A comparative study of indoor and ambient temperatures in three housing types in the Kathorus and Wakkerstroom areas, South Africa

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°C	degrees Celsius
ANC	African National Congress
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
DEA	Department of Environmental Affairs
DTR	Diurnal Temperature Range
ENSO	El Niño- Southern Oscillation
HDA	Housing Development Agency
PMG	Parliamentary Monitoring Group
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RDP	Reconstruction and Development Programme
SAWS	South African Weather Services
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
UTCI	Universal Thermal Climate Index

Abstract

The right to adequate housing, is defined in the Constitution of South Africa as a basic human right. Most townships in South Africa are predominantly comprised of low-cost houses, there has been limited research on the indoor temperatures experienced by residents of these homes. As a developing nation the price and availability of construction materials, often takes precedence over the potential thermal efficiency of the household. Occupants of low-cost houses are particularly vulnerable to climatic changes which may be exacerbated by increased warming in South Africa. This study focused on the relationship between indoor and ambient temperature in two study areas namely; Kathorus and Wakkerstroom. These areas were chosen because they experienced different micro-climatic conditions, with Kathorus having warmer ambient temperatures than Wakkerstroom (eSizameleni). Three housing types were included in the research (government funded apartheid era houses, government funded post-apartheid houses and informal houses (shacks)). The study included analysis of long-term temperature (maximum and minimum) trends, from 1960 to 2017, at the two sites. The daily indoor temperatures were studied over the course of a year. A total of 36 data loggers, 18 in each site were installed, by the end of the study however only 28 were retrieved. The houses studied were built with different materials, which are said to affect their thermal efficiency; apartheid era houses were made from clay brick, and post-apartheid low cost houses with maxi (cement) brick and shacks with corrugated iron as well as any scavenged materials. Clay brick, should offer increased thermal efficiency as a result of having the highest thermal mass (of the three), and shacks the least (as it had the lowest thermal mass). Furthermore, the study included semi-structured interviews where occupant's perspectives on housing could be surveyed. Temperatures across both areas have largely been rising at an insignificant rate. However, the colder month temperatures in Wakkerstroom (T_{min} and T_{max}) and Kathorus (T_{min}) were significantly increasing. Household temperatures in Kathorus and Wakkerstroom, both in the warmer and colder months fluctuated substantially throughout the day. There was an 8 °C, 9 °C and 14 °C fluctuation in daily indoor temperatures of apartheid-era, post-apartheid and shacks houses (respectively). The indoor temperatures of apartheid and post-apartheid homes were found to be 25 % and 36 % less associated with ambient temperatures when ceilings were installed, and yet less than 33 % of sampled houses (in Wakkerstroom, and none in Kathorus) had this feature. From the respondents it was determined that perceptions of thermal comfort were often not related to actual measured indoor temperature readings. The study's findings suggest that a majority of low-cost houses are thermally inefficient, but none more so than post-apartheid era and shacks homes. For these houses a clear link can be made between ambient and indoor temperature fluctuations. Since a substantial portion of the South African population lives in these housing types, thermal inefficiency and by extension increased vulnerability to climatic changes poses several climate related health risks. For South Africa to contribute to Africa's Sustainability Goals, low-cost adaptation strategies such as additions of ceilings should go a long way in increasing tenant's resilience to potential climatic changes.

Keywords: Ambient temperatures, climate change, climate zones, thermal comfort perceptions, low-cost housing, indoor temperatures

Dedication

"Success is liking yourself, liking what you do, and liking how you do it."

Maya Angelou

This dissertation is dedicated to my mother, Sylvia Mabuya.

And to my late Grandmother, even though you will never see this, you inspired it.

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I would be remise not to, firstly, thank my supervisor and mentor the esteemed Prof. Mary Scholes whose guidance has been invaluable. Without whom this large undertaking would be near impossible, she has constantly exemplified the importance of the feminine energy in science, and the science community is all the better for it. My thanks go out to the National Research Foundation (NRF) for their financial support throughout.

To the communities of Kathorus and Wakkerstroom, thank you for showing me warmth and granting me access to your homes for such an extended amount of time. To Rev. Gwynne Lawlor, Ms Buyisiwe Mbatha and Ms Charlotte Zihlangu thank you for sharing your time with me and helping me gain community buy-in. My heartfelt thanks to Mr Kgasane (of the Ekurhuleni Municipality) and Prof. David Root, I appreciate your willingness to share your time and knowledge with me. A huge thanks to the South African Weather Services (SAWS), the professionalism you showed did not go unnoticed.

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Chapter 1: Introduction

One of the most central of all basic human rights, which plays a key role in several international human rights treaties and accords, is the right to adequate housing. This right features prominently in Section 26(1) of the Constitution of South Africa ("*everyone shall have the right of access to adequate housing*"). If we are to use the United Nations Centre for Human Settlements definition of "adequate housing", then these houses must not only provide shelter, but "*privacy, adequate space; security of tenure; structural security; adequate lighting, heating and ventilation; adequate basic infrastructure … all of which should be available at an affordable cost…*" (UNCHS, 1997). The question then arises, do low-cost houses provided to the poor qualify as being "adequate" according to the definition above? And subsequently are they "constitutional"?

Provision of low-cost houses to the poor has been a major focus of previous and present-day government regimes (Pottie, 2003; Goebel, 2007) and large portions of the financial budget are and have continuously been allocated towards low-cost housing. In 1994, in a post-apartheid government, the White Paper on Housing unequivocally prioritized the needs of the poor and made the commitment of providing at least 1 million houses in 5 years (Jenkins, 1999). In 2017, the African National Congress (ANC) increased this pledge and has made the commitment to make improvements to informal settlements, as well as to deliver 1.5 million low-cost houses to the poor by 2019 (which was determined in the 2014 to 2019 medium-term strategic framework) (Treasury.gov.za, 2017). A commitment that appears to be contentious, especially in 2018 when the Human Settlements budget (for housing) was returned to treasury. It came as no surprise that at the national level protection of the environment as well as improvements to the quality of life (World Bank, 2015) of approximately 12 million underprivileged South Africans would feature quite prominently in Africa's Sustainable Development Goals (Munang and Andrews, 2014). The concept of quality of life is dualistic, it involves firstly perceptions-based analysis (of ones quality of life) and secondly, the overall social and physical context of the environment one inhabits. As such the concept of environmental quality of life includes housing (Cutter, 1982; Diener, 1995; Moller and Jackson, 1997; Westaway, 2006). Houses are therefore undeniably part of the key factors which increase or decrease the quality of life of millions of poor and marginalized South Africans.

It is now well established that climate change is a global phenomenon, resulting in increased temperature trends (Caesar *et al.*, 2006; Alexander *et al.*, 2006; Kruger and Sekele, 2013). The rate of warming has all but doubled in the last 50 years (when compared to the previous 100 years) (Kruger and Sekele, 2013). To make matters worse temperatures in South Africa are warming at about twice the global average, by all accounts this trend of warming will continue into the future. Additionally, Kruger and Sekele (2013) suggest that cold extremes are increasing in intensity but decreasing in duration and frequency, which will have implications on the current housing available to the poor as well as new housing projects.

1.1 Study rationale

The primary type of housing found in townships are of the low-cost variety, which include, apartheid era “matchbox” houses; post-apartheid “RDP (Reconstruction and Development Programme)” houses; and predominantly self-built informal “shack” houses. Inhabitants of the low-cost houses in the townships of Kathorus and eSizameleni (in the Wakkkerstroom area) are subject to climatic changes and particularly increasing temperatures (and increased intensity of cold extremes). Understanding these climatic trends and their impacts in relation to low-cost houses is critical to any government sanctioned future adaptation and mitigation strategies. The relationship between indoor and ambient temperatures formed the basis of this study, firstly because a clear link can be made between indoor and outdoor temperature; Nguyen *et al.* (2013), which is not possible for values such as relative humidity. And secondly, because determining daily indoor temperature fluctuations will go a long way in determining relative vulnerability of the inhabitants of each housing type to climatic variables.

There has been limited research in South Africa on indoor temperature conditions of low-cost houses, particularly during the warmer and colder months. To get a broader sense of the relationship between indoor and outdoor temperature, this study focuses on locations which experience different climatic conditions (Kruger and Sekele, 2013), and have the three low-cost houses of interest. Several studies suggest that low-cost houses are poorly built (Mathews and Weggelar, 2017; Maoto and Worku, 2018) and subject tenants to thermally undesirable conditions. Being able to define the ranges where indoor temperatures are conducive to human health and productivity, as well as to determine if the three housing type's remain within or close to those (temperatures) ranges is necessary. Especially because residents of low-cost houses often contend with other monetary commitments, such as access to food, clothing and healthcare; therefore, inadequate housing places increasing financial pressure on residents. By having to pay more for heating and cooling of their homes, they are diverting funds away from other necessities.

Research aim

The aim of this research is to compare the indoor temperatures of the three most commonly found low cost housing types in Kathorus and Wakkerstroom, and to determine if these (temperatures) are influenced by ambient temperatures or not. In addition, determining the thermal efficiency of the housing materials and occupants thermal satisfaction.

Research objectives and key questions

Objective 1: Determine the long-term temperature trends in the Kathorus and Wakkerstroom areas from 1960 to 2017.

- *Key question 1*: How have long-term temperatures trends (temperature maximums and minimums) changed in Kathorus and Wakkerstroom over the period 1960 to 2017?

Objective 2: Determine daily indoor temperatures in Kathorus and Wakkerstroom, during warmer and colder months in 2017- 2018?

- *Key question 2a*: What are the mean daily indoor temperatures of the three low cost housing types in Kathorus and Wakkerstroom?
- *Key question 2b*: Are indoor temperatures a function of ambient temperatures and/or housing type.

Objective 3: Determine housing materials used to construct low cost houses; from 1960 onwards.

- *Key question 3a*: How and why have low-cost residential construction materials changed over time?
- *Key question 3b*: How do these construction materials behave thermally, during warmer and colder months in 2017- 2018?

Objective 4: Determine the self-reported perceptions around thermal comfort of residents of low-cost houses in Kathorus and Wakkerstroom, during warmer and colder months.

- *Key question 4a*: What is the perceived thermal comfort experienced by residents of each housing type during warmer and colder months?
- *Key question 4b*: Is thermal comfort perception a function of housing type and/or behavioural modifications (made by occupants)?

Chapter 2: Literature review

Introduction

The literature on the aspects that influence our current understanding of both indoor and outdoor temperatures will be presented in this chapter. This study is interdisciplinary and will be using various approaches in order to connect the quantifiable physical factors (temperatures) to the more qualitative behavioural and perception based factors which make up thermal comfort. This chapter will firstly, expand upon the observed long-term temperature trends in South Africa. Then the relationship between ambient and indoor temperatures, including micro-climatic influences will be discussed. This will then be followed by a discussion about the construction of low-cost houses in South Africa. And finally, potential risk factors as well as common adaptation strategies used by residents will be explored.

