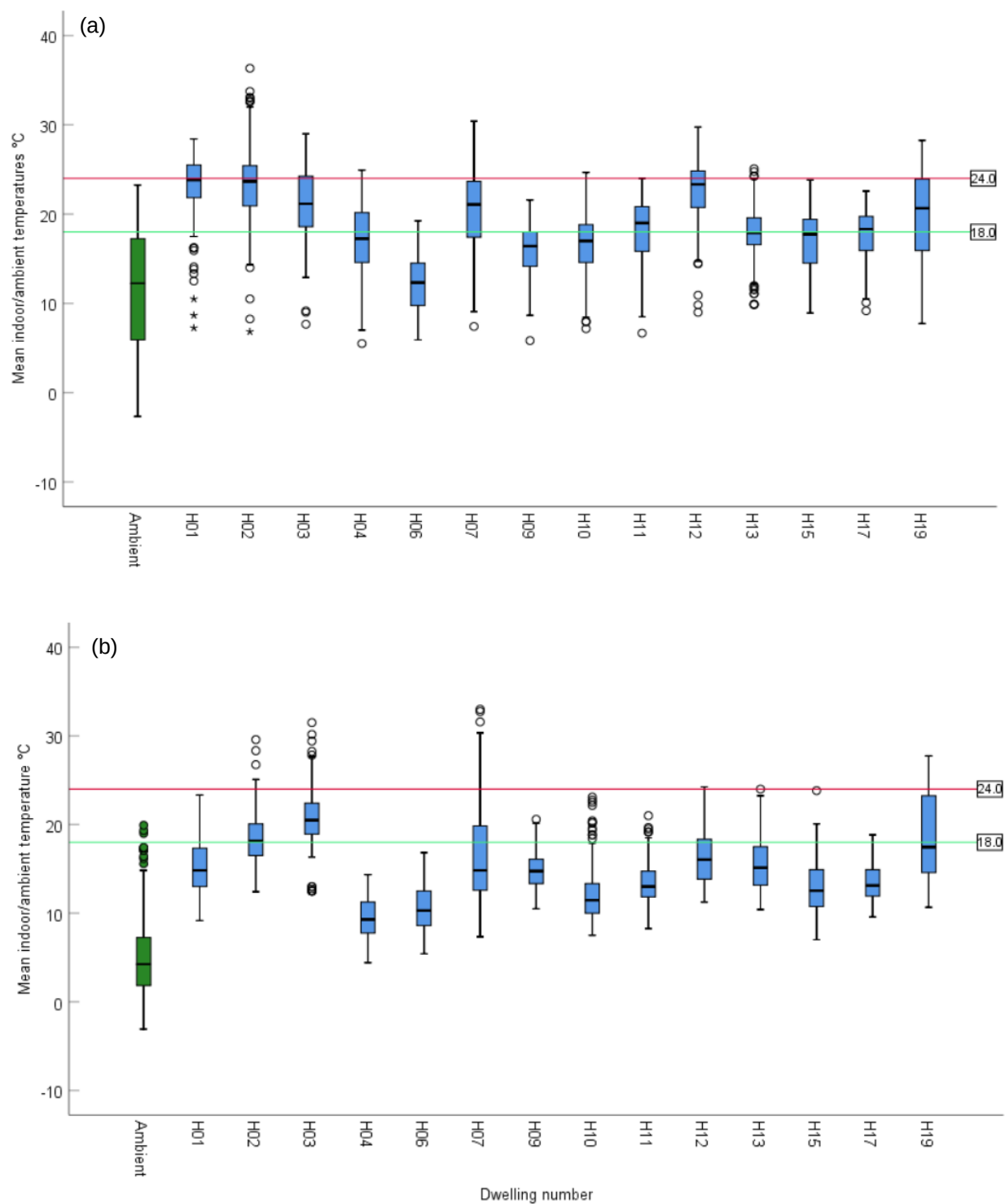


Figure 4.12: Indoor temperature variations within living rooms in KwaDela 2014: [a] day time, [b] night time

4.3.6 Indoor temperature distribution: KwaDela 2014

Figure 4.13 shows the indoor temperature distributions during day time and night time for two dwellings – H03 and H04.

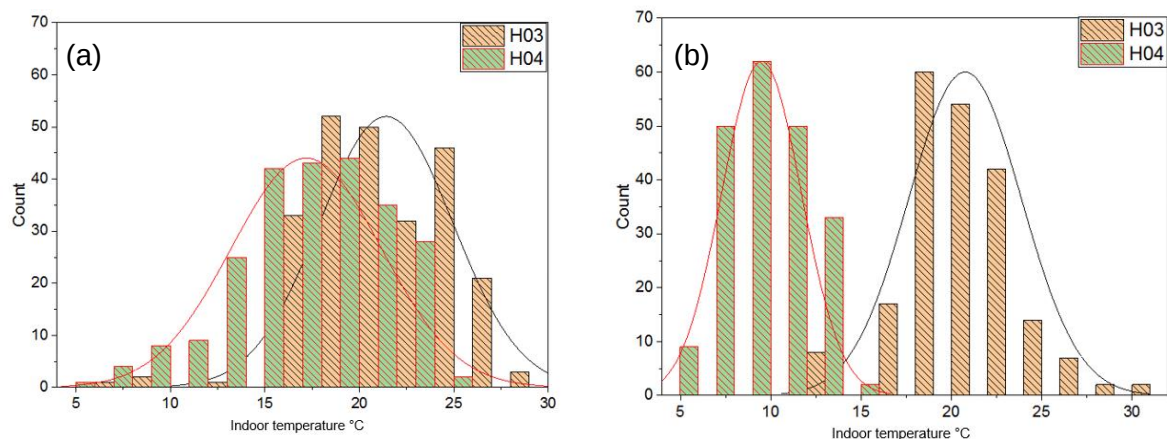


Figure 4.13: Indoor temperature distribution within living rooms in KwaDela 2014: [a] day time, [b] night time

Clear differences could be observed between the two dwellings, especially in terms of night time measurements. In H04, in which the coldest temperature was measured, the majority of night time measurements were between 5 °C and 13 °C while in H03 they were roughly between 16 °C and 25 °C. All of the indoor temperatures recorded at night time in H04 were below 18 °C, while the majority was above 18 °C in H03. Although the distributions were more similar during the day time, H04 registered a wider range of temperatures. This also shows that houses respond differently to ambient temperatures.

4.3.7 Indoor and ambient temperature association for bedrooms: all three campaigns

This section explores the relationship between indoor living room temperatures and ambient temperatures during day time and night time. As shown in Figure 4.14, there seems to be a stronger relationship between indoor bedroom temperatures and ambient temperatures during night time, as is evident in all three cases. For Jouberton (2016) the r-score for night time was 0.78, while for the day time it was 0.39. A similar trend is observed for Jouberton (2017) with scores of 0.93 and 0.75 for night time and day time respectively. Although the relationships between indoor and ambient temperatures in KwaDela were much weaker, the same trend was observed with scores of 0.47 and 0.36 respectively.

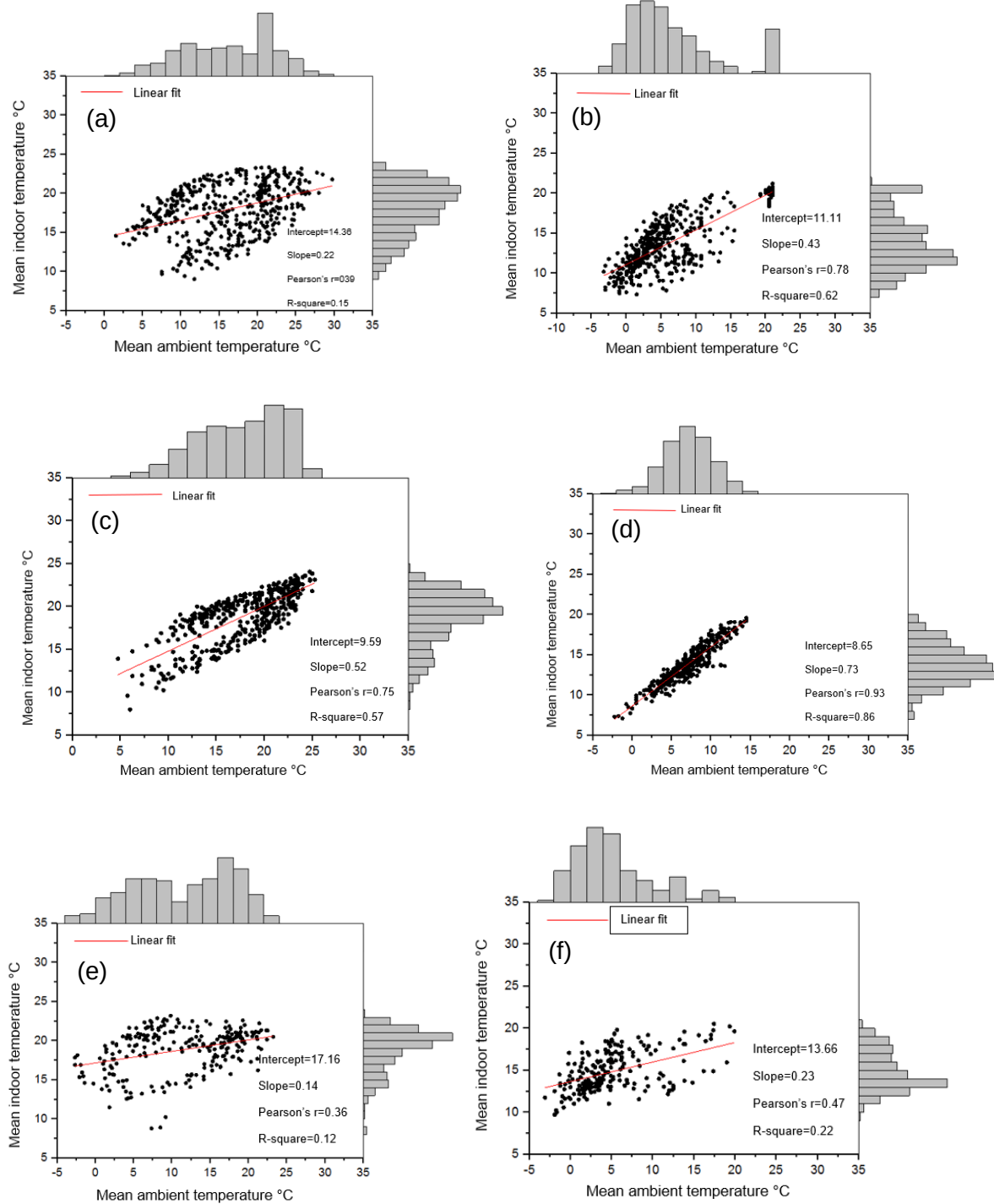


Figure 4.14: Association between indoor and ambient temperature association in living rooms: Jouberton (2016) [a] day time, [b] night time, Jouberton (2017) [c] day time, [d] night time, kwaDela (2014) [e] day time, [f] night time

4.4 Summer indoor temperature characteristics: Bedrooms

This section presents the results of bedroom indoor temperatures measured during the summers of 2014, 2016 and 2017. The study assumed bedrooms would be occupied mostly during night time, between 21:00 to 07:00, although it is acknowledged that day time occupation – 08:00 to 20:00 – was possible in some cases. Indoor temperatures were analysed through the use of descriptive statistics and graphs, while the association between indoor and ambient temperatures was investigated through the use of Pearson's correlation.

4.4.1 Day time and night time indoor variations: Jouberton 2016

This section presents indoor temperature variations in bedrooms in Jouberton during the summer of 2016. Figure 4.15 shows measurements during day time and night time periods. As illustrated, most of the dwellings registered median day time bedroom temperatures very close to 24 °C, while two houses registered median temperatures of above 24 °C. In all cases, the median day time temperatures for bedrooms were above the median ambient day time temperatures for the period. It is further noted that all of the houses experienced day time bedroom temperatures of above 24 °C somewhere during the day with H15 recording a high of 39 °C. Night time median temperatures were also very close to 24 °C although never exceeding the threshold. Only two houses registered median night-time temperatures below 18 °C. Some outliers were observed during the monitoring period, which can be attributed to occupant behaviour as they attempt to cool down bedrooms. The results suggest that bedrooms, which are assumed to be occupied during night-time, were in some cases subject to relatively hot conditions during the night-time in Jouberton during the summer of 2016.

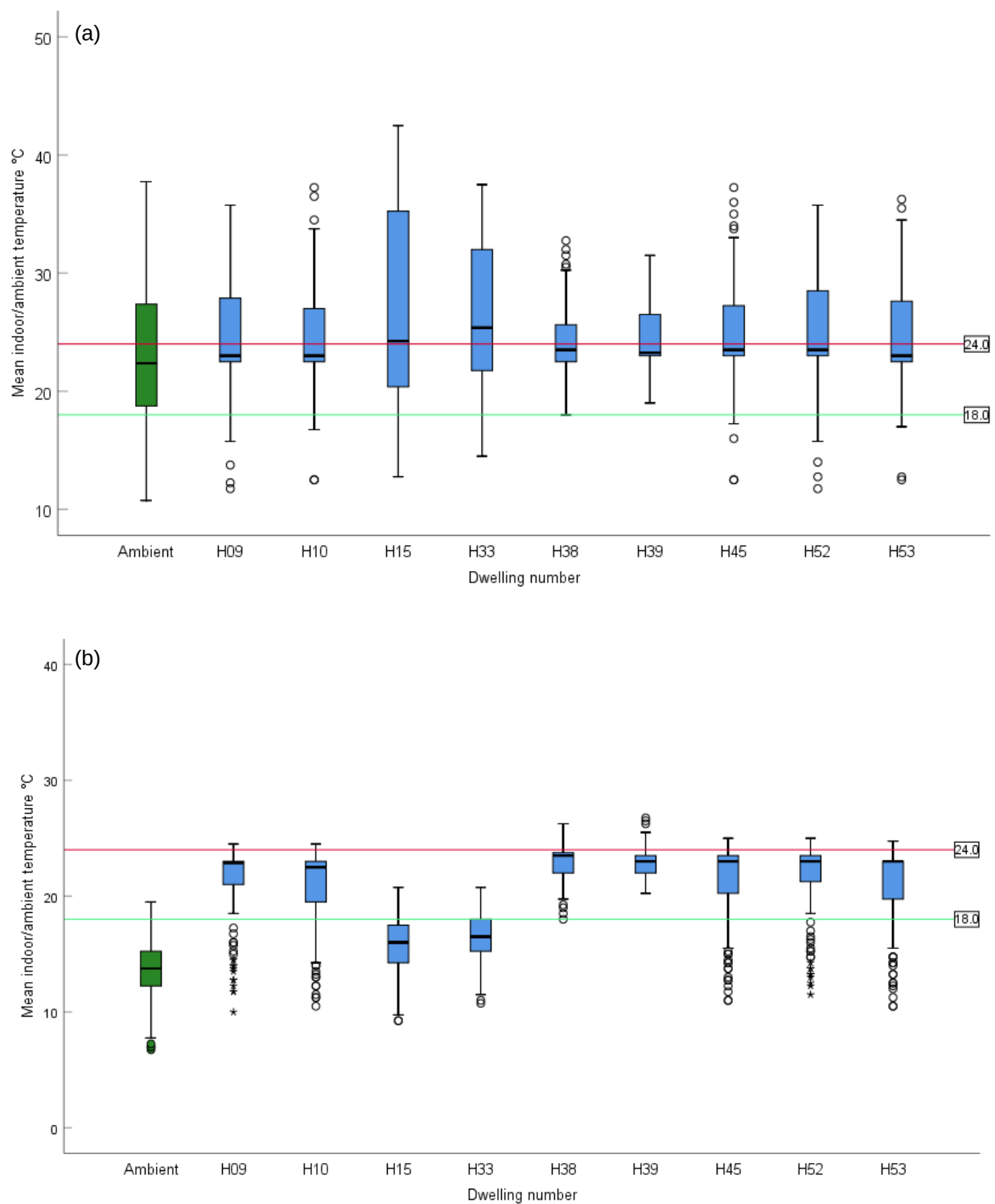


Figure 4.15: Indoor temperature variations within bedrooms in Jouberton 2016:
[a] day time, [b] night time

4.4.2 Indoor temperature distribution: Jouberton 2016

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation H15 and H33 as represented in Figure 4.16.

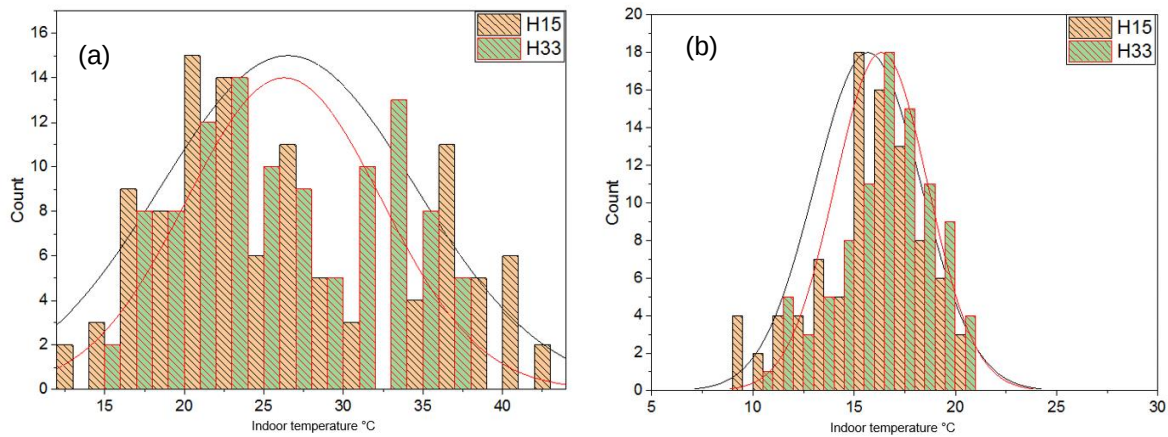


Figure 4.16: Indoor temperature distribution within bedrooms in Jouberton 2016: [a] day time, [b] night time

Figure 4.16 illustrates the indoor temperature distribution in these two dwellings. It can be observed that the two dwellings responded similarly to ambient temperatures during summer. Although H15 (dwelling that recorded the highest temperature) recorded higher temperatures in general, the overall distribution is similar to H33. It can further be observed that the differences between the two houses are less during night time.

4.4.3 Daytime and night time indoor variations: Jouberton 2017

This section presents indoor temperature variations in bedrooms in Jouberton during the summer of 2017, as illustrated in Figure 4.17.

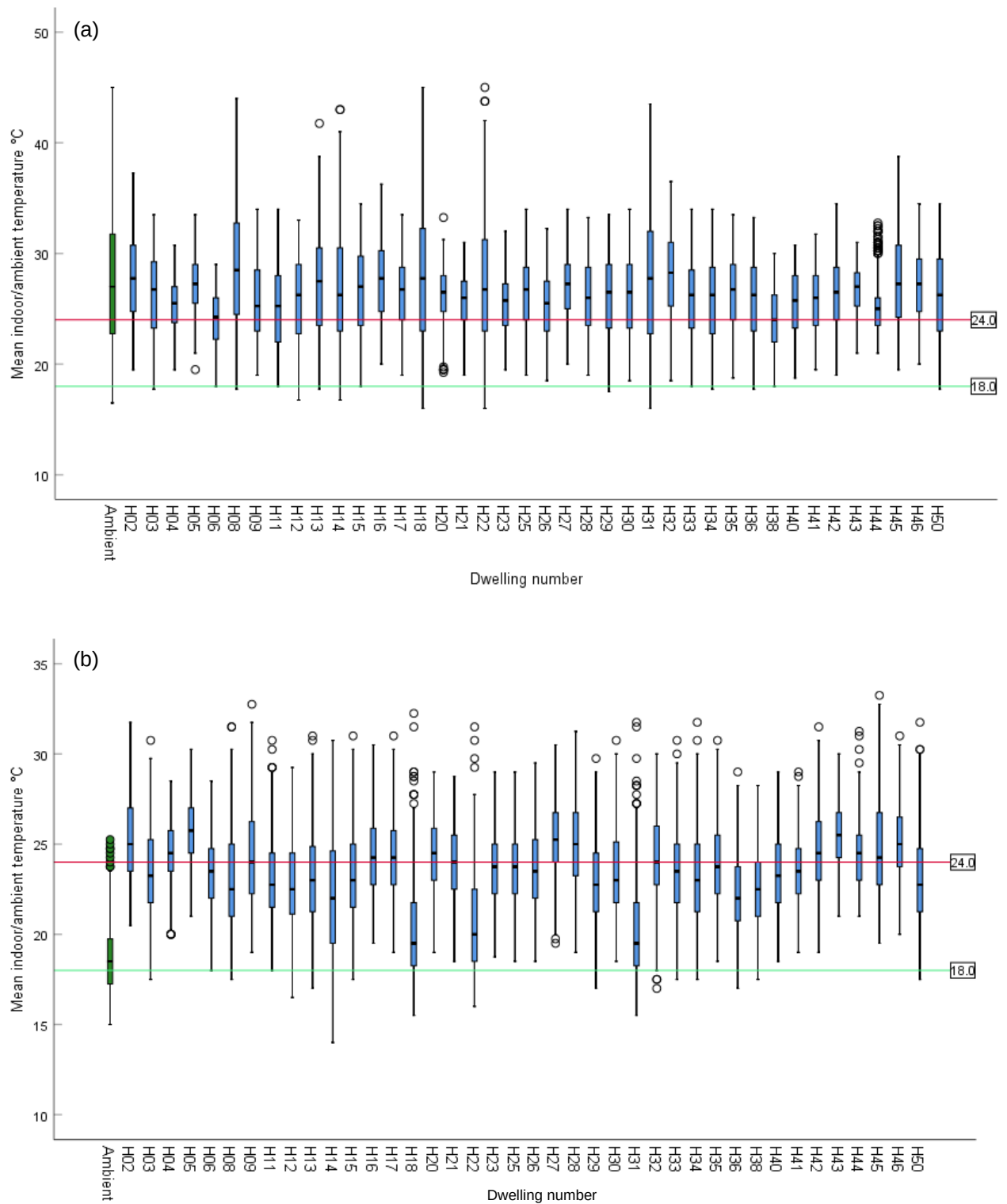


Figure 4.17: Indoor temperature variations within bedrooms in Jouberton 2017:
[a] day time, [b] night time

As illustrated in Figure 4.17, all of the dwellings, except for one, registered median day time bedroom temperatures above 24 °C. In all cases, the median day time temperatures for bedrooms were in close relation to the median ambient day time temperature for the period, suggesting that this was a summer with high ambient temperatures. It is further noted that all of the houses experienced day time bedroom temperatures of above 24 °C somewhere during the day with H18 recording a high of 45 °C. Night time median temperatures were also very close to 24 °C and exceeding the threshold in 13 of the houses (33 %). None of the houses registered median night time temperatures below 18 °C. The results suggest that bedrooms, which are assumed to be occupied during night time, were in some cases, subject to extremely hot conditions during night time in Jouberton during the summer of 2017.

4.4.4 Indoor temperature distribution: Jouberton 2017

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation H18 and H31 as represented in Figure 4.18.

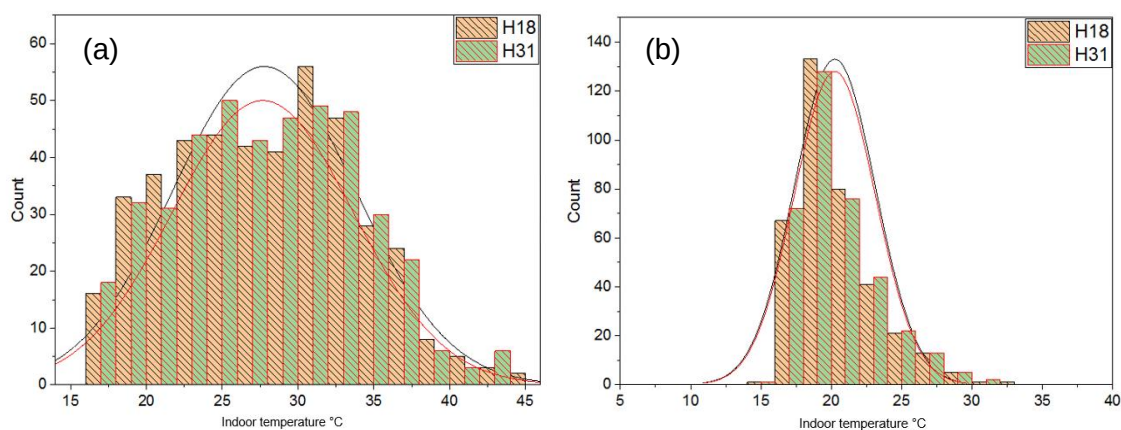


Figure 4.18: Indoor temperature distribution within bedrooms in Jouberton 2017: [a] day time, [b] night time

Figure 4.18 illustrates the indoor temperature distribution in these two dwellings. It can be observed that the two dwellings responded similarly to ambient temperatures during summer. Although H18 (the dwelling which recorded the highest temperature) recorded higher temperatures in general, the overall distribution is similar to H33. It can be observed further that the differences between the two dwellings are almost indistinguishable during night time

4.4.5 Daytime and night-time bedroom indoor variations: KwaDela 2014

This section presents indoor temperature variations in bedrooms in KwaDela during the summer of 2014. Figure 4.19 shows measurements during day time and night time periods.

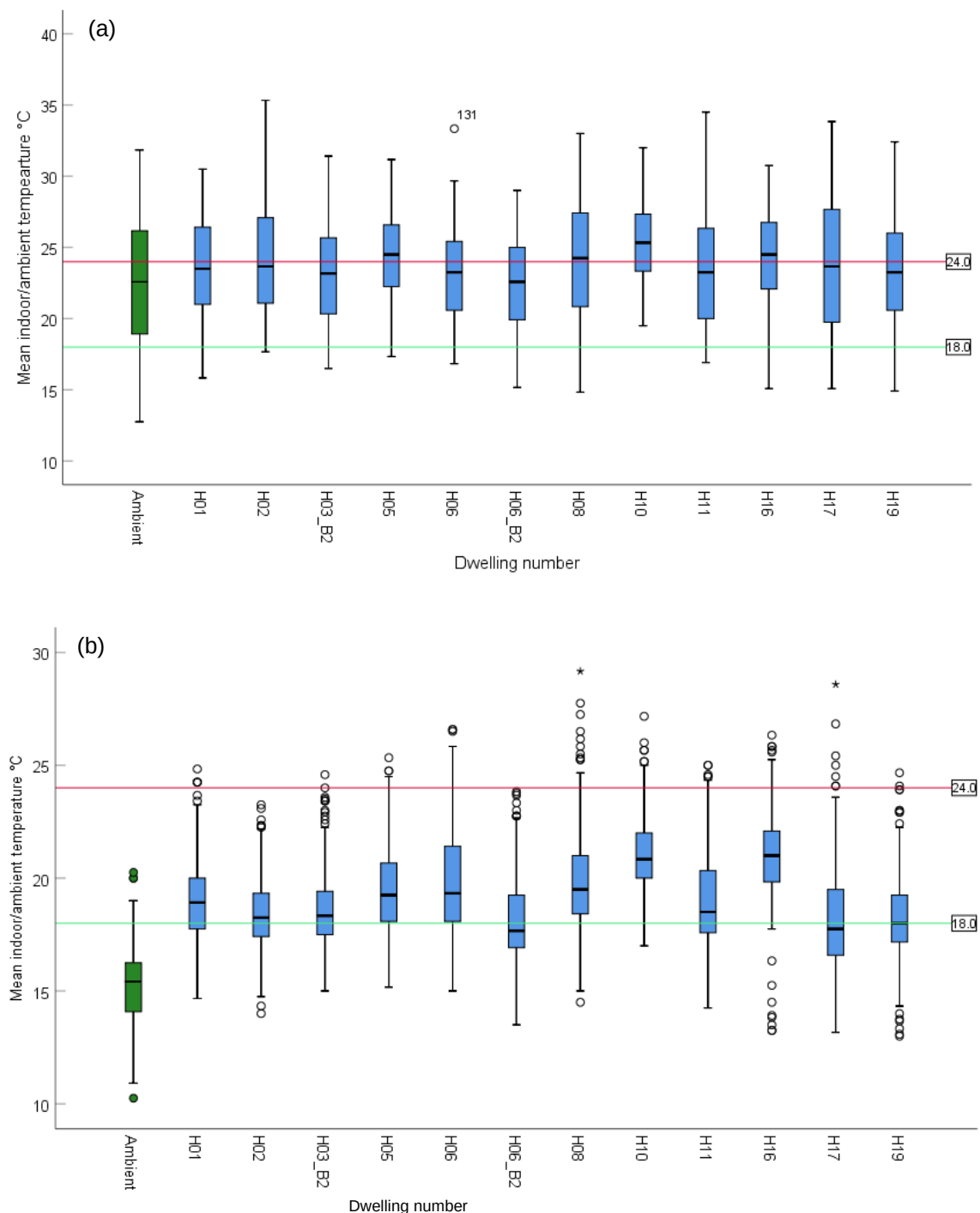


Figure 4.19: Indoor temperature variation within bedrooms in KwaDela 2014:
[a] day time, [b] night time

As illustrated in Figure 4.19, most of the dwellings registered median day time bedroom temperatures very close to 24 °C, while four dwellings registered median temperatures of above 24 °C. In most cases, the median day time temperatures for bedrooms were above the median ambient day time temperature for the period. It is further noted that all of the dwellings experienced day time bedroom temperatures of above 24 °C somewhere during the day with H02 recording a high of 36°C. Night time median temperatures were moderate, never reaching 24 °C and only twice registering indoor temperatures below 18 °C.