2.1 Historical air surface temperatures across South Africa

Much work has been done in southern Africa in order to understand climate indicators such as rainfall and temperature. Good quality data have allowed for distribution maps to be produced as well as long-term trends in temperatures to be understood. Because regional as well as local temperatures play a large role in the regulation of climatic elements, long-term local temperature indices will be the major focus of this study.

From 1959 to 2010 observed surface air temperatures in South Africa have been rising at an elevated rate (Lawal, 2015). A more continent-wide investigation into temperature by Engelbrecht *et al.* (2015) across Africa (from the period 1961 to 2010) also elucidated on the trend of increasing average annual (near-surface) temperature (°C /century). From the observed seasonal temperature trends shown in Figure 1 it is clear that the interior of the country has been warming at a slightly lesser rate than that of the exterior parts. Modelled temperature data by Lawal (2015) as well as Kruger and Sekele (2013) have verified these findings. Localised temperature trends are not uniform in space (provincial) and time (seasonally). What has been defined as summer (December, January and February) by Lawal (2015) has shown the most pronounced amount of heating. Adding to that Lawal (2015) has suggested that Gauteng province (where Kathorus is located) is warming at a more elevated rate than most parts of Mpumalanga province (where Wakkerstroom is located).

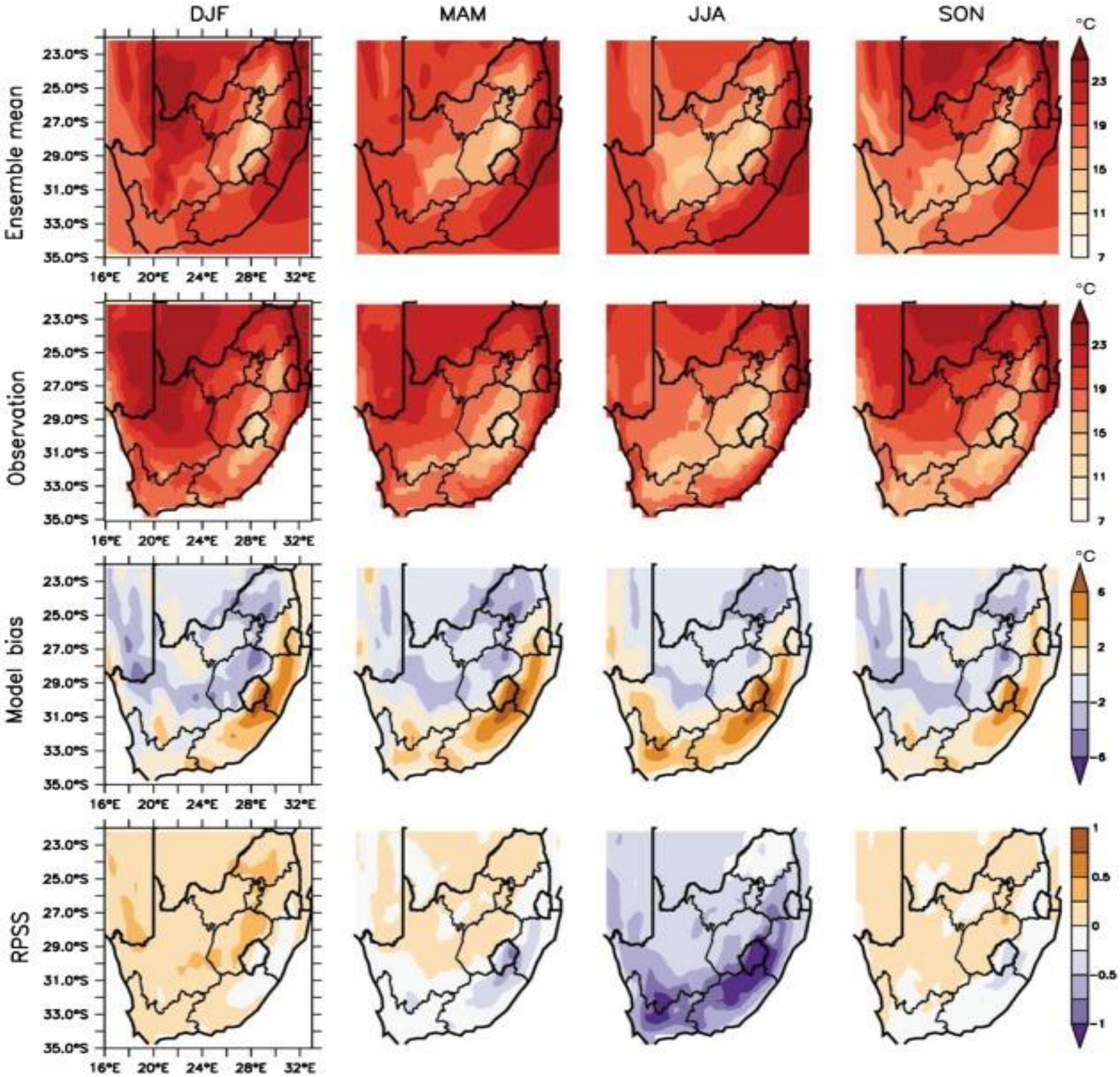


Figure 1: A map showing the seasonal distribution of near surface temperature across South Africa from 1959-2010. The top row indicates Ensemble mean (simulated by HadRM3P). The next row indicates observed temperatures adapted from the (Climatic Research Unit) CRU dataset. The third row is that of model bias relative to the CRU observations and the last row are the ranked probability skill scores (RPSS) of HadRM3P near surface air temperature simulations. The columns designate the austral seasons: DJF- summer, MAM-autumn, JJA- winter and finally SON-spring. (Lawal, 2015)

2.1.1 Observed long term temperature trends in South Africa

South Africa has one of the most accurate and complete climate records in all of Africa. This is especially true in large cities where the highest quality climate records can be found, with some mean temperature data stretching back more than a century. From 1960 onwards more country wide, reliable minimum and maximum temperature data became available (Hughes and Balling, 1996; Kruger and Shongwe, 2004, Mackeller *et al.*, 2014). When Kruger and Shongwe (2004), Hughes and Balling (1996) and Mühlenbruch-Tegen (1992) performed studies, mostly in larger cities, based on the long term temperature data in South Africa they all agreed that there seemed to be an increasing trend of hot days (with no statistical significance) and a statistically significant decrease in colder ones. But in the mid-90s the need to conduct these studies in areas with limited access to temperature data (small towns, for which interpolation methods were used) was evident. Access to climatic information in South Africa is not equal in space and time, Kruger and Sekele (2013) bridged this data gap by performing more wide-scale temperature analysis.

Since detecting and monitoring of any changes in daily temperature extremes was deemed to be of critical importance, more analyses were conducted. Research by Mühlenbruch-Tegen (1992) and Hughes and Balling (1996) focussed on temperature extremes but it was not until the late 1990s and early 2000s that this work began to gain traction. A valuable study was conducted by Kruger and Shongwe (2004) on the spatial and temporal trends of temperature maximums (T_{max}) and minimums (T_{min}) in South Africa from the year 1960 to about the year 2003. Kruger and Shongwe (2004) were able to reveal the variability of temperature trends between seasons and across months. These findings informed the current understanding on the observed variability present in the climatic records across the country. Additionally, the study was able to disprove the widely held belief that temperatures had mostly increased during the 90s, instead what was found was that temperatures in the early 80s were the main cause of the general trend of increasing (temperatures) from 1960 throughout, to about the early 2000 when the study concluded.

In the same token, extreme events such as El Niño and La Niña were placed into context. For instance, the general heating trend which occurred in the 1980s (1982-1983) was as a result of the El Niño, which caused one of the driest and hottest periods, ever observed in most regions in the country. It was suggested by Kruger and Shongwe (2004) that this El Niño event set a new trajectory for average temperatures in South Africa.

Detailed questions on temperature trends and the uncertainty thereof were also gaining attention. In the early 90s, Mühlenbruch-Tegen (1992) analysed data from 1940–1989 from a total of 18 urban as well as non-urban stations in order to detect any cases of general warming. The study provided no conclusive proof of any changes in mean temperature, but changes in minimum (T_{min}) and maximum (T_{max}) temperatures were detected. Easterling *et al.(*2000) determined that between 1950 to 1993 there had been a general increase in the annual mean daily temperature maximums (T_{max}) and minimums (T_{min}), albeit with a few instances where a detectable decrease in temperatures (it was getting cooler) in South Africa could be found. Later, MacKellar *et al.* (2014) stated that this increase was largely a factor of the amplified warming effect occurring in the central regions of southern Africa showing differential warming at sub-continental scales. What was still inconclusive however, was the possible cooling taking place over the coastal regions during 1901 to 2003 (MacKellar *et al.*, 2014). Work by Kruger and Shongwe (2004) was able to illustrate that this differential warming was also occurring in the country, perhaps not to the extent as it was occurring continentally or even sub-continentally, but it was occurring.

In the mid-90s Hughes and Balling (1996) also attempted to tackle the question of homogeneity of temperature trends across South Africa using 5 urban stations and 19 non-urban stations. The non-urban stations were not warming at any significant rate. Hughes and Balling (1996) and Kruger and Shongwe (2004) found that urban stations were warming at a significant rate, but a definitive trend was not evident. There seemed to be some urban contamination of the climate record (Mühlenbruch-Tegen, 1992; Hughes and Balling, 1996; Kruger and Shongwe, 2004). Which suggested that because urban stations were significantly warmer than surrounding non-urban ones, they influenced the general warming trend observed.

The case of country scale warming was mostly accepted at this point. By using the period between 1960-2003, Kruger and Shongwe (2004) were able to reveal strong instances of warming in the interior regions of South Africa. Where they highlighted the months of March to May, austral autumn, as being the warmest. Recently an additional investigation by Kruger and Nxumalo (2017) suggested that summer (December to January) was the season with the strongest warming. This historical survey has influenced our current understanding of the seasonality of South African temperatures.

2.1.2 Challenges in determining clear diurnal temperature ranges in South Africa

It is difficult to determine a clear pattern for diurnal temperature range (DTR) (defined as the difference between T_{max} and T_{min}). Easterling *et al.* (2000) stated that the DTR was increasing over South Africa. Hulme *et al.* (2001) challenged these findings a year later, showing a clear decrease in the DTR especially during the 50s and 60s, which is the global trend. New *et al.* (2006) published wide-ranging results for changes in DTR. This research was able to demonstrate that T_{min} changed at a more substantial rate than that of T_{max} (during the same period). Kruger and Sekele (2013) were able to confirm that there has been an overall increase in instances of hot extremes, and at the same time a decrease in the instances of cold ones. There were more visible increases in T_{max} indices than there were in indices related to T_{min}. As such many temperature studies to date still mainly use T_{max} and T_{min}.

2.2 Clustering of climate zones

Cluster analysis are a useful means to separate and define climate regions according to their climatological characteristics. There are varied approaches and techniques to cluster climate zones (Wilks, 2011). The most commonly used of these is the K-means method (Kruger and Sekele, 2013), the K in this instance is the number of clusters, which is standard and thus defined before the analysis can begin. In Figure 2 below, an illustration of a cluster analysis created by Kruger and Sekele (2013), is presented, in the context of South Africa. The analysis of these clusters in South Africa was applied using the annual means of minimum and maximum temperatures.

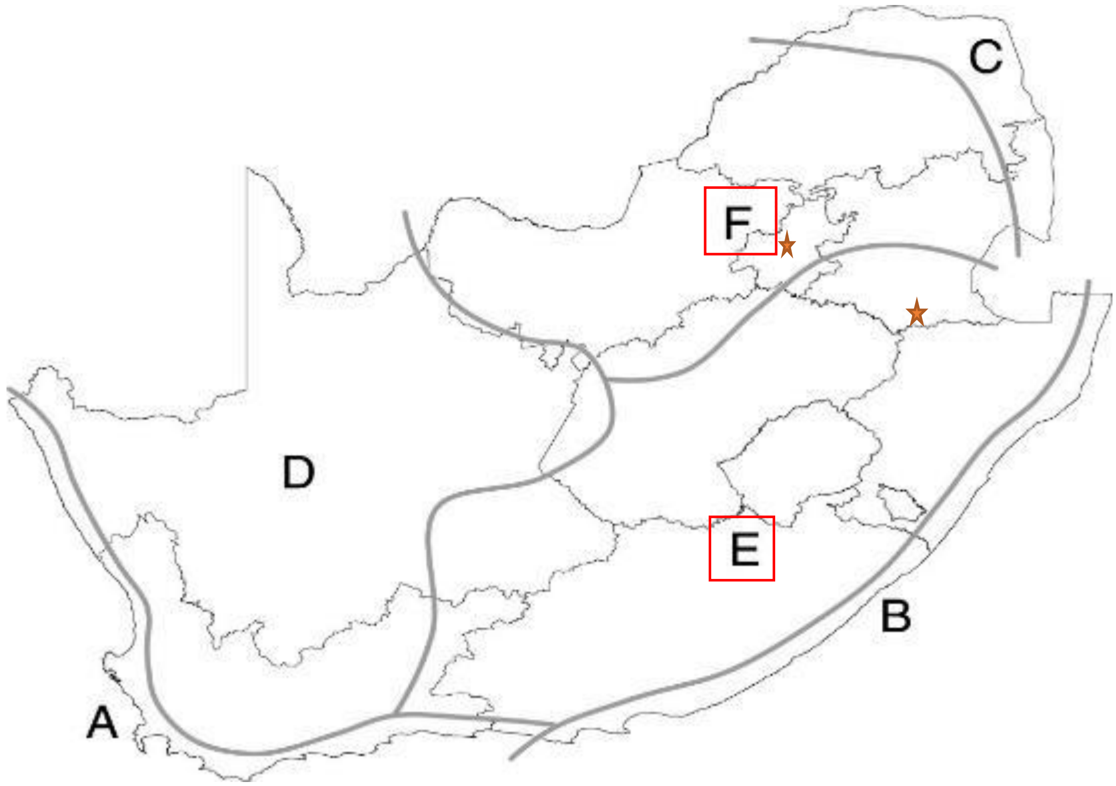


Figure 2: Weather stations which are grouped according to their general characteristics of mean temperatures in South Africa (adapted from Kruger and Sekele, 2013). The two climate clusters (regions) are emphasized in red boxes, and the study areas are represented by means of stars.

What is clear from Figure 2 is that the clusters can broadly be considered homogeneous groups of stations, which exhibit approximately similar annual thermal characteristics (Kruger and Sekele, 2013). As a result, knowing where studied regions fall within these clusters can go a long way in explaining their respective observed temperatures. Considering this, using the temperature cluster regions suggested by Kruger and Sekele (2013), Kathorus can be found in cluster F, which is characterised by displaying higher colder weather values than that of larger parts of cluster E. Wakkerstroom can be found in cluster E, which is said to experience relatively small DTR (Kruger and Sekele, 2013). Kruger and Sekele (2013) suggested that this DTR was a result of the moderating influence of the entry of oceanic air from the Indian Ocean.

Definitions of the other (clusters A and B are found on the coast, clusters C to F are found in the interior of the country):

Cluster A: Characterised by a Mediterranean climate, normally in the western and southern coastal regions.

Cluster B: Characterised by a subtropical climate, located in the southeast and eastern coast.

Cluster C: Found in the Lowveld (thus at a low altitude), characterised by high temperatures (all year round) found in the northeast interior.

Cluster D: Found in the western interior, with high summer temperatures and low winter temperatures.

2.2.1 Areas with relatively stronger warming in South Africa

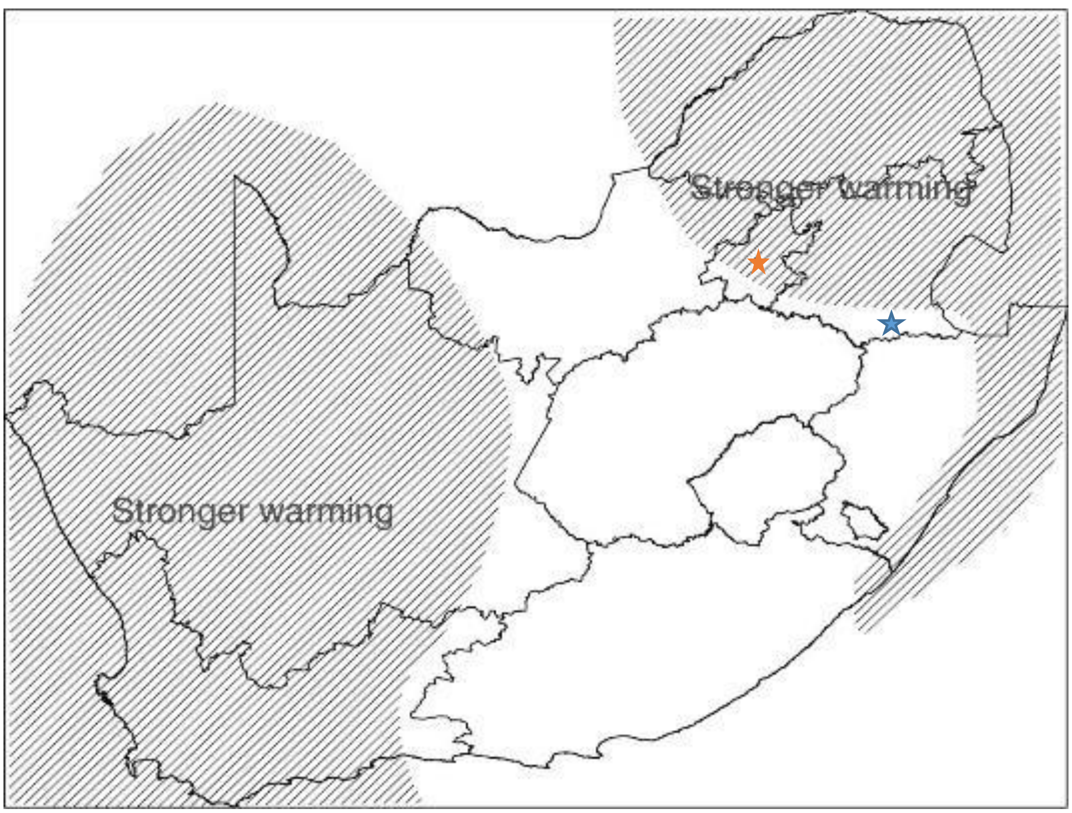


Figure 3: Summary of regions of relatively stronger warming in South Africa over the period 1962–2009 (Kruger and Sekele, 2013). Kathorus in Orange and Wakkerstroom in Blue.

The western, eastern and north-easterly parts of the country (Figure 3), are where the majority of either increased warm extremes or decreased cold ones were found to be dominant (Kruger and Sekele, 2013). Furthermore, other temperature studies performed by New *et al*. (2006) were mostly in agreement with this. If this is true, then Kathorus is located directly in the region where strong warming is said to be occurring and Wakkerstroom is not. This may well have a huge impact on the observed temperature across the two areas.

Kruger and Sekele (2013) as well as New *et al.* (2006) state that this remarkable differential warming is likely as a result of atmospheric circulation over the entire sub-Saharan Africa. Additionally, the changes may be as a result of the relative strength of cold fronts moving over the sub-continent over the western parts. Or perhaps even the less intense ridging by the semi-stationary Atlantic Ocean's high-pressure system from either the south or south-easterly parts of the country, particularly during what has been defined as summer in South Africa. They also attribute the differential warming in the eastern part of the country, to the less intense ridging by the Indian Ocean's high-pressure system which could possibly cause a reduction in the occurrence, or quite possibly even, the strength of the influx of more dense cooler maritime air coming from the eastern parts of the country (Kruger and Sekele, 2013). Nevertheless, what could be deduced is that Kathorus and Wakkerstroom experience different micro-climatic conditions.

2.3 Factors affecting thermal comfort

For there to be adequate levels of thermal comfort (the state of mind of being satisfied with one's thermal environment) inside houses, four environmental parameters need to be addressed (Markus *et al*., 1980; Ibrahim and Tinker, 2005). Namely, air temperature, average radiant temperature, air velocity, as well as relative humidity (Figure 4). Air temperature is the most commonly measured weather parameter and is basically the measurement of how warm or cool air is in degrees Celsius (°C). The average or mean radiant temperature is perhaps the most complex parameter to measure. Average radiant temperature is defined as "*the uniform temperature of a hypothetical spherical surface surrounding the subject, which would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment*" (Walikewitz *et al*., 2015). And as such it is also measured in °C. Air velocity is a measure of the distance air has travelled per unit time and is measured in metres per second (m.

s^{-1}). The relative humidity of air can be defined as the amount or percentage (%) of water vapour present in the air.