4.4.6 Indoor temperature distribution: KwaDela 2014

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation H02 and H06_B2 as represented in Figure 4.20.

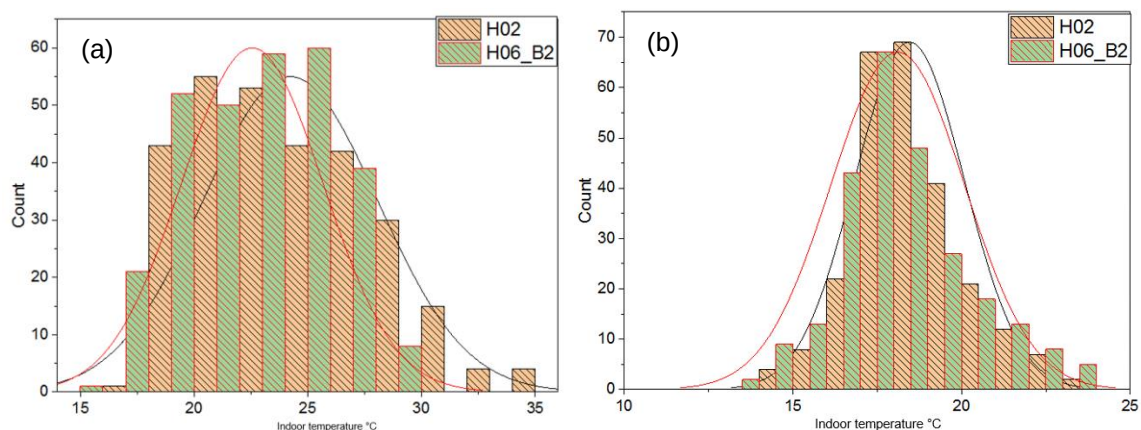


Figure 4.20: Indoor temperature distribution within bedrooms in KwaDela 2014:
[a] day time, [b] night time

Figure 4.20 illustrates the indoor temperature distribution in these two dwellings. It can be observed that the two dwellings responded similarly to ambient temperatures during summer. Except for the few high temperatures measured in H02, the overall distribution is similar to H06_B2. It can be observed further that the differences between the two houses are even less during night time.

4.4.7 Indoor and ambient temperature association for bedrooms: all three campaigns

This section explores the relationship between indoor bedroom temperatures and ambient temperatures during day time and night time.

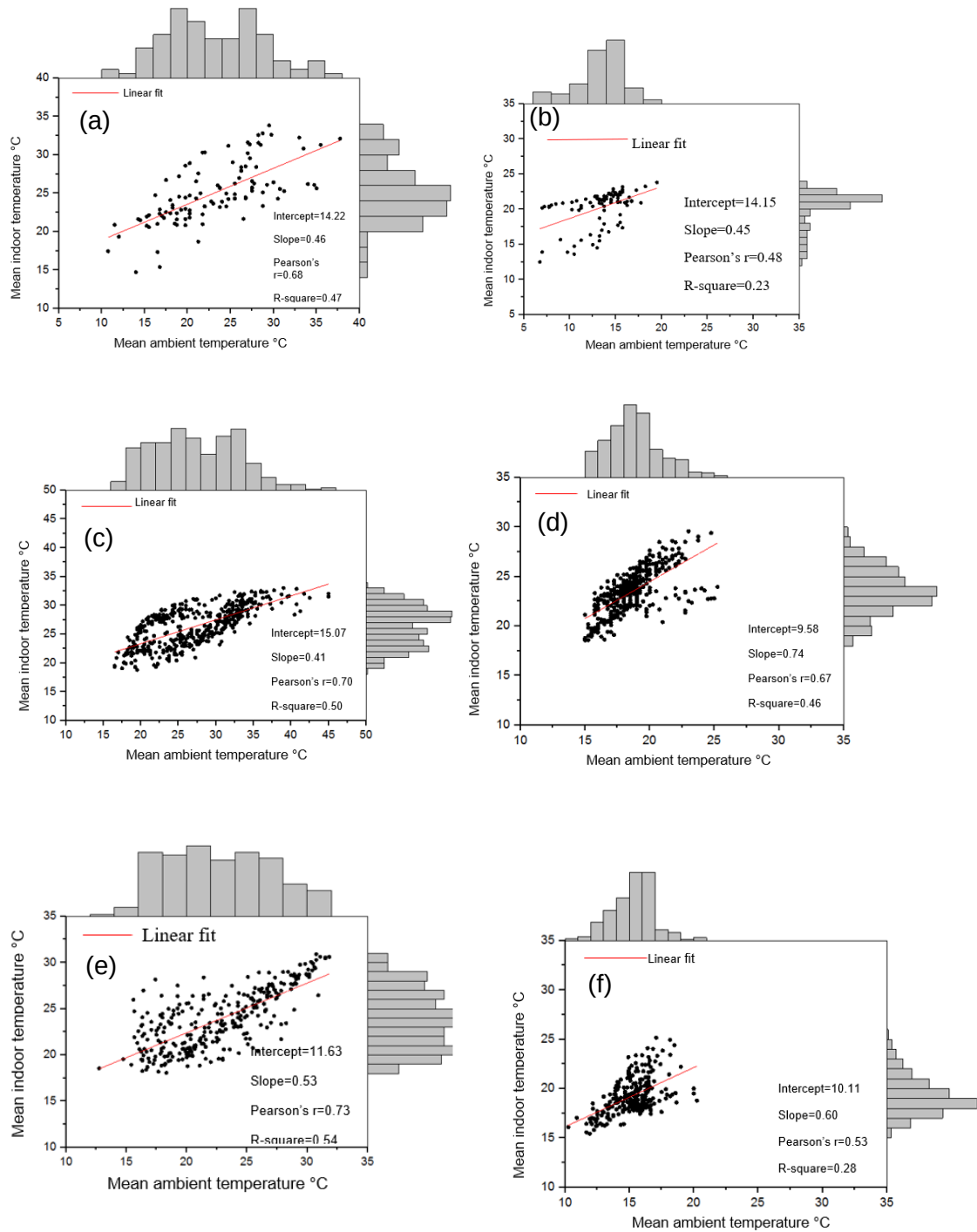


Figure 4.21: Association between indoor and ambient temperatures in bedrooms: Jouberton (2016) [a] day time [b] night time; Jouberton (2017) [c] day time [d] night time; KwaDela (2014) [e] day time, [f] night time

As shown in Figure 4.21, there seems to be a stronger relationship between indoor bedroom temperatures and ambient temperatures during day time during summer, as is evident in all three cases. For Jouberton (2016) the r-score for day time was 0.68 while, for the night time it was 0.48. A similar trend is observed for Jouberton (2017) with scores of 0.70 and 0.67 for day time and night time, respectively, as well as KwaDela with scores of 0.73 and 0.53, respectively.

4.5 Summer indoor temperature characteristics: Livingrooms

This section presents results of living-room indoor temperatures recorded during the summers of 2014, 2016 and 2017. The study assumed that living rooms would be occupied mostly during day time, between 08:00 to 20:00, although in some instances these rooms were also used by households for sleeping purposes. Indoor temperatures were analysed through the use of descriptive statistics and graphs, while the association between indoor and ambient temperatures was investigated through the use of Pearson's correlation.

4.5.1 Day time and night time indoor variations: Jouberton 2016

This section presents indoor temperature variations in bedrooms in Jouberton during the summer of 2016. Figure 4.22 illustrates the measurements for day time and night time periods. As illustrated, most of the dwellings registered median day time bedroom temperatures very close to 24 °C, while six houses (25 %) registered median temperatures of above 24 °C. In all cases, the median day time temperatures for bedrooms were above the median ambient day time temperature for the period. It is further noted that all of the houses experienced day time bedroom temperatures of above 24 °C somewhere during the day with H03 recording a high of 39 °C. Night time median temperatures were also relatively close to 24 °C although never exceeding the threshold. Only three houses registered median night-time temperatures below 18 °C. The results suggest that living rooms, which are assumed to be occupied during day time, were in some cases, subject to relatively hot conditions during the day in Jouberton during the summer of 2016.

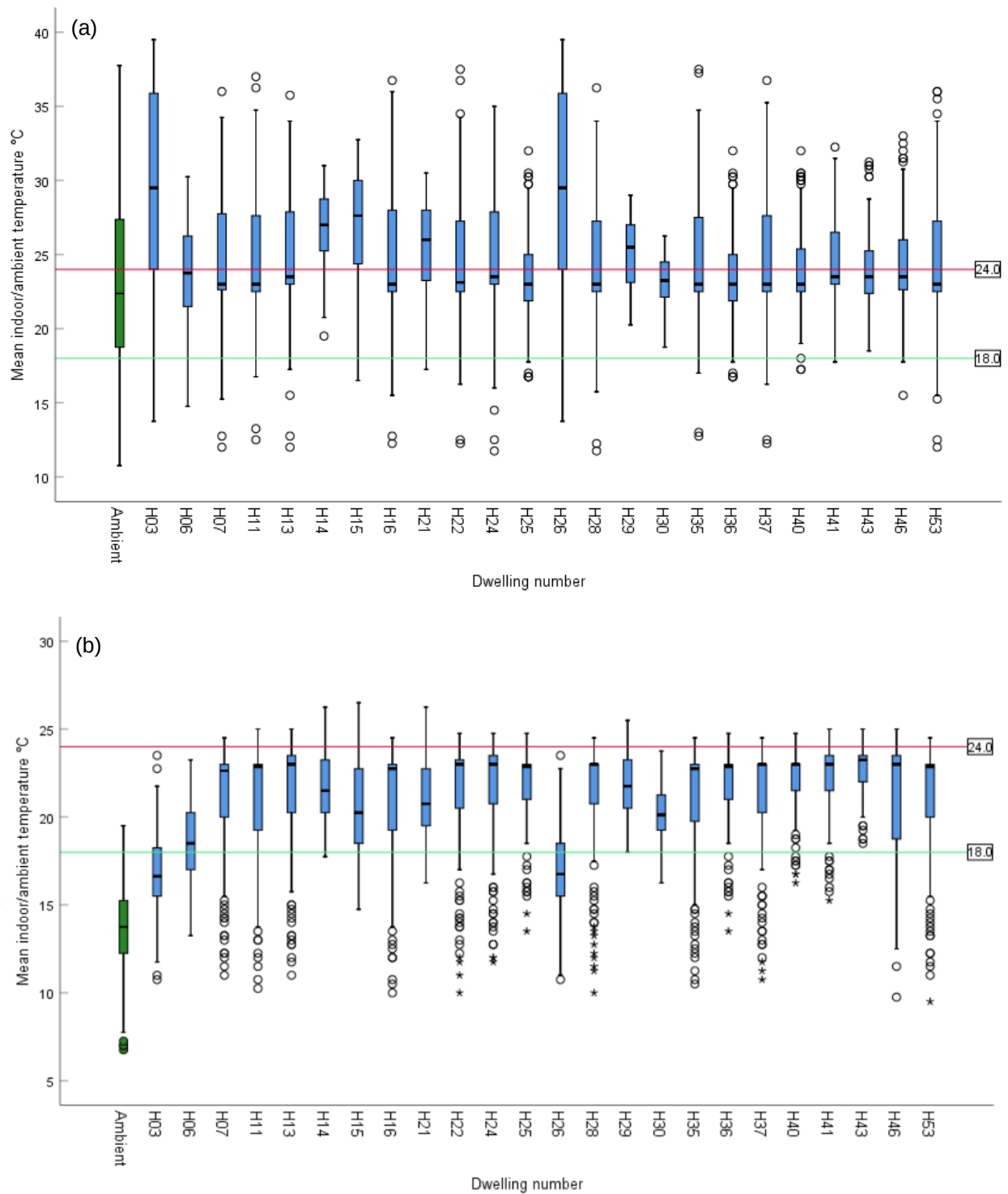


Figure 4.22: Indoor temperature variations within living rooms in Jouberton 2016: [a] day time, [b] night time

4.5.2 Indoor temperature distribution: Jouberton 2016

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation H03 and H26 as represented in Figure 4.23.

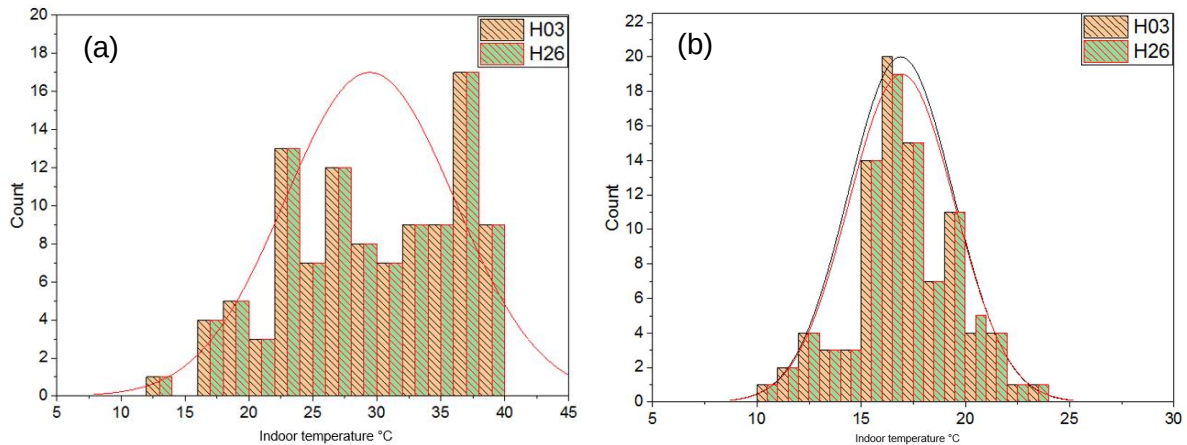


Figure 4.23: Indoor temperature distribution within living rooms in Jouberton 2016:
[a] day time, [b] night time

Figure 4.23 illustrates the indoor temperature distribution in these two dwellings. It can be observed that the two dwellings responded similarly to ambient temperatures during summer.

4.5.3 Day time and night time indoor variations: Jouberton 2017

This section presents indoor temperature variations in bedrooms in Jouberton during the summer of 2017. Figure 4.24 shows measurements during day time and night time periods. As illustrated, all of the dwellings registered median day time bedroom temperatures above 24 °C. It can be observed that the median temperature for dwellings is below the ambient median in some cases, suggesting a relatively hot summer period. It is further noted that the houses mostly experienced day time living room temperatures of above 24 °C during the day with H24 recording a high of 39 °C. Night time median temperatures were also relatively close to 24 °C with one house exceeding the threshold. None of the dwellings registered median night time temperatures below 18 °C. From the results, it is clear that living rooms, which are assumed to be occupied during day time, were subject to very hot conditions during the day in Jouberton during the summer of 2017.

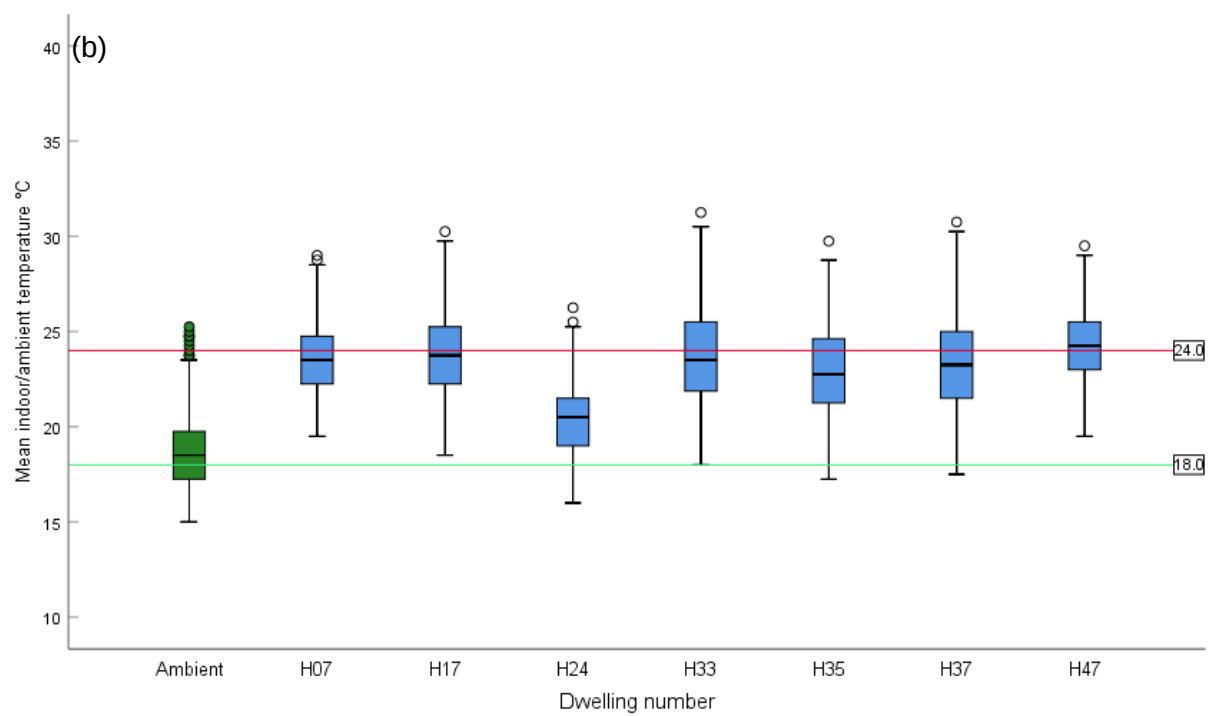
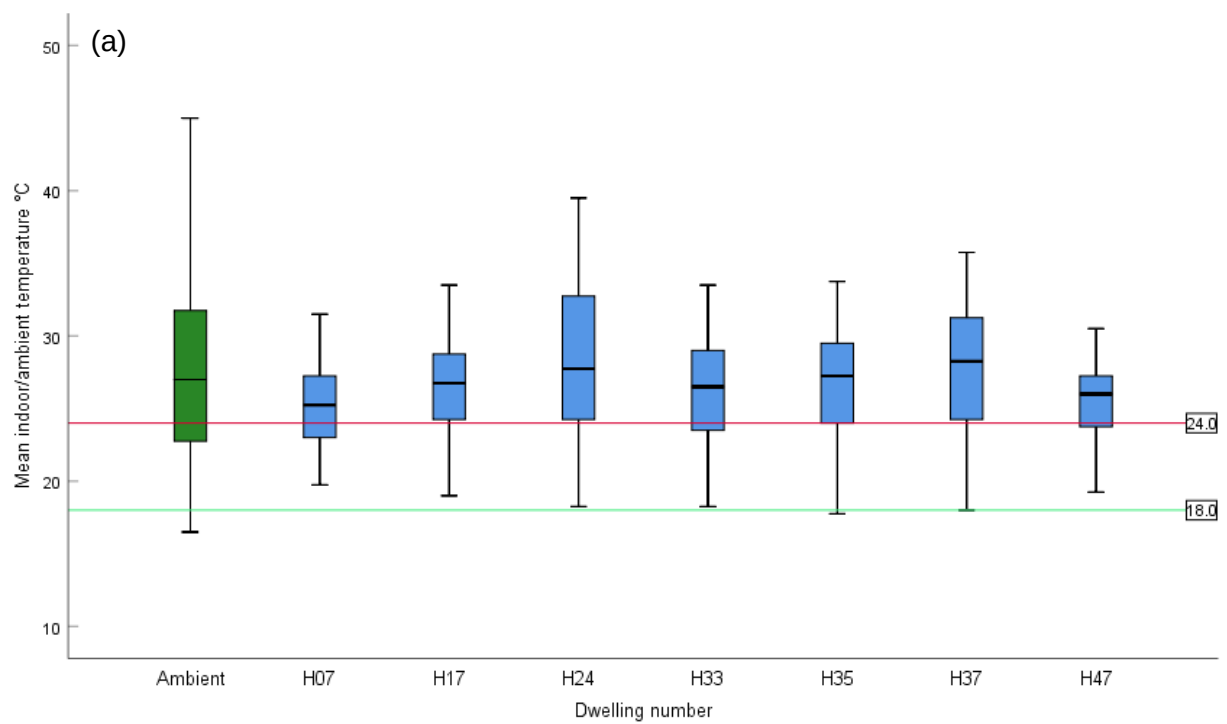


Figure 4.24: Indoor temperature variations within living rooms in Jouberton 2017: [a] day time, [b] night time

4.5.4 Indoor temperature distribution: Jouberton 2017

To illustrate the distribution of indoor temperatures, two dwellings were selected for further investigation H07 and H24 as represented in Figure 4.25.

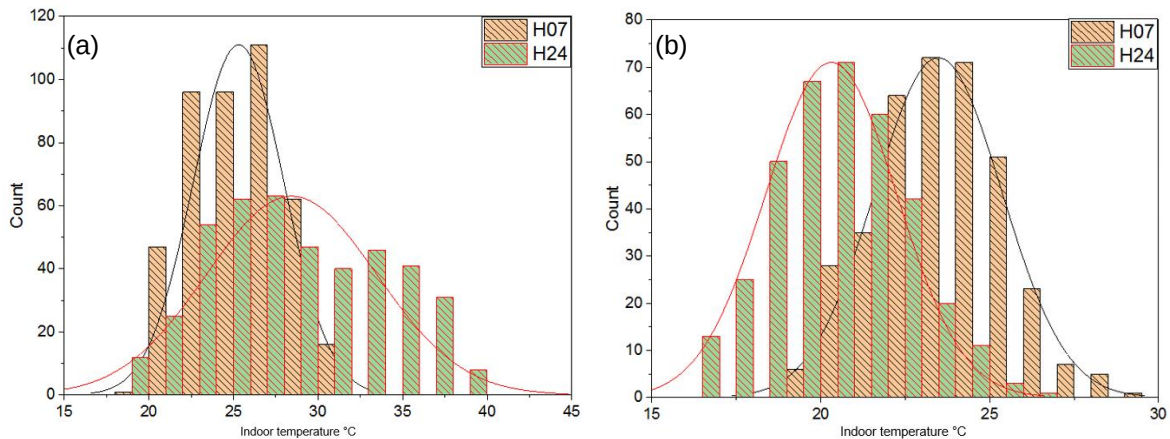


Figure 4.25: Indoor temperature distribution within living rooms Jouberton 2017: [a] day time, [b] night time

Figure 4.25 represents the indoor temperature distribution in these two dwellings. Apparent differences could be observed between the two dwellings, especially in terms of night time measurements. In H24, in which the highest temperature was measured, a large proportion of day time measurements were between 30 °C and 39 °C while in H07 no measurements were registered in that region. The histograms for the two houses look very similar during night-time, although the ranges differ substantially.

4.5.5 Daytime and night time indoor variations: kwaDela 2014

This section presents indoor temperature variations in bedrooms in kwaDela during the summer of 2014. Figure 4.26 shows measurements during day time and night time periods. As illustrated, the majority of the dwellings registered median day time bedroom temperatures very close to 24 °C, while eight houses (57 %) registered median temperatures of above 24 °C. In all cases, the median day time temperatures for living-rooms were above the median ambient day time temperature for the period. It is further noted that all of the houses experienced day time living-room temperatures of above 24 °C somewhere during the day with H13 recording a high of 37 °C. Night time median temperatures were moderate and never came close to exceeding the 24 °C threshold. Only one house registered median night time temperatures below 18 °C. The results suggest that living-rooms, which are assumed to be occupied during day time, were in some cases, subject to relatively hot conditions during the day in KwaDela during the summer of 2014, but that they cooled down substantially during night time.

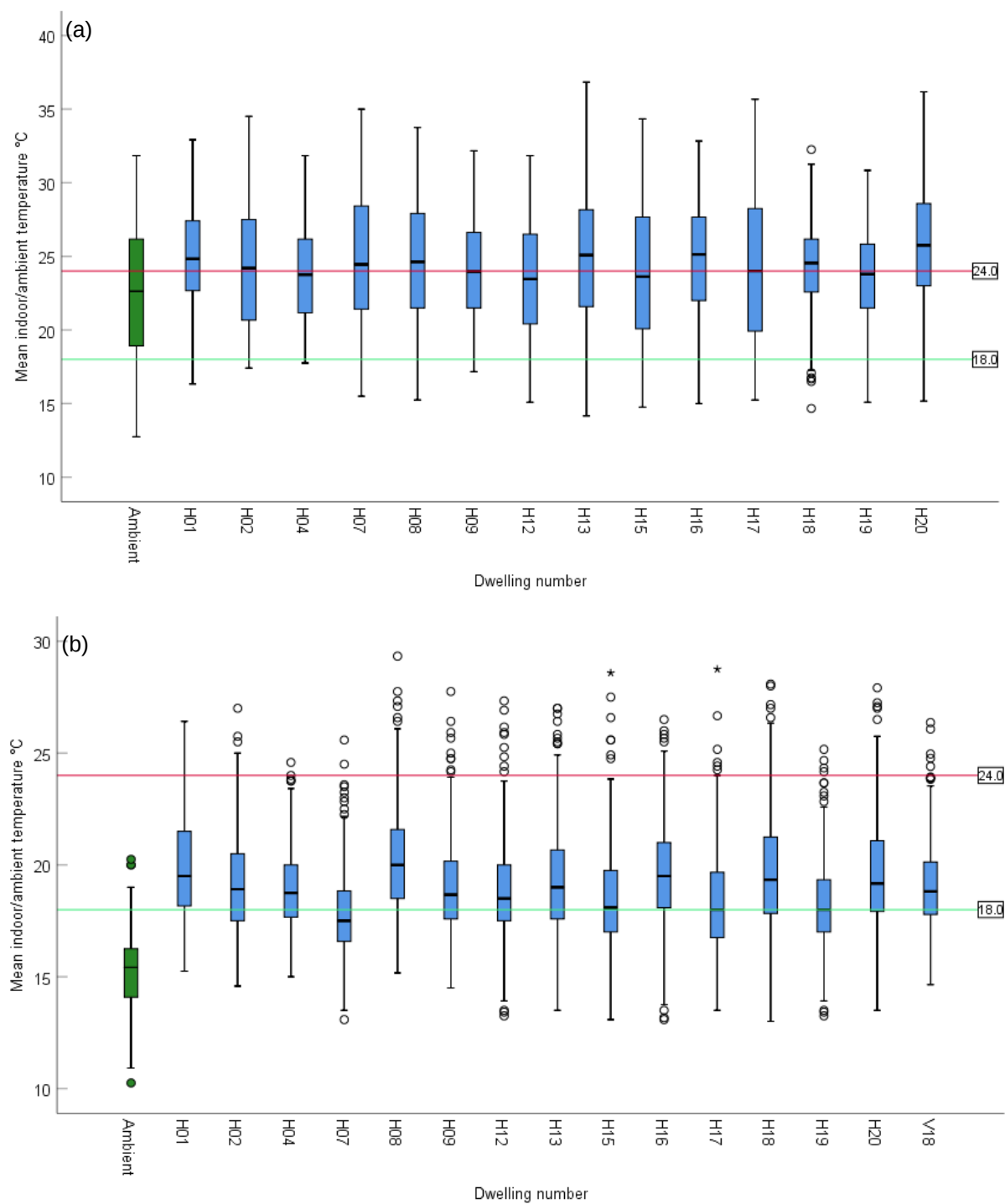


Figure 4.26: Indoor temperature variations within living rooms in KwaDela 2014: [a] day time, [b] night time

4.5.6 Indoor temperature distribution: KwaDela 2014

To illustrate the distribution of indoor temperatures, two houses were selected for further investigation H07 and H13 as represented in Figure 4.27.