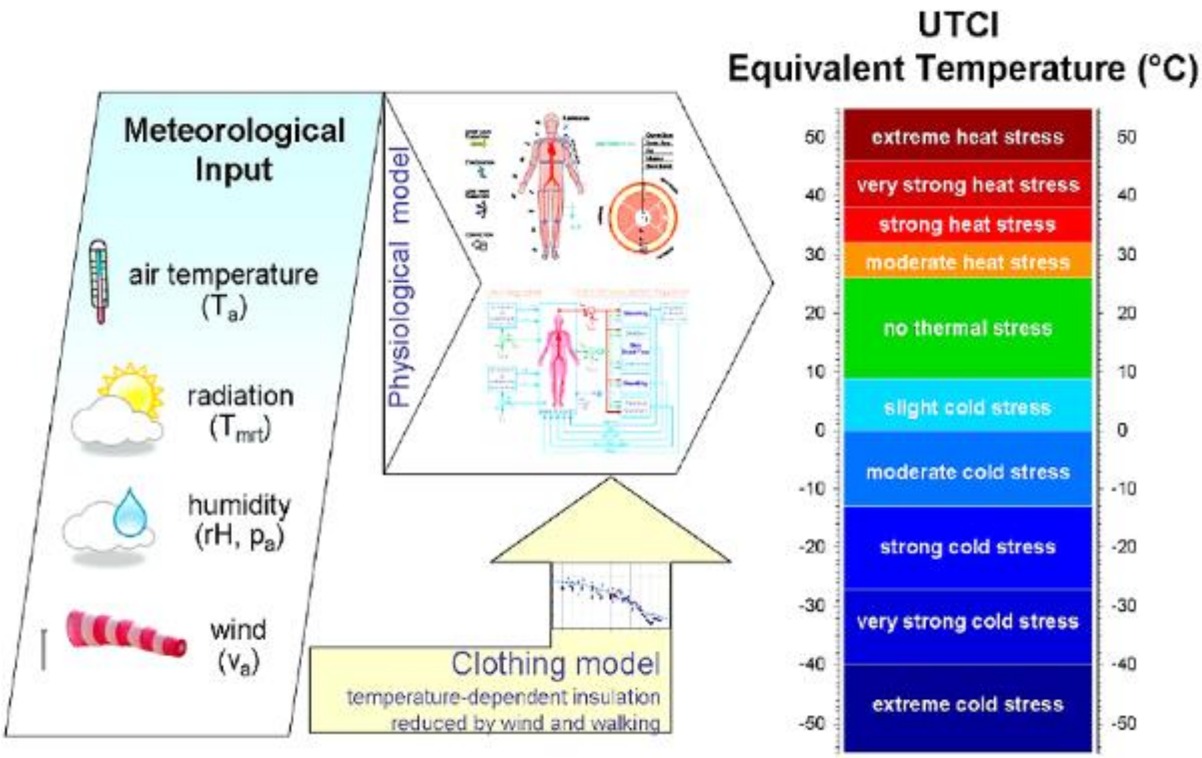


Figure 4: A diagrammatic representation of the UTCI (Universal Thermal Climate Index) (*Bröde et al., 2013*)

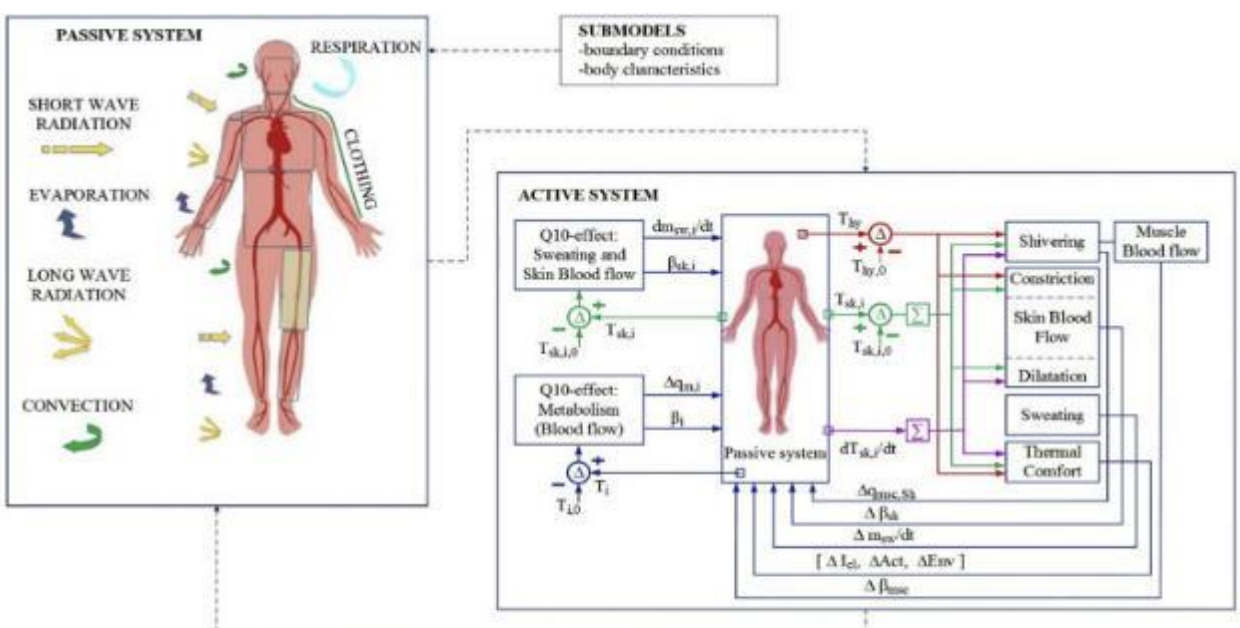


Figure 4- 1 : Expansion of the schematic diagram of physiological model seen in Figure 4 (Katic et al., 2016)

According to the Universal Thermal Climate Index presented in Figure 4 (and Figure 4-1), the human body is most effective (not experiencing thermal stress) between approximately 10 °C and 27 °C. As air temperatures reach above 27 °C heat stress is placed by the environment on human bodies, with varying degrees of seriousness. Similarly, temperatures falling below a certain point (10 °C) place additional cold stress to the human body, evidently the colder or warmer it becomes the more stressed the body becomes. These thermal ranges are important in defining the relative tolerance ranges associated with the human body. They however do not inform us on which temperature ranges were determined to be comfortable for indoor conditions. And subsequently which temperature ranges contribute to people's overall sense of quality of life.

2.3.1 Development of indoor thermal comfort models

Thermal comfort studies use algorithms in order to predict people's responses to the relative quality of their thermal environments. And so, because thermal comfort is due to environmental factors as well as to the building itself, both aspects need to be considered for reasonable determinations to be made. The Fanger method (1970) is a predictive tool using various psychological, physiological and thermal parameters to measure people's responses to their thermal environments (Danca *et al*., 2016). The Fanger method is accepted as the earliest, most valuable research into thermal comfort, Fanger (1970) conducted closed chamber experiments where physical factors (like sweat rate and skin temperature) which accounted for predicted metabolic rate were measured, and their sensations rated. These experiments formed the cornerstone of current thermal comfort knowledge.

There had long been the assumption that the thermal sensation experienced by occupants was a function of the physiological strain imposed by the environment itself and Fanger (1970) produced empirical data to this effect (Peeters *et al.*, 2009). But Fanger's (1970) closed chamber experiments had their limitations. The Fanger's (1970) equation only provided for optimal thermal comfort conditions. Growing concern was that in natural systems optimal conditions were not always a possibility, and actual thermal sensations needed to be studied. For example, in real world conditions, Fanger (1970) used what is referred to as the predicted mean vote (PMV) to determine thermal comfort. The PMV is defined as *"the difference between the* *internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level"* (Peeters *et al*., 2009). This definition clearly does not adequately account for gender of the occupant or even the differing external thermal conditions placed on an individual and does not give a full picture of real-world thermal comfort. What this method provided however, was a crude way to predict thermal comfort for a given set of (closed chamber) environmental conditions for differing clothing insulation and metabolic rates.

There was a growing need for more international and inclusive standards for determining thermal comfort, and so the ASHRAE (American Society for Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 (1994) was defined. The ASHRAE Standard 55 (1994) expanded the definition of thermal comfort by including both the PMV as well as PPD (percentage of people who are dissatisfied with their thermal environment) to make determinations on thermal comfort. These standards considered the clothing worn by occupants, the type of thermal environments they occupied, as well as their respective risk factors (such as age and gender). In this way the ASHRAE Standard 55 (1994) presented a more comprehensive look at thermal comfort, about a decade later further revisions were made to the ASHRAE Standard 55 (2004; 2010) where factors previously overlooked by Fanger (1970) were explored even further.

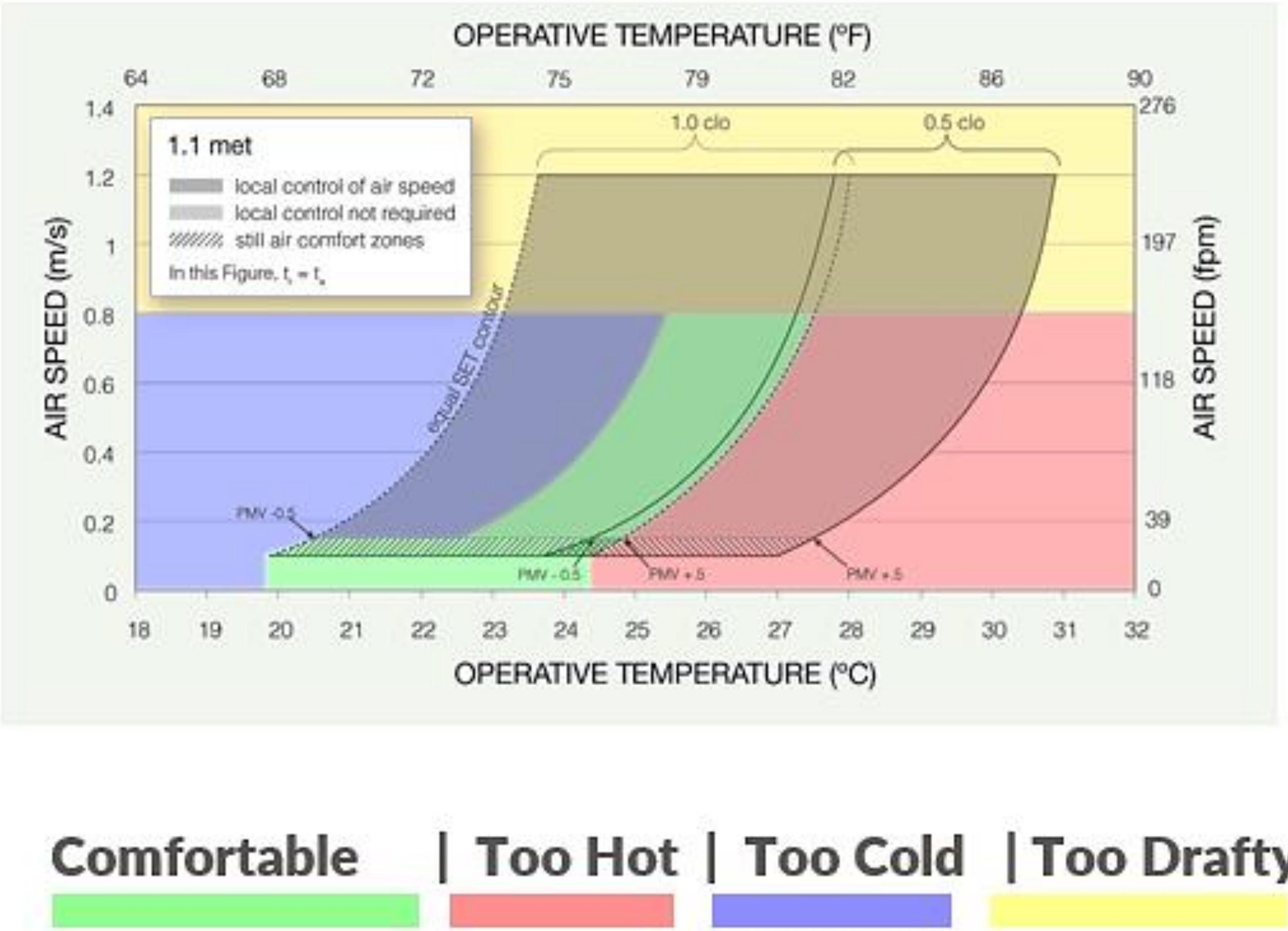
2.3.2 Factors affecting indoor temperatures of residential buildings

Residential buildings present a unique set of challenges with regards to determining relative thermal comfort. For one they usually have varying degrees of thermal characteristics between and within rooms, secondly occupants have sometimes unpredictable behavioural activities and have developed a multitude of ways and strategies in which to adapt to their existing environments (Peeter *et al*., 2009). Nevertheless, indoor temperature patterns can be determined or at least approximated using algorithms and thus comfortable thermal ranges can be calculated.