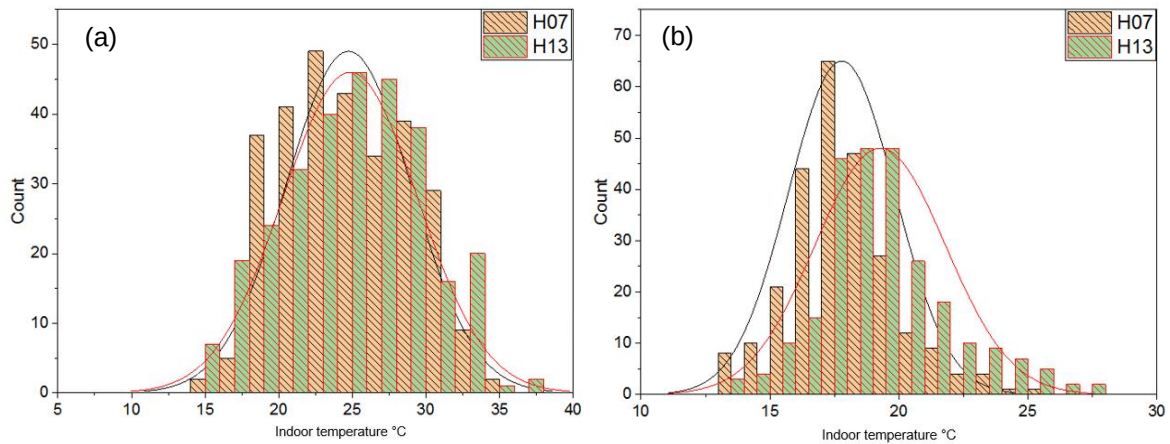


Figure 4.27: Indoor temperature distribution within living rooms in KwaDela 2014: [a] day time, [b] night time

Figure 4.27 illustrates the indoor temperature distribution in these two dwellings. It can be observed that the two dwellings responded similarly to ambient temperatures during summer. Although H13 (the house which recorded the highest temperature) recorded higher temperatures in general, the overall distribution is similar to H07 during day time. There is, however, a more significant difference during the night time.

4.5.7 Indoor and ambient temperature association for living rooms: all three campaigns

This section explores the relationship between indoor living room temperatures and ambient temperatures during daytime and night-time.

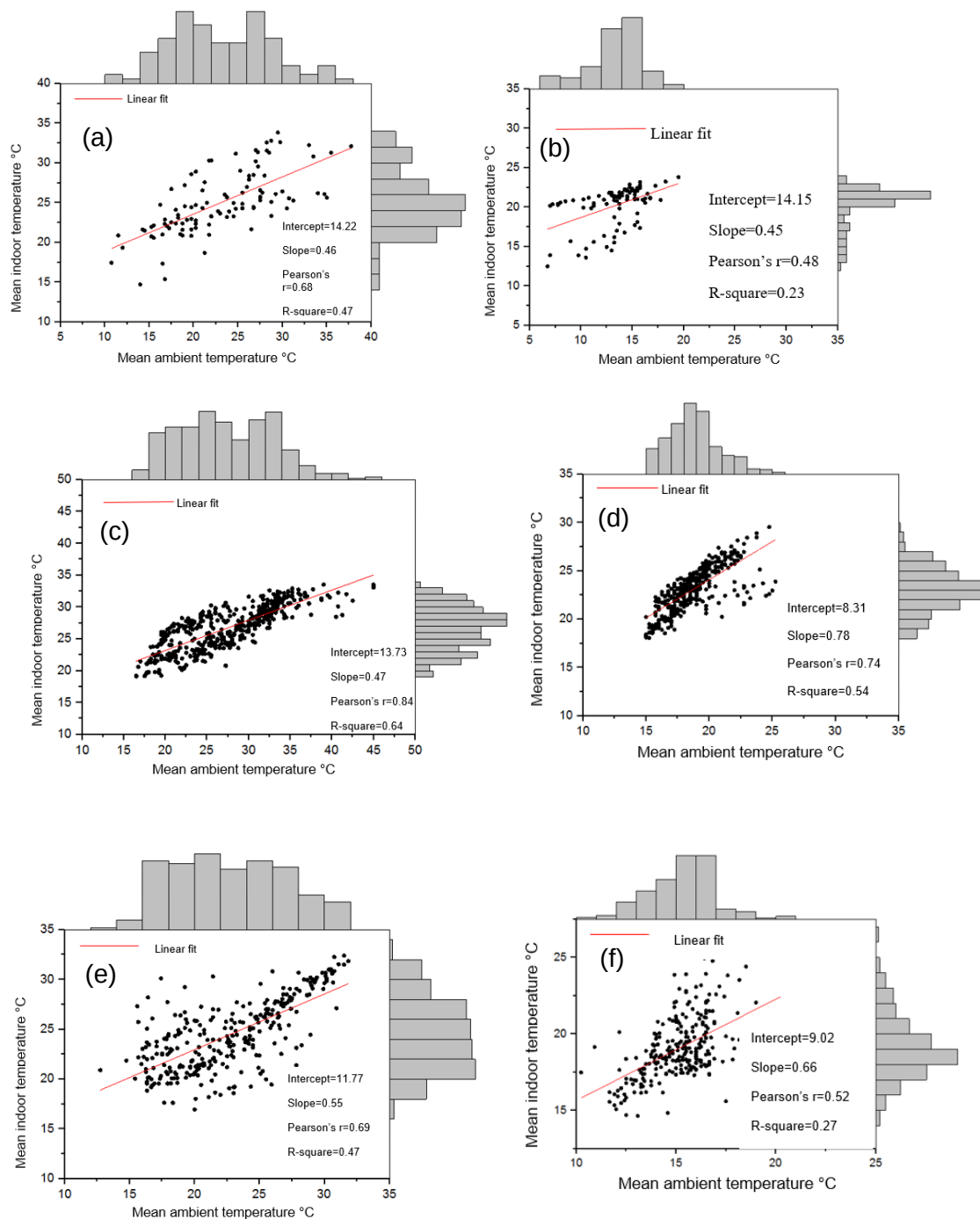


Figure 4.28: Association between indoor and ambient temperatures within living rooms: Jouberton 2016 [a] day time, [b] night time; Jouberton 2017 [c] day time, [d] night time; kwaDela 2014 [e] day time, [f] night time

As shown in Figure 4.28, there seems to be a stronger relationship between indoor bedroom temperatures and ambient temperatures during day time during summer, as is evident in all three cases. For Jouberton (2016) the r-score for day time was 0.68 while for the night time it was 0.23. A similar trend is observed for Jouberton (2017) with scores of 0.84 and 0.74 for day time and night time respectively, as well as KwaDela with scores of 0.69 and 0.52.

4.6 Summary and discussion

This chapter characterised indoor temperatures in low-income dwellings across two settlements (KwaDela and Jouberton) during winter and summer seasons. The characterisation of indoor temperature is vital as it is an indicator of occupant exposure to extreme thermal conditions (Smargiassi *et al.*, 2008; White-Newsome *et al.*, 2012).

The study established that during winter occupants are most vulnerable to extreme temperatures during night time. In Jouberton 2016 all bedrooms – which are assumed to be occupied during the night time – registered median temperatures below the 18 °C WHO guideline during night time. For Jouberton 2017 and KwaDela 2014, 98 % and 85 % of bedrooms respectively registered median temperatures below 18 °C. This trend was also confirmed in living rooms during winter nights with all living rooms in Jouberton 2016, 2017 and 86 % of living rooms in KwaDela 2014 registering night time median temperatures below 18 °C. During day time median indoor temperatures also frequently dropped below 18 °C, although not as much as night-time temperatures. In living rooms – which are assumed to mostly be occupied during day time – median day time temperatures were below the 18 °C threshold 43 % and 40 % respectively for KwaDela 2014 and Jouberton 2016. These findings are comparable to those of Yohanis and Mondol (2010), who found that 80 % of houses sampled in their study experienced average temperatures ranging between 15 °C and 20 °C during winter, indicating that dwellings were losing heat at a faster rate than occupants could sufficiently space heat. Similarities can also be drawn between these findings and a study done by Santamouris *et al.* (2014) in Athens, Greece which found that for almost 80 % of the time indoor temperatures were below 18 °C, while for 40 % of the time indoor temperatures were below 15 °C. In the same study, the extreme group of dwellings had mean temperatures of 12.2 °C. Additionally, in a study in Cyprus by Pignatta *et al.* (2017) found that mean indoor temperatures ranged between 16 and 19 °C with the group of most significant deprivation recording minimum temperatures as low as 12.7°C. Hunt and Gidman (1982) estimated mean temperatures of 18.3 °C in living rooms and 15.2 °C in bedrooms. Critchley *et al.* (2007) found that the mean indoor temperature in bedrooms was 16°C while the mean indoor temperature in living rooms was 18 °C. In Portugal, Magalhães *et al.* (2016) estimated that daily the mean temperature for living rooms was 14.9 °C and 16.6 °C for bedrooms during winter while in South Island, New Zealand the CDHB (2012) found that living room

temperatures were below 17 °C. These studies, even though done in different climatic regions, share the common similarity that they were all conducted in low-income settlements. They further all point to the inability of low-income households across the world to sufficiently heat their dwellings during the winter, thus contributing to physical health challenges for occupants. Exploring physical health effects incidences was beyond the scope of the study, however, previous studies have shown that prolonged exposure to indoor temperatures below 18 °C could lead to respiratory and cardiovascular problems (Geddes *et al.*, 2011; Ormandy & Ezratty, 2016). Other physical health issues that can result from exposure to low indoor temperatures include asthma attacks, colds and influenza, especially in young children and those with underlying chronic health conditions (Cheshire Jr, 2016).

During summer, occupants were found to be most vulnerable to extreme temperatures during the day time. In Jouberton 2017 all living rooms – which are assumed to be occupied during daytime – registered median temperatures above the 24 °C WHO guideline during day time. For Jouberton 2016 and KwaDela 2014, 25 % and 57 % of living rooms respectively registered median temperatures above 24 °C. This trend was also confirmed in bedrooms during summer days, with all bedrooms in Jouberton 2017 recording day time median temperatures above 24 °C, while Jouberton 2016 and KwaDela 2014 registered 22 % and 33 % respectively. During night time median indoor temperatures frequently hovered close to 24 °C during summer and in some cases even exceeded the 24 °C threshold, suggesting that occupants in low-income households are often exposed to very high temperatures in summer, even at night. Elevated night time temperatures could be ascribed to the effects of the urban heat island that reduces the night-to-day difference (Kenny *et al.*, 2019). Without the means to control their indoor thermal environments, occupants of low-income dwellings, therefore, remain vulnerable to high indoor temperatures. This might also explain why the relationship between ambient and indoor temperatures was stronger during the day time than during night time in summer. The study findings are comparable to findings by Lomas and Kane (2012), who found that 28 % of living rooms and 88 % of bedrooms overheated during summer times. Also, in Greece, Sakka *et al.* (2012) recorded indoor temperatures of greater than 40 °C with average maximum temperatures of 35.4 °C. Exposure to such temperatures leads to negative health impacts on occupants especially for those occupying indoor environments for long periods like the elderly and those with compromised immune systems.

The high day time indoor temperatures reported in this study suggests that thermal discomfort is likely to be experienced by low-income households (White-Newsome *et al.*, 2012) as exposure to high temperatures mean that the body will respond by increasing heat loss through the skin in the form of sweating (Nguyen *et al.*, 2014). Hence, the loss of fluids is inevitable and can lead to dehydration, heat strokes and, in extreme instances, fainting. A study by van Loenhout *et al.*

(2016) confirms this assertion where they established that when indoor temperatures were high, 42.7 % of participants reported experiencing thirst while 40.6 % reported sleep disturbance and 39.6 % reported excessive sweating. Furthermore, in a study by Mavrogianni *et al.* (2015) it was found that when night time bedroom temperatures exceeded the 24 °C WHO threshold, sleep disruption was a possibility (more so during episodes of heatwaves). Kenny *et al.* (2019) also confirm that the quality of sleep is affected when bedroom temperatures exceed 24 °C.

Finally, a relationship was observed between ambient and indoor temperatures and was most significant during winter nights and summer days. This implies that the thermal insulation of houses was mostly ineffective in shielding houses from extremely high and low ambient temperatures. The manner in which thermal insulation affects indoor thermal environments is explored in Chapter 5.

CHAPTER 5: CHARACTERISATION OF THERMAL INSULATION USING INDOOR TEMPERATURE MEASUREMENTS

This chapter presents findings on the extent to which indoor and ambient temperature measurements can be used to characterise the thermal insulation status of dwellings. Temperature monitoring was done over winter and summer seasons in the settlement of KwaZamokuhle.

5.1 Introduction

In the previous chapter, indoor temperature was determined for low-income households over winter and summer seasons using indoor iButtons. This chapter focuses on how thermal insulation affects indoor thermal environments, which is indoor temperatures. The study explored the feasibility of using indoor temperature as a proxy indicator to gauge the functionality of thermal insulation in naturally ventilated, low-income residential dwellings in fulfilment of Objective 2. Objective 2 explored the indoor temperature variations in dwellings with different thermal insulation levels. Dwellings that were selected were categorised as non-insulated, partially insulated, and fully insulated. Measurements were taken in KwaZamokuhle during 2017. For thermal comfort benchmarking purposes, WHO guidelines were used with a minimum indoor temperature of 18 °C and a maximum indoor temperature of 24 °C. Section 5.2 presents winter monitoring results, while Section 5.3 presents summer results. To establish the thermal performance in dwellings of different insulation levels, the following questions were analysed:

- To what extent does thermal insulation status influence variations in indoor temperature readings?
- What dwelling types (fully insulated, partially insulated or non-insulated) can maintain the prescribed WHO indoor minimum and maximum temperatures of 18 °C and 24 °C, respectively?
- To what extent is thermal insulation a determinant of indoor thermal environment in free-running/naturally ventilated low-income residential dwellings?

5.2 Winter livingroom indoor temperature variations

This section presents results on diurnal winter indoor monitoring which was conducted in living rooms in KwaZamokuhle in 2017. As highlighted in Chapter 3, the study assumed that living rooms were occupied mostly during day time but were also used for sleeping purposes in some cases. The sampled dwellings were naturally ventilated, with the primary sources of heat being solar radiation and indoor burning.

5.2.1 Indoor temperature variation across different dwelling types

This section highlights the indoor temperature variations categorised in terms of differences in levels of insulation.

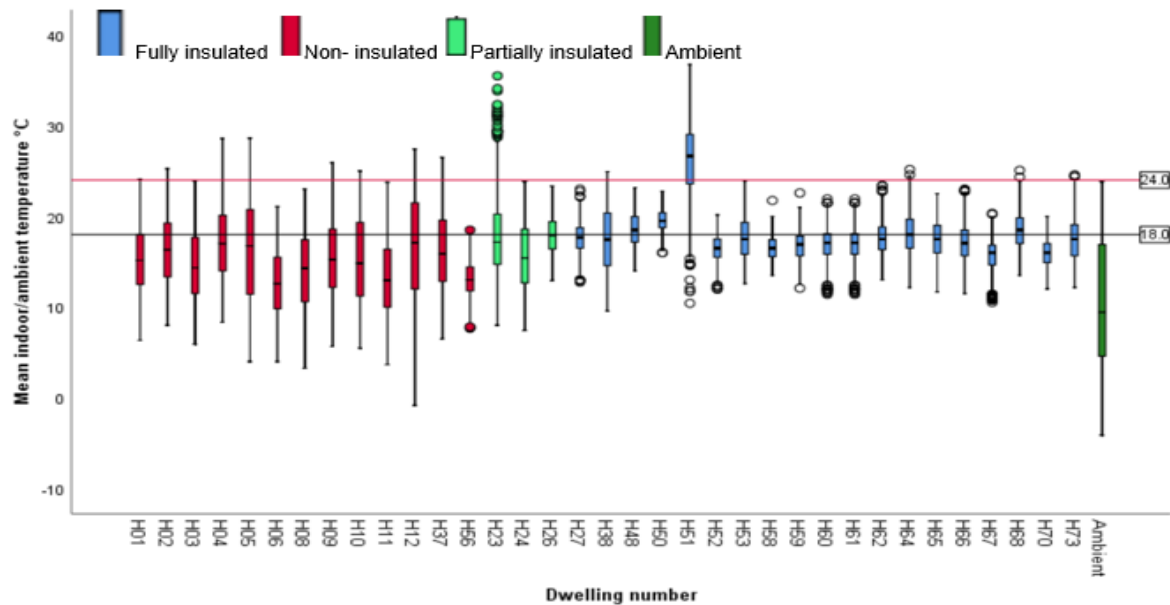


Figure 5.1: Indoor temperature variations within livingrooms during winter

Figure 5.1 represents the winter indoor temperature variations in the sampled non-insulated, partially insulated, and fully insulated dwellings. During the monitoring period, the study found that all non-insulated dwellings had median temperatures below 18 °C. The temperature variation in non-insulated dwellings was also substantially more substantial than in the other two types of dwellings. Partially insulated dwellings did not perform much better, with only one dwelling recording a median temperature of 18 °C, while the remainder were below 18 °C. In contrast, 53 % of fully insulated dwellings recorded median temperatures above 18 °C, suggesting that these houses responded better to ambient temperatures than partially, or non-insulated houses. It should, however, be noted that the median temperatures of all dwellings were significantly higher than the ambient median temperatures, although non-insulated and partially insulated dwellings did record indoor temperatures that could threaten thermal comfort. These low temperatures in non-insulated and partially insulated dwellings suggest heat wastage through the housing envelope. This is because the ability of these dwellings to retain heat generated from space heating or solar radiation gains is poor. Variations in day time and night time temperatures across different dwelling types will now be highlighted.

5.2.2 Day time and night time indoor temperature variations

This section presents temperature variations during daytime and night-time classified in terms of the level of insulation.

Table 5.1: Grouped mean winter day time and night time temperatures in living rooms

Day time		Non-insulated	Partially insulated	Fully insulated
Mean		17.4	17.7	18.3
Median		17.8	17.8	18.6
Std. Deviation		3.2	3.2	1.8
Skewness		-0.56	-0.02	-0.32
Minimum		8.0	9.9	13.2
Maximum		23.8	26.1	22.0
Percentiles	10	12.6	13.3	16.0
	90	21.1	22.0	21.0
Night time		Non-insulated	Partially insulated	Fully insulated
Mean		12.3	16.3	17.2
Median		12.1	16.1	17.3
Std. Deviation		2.6	2.7	1.6
Skewness		.118	.128	-.194
Minimum		6.0	9.5	13.0
Maximum		19.0	24.1	21.0
Percentiles	10	8.9	12.8	15.1
	90	15.8	19.9	19.2

Table 5.1 represents the combined descriptive statistics during the winter season for the different classes of sampled dwellings. As would be expected, day time medians were higher than night time medians in all dwelling classes, although the difference between night time and day time medians for non-insulated dwellings were significantly bigger. This finding shows the lack of heat-retention capacity in non-insulated houses when compared with partially insulated and insulated houses. The 10th and 90th percentiles represent significant variations in the means during the day time across all dwelling classes with skewness of -0.56 for non-insulated, while partially and fully insulated showed little skewness with values of -0.02, and -0.32, respectively. During day time 90 % of indoor temperatures recorded in non-insulated dwellings were less than 21.1 °C, while 90 % of indoor temperatures in partially insulated dwellings were less than 22 °C and 90 % of indoor temperatures in insulated dwellings were below 21 °C. In contrast, during night time, 90 % of indoor temperatures were below 15.8 °C, while in partially insulated dwellings, 90 % of indoor temperatures were below 19.9 °C. In fully insulated dwellings 90 % of temperatures were below 19 °C. The range between the 10th and 90th percentile shows the huge indoor temperature

variations in all dwelling classes with a positive skewness in non-insulated (0.118) and partially insulated dwellings (0.128) and a negative skewness (-0.194) in fully insulated dwellings. These results suggest that fully insulated and partially insulated dwellings have a better capacity to retain heat gained during day time, thus performing better during both day time and night time as compared with non-insulated dwellings. The next sections explore indoor temperature density distributions during day time and night time.

5.2.3 Day time indoor temperature density distributions

Day time indoor temperature density distributions are presented first. Density graphs were combined with marginal histograms to give a comprehensive overview (Figure 5.2).

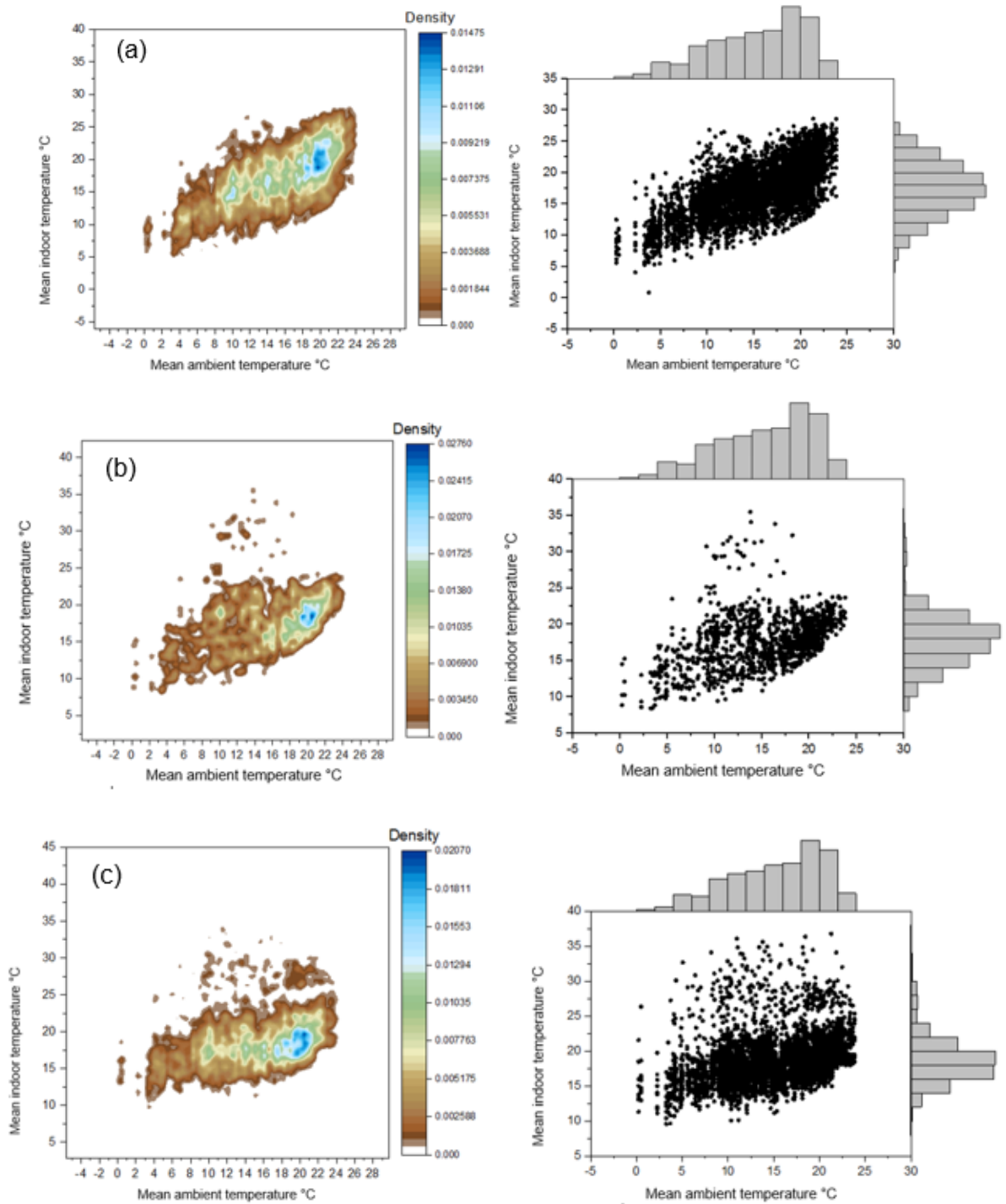


Figure 5.2: Day time indoor temperature density distribution: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings

Figure 5.2 shows little variation between houses with different levels of insulation during winter days. In the non-insulated group of dwellings high-density concentrations were in the 13 °C to 23 °C range while in partially insulated dwellings, high-density concentrations were recorded in the 15 °C to 25 °C range suggesting them to be marginally warmer by 2 °C. In the fully insulated

dwellings, high-density concentrations were recorded in the 15 °C to 30 °C range, suggesting that they are generally warmer than the other dwelling types and a broader temperature range can characterise them. The high indoor temperatures during day time can be attributed to solar radiation gains and other indoor activities that generate heat (for example cooking and space heating). The next section presents the indoor temperature concentration distributions during winter nights.

5.2.4 Night time indoor temperature density distribution

This section presents the indoor temperature density distributions across dwellings with different insulation levels during winter nights.

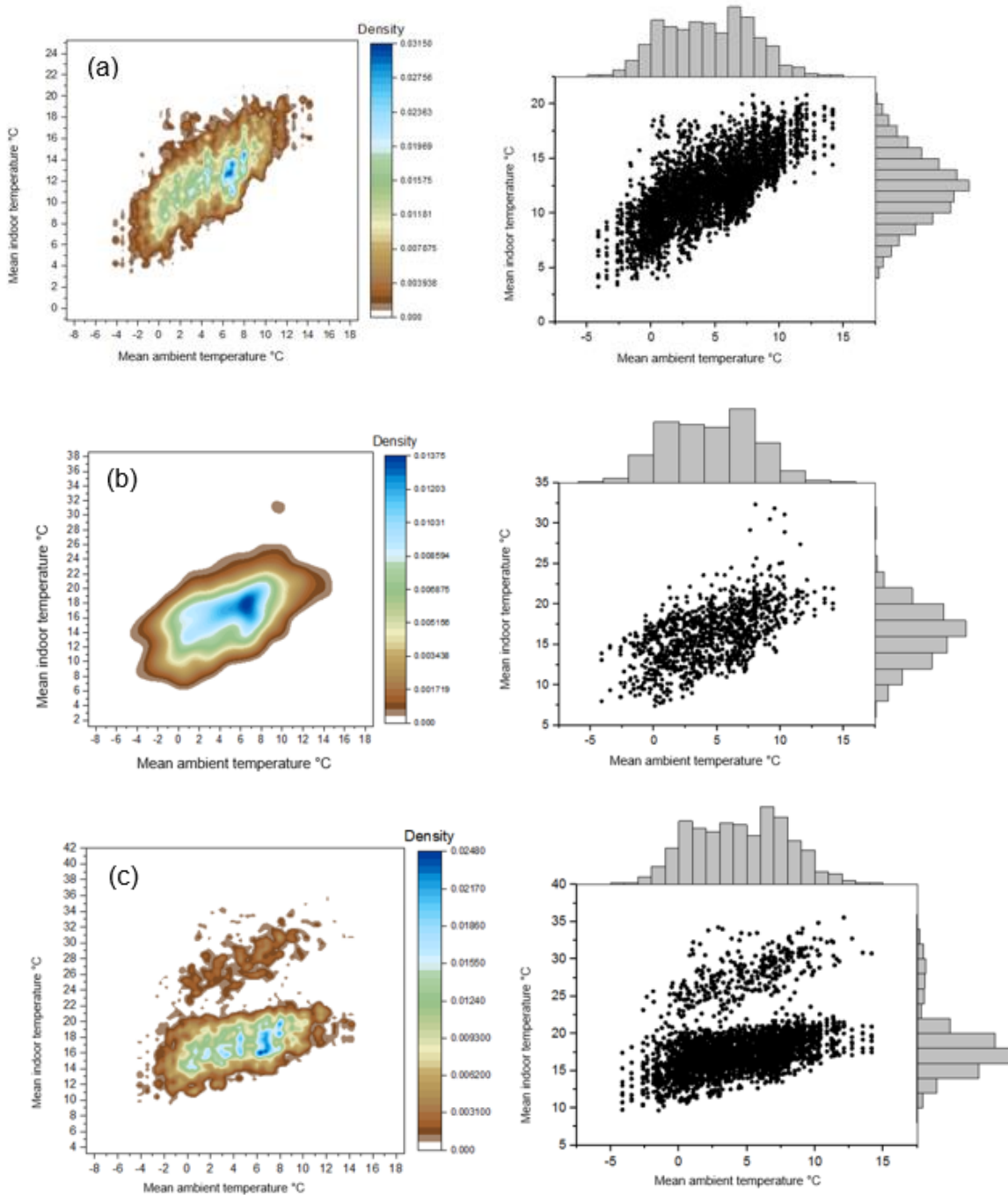


Figure 5.3: Night time indoor temperature density distribution: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings

According to Figure 5.3, the non-insulated dwellings registered the lowest temperature density distribution in the range of 10 °C to 16 °C, while partially insulated and fully insulated dwellings had ranges of 15 °C to 22 °C and 11 °C to 23 °C respectively. There was, therefore, less variation between partially insulated and fully insulated dwellings than between them and non-insulated dwellings during night times. This suggests that partially insulated and fully insulated structures are more capable of retaining heat gained during the day. The next section explores the relationship between winter ambient temperatures and indoor temperatures in different dwelling types during day time.

5.2.5 Relationship between day time indoor and ambient temperature

This section presents the relationship between indoor and ambient temperatures during daytime in houses with different levels of insulation.

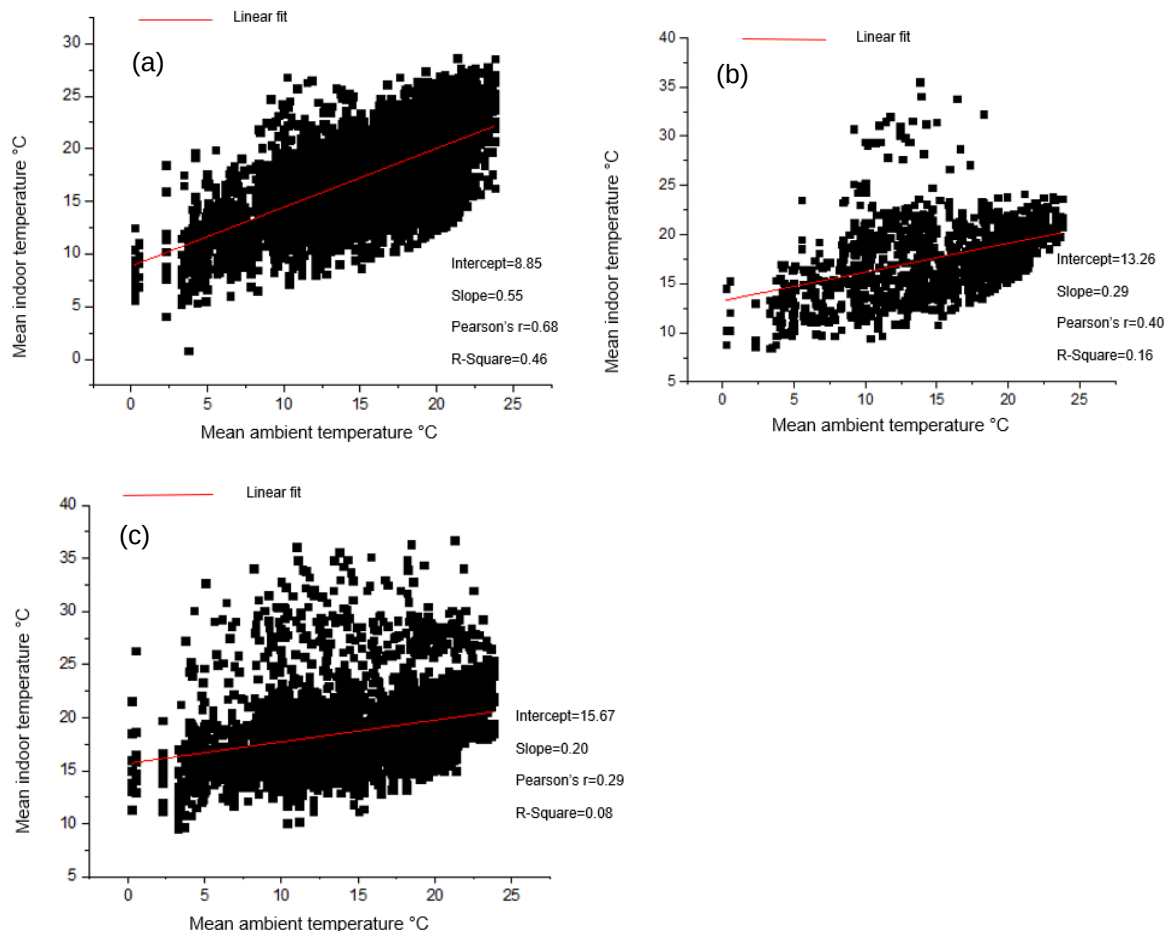


Figure 5.4: Regression analysis results for living rooms for day time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings

Non-insulated dwellings showed the most significant relationship between indoor and ambient temperatures during daytime ($r = 0.68$). Partially insulated dwellings showed a moderate relationship of $r = 0.40$, while insulated dwellings yielded $r = 0.29$. This finding suggests that non-insulated dwellings are more sensitive to ambient temperatures than partially or fully insulated dwellings.

5.2.6 Relationship between night time indoor and ambient temperature

This section presents the relationships between indoor and ambient temperatures during night time in dwellings per their insulation status.

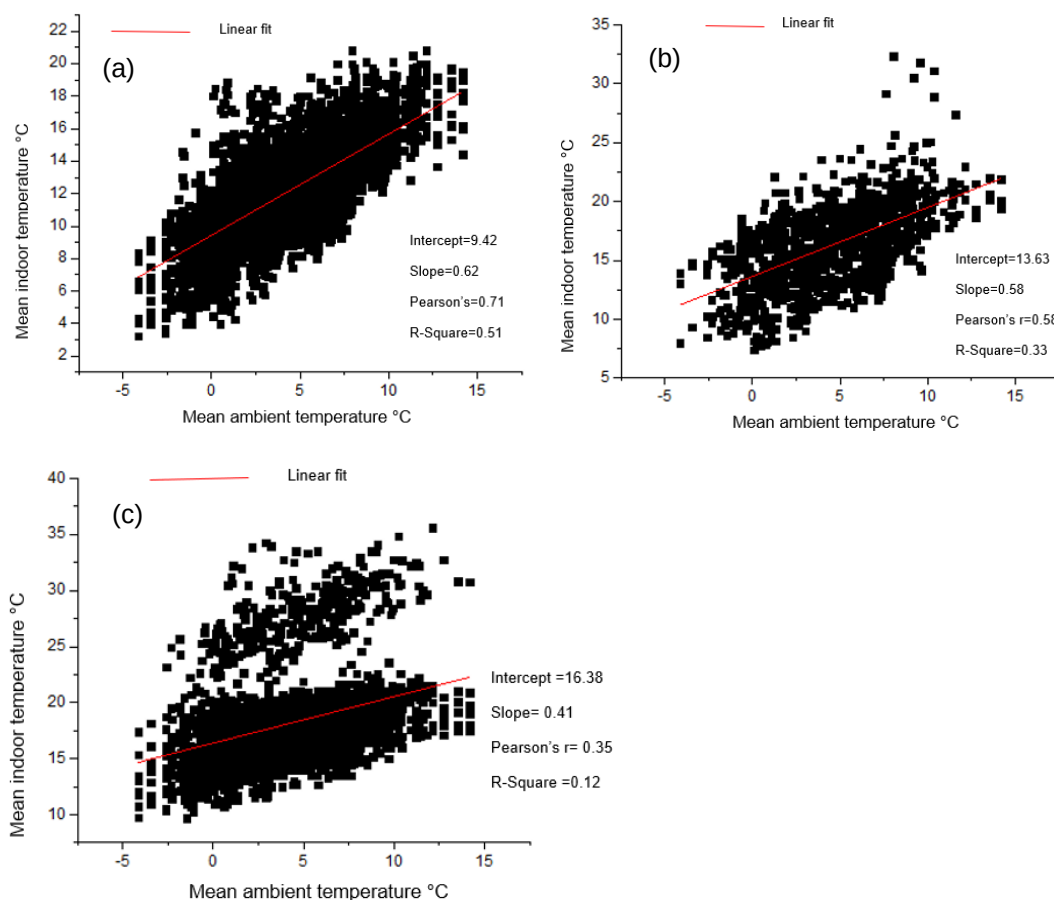


Figure 5.5: Regression analysis results for living rooms at night time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, [c] fully insulated dwellings

Non-insulated dwellings showed the most significant relationship between indoor and ambient temperatures (r = 0.71). Partially insulated dwellings showed a relatively strong relationship during night time ($r = 0.58$), while insulated dwellings yielded $r = 0.35$. This finding supports the finding for winter days that non-insulated dwellings are more sensitive to ambient temperatures than partially or fully insulated houses. It is, however, observed that the influence of ambient

temperatures on non-insulated dwellings seems to be more noticeable during night time, but always present during the winter.

5.3 Summer

This section presents results on diurnal summer indoor monitoring which was conducted in living rooms in KwaZamokuhle in 2017. In summer, indoor thermal discomfort was expected from indoor overheating, especially during day time. The indoor temperature variations across low-income dwellings with different levels of insulation are presented below.

5.3.1 Indoor temperature variation across different dwelling types

This section highlights the indoor temperature variations categorised in terms of differences in levels of insulation. The lack of consistency in the number of dwellings monitored between winter and summer periods was due to some households opting to withdraw from the study. This did, however, not affect the study as the key trends could still be drawn and inferred from the available data. The withdrawal of households did not have a statistically observable negative impact on the findings. Figure 5.6 shows the indoor temperature variations for the summer monitoring period.

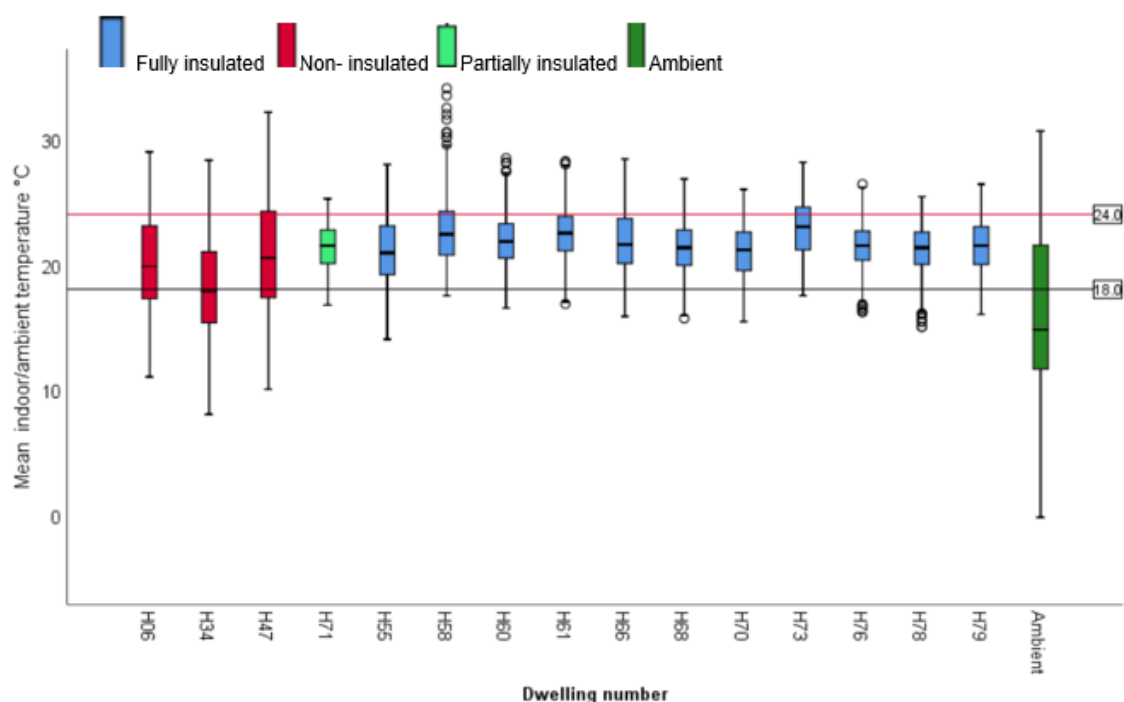


Figure 5.6: Summer indoor temperature variations in living rooms according to insulation type

Figure 5.6 represents the summer indoor temperature variations in different classes of dwellings. The temperature variation in non-insulated dwellings was significantly larger than in partially and

fully insulated dwellings. Although none of the dwellings had a median temperature exceeding 24 °C, one non-insulated house had a median temperature below 18 °C. It was noted that the median temperatures of all dwellings were significantly higher than the ambient median temperatures at all times and that temperatures generally fell within the WHO range of 18 °C to 24 °C. Variations in day time and night time temperatures across different dwelling types are presented next.

5.3.2 Day time and night time indoor temperature variations

This section presents temperature variations during day time and night time classified in terms of the level of insulation. Table 5.2 represents the combined descriptive statistics for the different classes of sample dwellings during the summer season.

Table 5.2: Grouped mean summer day time and night time temperature in summer in living rooms

Day time		Non- insulated	Partially insulated	Fully insulated
Mean		21.8	21.0	21.6
Median		22.1	21.0	21.6
Std. Deviation		3.4	1.8	1.0
Skewness		-0.34	0.08	0.44
Minimum		11.4	16.8	20.2
Maximum		28.9	25.3	23.5
Percentiles	10	17.1	18.6	20.8
	90	26.3	23.5	22.6
Night time		Non- insulated	Partially insulated	Fully insulated
Mean		17.4	21.9	22.1
Median		17.2	22.0	22.1
Std. Deviation		2.7	1.6	1.0
Skewness		0.03	0.13	0.23
Minimum		9.7	18.0	20.3
Maximum		24.8	25.3	24.0
Percentiles	10	14.1	19.5	21.1
	90	21.0	24.0	23.1

In contrast with the winter season, day time medians were not always higher than night time medians as is evident in partially and fully insulated dwellings where night time medians were marginally higher. This finding confirms the ability of insulated dwellings to retain heat, in contrast to non-insulated dwellings that are unable to do so. It was further observed that during daytime the two classes of structures (partially and fully insulated) can shield and reflect much of incoming

solar radiation. The 90th percentile further confirms that day time indoor temperatures in non-insulated dwellings were higher than the other two classes of dwellings. During night time, however, a noticeable loss of heat can be observed in non-insulated dwellings when compared with fully and partially insulated dwellings. During night time 90 % of indoor temperatures recorded in non-insulated dwellings were below 21 °C, while for partially insulated and fully insulated houses it was 24 °C and 23 °C respectively. This suggests that during night time, the interiors of non-insulated dwellings were colder when compared to the other two insulation categories. Partially insulated dwellings registered fractionally higher night time indoor temperatures when compared to fully insulated dwellings. This could be ascribed to the fact that the structures had the same insulation material except for the difference in wall insulation. This can be attributed to the inability of non-insulated dwellings to retain heat. The implication of these day time high indoor temperatures is that they have the potential to cause thermal discomfort to occupants. The next sections explore indoor temperature density distributions during day time and night time.

5.3.3 Day time indoor temperature density distributions

Daytime indoor temperature density distributions are presented first. Density graphs were combined with marginal histograms to provide a comprehensive overview (Figure 5.7)

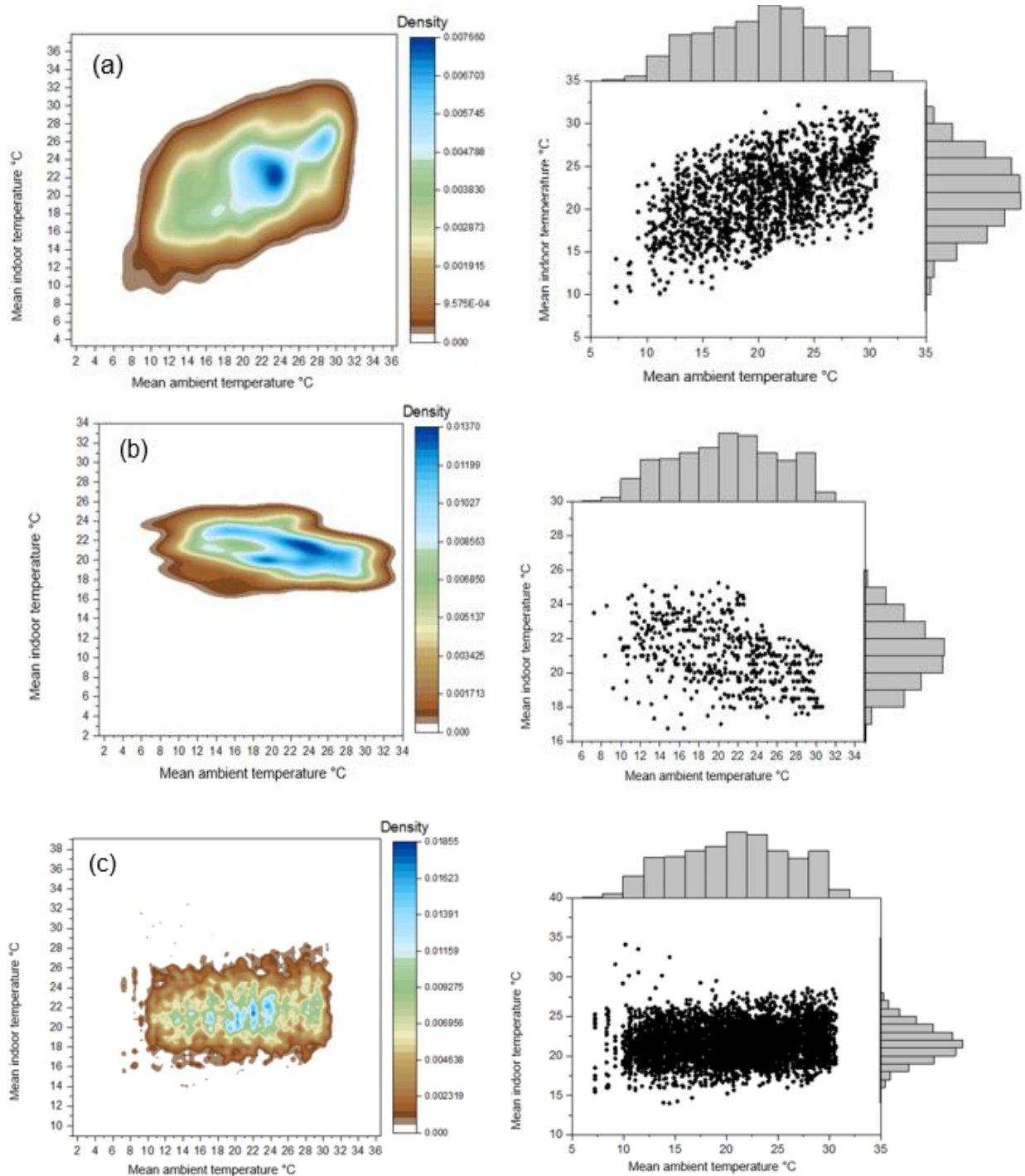


Figure 5.7: Day time indoor temperature density distributions: [a] non insulated, [b] partially insulated, [c] fully insulated dwellings

Figure 5.7 shows some variation between dwellings with different levels of insulation during summer days. In the non-insulated group of dwellings, high concentrations were in the 15 °C to 28.9 °C range while, in partially insulated dwellings, high concentrations were recorded in the 20 °C to 25.3 °C range. In fully insulated dwellings, high concentrations were recorded in the 15 °C to 23.5 °C range, suggesting that they are generally cooler than the other dwelling types. Non-insulated houses showed the most significant variation in temperature as well as the highest day time temperature.

5.3.4 Night time indoor temperature density distribution

This section presents the indoor temperature density distributions across dwellings with different insulation levels during summer nights (Figure 5.8). According to Figure 5.8, the non-insulated dwellings registered the lowest concentration range of 9 °C to 25 °C, while partially insulated and fully insulated dwellings had ranges of 18 °C to 25 °C and 20 °C to 24 °C, respectively. Less variation was, therefore, observed between partially insulated and fully insulated dwellings than between them and non-insulated dwellings during night times. This suggests that partially insulated and fully insulated structures are more capable of retaining heat gained during the day. The next section explores the relationship between ambient temperatures and indoor temperatures in different dwelling types.

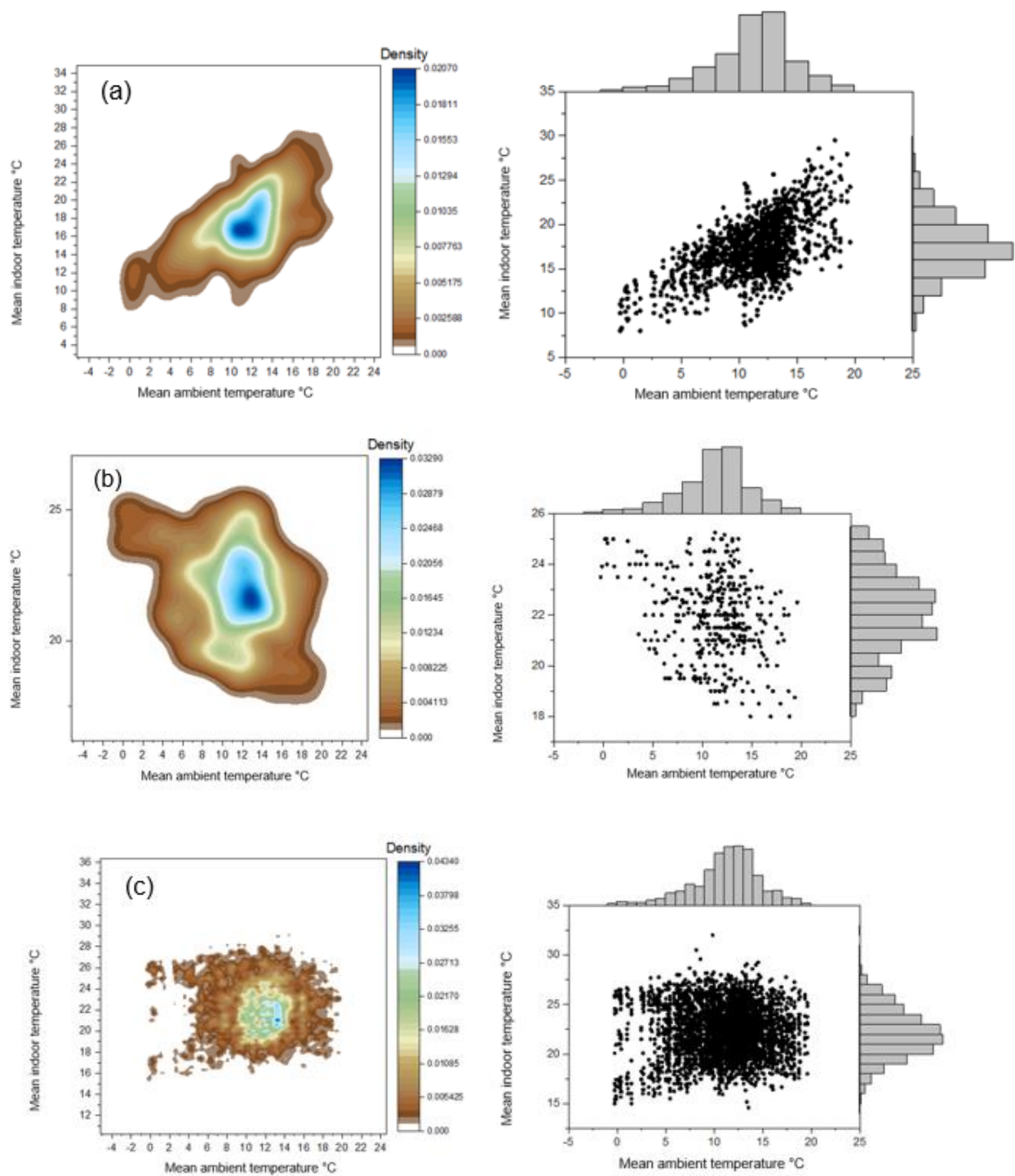


Figure 5.8: Night time indoor temperature density distributions: [a] non- insulated, [b] partially insulated, [c] fully insulated dwellings

5.3.5 Relationship between day time indoor and ambient temperature

This section presents the relationship between indoor and ambient temperatures during daytime in dwellings with different levels of insulation.

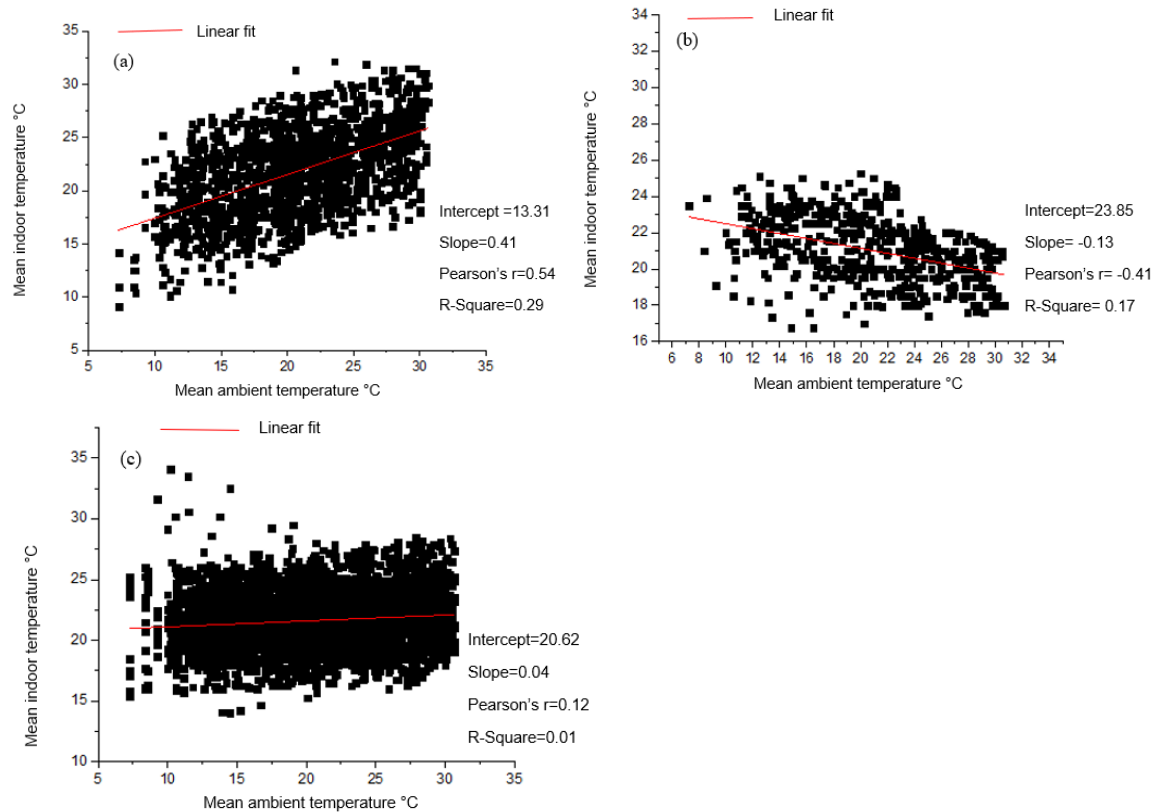


Figure 5.9: Regression analysis results for day time indoor and ambient temperatures: [a] none-insulated, [b] partially insulated, [c] fully insulated dwellings

Non-insulated dwellings showed the most substantial relationship between indoor and ambient temperatures during daytime ($r = 0.54$). Partially insulated dwellings showed a moderate correlation coefficient of $r = -0.41$, while insulated dwellings yielded a weak correlation of $r = 0.12$. This finding suggests non-insulated dwellings are more sensitive to ambient temperatures than partially or fully insulated dwellings. These relationships are similar to those that were observed for day time during the winter period.

5.3.6 Relationship between night time indoor and ambient temperature

This section presents the relationships between indoor and ambient temperatures during night time in accordance with the level of insulation status (Figure 5.10).

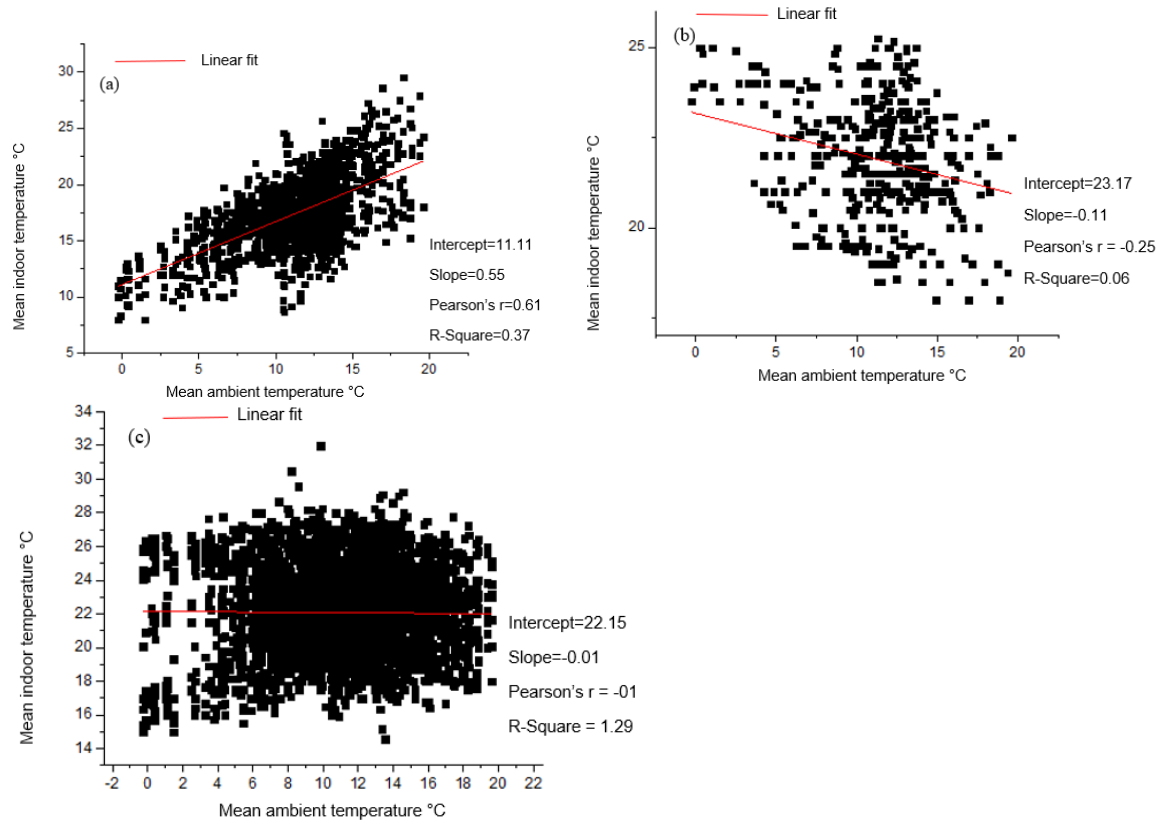


Figure 5.10: Regression analysis results for night time indoor and ambient temperatures: [a] non-insulated, [b] partially insulated, and [c] fully insulated dwellings

Non-insulated dwellings showed the most significant relationship between indoor and ambient temperatures during night time as well ($r = 0.61$). Partially insulated dwellings showed a weak link during night time ($r = -0.25$), while insulated dwellings yielded almost no link. This finding supports the findings for summer days, winter days and winter nights, which is that non-insulated houses are more sensitive to ambient temperatures than partially and fully insulated dwellings.