2.3.2.1 Residential buildings thermal comfort

Previous thermal comfort studies did not include residential buildings. Inside residential buildings, the situation somewhat changed (Peeters *et al.*, 2009). Residential thermal comfort thus far was not directly comparable to the commonly used thermal comfort calibration PMV and PPD algorithms (Peeters *et al.*, 2009). Researchers have long known that households were certainly not continually at a stable state. They were in fact dynamically fluctuating entities. These fluctuations often happened within short spaces in time (Peeters *et al.*, 2009). Adding to that occupants could change their clothing, activity levels or occupancy numbers relatively quickly, fluctuations in internal heat gains (solar or internal heat), as well as heat losses (opening windows) could also change at a relatively fast rate (Peeters *et al*., 2009). More attention is still required with regards to residential buildings which would lead to a better understanding of thermal comfort ranges.

Nevertheless, Peeters *et al.* (2009) state clearly that indoor temperatures inside residential buildings are to a large extent dependent on the corresponding outdoor temperature. Guo *et al.* (2014) found that when ambient temperatures were low tenants were particularly vulnerable. As it stands (Figure 5) the current ASHRAE Standard 55 (2010; 2013) has informed our contemporary understanding of indoor thermal comfort, even though this framework was mostly developed for non-residential use, it remains the standard of thermal comfort studies.



<u>**Figure 5:** ASHRAE thermal comfort range, using air velocity and temperature (ASHRAE Standard 55, 2010)</u>

ASHRAE Standard 55 (2010) recommends that for indoor temperature to be considered comfortable, the air speed must be approximately 0.2 $m.s^{-1}$ and it must be between 20 °C and 24.5 °C. As air speed surges to about 0.8 $m.s^{-1}$, the range in which indoor temperatures are comfortable narrows, to between 25.5 °C to about 27 °C. Any conditions above (too hot) or below (too cold) these limits are considered uncomfortable.

2.3.2.2 Age profiles

It is reasonable to assume that a person's physical characteristics play a role in impacting their perception of thermal comfort. Fanger (1970) found that there seemed to be no difference in perception of thermal comfort with age, which implied that younger people and elderly people (65 years and above) experienced the same thermal sensations, in the same way. However, what was different was the metabolic activity and the basal metabolism (the minimum amount of energy required to maintain vital functions in an organism at complete rest) of older people. Elderly people seemed to display a lower metabolic activity as well as a lower basal metabolism and were, more sensitive to temperature extremes. Elderly people had increased distal vasoconstriction preferring higher indoor temperatures than young adults (20-25 years) (Schellen *et al.*, 2010).

2.3.2.3 Age of building

In the early 1990s when the ASHRAE Standards (1994) first explicitly dealt with thermal comfort, questions around the relationship of the building itself and its indoor temperatures emerged. Building materials used and, the age-related properties of those building materials are two important factors. Kane (2013) noted that improved building materials have become available over time, more is known about their insulation properties, and technological advancements (in construction and architecture) allowed for a reduction in heat loss to the environment. Thermal transmittance (rate of transfer of heat through a structure) has also improved with newer buildings (Steemers and Yun, 2009). The thermal transmittance is defined by, a U-value, lower U-values indicate that the building has better insulation properties.

In the United Kingdom (UK), indoor temperature studies have shown that building age does affect temperature (Oreszczyn *et al*., 2006). Older houses tend to be less thermally efficient than newer ones. There is limited information with regards to building age and thermal efficiency in southern Africa, but one expects the same to hold. Hunt and Gidman (1982) studied houses in the UK built between 1910 and 1970, it was found that those houses built in 1970 were 3 °C warmer than those built earlier. From these findings it seems, for building age to play a significant role in household temperatures, the types of building materials used, and their thermal properties need to be of a better quality than those previously used.

2.3.2.4 Number of occupants

The number of people occupying a household is also said to play a role in regulation of indoor temperatures. Logically, there will be increased energy expenditure with increased occupancy (Steemers and Yun, 2009). A number of reasons could cause this; firstly increased occupancy means more appliance usage. Secondly, the duration of time where the house is occupied may also increase (Kane, 2013). Admittedly, these reasons for increased heat gains are speculative and reliant on the behaviour of occupants. The effect of occupancy, is not a heavily studied area, one reason for this could be because occupancy is highly variable and fluctuates relatively quickly. What is known about internal heat gains, however, is that each occupant (independent of age or gender) contributes approximately 1 kW (Kilo-Watt) equivalent to about 0.00052 °C, at any given time (ASHRAE Standard-55, 2010). With increased activity levels (of each occupants), there is an accompanying increase in indoor temperature (ASHRAE Standard-55, 2010). This relatively small increase in temperature, as a result of increased occupancy in even small residential houses, is not enough to cause significant changes. Oreszczyn *et al*. (2006) have found evidence to that effect, they state that the number occupants does not have a significant effect on indoor temperatures.

2.4 Low-cost residential houses

Low cost housing presents a unique set of challenges both structurally and psychologically. These houses are inhabited by the poorest, most vulnerable members in society, and so there is commonly a pre-conceived negative outlook on their thermal comfort. These houses are not simply required to offer occupants shelter and protection from outdoor conditions but to offer psychological well-being and a sense of security. Many people still live in low-cost houses, and many of these low-cost options are badly built and have cracks and leaks and are defective (Maoto and Worku, 2018).

The issue of substandard housing becomes even more pronounced when looking at the average energy share of poorer households. Energy consumption as well as thermal and indoor environmental quality of households is strongly related to the income and social characteristics of the occupants (Sakka *et al.*, 2012), which means that poorer households are having to spend a large proportion of their time and money on heating and maintenance.

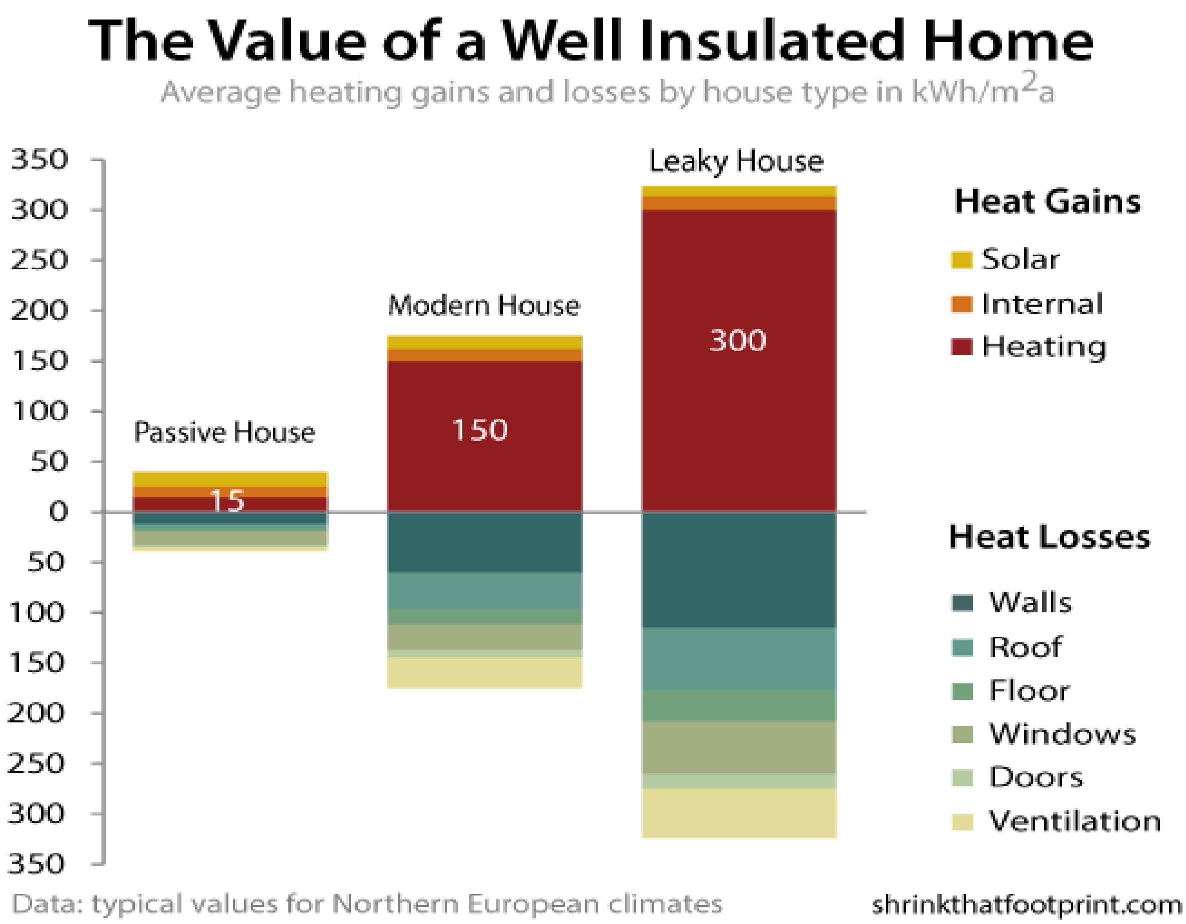


Figure 6: A bar graph representing the Northern European account on share of heat losses and gains, measured in kWh/m^{2}a (kilowatt-hour per metre squared annually) (Energycentral.com, 2013)

In Figure 6 we see that the energy expenditure of poorly built houses, most probably inhabited by poorer families, is higher than that of well-built houses. Using a southern African example, assuming that badly built houses are linked to wealth status the principles remain the same. Mathews and Weggelaar (2017) show that the lower the income of occupants the higher the energy consumption of the household per square meter, and occupant. This is because it is exceedingly difficult to heat or cool a badly constructed home, due to cracks and poor insulation. In South Africa, where a substantial gap exist between access to affordable energy and demand for clean energy (Wrinkler, 2005), many underprivileged households cannot pay, so they do not, or they use illegal means in order to acquire energy (Fjeldstad, 2004).