5.4 Summary and discussion

The thermal performance of dwellings with differing levels of insulation in KwaZamokuhle (non-insulated, partially insulated and fully insulated) was analysed in this chapter through the use of indoor temperature measurements. Some authors have suggested that indoor temperatures could be considered as a proxy for the thermal performance of dwellings (Talocchino, 2005; Pignatta *et al.*, 2017).

The study found that non-insulated dwellings had winter median living-room temperatures below the WHO threshold of 18 °C. It was also established that these temperatures were closely related to ambient temperatures, especially in non-insulated dwellings during the day, affirming the findings by Howden-Chapman *et al.* (2007) that cold indoor temperatures are a result of low ambient temperatures, structural deficiencies (including lack of adequate thermal insulation) and poorly constructed structures. In partially insulated dwellings, 66 % of dwellings recorded winter median temperatures of less than 18 °C, while for fully insulated houses the percentage was only 47 %. This concurs to studies by Oreszczyn *et al.* (2006) and Howden-Chapman *et al.* (2012), which established that dwellings with some sort of insulation intervention recorded higher day time temperatures than those without, indicating the benefits of thermal insulation. Howden-Chapman *et al.* (2007) further found the aforementioned to be true specifically for winter months. It was further established that differences in indoor temperatures between dwellings with different insulation types were most significant during winter nights as non-insulated dwellings were found to be substantially colder. It was also established that the temperature ranges in non-insulated dwellings were significantly higher for both winter and summer when compared with partially and fully insulated houses. It was observed that non-insulated dwellings had the highest summer day time temperatures but cooled down significantly during the night, becoming the coldest of all dwelling types at night. In terms of the relationship between indoor and ambient temperatures, it was established that non-insulated dwellings were the most sensitive and that the relationship was the strongest during winter nights and summer days, suggesting that inhabitants of non-insulated, low- income dwellings would be most vulnerable during these periods.

The results stress the importance of adequately insulating low-income residential dwellings to assist in the regulation of indoor thermal environments. From the analysis, it was observed that non-insulated structures could be regarded as energy wasters, especially during winter which, according to Jim (2014), can mostly be ascribed to poorly insulated roofs which facilitate nocturnal thermal discharge. A case can, therefore, be made for the retrofitting of low-income dwellings to improve thermal efficiency, and an opportunity thus exists to improve the status of the already-built, low-income residential dwellings on the South Africa Highveld. This would also reduce the heating expenditure of low-income households (Vandentorren *et al.*, 2006) while possibly also yielding health co-benefits (Howden-Chapman *et al.*, 2012) as established in Howden-Chapman *et al.* (2007) where occupants' health status and respiratory symptoms showed some improvement. The different responses of insulated and non-insulated dwellings to ambient temperatures might be observed through remote sensing techniques. In the following Chapter, results on the extent to which thermal insulation can be characterised using aerial thermography are presented.

CHAPTER 6: DETERMINE THE EXTENT TO WHICH AERIAL THERMOGRAPHY CAN BE USED TO EVALUATE THERMAL INSULATION

This chapter presents findings on the extent to which aerial thermography can be used to evaluate and characterise the thermal insulation status of dwellings. Data obtained from aerial thermal imagery was integrated with indoor temperature measurements for analysis.

6.1 Introduction

In the previous chapter, thermal insulation in low-income households was characterised using indoor temperature measurements. This chapter explores the feasibility of aerial thermography as a tool to determine the level of thermal insulation in low-income residential dwellings. Aerial thermography, i.e. the use of remotely sensed thermal infrared imagery, could be a possible approach for identifying non-insulated dwellings on a larger scale. The aerial campaign was conducted in KwaZamokuhle, the same settlement used in Chapter 5 (refer to Chapter 3 for methodological approach). This settlement was selected on the basis that it was the only settlement where the insulation status of dwellings was known. The aerial survey's main goal was to explore the potential of using aerial thermal infrared imagery (TIR imagery) to evaluate the thermal insulation status of low-income residential housing. The methodological approach that was followed is detailed in Sections 3.3.1.3 and 3.3.2.3.

6.2 Analysis of flights

Aerial surveys were performed in two campaigns and included three flights. Flight times were selected to coincide with the coldest time of the year (winter season), with ambient temperatures expected to be below 0°C regularly. In addition to ambient temperatures, the sampling period was selected as it was expected that indoor space heating activities on the South African Highveld would be at its highest during this time. The abovementioned would increase the likelihood of identifying energy-inefficient dwellings through thermography. As mentioned in Chapter 3, Flights 1 and 2 were scheduled for early evenings (between 18:00 and 21:00 SAT) when indoor space heating was expected to occur, while Flight 3 was scheduled after midnight (between 00:00 and 02:00 SAT) when space heating was expected to be lower. This allowed for a comparison of dwelling behaviour at different times of the evening. The remote sensing methodology has to incorporate the variability induced by the state of housing insulation, variations in ambient temperature, and the state of indoor heating. It builds on the insights gained from the relationship between insulation, indoor- and ambient temperature discussed in Chapter 5. The meteorological conditions during the flights are presented in Chapter 3.

6.2.1 Campaign 1 (Flight 1)

The aim of Flight 1 was to explore the relationship between indoor temperature measurements, insulation status, and measurements obtained from the TIR imagery. Ground truthing is discussed first followed by the presentation of the results.

6.2.1.1 Ground-truthing

Readings from only four *iButtons* were available for ground-truthing purposes as other three sensors which had been deployed malfunctioned. Of these, three were for paved surfaces and one for a water body. The deployment of ground sensors was done randomly across the settlement without any criterion. Figure 6.1 shows the relationship between the *iButton* measurements and the radiometric values extracted from the TIR image.

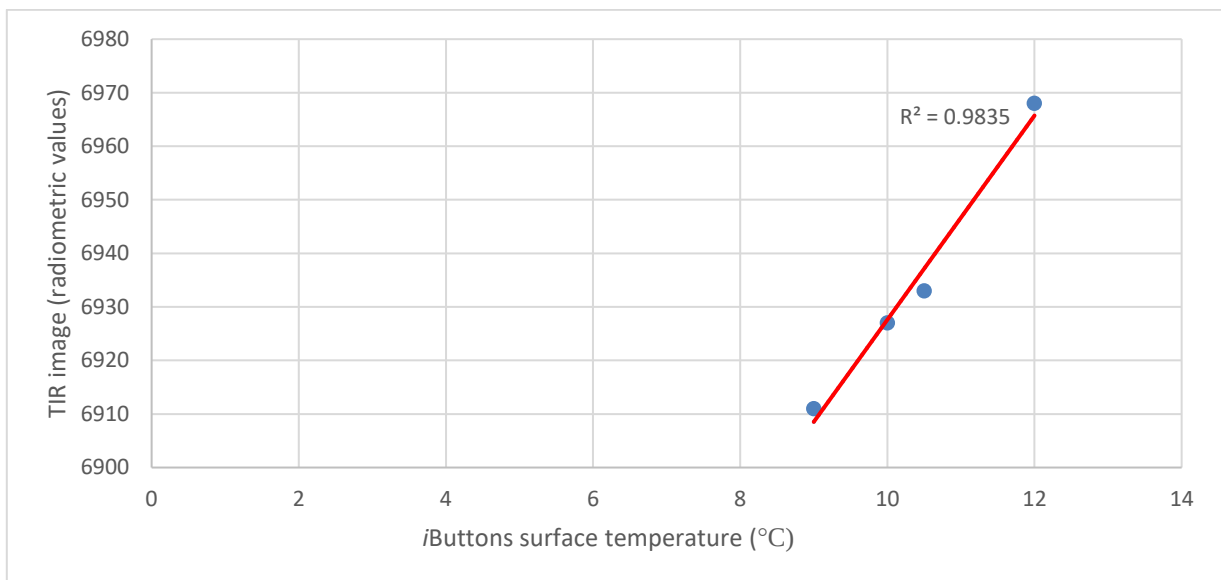


Figure 6.1: Scatter plot of *iButton* surface measurements against TIR image radiometric values

Although only four data points were available for this comparison, which can be regarded as a limitation of the study, a strong positive correlation of $r^2=0.984$ was still observable between *iButton* readings and the values obtained from the TIR image. This suggests that the TIR image is an accurate representation of surface temperatures. The next section presents HEAT Scores for the 17 dwellings for which indoor measurements were taken during Flight 1.

6.2.1.2 HEAT scores for sampled dwellings

This section presents the HEAT scores that were calculated for the 17 dwellings which were selected as ground-truthing structures. Indoor temperature measurements were scheduled to coincide with the flyover. HEAT scores were calculated in two ways, firstly using rooftop boundaries and secondly using property boundaries, which were then categorised into HEAT classes as in Hay *et al.* (2011) (refer to Chapter 3). Property and rooftop boundaries produced similar results when classified. As shown in Table 6.1, only H11, H13 and H15 produced results falling in different classes. Consequently, property boundaries were used for all further analysis in the study as it allowed for analysis to be conducted across the whole settlement.

Table 6.1: Roof and property boundary HEAT scores

House code	Property boundary HEAT score	Rooftop boundary HEAT score	Property boundary HEAT class	Rooftop boundary HEAT class
H01	45	27	Moderately low	Moderately low
H02	41	42	Moderately low	Moderately low
H03	46	48	Moderately low	Moderately low
H04	65	65	Moderately high	Moderately high
H05	28	36	Moderately low	Moderately low
H06	39	30	Moderately low	Moderately low
H07	68	69	Moderately high	Moderately high
H08	59	51	Moderately high	Moderately high
H09	52	60	Moderately high	Moderately high
H10	71	69	Moderately high	Moderately high
H11	45	50	Moderately low	Moderately high
H12	52	58	Moderately high	Moderately high
H13	17	35	Low	Moderately low
H14	60	61	Moderately high	Moderately high
H15	51	38	Moderately high	Moderately low
H16	64	70	Moderately high	Moderately high
H17	48	41	Moderately low	Moderately low

6.2.1.3 Relationship between radiometric mean values, HEAT scores and indoor temperatures

In this section kitchen and living room, indoor temperatures measured during Flight 1 (the measurement taken at the exact moment the plane was overhead) are compared to the raw

radiometric values obtained from the TIR image (mean value for property boundary), as well as the derived HEAT score values. This analysis provides insight into the relationship between measurements obtained from TIR images and indoor measurements (*iButtons*).

Table 6.2: Property boundary HEAT scores, insulation, and burning status

House code	TIR raw value (mean)	HEAT score	HEAT class	Kitchen temp.	Living room temp.	Heating status	Insulation status
H02	6815	41	Moderately low	20	21	Non-heating	Full
H05	6786	28	Moderately low	30	22.5	Heating	Full
H07	6873	68	Moderately high	35.5	20	Heating	Full
H08	6854	59	Moderately high	19.5	19	Non-heating	Full
H11	6823	45	Moderately low	17	14.5	Non-heating	Full
H03	6826	46	Moderately low	33	22.5	Heating	Partially insulated
H04	6868	65	Moderately high	20.5	22.5	Non-heating	Partially insulated
H09	6838	52	Moderately high	21	19.5	Non-heating	Partially insulated
H12	6840	52	Moderately high	17.5	18	Non-heating	Partially insulated
H13	6763	17	Low	22.5	19.5	Heating	Partially insulated
H14	6857	60	Moderately high	44	24	Heating	Partially insulated
H17	6830	48	Moderately low	25	20.5	Heating	Partially insulated
H01	6823	45	Moderately low	15	14.5	Non-heating	Non-insulated
H06	6810	39	Moderately low	22	18.5	Non-heating	Non-insulated
H10	6879	71	Moderately high	33	23.5	Heating	Non-insulated
H15	6838	51	Moderately high	30.5	17.5	Heating	Non-insulated
H16	6864	64	Moderately high	22.5	20.5	Heating	Non-insulated

Table 6.2 shows the indoor temperature measurements, radiometric values, HEAT scores, insulation status and space heating status for the 17 dwellings, while Figures 6.2 to 6.4 shows the aforementioned relationships. A total of eight of the sampled households did not conduct any space heating at the time of Flight 1 while nine were heating. Chimney sensors were used to

verify that these households were burning solid fuels for heating purposes during the course of the flight.

The relationships between indoor temperatures and HEAT scores and indoor temperatures and raw radiometric values are the same, as would be expected as HEAT scores are derived from the radiometric values. Across Figures 6.2 and 6.3 it is clear that there is a relationship between both indoor temperatures and the HEAT scores and radiometric values. The relationship is always the strongest in non-insulated houses and weaker in partially and fully insulated houses. In terms of indoor measurements, the relationship is the strongest when living room temperatures are considered ($r^2=0.6409$). This would suggest that when living rooms are heated during night-time most of the heat escapes the housing envelope and is measurable with the TIR sensor. This is especially clear when considering only houses that were heating during the period of the flight. Figure 6.4 shows the relationship between HEAT scores and living rooms for houses that were being heated during the time of the flight. The relationship is significantly stronger ($r^2=0.974$) confirming the aforementioned.

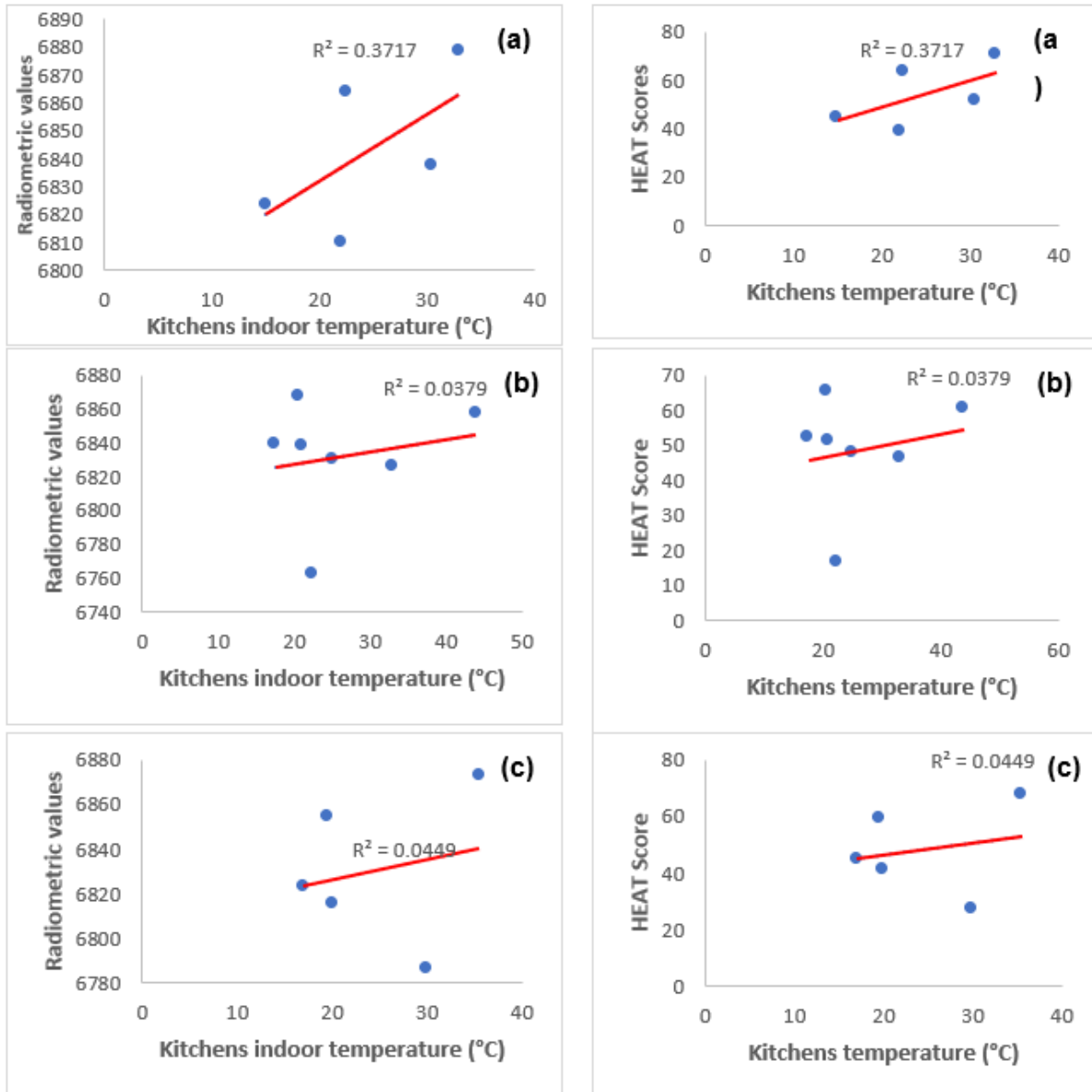


Figure 6.2: Kitchen indoor temperature and radiometric values association during Flight 1: [a] non-insulated [b] partially insulated [c] fully insulated & Kitchen indoor temperature and HEAT scores association during Flight 1 [a] non-insulated, [b] partially insulated, [c] fully insulated

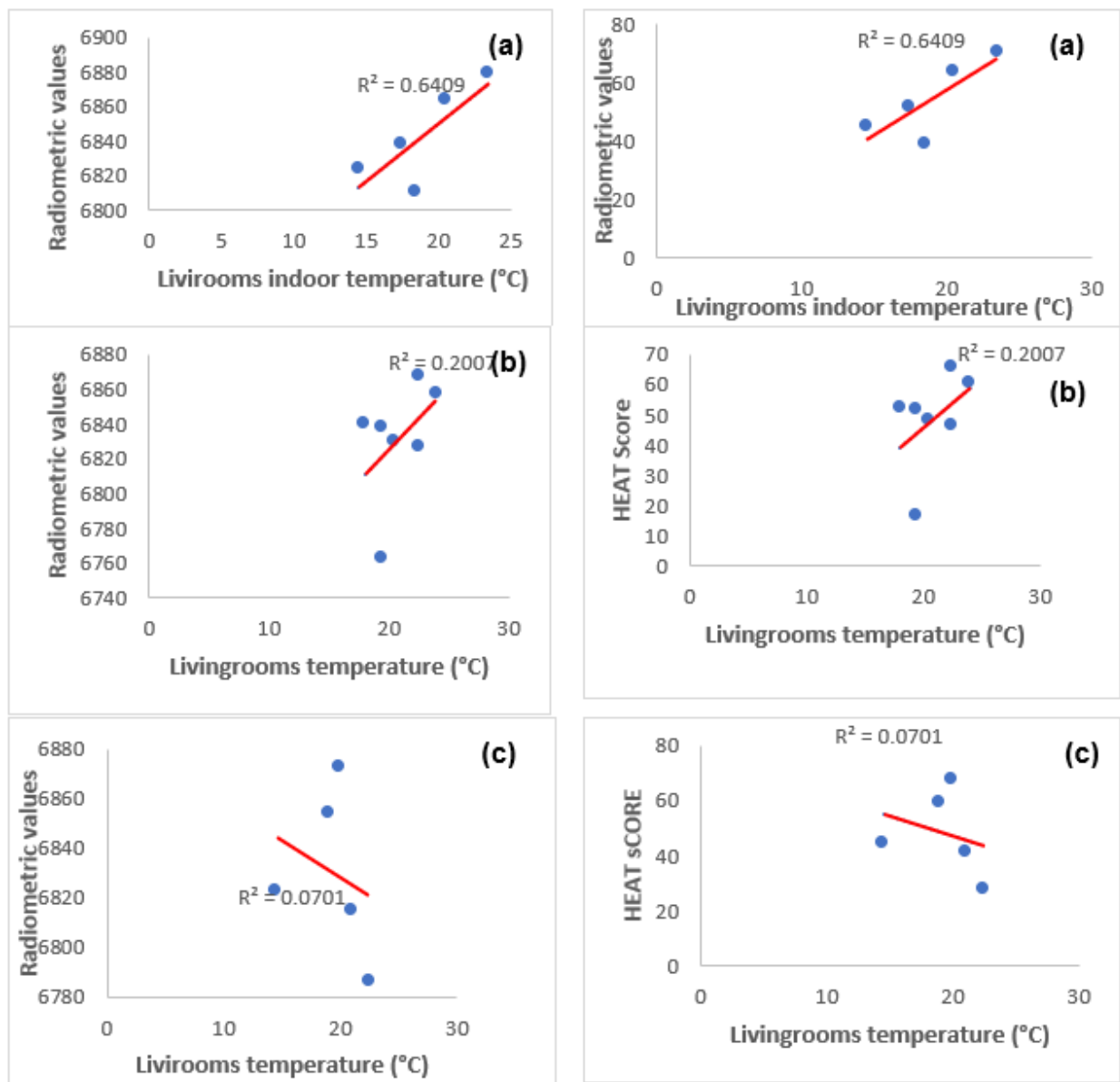


Figure 6.3: Living room indoor temperature and radiometric values association during Flight 1 performance: [a] non-insulated, [b] partially insulated, [c] fully insulated & Living room indoor temperature and HEAT scores association during Flight 1 performance [a] non-insulated, [b] partially insulated, [c] fully insulated

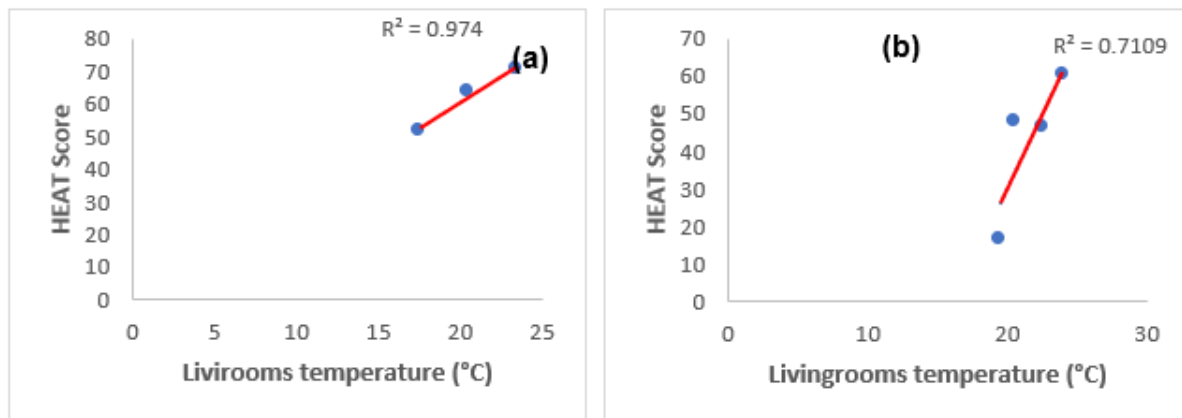


Figure 6.4: Living room indoor temperature in heating houses and HEAT score association during Flight 1 performance: [a] non-insulated, [b] partially insulated, [c] fully insulated (not shown - insufficient data points)

6.2.2 Campaign 2 (Flights 2 and 3)

The aim of Flights 2 and 3 was to explore the extent to which multiple flights could be used to determine the insulation status of dwellings.

6.2.2.1 Comparing flights

As discussed in Chapter 3, statistics were extracted from the TIR images for Flights 2 and 3 for 127 dwellings for which the insulation statuses were known. Property boundaries were used to extract these values, as discussed in Section 6.2.1. The minimum, maximum, mean, standard deviation and range (difference between the minimum and maximum) values were extracted for each of the 127 properties. Some variability was observed between the dwellings of different insulation statuses. Non-insulated dwellings generally showed higher variability than partially and fully insulated dwellings, especially when minimum temperatures, range, and standard deviation were considered (Figure 6.5). The variability was further found to be more observable during the early evening flight (Flight 2). This could be explained through the assumption that most dwellings were conducting indoor heating during that period.

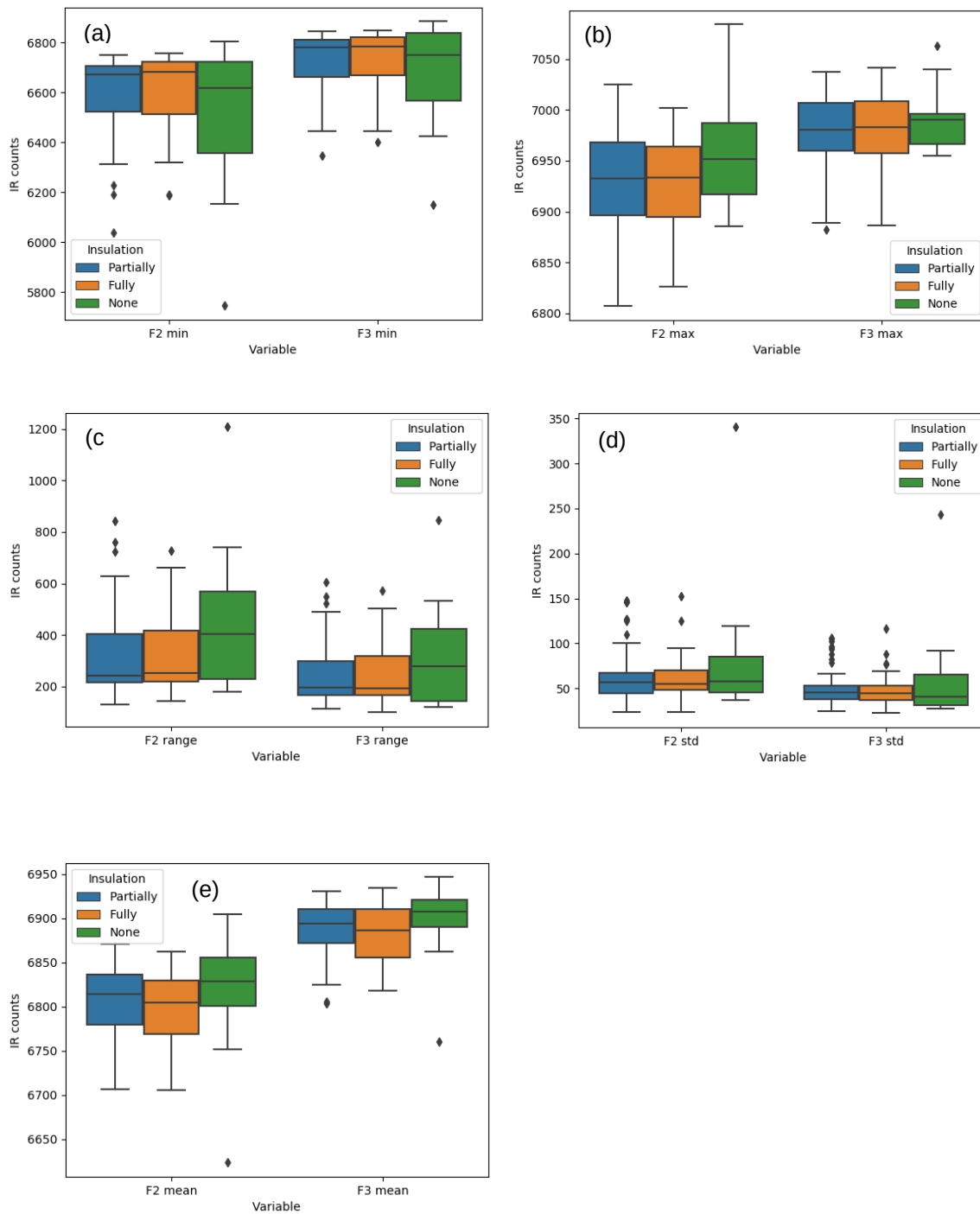


Figure 6.5: Box-plots showing radiometric values for properties with known insulation status in the study area during Flight 2 and 3: [a] minimum values, [b] maximum values, [c] range, [d] standard deviation, [e] mean

6.2.2.2 Determining insulation status through TIR imagery

In this section, the extent to which multiple TIR images at various times could be used to identify dwellings that are likely to be non-insulated is explored. When the differences between Flights 2 and 3 are considered, non-insulated dwellings always showed a higher degree of variability (Figure 6.6). When the differences of the means for each of the variables were compared using two-sample, unpaired T-tests at the 95% confidence interval, significant differences of the means were confirmed for the differences between Flight 2 and Flight 3 for the minimum, maximum, range and standard deviation of all pixels in the property polygons (Table 6.3). The difference in range between Flight 2 and Flight 3 proved to be the most significant. When fully insulated and partially insulated dwellings were considered, minimal variation was observed ($p = 0.0729$), while the comparison between non-insulated and fully insulated ($p = 0.0008$), and non-insulated and partially insulated ($p = 0.0031$) showed significant variation. This implies that the difference in range (maximum pixel value – minimum pixel value in property boundary) between Flights 2 and 3 could be used to identify dwellings that are likely to be non-insulated. Significant differences were found in the range statistic for Flight 2 and Flight 3.

Table 6.3: Two-sample, unpaired T-tests at the 95% confidence interval

Variable	Full vs Partial (<i>p</i> – value)	Full vs Non (<i>p</i> – value)	Partial vs Non (<i>p</i> – value)
F2 max	0.99	0.0288	0.034
F3 max	0.6826	0.3348	0.2065
F2 min	0.779	0.0883	0.1496
F3 min	0.5611	0.1378	0.2805
F2 mean	0.3784	0.1152	0.2928
F3 mean	0.6865	0.0843	0.1548
F2 heat	0.3784	0.1152	0.2928
F3 heat	0.6865	0.0843	0.1548
F3-F2 min	0.6577	0.0368	0.0329
F3-F2 max	0.5255	0.0071	0.0397
F3-F2 range	0.8721	0.0008	0.0031
F3-F2 mean	0.0729	0.3247	0.9541
F3-F2 std	0.6933	0.005	0.0206

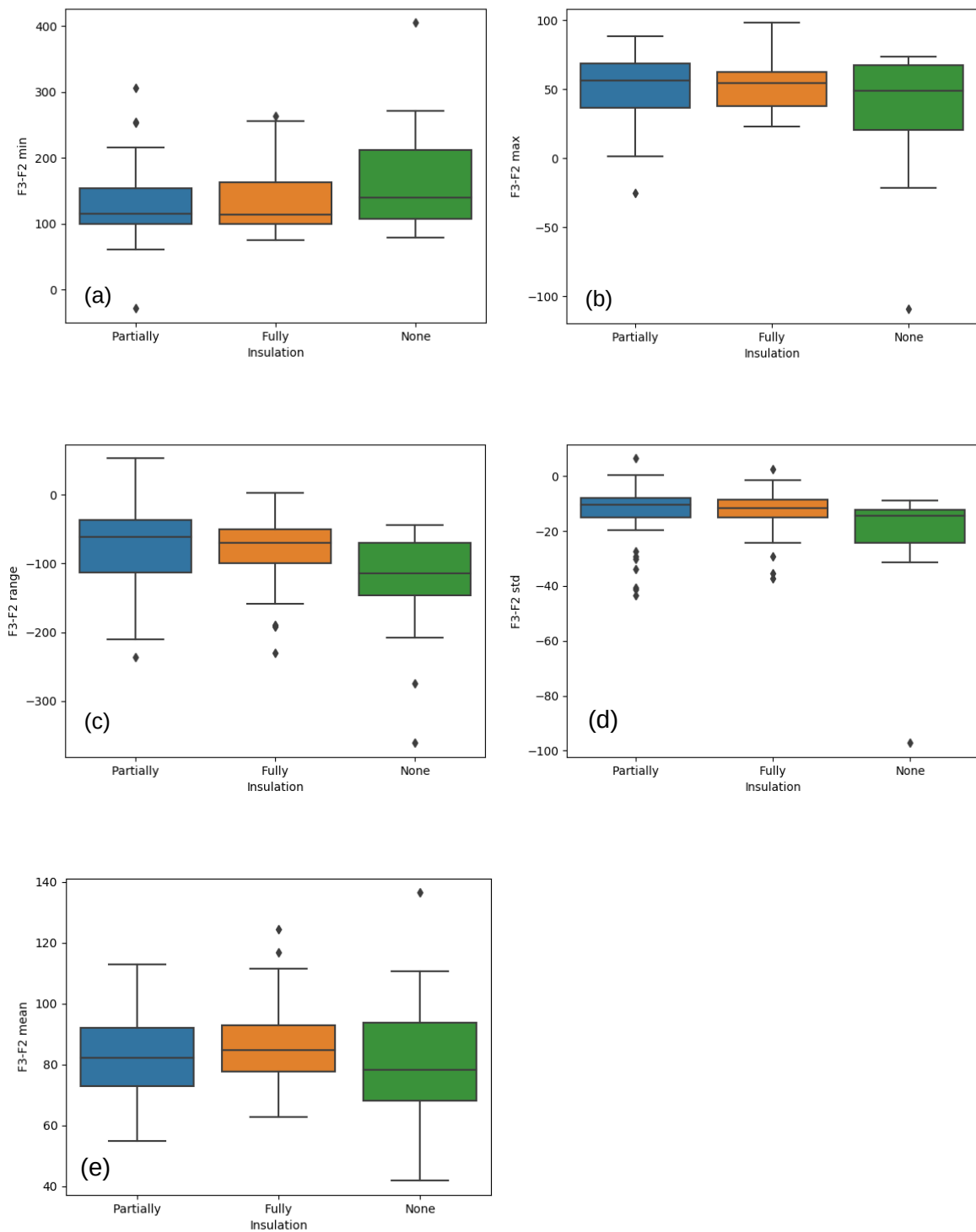


Figure 6.6: Box-plots showing the differences in radiometric values between flights for properties with known insulation status in the study area: [a] minimum values, [b] maximum values, [c] range, [d] standard deviation, [e] mean

Statistics were extracted for all 3,555 dwellings in the settlement based on their property boundaries. Using the range statistic as discussed above, dwellings were classified in terms of

their probability of being non-insulated. It was estimated that 18% and 10% of dwellings in the settlement had a very high and high probability, respectively, of being non-insulated (Figure 6.7). Of the remaining 72% of dwellings, 26% were estimated to be low probability and 46% very low probability. It is important to note that two factors influence the TIR measurements, that is, level of insulation and energy use. In other words, if a non-insulated dwelling was conducting space heating during Flight 3, it might not have shown as non-insulated. This is confirmed by the fact that only 70% of known non-insulated dwellings (obtained from the 127 samples) were estimated to be either very high or high probability homes. However, the study has relatively high confidence that the 18% very high probability dwellings are non-insulated, showing the potential of using TIR imagery to screen large settlements for possible non-insulated dwellings.



Figure 6.7: Estimated insulation status of dwellings in KwaZamokuhle

6.3 Summary and discussion

Using statistics extracted from TIR imagery, the study was able to show the thermal variability between dwellings with different levels of insulation. The results suggest that high-resolution aerial TIR imagery has considerable potential for being used as a tool to evaluate the thermal insulation status of dwellings, especially in large settlements. The following key findings can be highlighted:

- When variability across houses of different insulation status is considered, non-insulated dwellings show more substantial variability when compared to partially and fully insulated dwellings.
- The difference between midnight and early evening remotely sensed TIR images provides the best opportunity to identify non-insulated dwellings, i.e. Flights 2 and 3.
- Using the range statistic (the difference between the maximum and minimum measurement within the property boundary) yields the best results to differentiate between insulated and non-insulated dwellings.
- When the difference in the range statistic between midnight and early evening flights is used, dwellings that have a high probability of being non-insulated can be identified.

This chapter shows the potential of using TIR aerial imagery to characterise the thermal insulation status of dwellings in a low-income settlement. Although a census of all dwellings in the settlement fell outside the scope of the study, a future study in which actual insulation status is known for the whole settlement will assist in refining the methodology. Information on burning and heating practices on the night of the flights will also contribute. In the next chapter, the link between thermal insulation and energy use in low-income households is explored.

CHAPTER 7: CHARACTERISE THE LINK BETWEEN THERMAL INSULATION & DOMESTIC ENERGY USE

This chapter presents results on domestic energy use according to dwelling insulation levels. The main themes explored included the energy carriers which households rely on to meet their everyday energy needs, quantity of consumption per housing type, expenditure patterns per housing type, energy carriers for space heating as well as auxiliary functions of coal for various needs.

7.1 Introduction

Chapter 6 explored the use of aerial imagery in the characterisation of the thermal insulation status of residential dwellings in a low-income settlement. This chapter explores the link between thermal insulation and energy use in low-income households. The link provides an insight into the double challenges of residing in low-cost residential dwellings and the challenge of access to energy resources to fulfil domestic energy needs. Furthermore, the link was also important considering the high levels of income poverty in the study sites. To achieve the aforementioned, questionnaires were employed as outlined in Chapter 3 with a total of 113 households being surveyed. The analysis was focused on the three primary energy sources used in low-income settlement (namely, electricity, coal, and LP gas), while coal and LP gas (LPG) was further emphasised. These two fuel types were emphasised because:

- They can be regarded as diametric opposites in terms of indoor burning fuels, as one is considered to be a clean fuel (LPG), while the other is considered to be a dirty fuel (coal);
- Their utilisation was quantifiable through the study;
- Coal was the most dominant solid fuel used in the settlement;

The sources of energy are discussed first, followed by an overview of their utilisation. The link between energy use and thermal insulation is finally explored, followed by a discussion

7.2 Energy sources

The three primary energy sources used in KwaZamokuhle were electricity, coal, and LPG, although other sources such as paraffin, animal dung, and wood were also used in some cases. Of these sources, only coal and LPG could be quantified accurately. It was, however, established that coal was the most dominant fuel burned inside houses (Figure 7.1). As coal-burning

contributes negatively to ambient and indoor air pollution and is a known source of greenhouse gases, an effort was made to compare the use of coal and LPG.

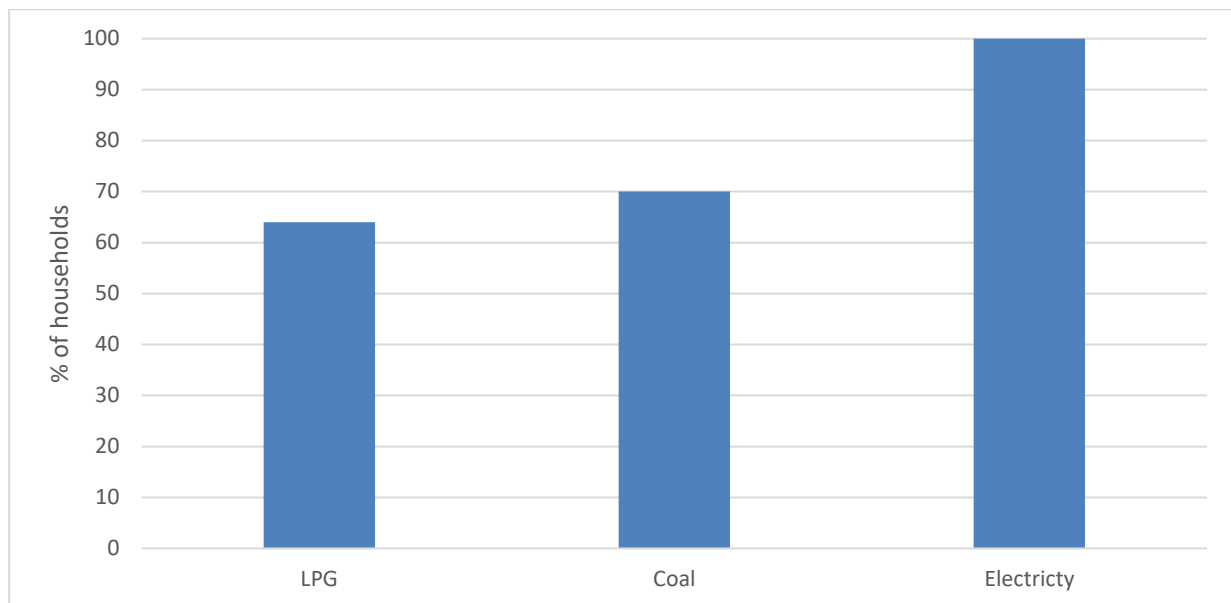


Figure 7.1: Energy sources used by low-income households (expressed as a percentage of households)

7.2.1 Energy expenditure

Figure 7.2 shows the average amounts of money in (ZAR) that low-income households spend on energy per month. Electricity showed the highest expenditure, followed by LPG, coal, and finally wood. Overall, energy expenditure was estimated to be higher during winter than in summer. This trend was observed for all energy sources and in all dwelling types. It was further observed that even though most households had access to electricity, many still relied on alternative energy sources and, specifically solid fuels. The aforementioned could be ascribed to the fact that some of these solid fuels are less expensive than electricity and that the settlements are relatively poor, as is evident from the 2011 Census, in which 15 % of households reported no source of income (Stats SA, 2011). Households residing in fully and partially insulated dwellings generally spent more on energy than residents of non-insulated dwellings. This might imply that these households have more substantial disposable income, suggesting a link between the insulation status of dwellings and energy use. Low-income households would, therefore, be more likely to use solid fuels and have poor insulation in their houses

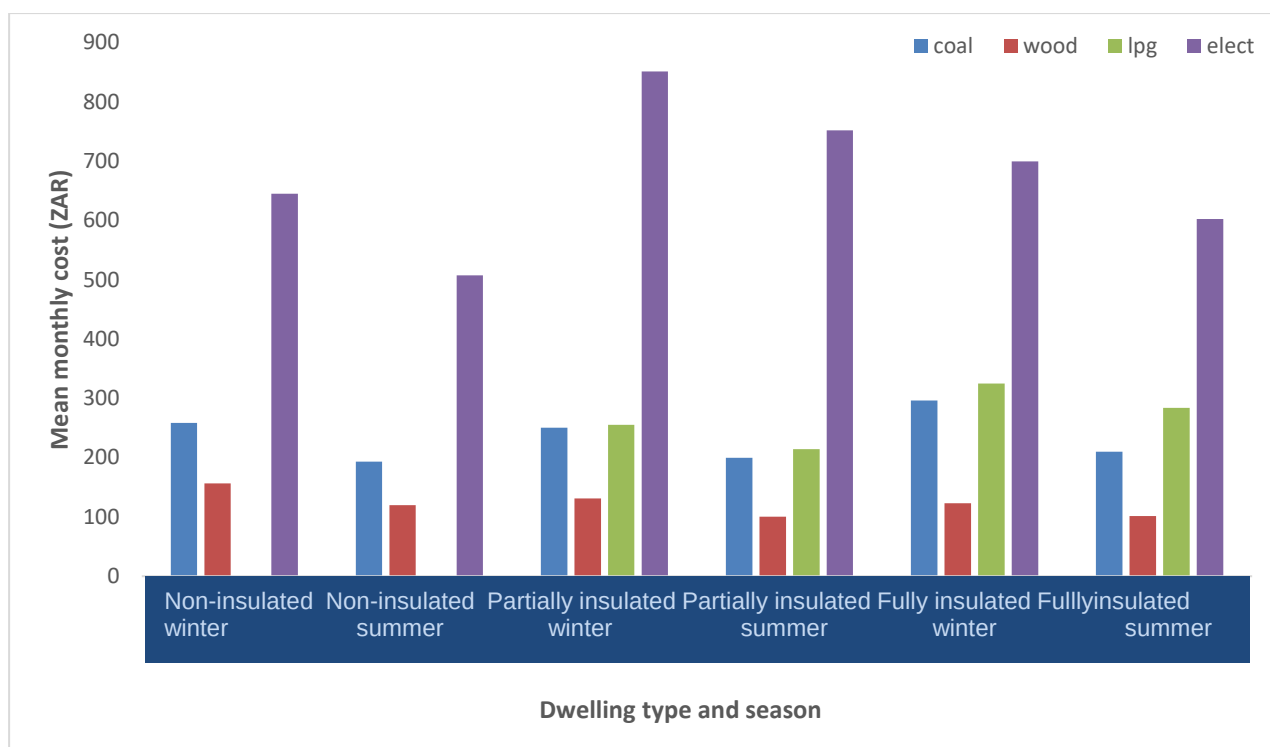


Figure 7.2: Mean monthly coal expenditure by insulation type and season

7.2.2 Coal and LPG procurement

Coal was reported in quantities of 5 kg, 25 kg and 50 kg as these were the loads in which coal was usually sold in the area. LPG was reported as LPG 9, LPG 11, LPG 90 and LPG 447.

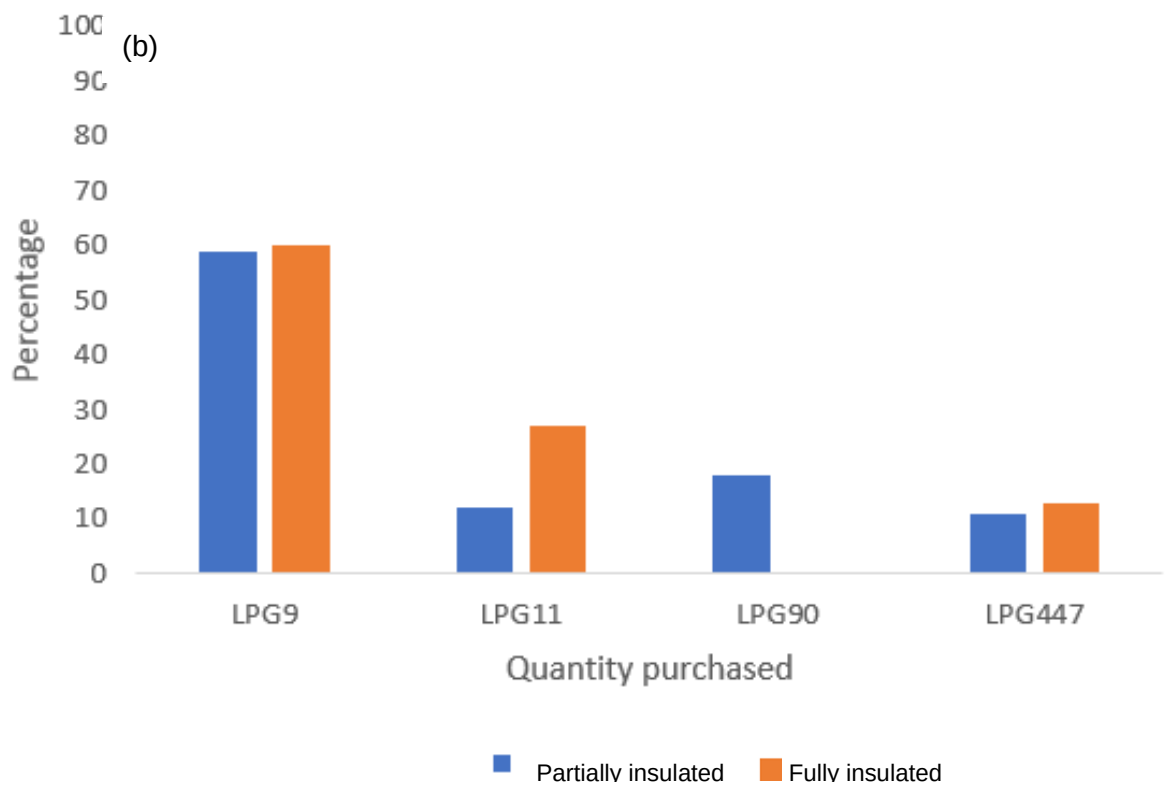
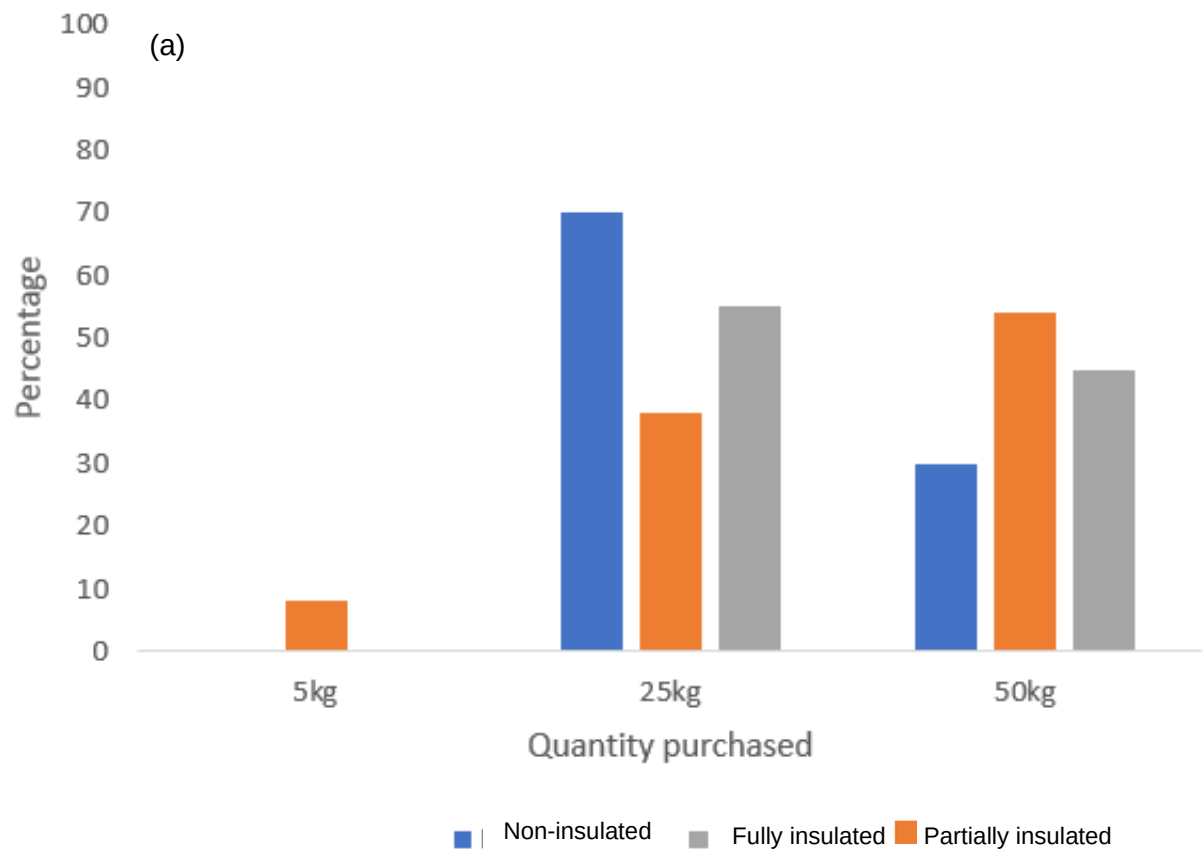


Figure 7.3: Coal and LPG procured across different dwelling types: [a] coal, (b) LPG

KwaZamokuhle is located in an area where coal is easily accessible. Households source coal and wood from local merchants and dealers, while LPG is obtained mainly from service stations and gas dealerships. In some cases, wood is also gathered in natural areas from close proximity to the settlement. It was established that all dwelling types made use of coal and LPG, while only partially insulated and fully insulated dwellings made use of LPG exclusively. As shown in Figure 7.3a coal was mainly procured in 25 kg quantities. In terms of LPG, the most popular format was LPG 9, with 59 % of supplies used in partially insulated dwellings, and 60 % used in fully insulated dwellings. The least used format was the LPG 447 format across all dwelling types.

7.2.3 Coal and LPG consumption

Figure 7.4 shows the consumption of coal and LPG across different dwelling types. In all cases, consumption was higher during the winter season. It was observed that households residing in fully insulated dwellings consumed the most coal across both seasons, while households in non-insulated dwellings consumed the least in winter and showed similar consumption to partially insulated households during summer. As mentioned earlier none of the households residing in non-insulated dwellings reported using LPG gas as an energy source. It was, however, established that LPG was used mostly in partially insulated dwellings and that more LPG was consumed during the winter season. Households in fully insulated houses showed little variation in the way in which LPG was consumed across seasons. This suggests that LPG is used as a source for space heating during winter months in partially insulated dwellings but not necessarily in fully insulated dwellings. These utilisation patterns will now be further explored.

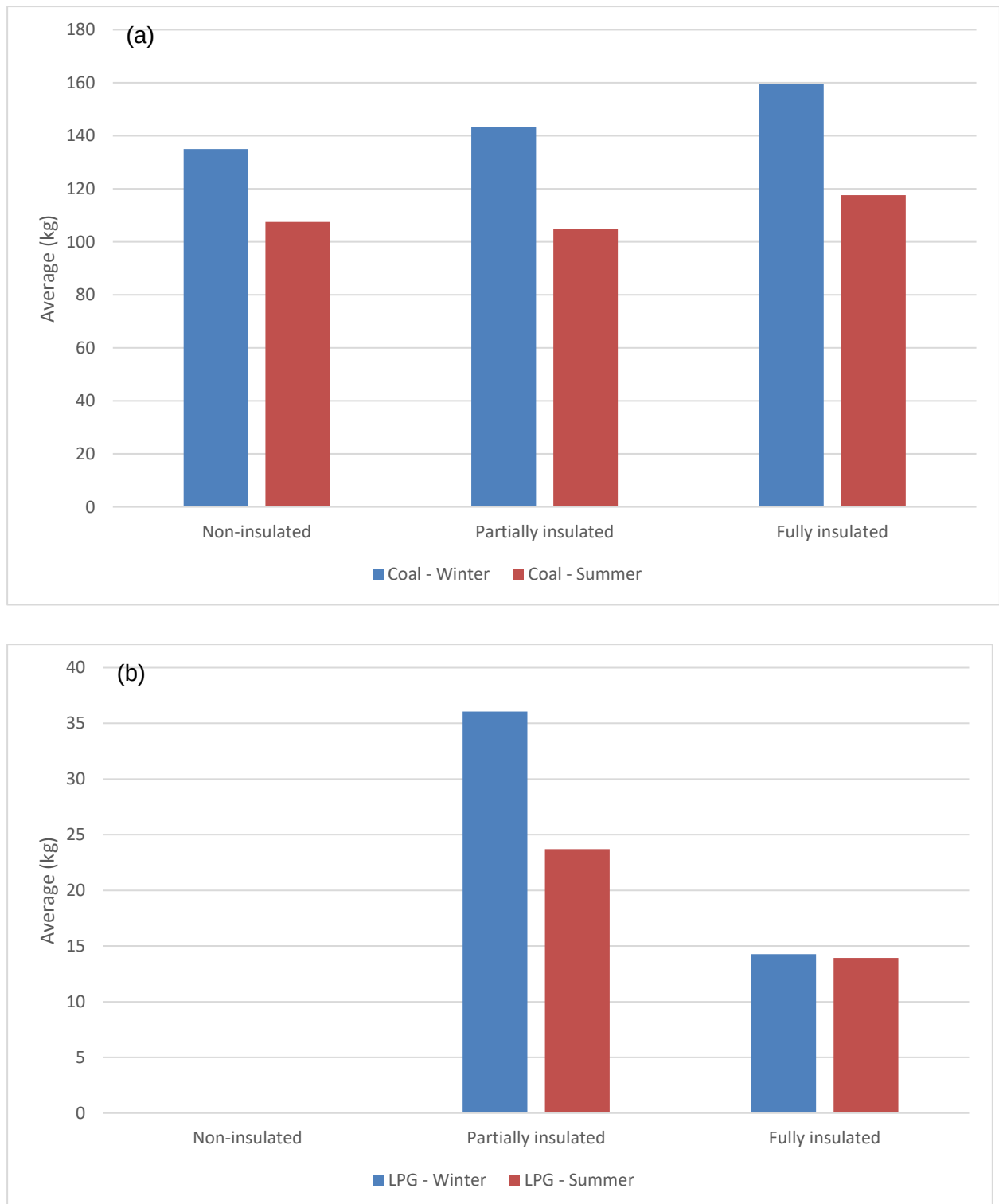


Figure 7.4: Coal and LPG consumption across different dwelling types: [a] coal, [b] LPG

7.3 Energy uses

The manner and extent to which different energy sources are used in low-income households are presented in this section. Space heating is discussed first, followed by cooking and finally some less frequently used applications.

7.3.1 Space heating

It was established that mainly three energy sources are used for space heating (Figure 7.5) and that households mix these sources. The findings are presented as proportions of energy source used by household type.