2.4.1 Thermal mass and its role in regulating indoor temperature

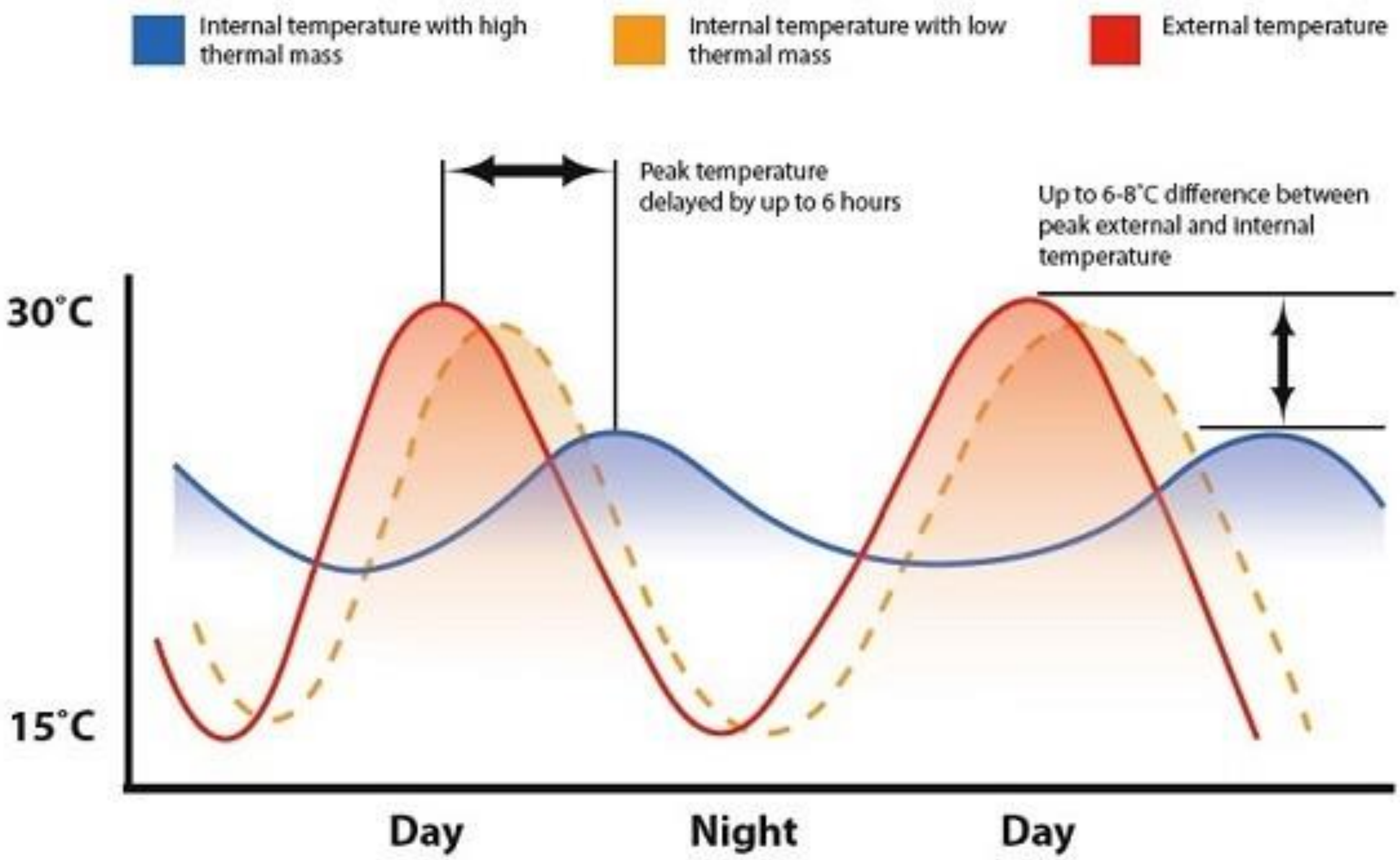


Figure 7: A diagrammatic representation of the behaviour of thermal mass of high and low thermal mass buildings (Niall et al., 2016)

Thermal mass can be defined as the mass of a building or structure multiplied by its specific heat capacity. Formal low-cost houses have a higher thermal mass than shacks. Conversely, thermal diffusivity is the rate at which temperature changes can occur in a material. Thermal diffusivity has a direct influence on the thermal mass of a building, specifically its heat capacity. A high thermal diffusivity would mean that the building could rapidly approach temperature equilibrium with its environment (Niall *et a*l., 2016), which implies that outdoor temperatures would mirror indoor ones. Thermal mass is also a function of thermal inertia which is a measure of responsiveness of a material to variations in temperature. Buildings with a higher thermal mass (Figure 7) have a high thermal inertia (and low thermal diffusivity) and consequently are not highly responsive to ambient variations in temperature (Niall *et al.,* 2016).

Niall *et al.* (2016) also caution against thinking of thermal mass as an "infallible" solution to temperature variation because it is technically difficult to shift the temperature by even a small amount. This very much depends on the specific heat of the wall material (Niall *et al.*, 2016). If the thermal mass gets too high, "*the embodied energy in the mass"* may lead to thermal instability of the material (Niall *et al.*, 2016). Nevertheless, what a high thermal mass provides is a means to slow down the time taken for the inside of a building to reach the peaks reached by the outside.

2.4.2 The regulating effect of ceilings

Most low-cost houses use low quality construction methods and materials; subjecting occupants to potentially adverse living conditions, which may well have a profound effect on their health and well-being. In South Africa, Taylor *et al.* (2000) recognised the importance of ceiling insulation on indoor thermal comfort of residence regardless of construction material. The percentage of people satisfied with the indoor temperature levels in their homes increased more than threefold when ceiling insulation was installed. For this reason, ceiling insulation can be said to change the indoor environment from `uncomfortable' to `comfortable' for the average household in South Africa (Taylor *et al.*, 2000). The majority of low-cost houses in South Africa (Mathews and Weggelaar, 2017) are being, and have been, built without ceilings. Conventional scientific knowledge recognises the importance of ceilings in the built environment. Additionally, ceilings are known to effectively increase the energy efficiency of low-cost housing options.

Howden-Chapman *et al.* (2007) suggested that installing ceiling insulation to existing low-cost housing, will result in more of an improvement to the lives of occupants than can be achieved by changing external factors alone. Houses built during the apartheid era (matchbox) houses) and the more recent but poorly constructed post-apartheid (RDP) houses and shacks are expensive to heat. Installing ceilings seems to offer a more cost effective and practical way of maintaining the thermal environment. Since the colder months are known for increased cases of minor illness, insufficient or inadequate heating can have an effect on the health and wellness of occupants (Boardman, 1991 and Wilkinson *et al.*, 2001). It is well recognised that colder houses are known to place more physiological stress on the elderly, infants and people with pre-existing illnesses (Ormandy and Ezratty, 2012). Paradoxically, this is the group of people likely to spend a majority of their time indoors.

Mathews and Weggelaar (2017) showed that ceilings influence various heat transfer mechanisms, within a home. Namely, providing insulating effect, reducing infiltration of warm air to the room in the warmer months and reducing the loss of warm air from the house in colder months. The ceiling also provides a stratification effect within the home. These factors interact to ensure that the thermal environment inside the house is greatly improved. In a study conducted by Howden-Chapman *et al.* (2007) in New Zealand it was found that when ceilings were installed in low-income residential buildings the frequency of indoor temperatures reaching below 10 °C were reduced by around 30 % and the mean relative humidity decreased by approximately 4 %. This reduced exposure to low temperatures and high humidity resulted in occupants reporting an increased sense of thermal comfort.

2.4.3 Indoor temperatures of low-cost houses in South Africa

Makaka and Meyer (2006), studied indoor temperatures of low-cost houses in the Eastern Cape (South Africa), during warmer months. At these times maximum indoor temperatures of RDPs houses were 34 °C and minimum indoor temperatures were 14 °C. The research showed that RDP houses had a high thermal conductivity, and therefore were highly responsive to changes in ambient temperatures. They additionally performed studies on houses built with fly ash and clay (called FABH), were it was found maximum indoor temperatures were 29 °C and minimum temperatures of 14 °C (during the same period). Which suggests houses built with clay are better at regulating indoor temperatures. A thermal study performed on shacks during warmer days showed that indoor temperatures were often higher than ambient temperatures (Figure 8). The study was performed by UCTs Environmental and Geographical Science Department, they were able to show that shacks, captured and stored large amounts of heat as a result of their corrugated iron structure (UrbanAfrica.Net, 2018). Additionally, they were able to find that maximum indoor temperatures in shacks were able to reach highs of 47.7 °C, when ambient temperatures were just below 37 °C.

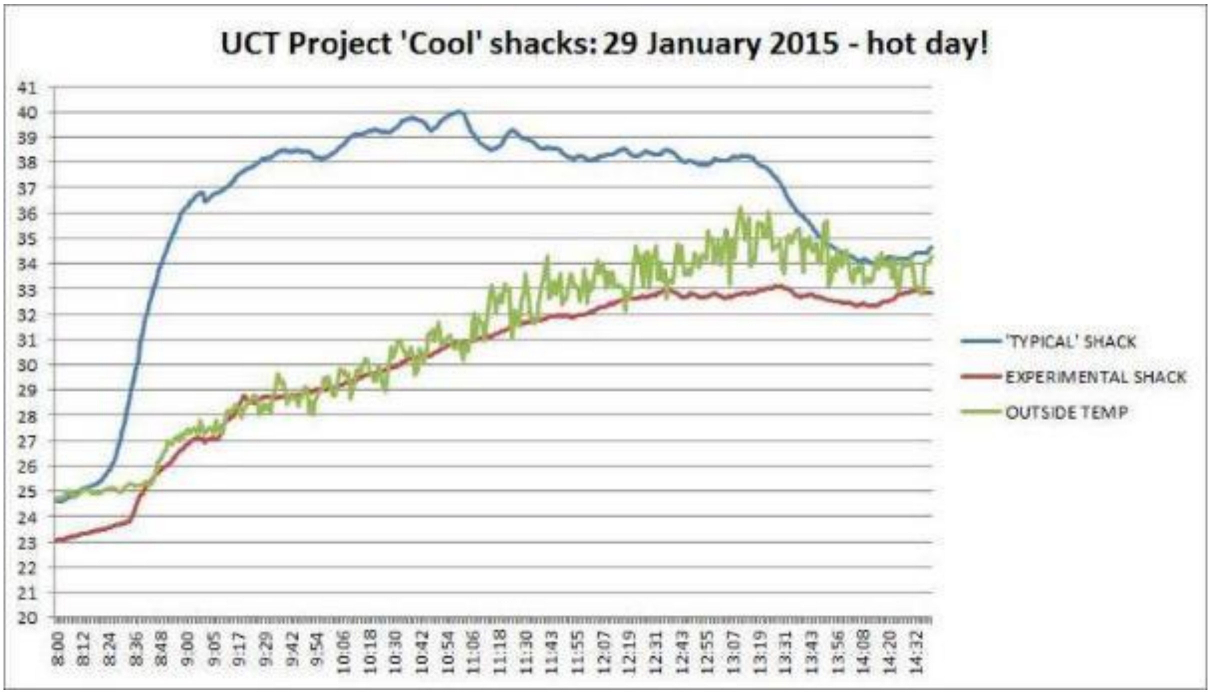


Figure 8 : Graphical representation of a conventional metal shack in blue, "experimental shack" in red, and outdoor temperatures are represented in green. This experiment was performed in a single day from morning (8:00 am) to afternoon (14:30 pm). (UrbanAfrica.Net, 2018)

A recent study by Naicker *et al.* (2017) into indoor temperature is presented below in Table 1, showing the ranges of indoor temperatures experienced in matchbox, RDPs and informal houses. Indoor temperatures across all housing types were significantly higher than ambient temperatures. The ranges of indoor temperatures experienced in informal and RDP houses exceeded those of matchbox houses. These houses experienced a substantial amount of fluctuation, and often their temperatures were between 4 °C -5 °C higher than ambient temperatures (Naicker *et al.*, 2017). RDP houses' indoor temperatures were found to have the strongest relationship with ambient temperatures, and matchbox houses the least. RDP and informal houses were the most similar to each other (when it came to indoor temperature). Temperatures inside the houses reached maximums of 45 °C, 39 °C and 33 °C in informal, RDP and matchbox houses, respectively. According to Makaka and Meyer (2006) for indoor temperatures to be considered comfortable for South African standards they should be between 18 and 25 °C.

Table 1: Mean (standard deviation) and range in monthly indoor and ambient temperatures (°C) (adapted from Naicker *et al.* (2017)

	February		*March*		*April*		*May*	
Month	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**
Ambient	20.2 (0.7)	14.1-28.5	18.3 (1.4)	11.4-26.2	15.6 (1.7)	2.5-25.3	15.9 (2.3)	4.7-25.7
RDP (Braamfisherville) (n=15)	25.7 (4.2)	16.2-39.0	22.5 (3.7)	14.7-36.6	20.1 (4.5)	6.6-33.1	19.6 (4.7)	6.7-33.1
Old pre-1994 low cost housing (Riverlea) (n=13)	25.1 (2.2)	19.3-33.3	22.6 (2.2)	17.5-31.6	20.3 (2.8)	11.7-29.2	19.6 (3.1)	10.9-28.5
Informal settlement (Hospital Hill) (n-=8)	23.6 (4.3)	15.0-45.4	21.3 (3.9)	12.8-40.2	19.3 (4.8)	6.1-39.4	19.2 (5.2)	6.6-37.5

Naicker *et al.*, (2017) also noted that mean T_{min} happened at around 6 am and mean T_{max} happened at approximately 2 pm daily. Informal houses had high daily indoor temperature fluctuations, similar to those of RDPs (approximately 10 °C). However, matchbox houses had relatively lower temperature fluctuations (approximately 5 °C). They suggested the lack of ceilings and poor ventilation (and insulation) was the reason for the high recorded fluctuation (Naicker *et al.*, 2017).

2.5 Construction of low-cost houses in South Africa

A brief history of low-cost housing in South Africa

From the early 1950s to about 1994, which falls well within the apartheid era, there have been three general housing delivery waves (Pottie, 2003).

1. During the apartheid era, community participation was limited and state sponsored low-cost houses were delivered to poor communities. Recognised contractors (by the state) were used, and houses were provided to vulnerable, mostly black and coloured people. This period lasted about twenty years.

2. In the latter part of the 1970s what Saul and Gelb (1986) describe as the "h*igh apartheid or organic crisis*" model was beginning to disintegrate. The disintegration of this model could be seen clearly in the late 1980s wherein legislation on influx control began relaxing. Migration increased, mostly by black peoples, to the cities, which were predominantly white areas. The government introduced a number of state funded and controlled development agencies to provide housing for the urban black population within the townships
3. Finally, by the early 1990s, the same contractors were being used by the state, and stringent apartheid legislation had been all but been abolished. This marked the advent of widespread informal settlements, as a result of the relaxation of "movement and settlement laws". As social discourse in the country (at the time) reached its peak, an accompanying housing delivery backlog followed. As the need for housing grew more pronounced so too did the erection of backyard shacks, in the same yards as the formally established government funded low-cost houses.

From 1994 onwards marked the beginning of a new regime, spearheaded by the ANC government. The White Paper on Housing written in 1994 (Department of Housing, 1994) informed the new government's policies on housing. The consensus was that the apartheid housing system was unsustainable and caused large scale housing backlogs (Huchzermeyer, 2001). This laid the ground work for a new, more inclusive system of free trade, where tenders would be made, and the government would release funds for new low-cost housing developments to successful contractors.

2.5.1 Formal low-cost housing

2.5.1.1. Apartheid era housing

During the apartheid era from about 1948 to 1985, the government-built brick houses that have come to be colloquially known as matchbox houses. These houses were made with corrugated iron (or asbestos) roofs, clay or stock brick walls, concrete floors (Lombard et al, 1999), and had three to four windows. The houses were generally no less than 40 m^2 and no more than about 50 m^2, with two to three bedrooms. According the Soweto Research Project (Soweto.co.za, 2003) the houses were poorly made and placed in close proximity to each other. This close proximity influenced each houses' micro-climatic conditions. The claim that the houses were poorly made during this entire period is refuted by Lombard *et al.* (1999) and

Hendler (1985), who claim that from the late 1970s the then apartheid state provided adequate capital for building "black" matchbox houses in townships for approximately R215 million (South African Institute of Race Relations: SAIRR, 1984). Nevertheless, The Soweto Research Project (Soweto.co.za, 2003) did however find that the bricks used to construct formal low-cost houses were of a low grade (stock or clay bricks). What Lombard *et al.*'s (1999) findings did not refute, however, was the assertion that the insulation offered by these houses was insufficient when compared to formal suburban houses. Low insulation means that ambient temperatures have a greater influence on indoor temperatures of the building (Odeku *et al.*, 2014).

2.5.1.2. Post-apartheid era housing

The present-day South African government is responsible for the procurement of low-cost housing. It is in the government's best interests to use the services of those construction companies that maintain good quality, whilst offering competitive pricing. Quality is a very critical aspect in construction. In order for there to be quality, defects need to be eliminated, and time, money and materials need to be used accordingly (Love *et al.*, 2005; Maoto and Worku, 2018). The quality of low-cost housing directly impacts South African communities. Maoto and Worku (2018) state that construction workers in this country and the construction industry at large, places emphasis on time taken per project and amount of work done, and very little on the quality of work performed. This then reflects poorly on the building itself often resulting in badly built, thermally inadequate houses. Hollard *et al*. (1992) suggest a myriad of reasons for this lack of quality, most of which can be grouped into two general areas; namely failures in construction and failures in design.

Construction research (Page and Murray, 1996; Maoto and Worku, 2018) commonly use finding by Cook and Hinks (1992) to explain structural shortfalls of buildings, the shortfalls are attributed to: use of subpar construction materials, inadequate design, unregulated supervision, subpar workmanship, unanticipated environmental conditions, and insufficient maintenance and finally little to no soil investigation. The widespread use of subpar construction materials has been a major focus in low cost housing (Maoto and Worku, 2018), with several government funded construction companies failing to comply with building standards intended to reduce the prevalence of poor-quality housing.

According to the Building Research Establishment (BRE, 1974) half the building structural issues are as a result of inadequate design, 35% can be attributed to substandard construction, and 12 % are due to subpar construction materials. Interestingly, only the remaining 11% of structural issues are attributable to the tenants themselves. It is evident that in post-apartheid South Africa construction of low cost houses has been met with a variety of issues. These are noted by Dlodlo (2011) pointing out that incompetency is a major challenge, with several projects being led by construction companies with little to no input by architects. There is a skills mismatch with regards to design (which accounts for half of reported structural issues) of low-cost housing which will result in several structural issues. Governder *et al*. (2011) found that low-cost houses in Cape Town constructed of cement bricks, were un-plastered and un-partitioned (unless the owners made their own arrangements for partitioning).

Post-1994 modern low-cost houses that were being built under the reconstruction development program (RDP), used cement blocks (wall thickness of about 150 mm) and had a thermal conductivity of about 0.8 W/mK (Watts per meter-Kelvin), higher than the maximum recommended value of 0.69 W/mK. (Makaka and Meyer, 2006). The houses commonly had concrete flooring about 80 mm in thickness (Makaka and Meyer, 2006).

2.5.1.3. Informal housing in South Africa

The idea of "slums" or informal dwellings has long been envisaged as long stretches of shack dwellings, arranged in an irregular pattern, with limited access to resources, at the outskirts of larger cities (Lemanski, 2009). While this may very well be true, in the case of South African urban townships, backyard shacks make up a large portion of informal housing. As such backyard dwellings, have become a distinctive feature in South Africa.

Backyard shacks are informal houses (shacks) built on the premises of more formal housing (Crankshaw *et al.*, 2000). Because these shacks (often clustered together) are within residential areas, they are not as visible as those found in informal settlements, and as a consequence they are quite often overlooked when it comes to policy. Living standards in backyard shacks are commonly far better than those in primarily informal settlements. For the reason that backyard shacks quite often have access to provisions afforded to the "main house", such as water, sanitation as well as electricity in exchange for a monthly rental fee (Lemanski, 2009). Lemanski (2009) states "*South Africa's formal housing policies have indirectly* *encouraged backyard housing and thereby have augmented informality in South African cities*". The author states that failure of the housing policy and money making (by the landlords) were some of the reasons for the escalation of backyard shacks.

Assessing the quality of this type of accommodation is difficult, as there are no specified regulations and therefore no quality standard to adhere to. Nevertheless, the quality of backyard shacks is very diverse. Materials used are similar namely galvanized iron (corrugated or otherwise) and wood (to form the structure) (Crankshaw *et al.*, 2000). Most backyard shacks are one room (Lemanski, 2009), because these homes are mainly built by the owners, with little to no construction experience the quality is often poor. Inequalities in materials used to build these houses is also evident (Crankshaw *et al*., 2000) with some homes being built with discarded metal sheets and others being purchased. These inequalities generally express themselves in the quality of the finished product.

2.6 Perception of housing and common thermal adaptation strategies

2.6.1 Behavioural adaptation

One of the first studies (in humid regions) that was interested in how behavioural adaptations influenced people was done by Humphreys (1975). He was able to show that if tenant's changed their clothing, limited their activity levels they were able to remain relatively thermally comfortable. Humans adapt by changing behaviours which may also lead to physiological changes. An example of these behavioural changes, was demonstrated by Pakistani office workers; as their clothing and posture changed (to maximize sweating) so did their perception of thermal comfort (Nicol and Raja, 1996).

It is evident that adapting to the environment plays a role in maintaining thermal comfort, however, behavioural adaptations which include how one directly manipulates ones environment are also important (de Dear and Brager, 1998). Baker and Standeven (1996) showed that by changing the position of their furniture, and by manually operating doors and windows occupants were able to change their thermal environments. Earlier work by Benton and Brager (1994) supported these conclusions, they found that people generally did not attribute their thermal comfort to active behavioural modifications such as opening windows and doors, turning on heaters but when those activities were performed thermal comfort improved significantly.