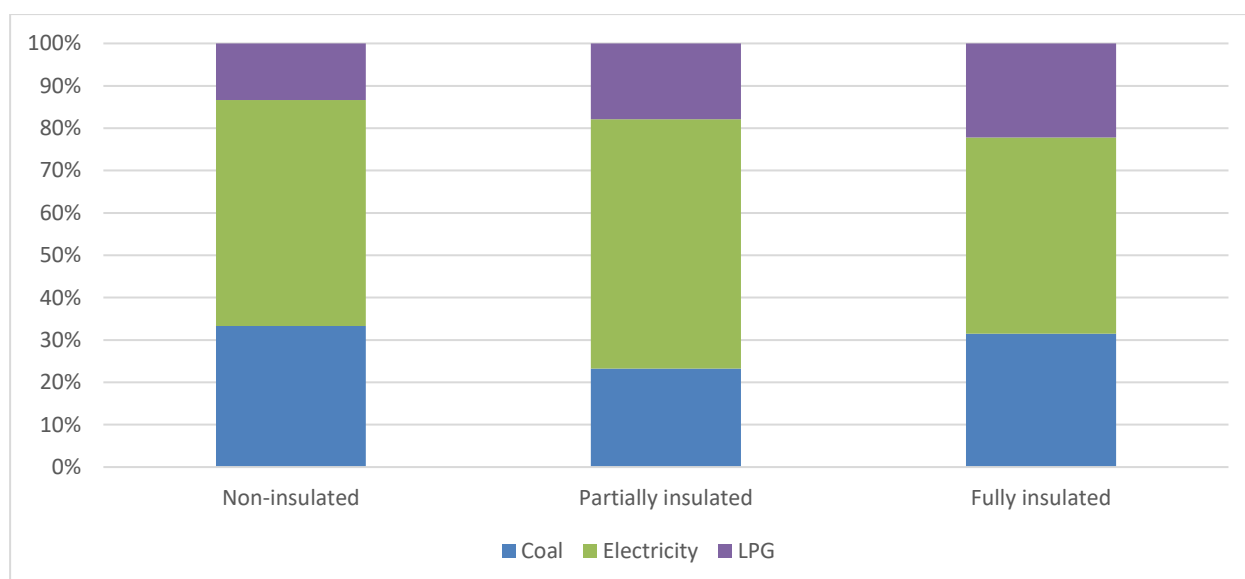


Figure 7.5: Primary energy sources used for space heating across different dwelling types

Figure 7.5 illustrates the contribution of various energy sources towards space heating in different dwelling types. The graph illustrates the primary energy sources used by households. Electricity was the primary heating source in non-insulated dwellings (53 %) followed by coal (33 %) and LPG (14 %). In partially insulated houses, electricity was also the primary source (56 %), followed by coal (22 %) and LPG (22 %). Fully insulated dwellings followed the same tendency with electricity being used the most (46 %), followed by coal (31 %) and finally LPG (22 %). Of the three types of dwellings, households in partially insulated dwellings used the most significant proportion of coal burned for space heating purposes (40 %). Although none of the households reported using wood as their primary energy source for space heating, it was reported as a

secondary source in some households. It was established that non-insulated dwellings were responsible for burning most of the wood used in the settlement (48 %). This could be because wood is cheaper to obtain and also because the heating requirements in non-insulated dwellings are generally higher. That is, more fuel needs to be burned for effective space heating.

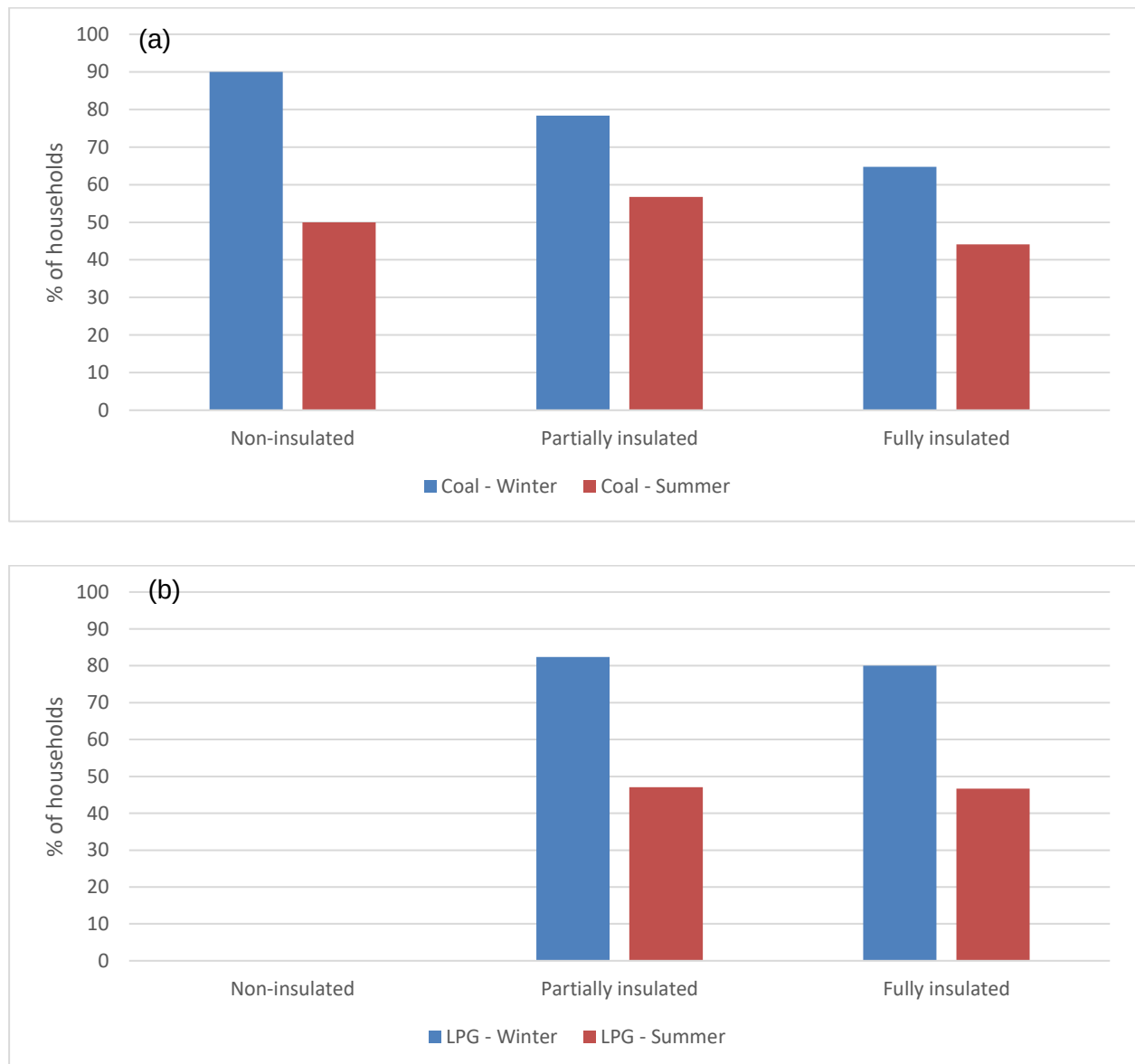


Figure 7.6: Coal and LPG used for space heating across different dwelling types: [a] coal, [b] LPG

Coal and LPG as energy sources for space heating

In Figure 7.6, coal and LPG utilisation is compared across seasons and for different dwelling types. It is evident that both energy sources are utilised more during the winter season. This is because households generally need to heat indoor spaces more frequently during the winter season. It was observed that 90 % of households residing in in non-insulated dwellings used coal

as an energy source for indoor heating during winter, compared with 60 % of households residing in fully insulated dwellings. An important finding is that the vast majority of households in low-income settlements, regardless of insulation status, use coal as an energy source for indoor heating.

7.3.2 Cooking

Figure 7.7 presents the proportional use of energy sources for cooking purposes. Electricity was the primary energy source used for cooking in non-insulated dwellings (50 %), followed by LPG (31 %) and coal (19 %). In partially insulated dwellings electricity was also the primary source (49 %), followed by LPG (29 %) and coal (22 %). Households residing in fully insulated dwellings followed the same tendency with electricity being used the most (36 %), followed by coal (35 %) and, finally, LPG (29 %).

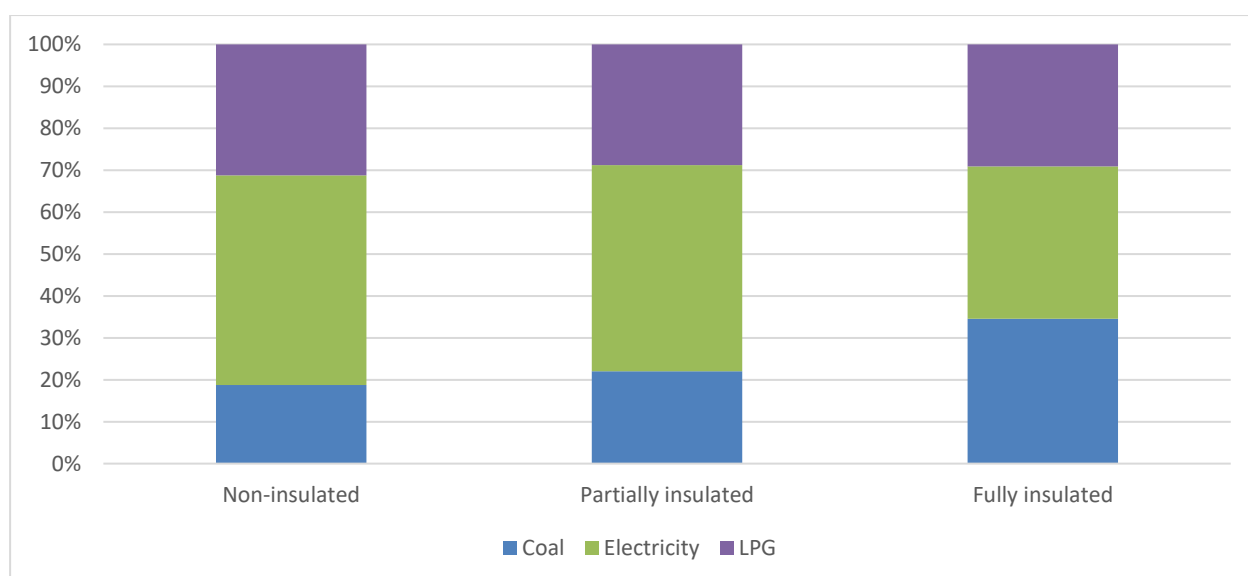


Figure 7.7: Primary energy sources used for cooking

Coal and LPG as an energy source for cooking

In Figure 7.8, the use of coal and LPG as an energy source for cooking purposes is compared across seasons and for different dwelling types. Minimal variation was observed across seasons, and it was observed that almost 90 % of all households relied on coal as an energy source to some extent for cooking. It was also observed that LPG is used frequently, which implies that households generally rely on a mix of energy sources for cooking purposes.

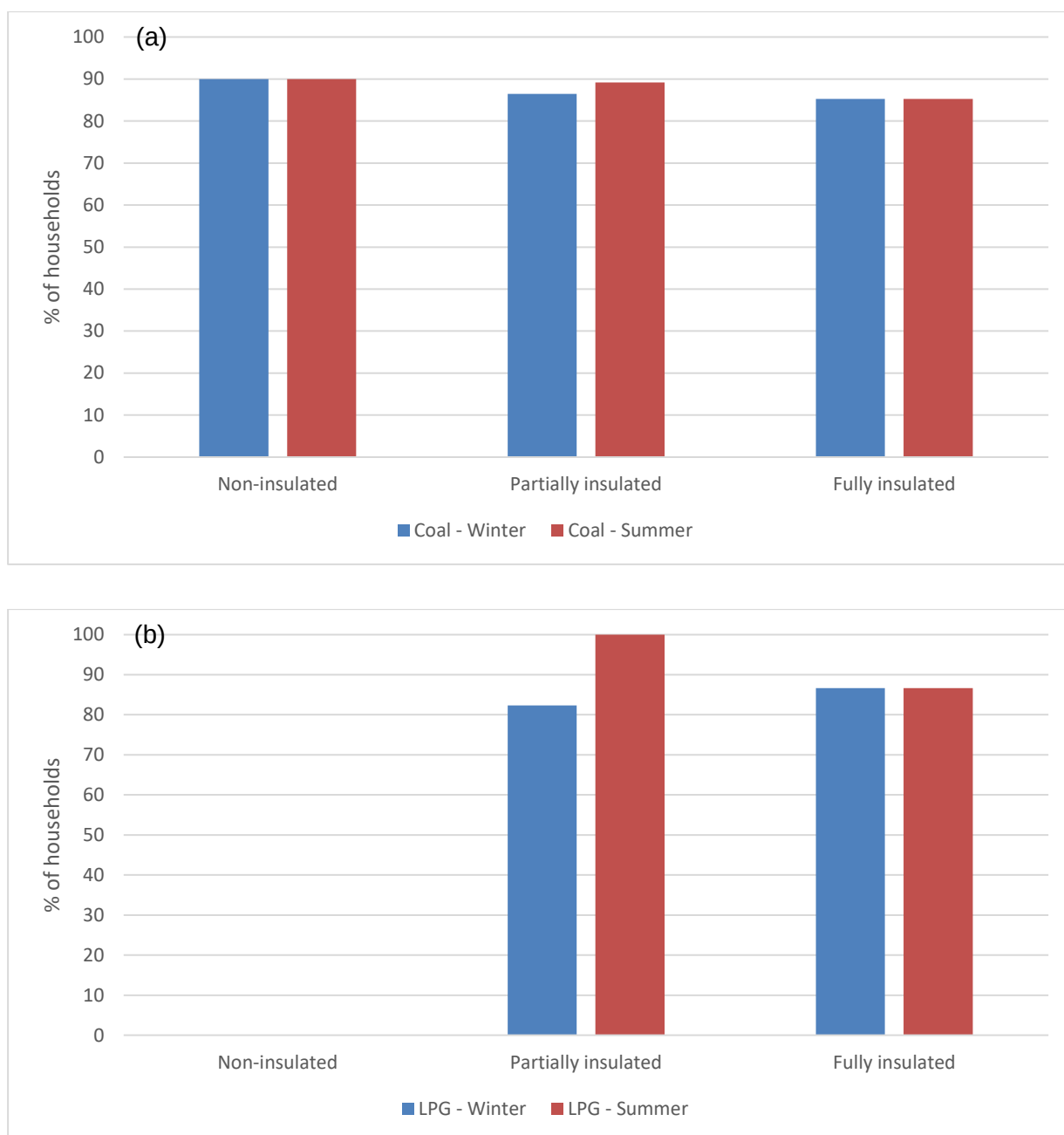


Figure 7.8: Coal and LPG used for cooking across different dwelling types: [a] coal, [b] LPG

The study found further that that so-called 'slow cooking' was often used to prepare foods that require simmering and is often used when certain traditional meals are prepared. Slow cooking is therefore defined as a cooking activity that lasts a few hours, consuming energy throughout the cooking period. Coal is often used in the preparation of these meals due to the issue of cost.

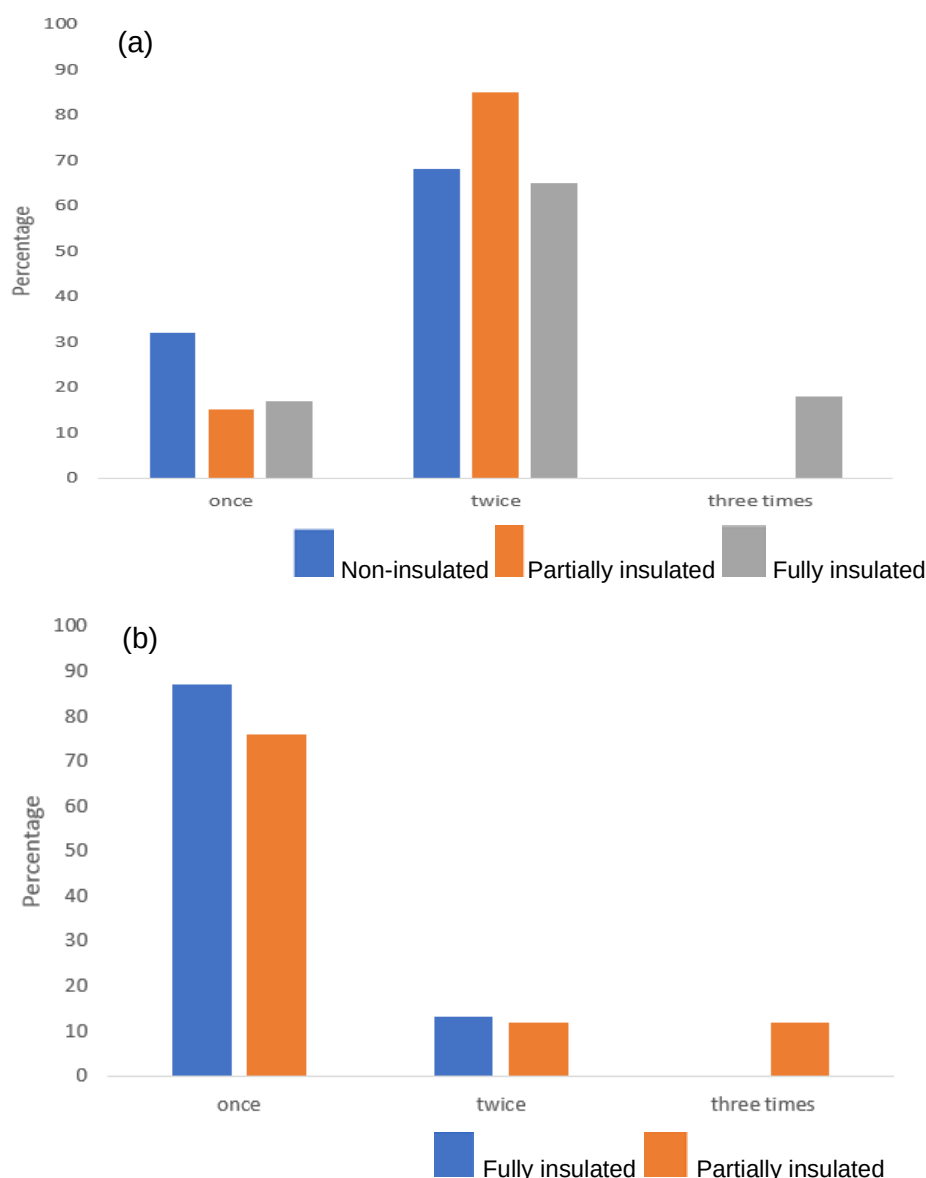


Figure 7.9: Slow-cooking activities per week across different dwelling types: [a] coal, [b] LPG

Figure 7.9 illustrates the frequency of slow-cooking activities across different dwelling types and using different energy sources. It was observed that 33 % of households residing in non-insulated dwellings used coal for slow-cooking purposes once a week while the remaining 67 % used coal for this purpose twice a week. However, 83 % and 6 % of residents of partially insulated and fully dwellings respectively, reported two coal-based activities per week. Households in fully insulated dwellings were the only ones reporting three activities per week – this might be attributed to affordability. It was, therefore, established that coal is used as an energy source for slow cooking across all dwelling types, essentially contributing to possible poor air quality in all dwellings. LPG was used less frequently (only once a week) for slow cooking. The next section reflects on other less frequent uses for coal and LPG.

7.3.3 Other fuel uses

In addition to cooking and space heating other uses for coal and LPG, although less frequent, included heating bathwater, heating water for washing dishes, and for ironing clothes. This section reflects briefly on these uses mentioned above across different dwelling types.

Bathwater heating

In Figure 7.10, the use of coal and LPG as an energy source for heating bathwater is compared across seasons and for different dwelling types. It was observed that 70 % of households residing in non-insulated dwellings used coal as an energy source to heat bathwater across both seasons. Some seasonal variation was observed for partially (81 % in winter and 69 % in summer) and fully insulated (68 % in winter and 56 % in summer) dwellings, with more coal used during the winter season. Nonetheless, coal was used to heat bathwater in almost 70 % of dwellings. Although LPG was used less frequently, it was still used to heat bathwater in 65 % and 53 % of partially and fully insulated dwellings, respectively.

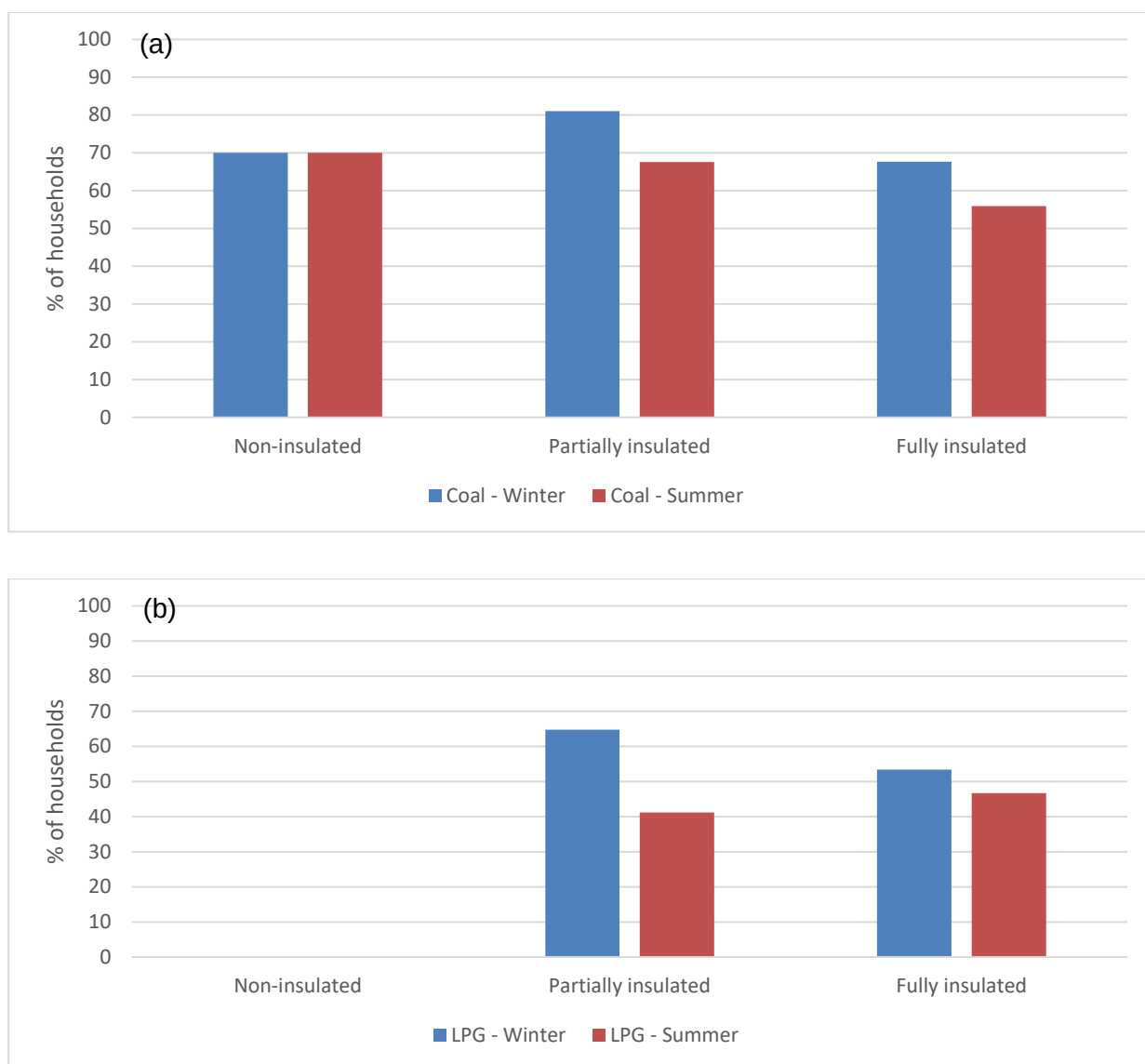


Figure 7.10: Coal and LPG used for heating bath water across different dwelling types: [a] coal, [b] LPG

Heating dishwashing water

In Figure 7.11, the use of coal and LPG as an energy source to heat water for washing dishes is compared across seasons and for different dwelling types. Coal was used to heat water for washing dishes more frequently during the winter season and was generally used more often during the winter season. Approximately 40 % of all households, across all seasons, used coal for this purpose. Although LPG was also used it was at a lower frequency and not used at all in non-insulated dwellings.

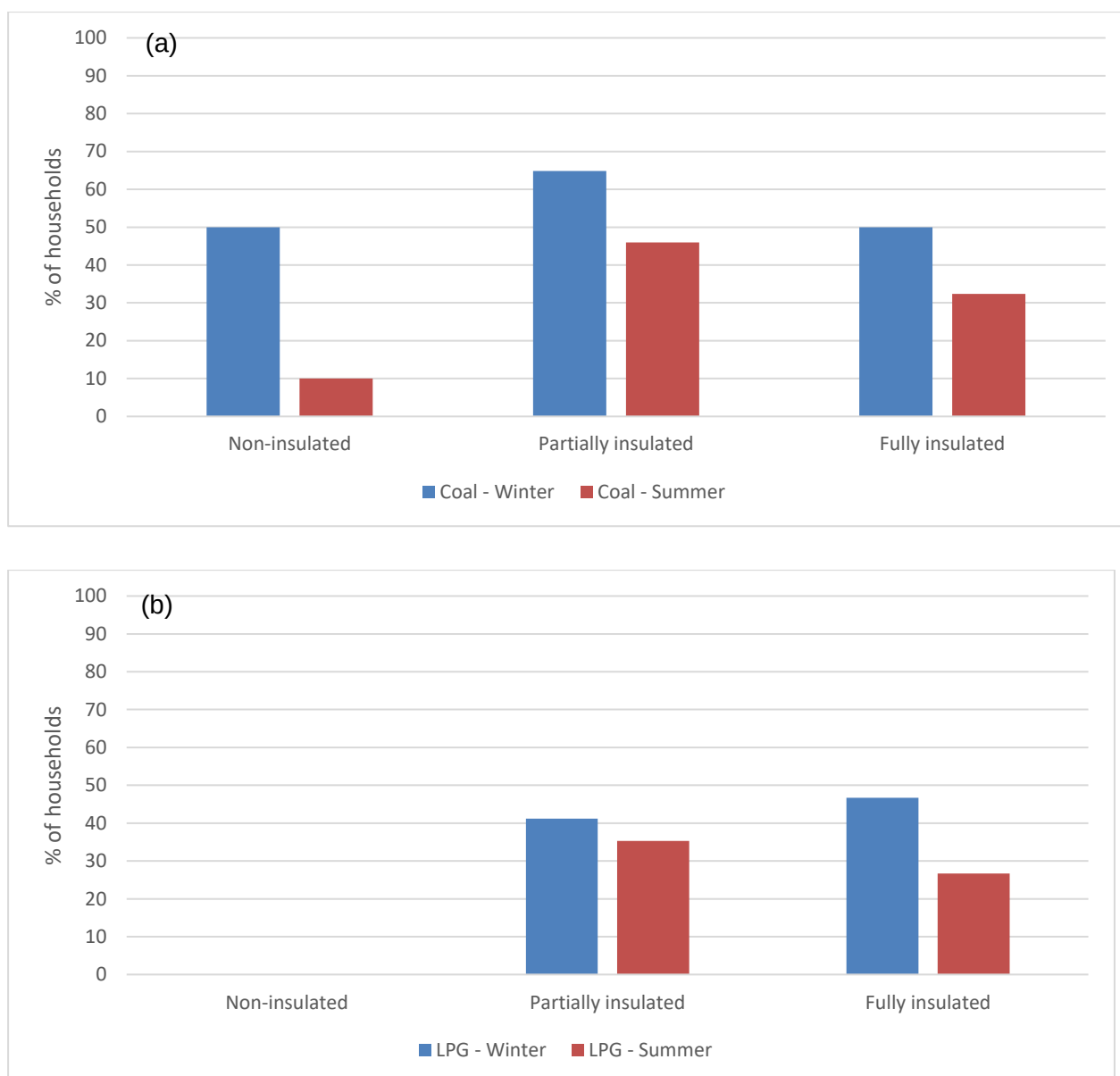


Figure 7.11: Coal and LPG used for doing dishes across different dwelling types: [a] coal, [b] LPG

Heating clothes iron

In Figure 7.12, the use of coal and LPG as an energy source for the ironing of clothes is compared across seasons and for different dwelling types. Few households made use of coal and LPG for this purpose with less than 5% of all households using coal and less than 10% using LPG. Interestingly enough none of the non-insulated dwellings made use of either of the two energy sources. Although less sizeable than with other uses for coal, a similar trend was observed which indicated that coal was used more frequently during the winter season.

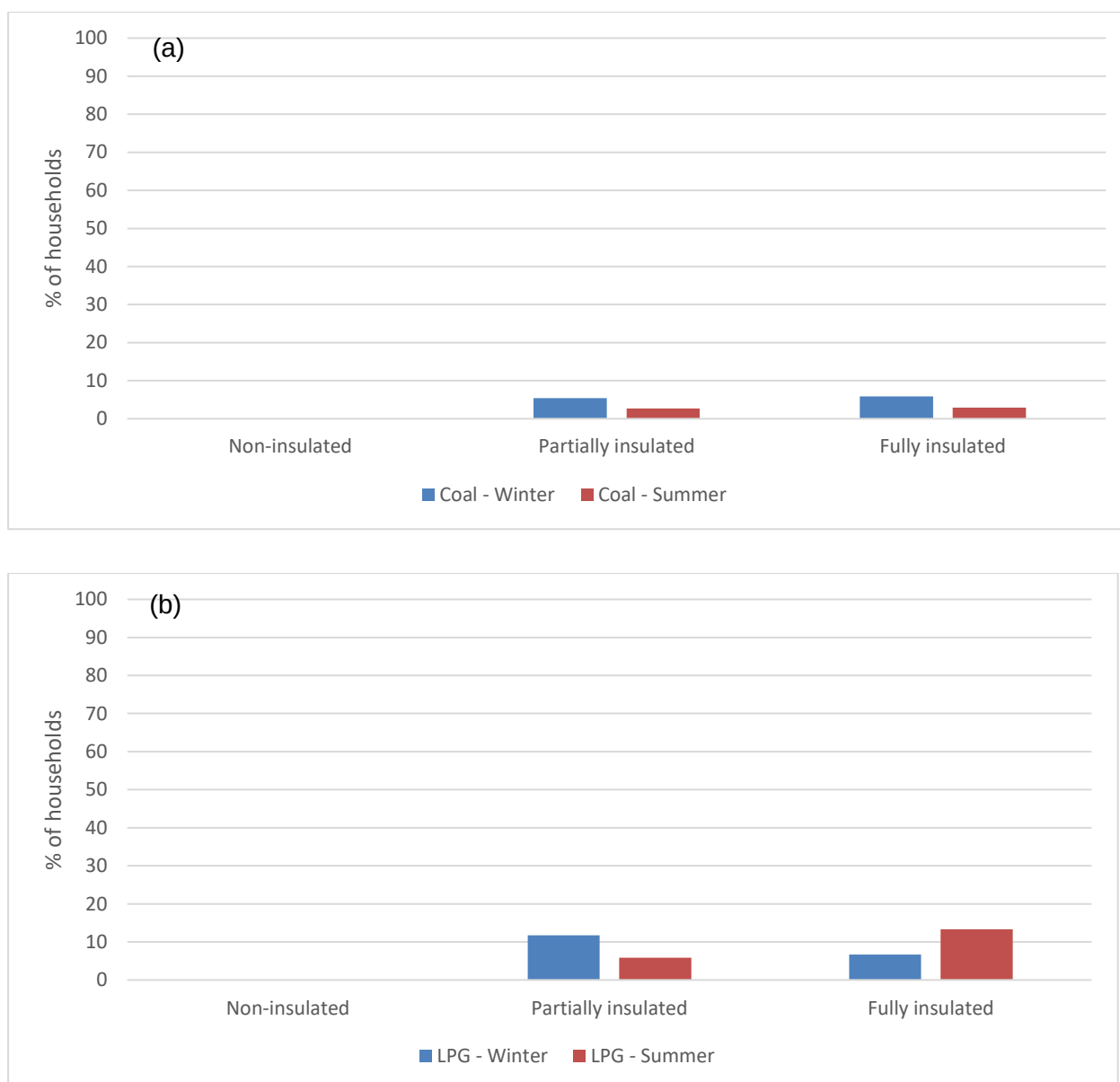


Figure 7.12: Coal and LPG used for ironing across different dwelling types: [a] coal, [b] LPG

7.4 The link between energy use and thermal insulation

In this section, the link between energy use and the thermal insulation status of dwellings in low-income settlements is explored. Through the analysis presented in Sections 7.2 and 7.3, some links between energy use and insulation status were observed:

- It was observed that households residing in partially and fully insulated dwellings generally spend more money on energy than households residing in non-insulated dwellings. This implies that households residing in non-insulated dwellings have fewer fuel resources at their disposal. This further suggests that households in non-insulated

dwellings – which were found to be colder than other types of dwellings during winter (Chapter 5) – will struggle to heat their dwellings, especially during winter.

- It was observed that 90 % of households residing in non-insulated dwellings used coal for space heating during winter, which was the highest percentage of all housing types. However, only 50 % of these households used coal for space heating during summer (decrease of 40 %), while this number was 57 % for partially insulated dwellings (decrease of only 22 %) and 44 % for fully insulated dwellings (decrease of only 21 %). The vast difference in energy consumption during the winter and summer seasons observed for non-insulated dwellings suggests that the insulation status has a substantial effect on energy use. The aforementioned might be ascribed to the extremely cold conditions observed in low-income dwellings during winter, which require excessive heating efforts, resulting in much higher volumes of coal burned when compared with other dwelling types (partially and fully insulated).
- It was observed that energy consumption for space heating was highest for non-insulated dwellings, second highest for partially insulated dwellings, and lowest for fully insulated dwellings for all energy types. This trend suggests that there is a direct link between thermal insulation and energy requirements for space heating.

These observations suggest a definite link between the thermal insulation status of dwellings and the manner in which they use energy. The observed links were mostly relevant when space heating was considered. For other uses such as cooking, water heating and ironing, no clear links could be established. It should further be acknowledged that insulation status will also have a link with possible health impacts as residents of non-insulated houses will have to burn more energy sources (mostly coal), resulting in higher exposure to indoor air pollutants.

7.5 Summary and discussion

It was established that there is some link between thermal insulation status and energy use in low-income households. Although the link did not exist under all circumstances, it was observable when non-insulated dwellings energy consumption for space heating was considered. It was further established that households generally rely on a mix of energy sources which includes electricity, coal, LPG and wood. Of these, electricity was found to be the most widely used energy source followed by coal and LPG. Although most households had access to electricity, coal and LPG was also used. This finding concurs with Mgwambani *et al.* (2018) who found that residents in low-income settlements usually rely on a mixture of energy sources and Kasangana *et al.* (2017) who found that even though electricity might be available, other energy sources will often also be used. Although electricity was found to be the primary energy source used for space

heating, coal and LPG were also found to be essential energy sources as well. Energy consumption for space heating was substantially higher during winter months when compared with summer, while coal-burning was exceptionally high in non-insulated dwellings during winter. Seasonality had little influence on energy use patterns for cooking, suggesting that thermal insulation status did not influence this behaviour. Electricity was once again the primary energy source for cooking although coal and LPG were also widely used. It was established that coal is often used when slow cooking took place and that these activities usually occurred twice a week. It was further established that households occupying partially and fully insulated dwellings, on average spend more on energy than those households residing in non-insulated dwellings. This finding concurs with Wentzel (2006) who found that households occupying energy-efficient dwellings were able to spend more on energy than households residing in non-insulated dwellings. This suggests that residents of non-insulated dwellings will have fewer energy resources than residents of other housing types, which will further affect how they utilise energy.

The implication for low-income households relying on solid fuels like coal is the increased degradation of indoor air quality, thus exposing occupants to respiratory infections which are related to breathing contaminated air as a result of household air pollution. Access to clean sources of energy (LPG and electricity) remains a challenge for low-income earning households on the South African Highveld and therefore physical health ailments can be expected. In Chapter 8, conclusions and recommendations of the study are presented.

CHAPTER 8: CONCLUSIONS

8.1 Introduction

Thermal insulation is a critical component in regulating indoor thermal environments. A significant proportion of low-income households in South Africa reside in dwellings that could be classified as poorly insulated, resulting in these households being exposed to poor indoor thermal conditions. To date, the characterisation of indoor temperatures in low-income households, the link between the insulation and indoor temperatures, and the subsequent link to energy use, had not been fully explored in South Africa. The study aimed at investigating these links in low-income households on the South African Highveld. Seasonal indoor temperature monitoring and aerial thermography were used to characterise indoor temperatures and thermal insulation. To determine the link between thermal insulation and domestic energy use, the study employed household-based questionnaires. Conclusions for the four objectives, highlighting the key learning points arising from the study, are presented.

8.2 Indoor temperatures in low-income households (Objective 1)

The **first objective** of the study was to '***characterise indoor temperatures in low-income residential dwellings on the South African Highveld***' during both winter and summer seasons. Measurements were taken in low-income households in two settlements on the South African Highveld: KwaDela and Jouberton. The study found low-income households to be most vulnerable to extreme temperatures during winter nights as it was established that the majority of dwellings registered indoor temperatures fell below the WHO guideline of 18 °C during this time. In some cases, the day time winter indoor temperature also dropped below 18 °C, although this was less frequent. These findings compare to that in other studies, such as Yohanis and Mondol (2010) and Santamouris *et al.* (2014), who found that indoor temperatures in low-income settlements often fall below 18°C during winter mainly as a result of insufficient space heating. These findings suggest that low-income households generally struggle to heat their living spaces during winter and are therefore regularly exposed to extremely cold living conditions. Evidence from the literature further suggests that exposure to extreme low indoor temperatures could lead to numerous physical health issues, such as respiratory stress (Geddes *et al.*, 2011; Ormandy & Ezratty, 2016), cardiovascular stress (Collins, 1993; How-den-Chapman *et al.*, 2015; Geddes *et al.*, 2011; Ormandy & Ezratty, 2016) and possibly hypothermia in extreme cases (Geddes *et al.*, 2011). These findings imply that there is a real possibility of an increase in incidences of cold-related ailments within low-income households, especially during winter seasons.

During the summer season, low-income households were found to be most vulnerable to extreme indoor temperatures during the day time. Median indoor temperatures exceeding the WHO maximum guideline of 24 °C, were often observed in low-income households during the day time, for both living rooms and bedrooms. A significant relationship was observed between ambient temperatures and indoor temperatures during summer days. It was further established that – although less frequent – night time median temperatures occasionally exceeded the 24 °C threshold and often hovered very close to it. These findings are similar to those of Lomas and Kane (2012) and Sakka *et al.* (2012) who also reported that summer median indoor temperatures often exceed 24°C in low-income settlements. This exposure to high indoor temperatures can lead to severe thermal discomfort (White-Newsome *et al.*, 2012) and even sleep deprivation (Mavrogianni *et al.*, 2015). The elderly, young children and people with compromised immune systems are further expected to be more vulnerable to extreme high indoor temperatures (Ormandy and Ezratty, 2014; Zivin and Shrader, 2016; Kenny *et al.*, 2019) as their sweat response mechanisms are often compromised. Inference can be drawn from the study findings that young people, those with underlying physical health challenges (compromised immune systems) and the elderly who reside in low-income dwellings, face heat-related ailment threats due to extreme indoor heat experienced during summer both during the day and at night.

The study further established that ambient conditions strongly influence indoor temperatures in low-income households on the South African Highveld. It was determined that, during winter, the relationship between indoor and ambient temperature is stronger at night time than day time. Night time Pearson r ranged from $r=0.39$ (KwaDela), $r=0.77$ (Jouberton 2016) to $r=0.91$ (Jouberton 2017), and was always stronger than day time. This finding corroborates with that of Nguyen *et al.* (2014) who reported a correlation of $r=0.91$ between ambient and indoor temperatures thus signalling the positive influence of ambient temperature changes on indoor temperatures. During summer, it was established that the relationship is stronger during day time and less significant during night time. These findings highlight the fact that low-income housing on the South African Highveld remains sensitive to ambient temperature fluctuations, especially during winter nights and summer days.

The study concludes that extremely low indoor temperatures threaten low-income households on the South African Highveld during winter nights and extremely high indoor temperatures during summer days. In the next section, conclusions on characterising thermal insulation in low-income households are discussed.

8.3 Thermal insulation in low-income households (Objective 2)

Objective two involved the '*characterisation of thermal insulation in low-income residential dwellings on the South African Highveld*'. For this, the study focussed on the settlement of KwaZamokuhle. Indoor temperature measurements were analysed for dwellings with different levels of insulation and used as a proxy for the thermal performance of dwellings (Tolocchino, 2005; Pignatta *et al.*, 2017). The study found that non-insulated dwellings consistently had median indoor temperatures below 18 °C during the winter season. Temperatures in non-insulated dwellings were further found to be closely related to ambient temperatures confirming the finding from Howden-Chapman *et al.* (2007) that cold indoor temperatures are a product of low ambient temperatures, structural deficiencies (including lack of adequate thermal insulation) and poorly constructed structures. Overall, partially insulated and fully insulated dwellings performed better and were more successful in regulating indoor temperatures as compared to non-insulated. The differences between dwellings with different insulation levels were most apparent during winter nights, although non-insulated dwellings generally performed poorly during summer days as well. This affirms that the insulation status of dwellings has a definite effect on the thermal comfort experienced by low-income households and stresses the importance of adequate thermal insulation materials for low-income residential dwellings. It can be concluded that non-insulated dwellings are mostly energy wasters, especially during winter which, according to Jim (2014), can primarily be ascribed to poorly insulated roofs which facilitate nocturnal thermal discharge at night time. The study suggests that the retrofitting of low-income dwellings is an effective way of improving their thermal efficiency, as illustrated by the analysis. In addition to improving the indoor living conditions of low-income households and limiting their exposure to extreme indoor temperatures, this approach will also contribute to the reduction of indoor burning as well as improve their physical health wellbeing.

8.4 Characterising thermal insulation through aerial thermography (Objective 3)

Objective three examined the '*extent to which thermal insulation can be characterised through aerial thermography*', i.e. aerial TIR imagery. It was established that thermal variability between dwellings with different levels of insulation was observable through aerial TIR. Non-insulated housing showed significant variability and was distinguishable from partially and fully insulated dwellings as they showed more considerable variability when compared to partially and fully insulated dwellings. It was further established that the difference between TIR imagery obtained during midnight and TIR imagery gathered during the early evening, were the most feasible way of identifying non-insulated dwellings. This was further confirmed through statistical tests which showed that the difference in the range statistic (the difference between maximum

and minimum measured values) across the midnight and the early evening flight, was the best approach towards distinguishing between non-insulated and insulated dwellings. The study followed this approach to identify dwellings with a high probability of being non-insulated. The methodology is influenced by the ambient temperatures, and the variability is influenced by the lack of energy use in financially constrained households that are poorly insulated. The study can conclude that high-resolution aerial TIR imagery can be used to characterise the thermal insulation status of households in low-income settlements. It has also shown that this process of screening for non-insulated dwellings can be conducted across a whole settlement.

8.5 The link between thermal insulation and domestic energy use (Objective 4)

The **fourth objective** dealt with the '*link between thermal insulation and domestic energy use*'. The study concludes that there is, at least to some extent, a link between the thermal insulation status of a dwelling and its energy use. Although not always observable, a link was evident when the energy consumption for space heating in non-insulated dwellings was considered. It was established that low-income households generally rely on a mixture of energy sources which included electricity, coal, LPG and wood. Electricity was found to be the most frequently used, although coal and LPG were also often used, possibly due to affordability. These trends were also observed by other authors such as Mgwambani et al. (2018) and Kasangana et al. (2017). Energy use for cooking and water heating remained mostly unchanged across seasons; however, changes could be observed when space heating was considered. Energy consumption for space heating was generally found to be higher in the winter months than in the summer months, as would be expected. It was further established that coal usage for space heating was especially high in non-insulated dwellings during the winter, suggesting a relationship between insulation status and energy use for space heating. It was further established that households in partially and fully insulated dwellings generally spend more on energy than households residing in non-insulated dwellings. According to Wentzel (2006), this could be because these households have more disposable income and are therefore able to spend more on energy than households residing in non-insulated dwellings. This suggests that residents of non-insulated dwellings will have fewer energy resources than residents of other housing types, which will further affect the manner in which they utilise energy.

8.6 Limitations of the study

Although the study faced several limitations, they did not have a statistically significant impact on the results. Nonetheless, the limitations are briefly discussed. The study did not monitor ventilation practices in the selected low-income residential dwellings which could potentially influence indoor temperatures. Also, the study did not consider nor record other indoor sources of radiant heat that also could influence indoor temperatures. Concerning aerial surveys, the study did not account for the atmospheric interference on the quality of the thermogram, however, the aircraft was flown at very low altitudes which would limit influence. A final limitation of the study was that domestic energy use surveys were not performed at the same time as when temperature monitoring measurements were made.

8.7 Final remarks

The study established that low-income residential dwellings on the South African Highveld generally have poor thermal insulation as is evident from the extreme indoor temperatures observed. Non-insulated dwellings recorded both the lowest indoor temperatures in winter and the highest indoor temperatures in summer, thus confirming the role that thermal insulation plays in the regulation of indoor thermal environments. Those as mentioned earlier was further illustrated through the aerial survey, which showed significant heat loss in non-insulated dwellings when compared to partially and fully insulated dwellings. Indoor temperatures experienced in these dwellings present a risk to the physical health of residents, especially those suffering from chronic illnesses such as respiratory diseases or a weak immune system. It was further observed that there is a link between energy use and the thermal insulation status in low-income settlements. This link was especially evident when energy use for space heating was considered during the winter season. Residents of non-insulated dwellings often used coal to heat their dwellings during the winter, possibly resulting in indoor pollution. In addition to the extreme indoor thermal conditions to which residents of non-insulated dwellings are exposed, it can be argued that they also face a secondary threat in the form of indoor air pollution coming from reliance on solid fuels. The identification and retrofitting of non-insulated dwellings should, therefore, be prioritised as temperatures rise as a result of climate change. The study showed the positive effect that insulation has on reducing the levels of indoor thermal discomfort and, to a lesser extent, the energy uses in low-income households. The study finally showed that aerial thermography could assist in the identification of non-insulated dwellings in low-income settlements. This approach could assist in the scoping and planning of intervention programmes and the prioritisation of households in need of intervention.

8.8 Recommendations for future studies

The study was able to establish that occupants of low-income residential dwellings on the South African Highveld are threatened from exposure to extreme indoor temperatures during both winter and summer seasons. The above mentioned is the result of the poor thermal insulation of houses and the study, therefore, recommends that future studies investigate the use of cheap alternative thermal insulation material for the improvement of the insulation efficiency of houses. Additionally, the study recommends further research on the development of indoor thermal guidelines applicable to the South African context. Such guidelines will ensure that adequate materials are used suitable for different climatic regions in South Africa. The study also further recommends future studies to fully explore the impacts that climate change will have on indoor environments in low-income settlements in South Africa. The study finally recommends the further development of aerial thermography as a diagnostic tool for the evaluation of the insulation status of residential dwellings in South Africa.

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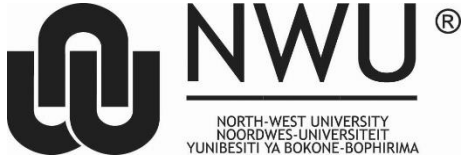
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ANNEXURES

Annexure 1 – Consent form



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**Department of Geography and
Environmental Management**

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South Africa 2520

Tel: 018 299 1505

Cell phone:

078.....

Email: runyamore@gmail.com

PARTICIPANT INFORMATION AND CONSENT FORM

My name is Newton Matandirotya a student from the North-West University, Potchefstroom Campus, Department of Geography and Environmental Management. I herewith wish to kindly request your consent to participate in this research, which will involve installing temperature loggers in your house (kitchen, bedroom and livingrooms) for a considerable period of time as well responding to questionnaires on domestic energy use. Before you give consent, please acquaint yourself with the information below.

The details of the research are as follows:

TITLE OF THE RESEARCH PROJECT: Exploring thermal insulation in low-income residential dwellings and domestic energy use on the South African Highveld

PROJECT SUPERVISOR: Dr D.P Cilliers

CO-SUPERVISOR: Prof R.P Burger

ADDRESS: Building E4, Room G49

CONTACT NUMBER: 018 299 1505

FACULTY OF NATURAL SCIENCE AND AGRICULTURE RESEARCH ETHICS COMMITTEE

This study has been approved by the Research Ethics Committee of the Natural Science and Agriculture of the North-West University and will be conducted according to the ethical guidelines of this committee.

What is expected of you as a participant?

Give the researcher access to your dwelling to install loggers indoors in the kitchen, living room and bedrooms.

Risks expected during the study for participants

None

Confidentiality and protection of identity

The researcher guarantees that the participants true identity/physical address will not be disclosed at any stage of the study as the will only use codes as identifiers.

Dissemination of findings

Findings of the study will not be disseminated for any other purposes except for the compilation of the thesis, conference articles and journal publication only.

If you have any further questions or enquiries regarding your participation in this research, please contact the researchers for more information on the above-mentioned phone number.

Yours sincerely
(Researcher)

DECLARATION BY PARTICIPANT:

By signing below, I agree to take part in a research study entitled: **Exploring thermal insulation in low-income residential dwellings and domestic energy use on the South African Highveld**

I declare that:

- I have read this information and consent form and understand what is expected of me in the research.
- I have had a chance to ask questions to the researcher and all my questions have been adequately answered.
- I understand that taking part in this study is voluntary and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- I may be asked to leave the research process before it has finished, if the researcher feels it is in my best interests, or if I do not follow the research procedures, as agreed to.

Signed at (place)_____on (date) ____/____/20____

Signature of participant

Researcher

Annexure 2 – Questionnaire

Questionnaire questions

Coal use

Does your household sometimes use coal?

Do you use coal in winter?

Do you use coal in summer?

Please explain what else do you use coal for?

How often does your family cook a dish with coal that takes longer than an hour to cook?

How many of these containers do your household (all members taken together) use per day for bathing in winter?

How many of these containers do your household (all members taken together) use per day for bathing in summer?

Please mark the times of day during summer that your household members bath using water heated with coal.

Where do you buy or get your coal?

Do you know the name of the merchant or company or mine that you buy coal from?

What is the name of the coal merchant where you buy most of the time?

In what format do you get your coal?

Please explain in what format you get your coal.

How much (in Rands) do you pay for one unit of coal?

How often do you buy or get coal?

How many units per month do you currently use in WINTER?

How many units per month did you use during the most recent SUMMER?

Please mark the times of day during winter that your household members bath using water heated with coal.

Electricity use

Do you use electricity in your house?

How often do you use your electrical heater in the WINTER:

Do you sometimes use another energy carrier for heating and cooking because you do not have money for electricity?

Please indicate which of the following energy carriers you use for heating and cooking when you do not have money for electricity:

Do you sometimes use another energy carrier for lighting because you do not have money for electricity?

Please indicate which of the following energy carriers you use for lighting when you do not have money for electricity

Wood use

Does your household sometimes burn wood?

Do you use wood in winter?

Do you use wood in summer?

In which wood burning device do you mostly burn your wood?

Please explain how you burn your wood:

What format of wood do you mostly use?

Please explain in what format you get your wood:

How much (in Rands) do you pay for one unit of wood?

You have indicated that you use both wood and coal. Do you sometimes make fire with wood only?

How many of these containers to do your household (all members taken together) use per day for bathing in summer?

Where is the stove located?

When last did you use wood?

LPG Use

Do you sometimes use gas in your house?

Do you use gas in winter?

Do you use gas in summer?

How many kilogrammes of gas do you burn per month in WINTER?

How many kilogrammes of gas do you burn per month in SUMMER?

What is the weight (in kilogramme) of gas that you usually buy? (Sometimes it is written on the side of the container)

What else do you use gas for?

How often do you use your LPG heater in the WINTER:

How often does your family cook a dish with LP gas that takes longer than an hour to cook?

Please choose the option that best describes the container that you use to heat water for bathing using LP gas:

You have chosen Other. Please explain what other container you use for bathing when heating water with LP gas:

How many of these containers does your household (all members taken together) use per day for bathing in winter?

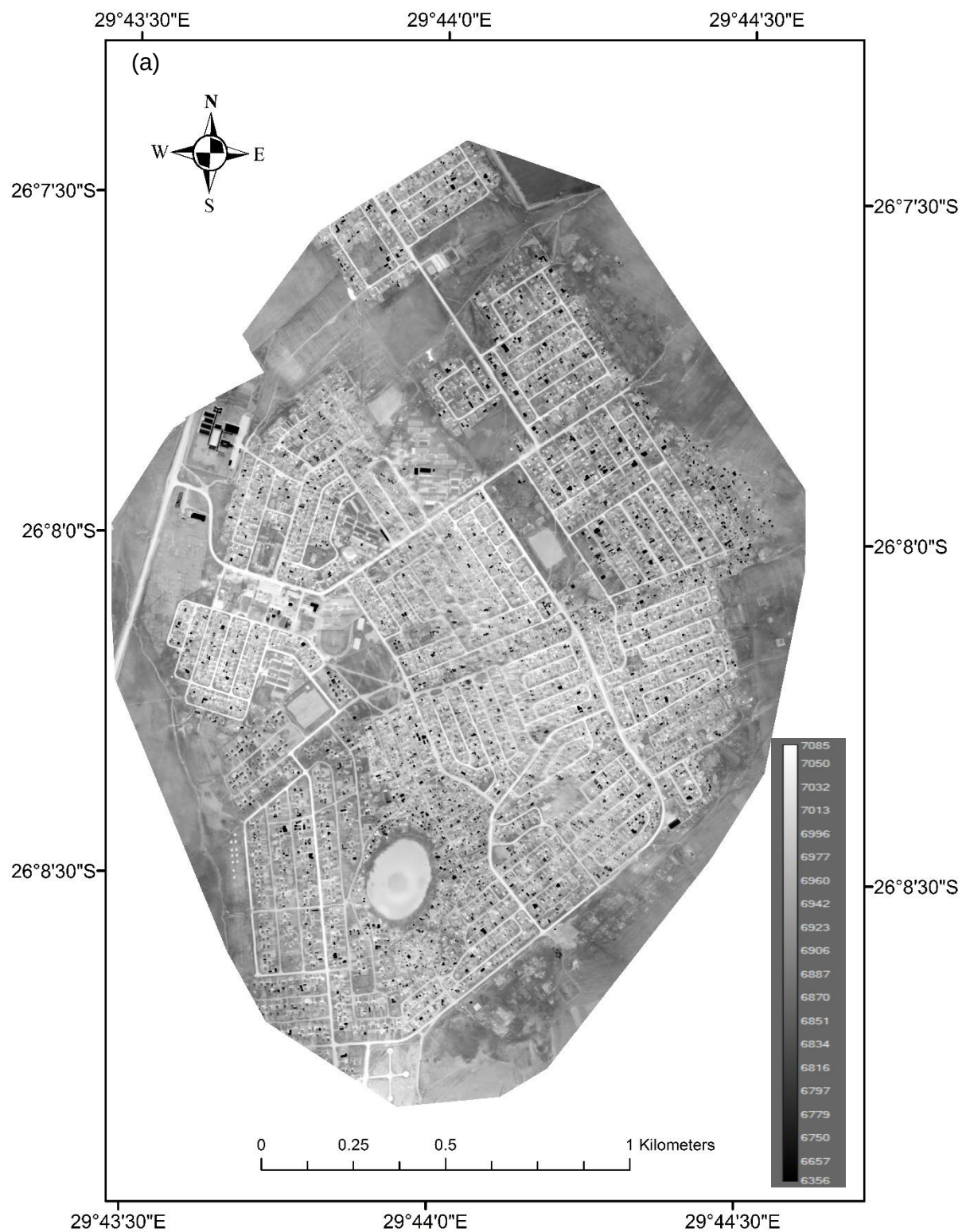
Please mark the times of day in SUMMER that your household members bath using water heated with gas.

On how many days in the last 3 months (90 days) were you without gas?

Which of the following options best describe the reason for you being without gas? (read options)

This is the end of the questionnaire. Thank you very much for your participation.

Annexure 3 – TIR images [a] Flight 1, [b] Flight 2, [c] Flight 3







Annexure 4 – Examples of sampled structures



Typical coal stove used in low-income dwellings



Fully insulated dwellings with northern outside elevation painted black and the inside



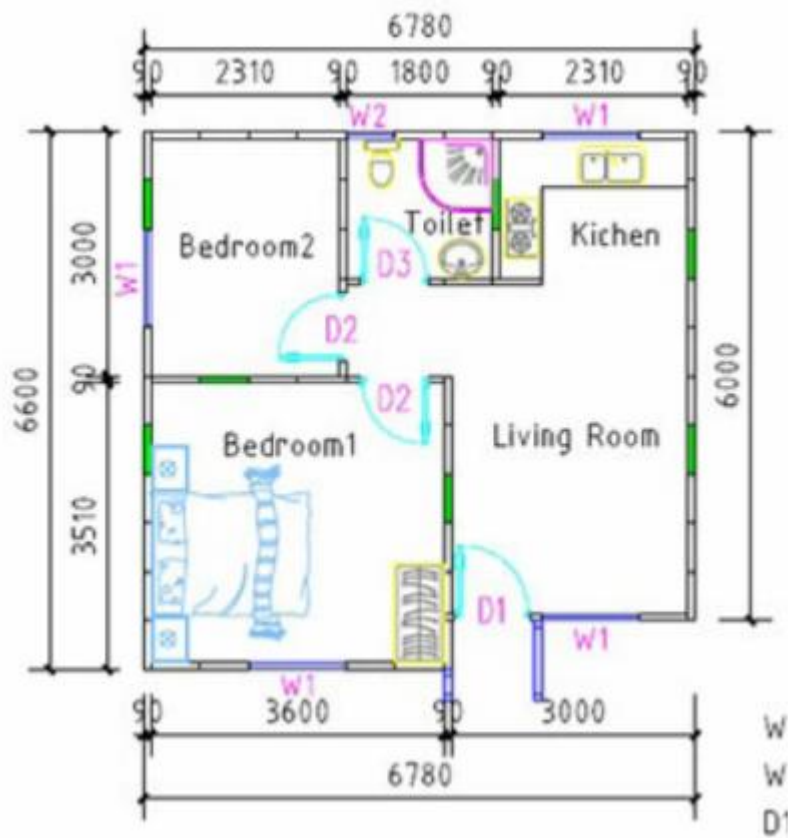
Non-insulated dwellings



Non insulated inside



A formal dwelling with a shack adjacent to it



Typical RDP residential dwelling floor (Source: Linstra, 2016)