2.6.2 Psychological adaptation

A person's mental state plays a role in their experience of thermal comfort. de Dear and Brager (1998) define psychological adaptation as an "*altered perception of or response to the thermal environment*". This alteration in perception is mainly attributable to a person's previous thermal experiences and their expectations. Paciuk (1990) was able to provide empirical evidence of the differences between adaptive opportunity, adaptive behavioural control and expectation of thermal environment. It was determined that how one perceived their relative control on their thermal environment had a direct correlation to how satisfied they felt within that thermal environment. These findings were validated by Williams (1997); de Dear and Brager (1998) went on to state that "*perception control*" is a variable influenced by many inputs namely; the building itself, the presence of heating and cooling instruments and also the number of people occupying a space. They quoted work by Leaman and Bordass (1993) who by using standardized questionnaires demonstrated that tenants had a negative relationship with their perceived thermal control as the number of people in a building increased; with increasing numbers of occupants, each occupant felt they had reduced amount of control over their environment, which then reduced the satisfaction they felt within the environment.

Chapter 3: Research methods and materials

Introduction

This chapter presents the research methods and materials used in this study. The study was designed to determine (as well as compare and contrast) the ambient temperatures of the areas that were studied. And to investigate the indoor thermal conditions of low-cost houses, being inhabited by the most vulnerable members of society. In order to research this, four key interacting aspects where identified; namely: what were the long-term temperature trends of the Kathorus (Katlegong and Thokoza) and Wakkerstroom (eSizameleni) areas?; what were the recorded ambient and indoor temperatures (of the houses) over the course of a year (during the warmer and colder months)?; and, what materials were used to construct these low-cost housing types? Answers to these questions gave some indication to how well the houses performed as a source of shelter for dwellers. However, these findings only provided a partial account of housing satisfaction. As such the fourth aspect, was included namely; what are occupant's perceptions about their thermal comfort? Allowed for a crosswise comparison between recorded housing temperature and perceived household comfort.

3.1 Study design

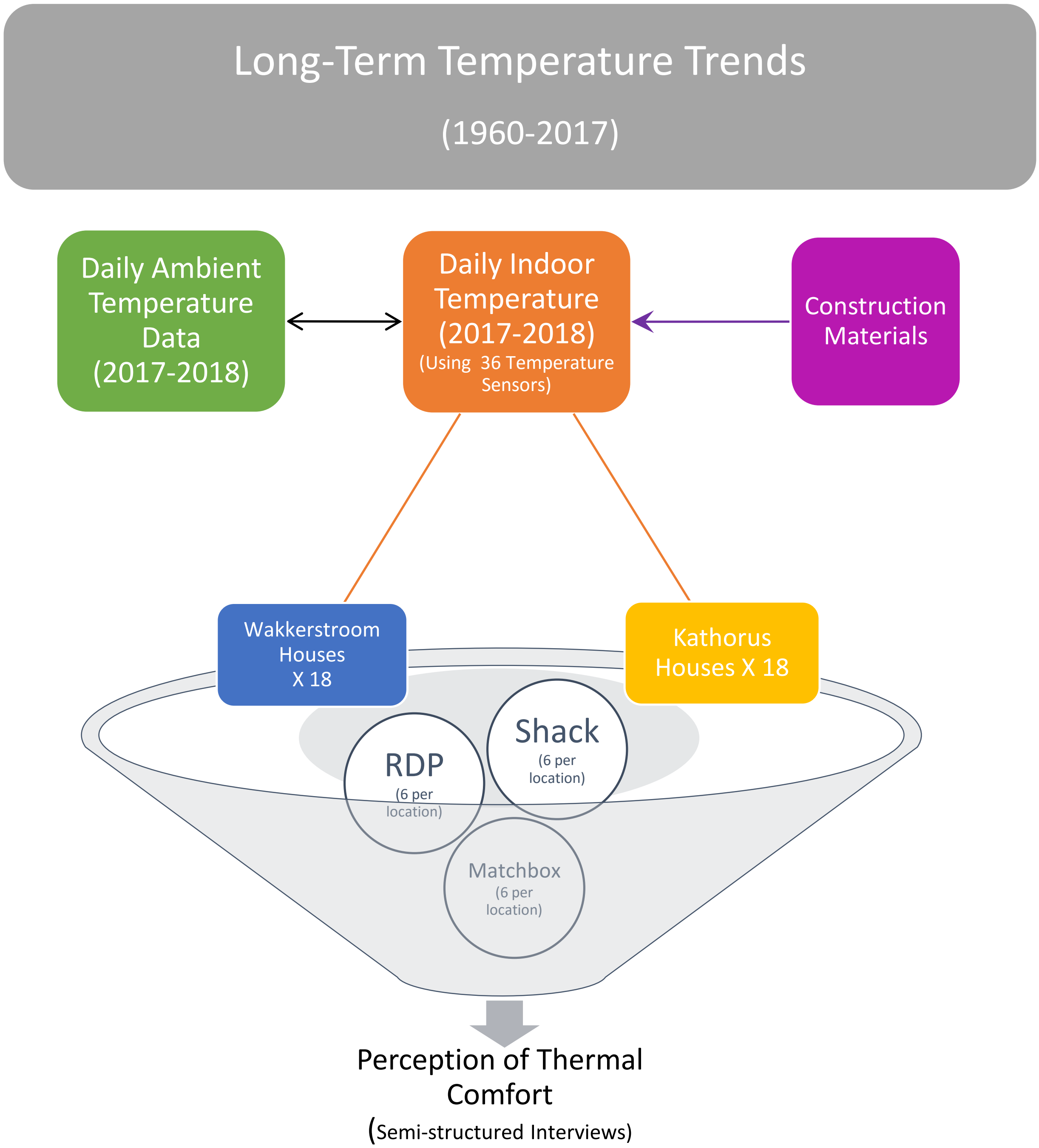


Figure 9: Diagrammatic representation of the study design

Historical temperature data were sourced from South African Weather Services SAWS (SAWS), in order to understand long-term temperature trends of the two areas. Three low-cost housing types were installed with temperature (sensors) data loggers, namely; apartheid era "matchbox" houses, RDP houses and shacks. These houses were located in the Kathorus and Wakkerstroom areas. A total of thirty-six data loggers were installed, but by the end of the study 28 data loggers were retrieved. In both the Kathorus and Wakkerstroom areas, 18 data loggers were installed, 6 data loggers in each housing type. These areas were selected because of their micro-climatic differences, Wakkerstroom is characterised by very low temperatures during the colder months, whereas the Kathorus area is characterized by warmer temperatures in the winter months. The temperature data loggers were placed in a common area in the house, away from any external heat sources, including direct sunlight. The data loggers were placed on top of a cupboard, so that they were in a place that wouldn't disturb the occupants. These houses were chosen because they are the primary residences of low-income South Africans. Shacks are self-built informal houses. RDPs and matchbox houses are state funded houses provided to low-income families, the latter built between 1960 and 1989 during the apartheid system in South Africa, the former built between 1994 to date during the post-apartheid system. Semi-structured questionnaires were used to determine the occupant's perception of their thermal comfort.

3.2 Study sites

This study spanned an entire year (June 2017 to July 2018), and was conducted in two separate areas within South Africa, characterised by their differing climatic conditions during comparable periods of time. The two areas chosen for the study have the same (or similar) three types of housing. The Kathorus region was chosen because it is characterized as an urban settlement, has a relatively large population (relative to its size), and has relatively warmer winter months. Wakkerstroom (eSizameleni) was chosen because of its small population (relative to its size), it is characterized as rural, and the area is known for having cold winter months.

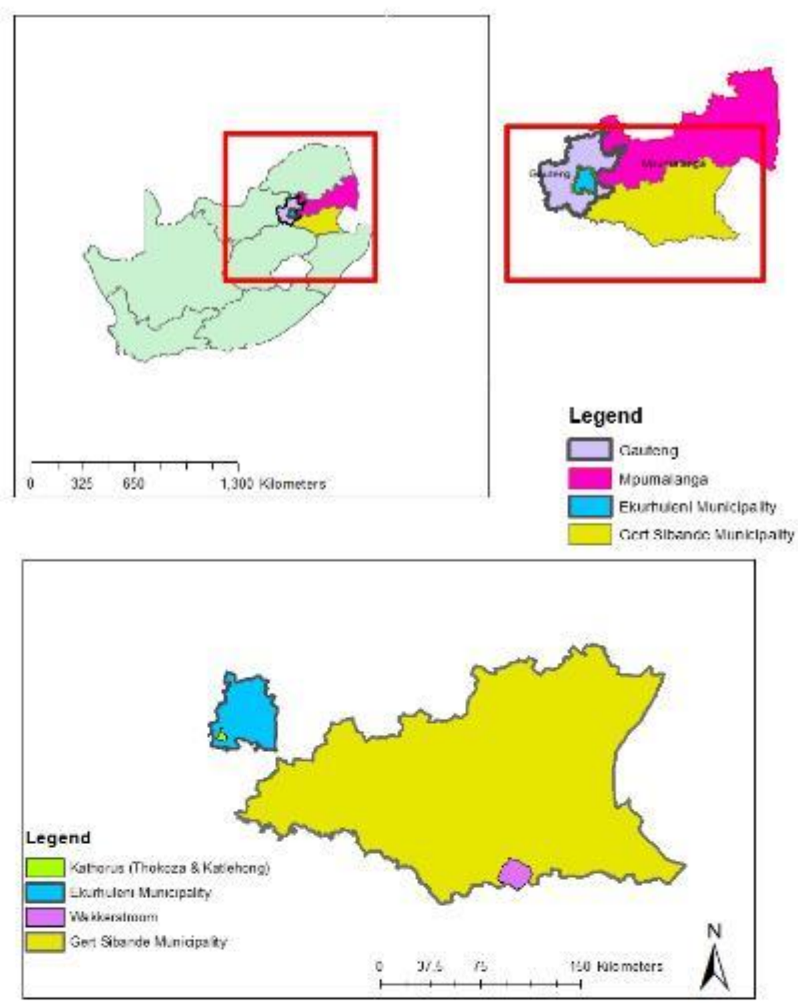


Figure 10: Study sites located within the boundaries of (1) Gauteng where Kathorus (lime-green) is situated in the Ekurhuleni municipality; and (2) Mpumalanga where Wakkerstroom (purple) is situated in the Gert Sibande municipality

3.2.1 Kathorus

The first study site is located within Gauteng, a province whose name literally translates to "place of gold". Gauteng is physically the smallest province accounting for only 1.5 % of the total land area in South Africa, whilst on the other hand being the most densely populated (having about 14 million inhabitants) making up approximately 25.3 % of South Africa's population. The province is in the Highveld (having an altitude of between 1500-2100 metres above sea level (masl)). It is characterised as being highly urban, housing the largest city, Johannesburg. Gauteng accounts for approximately 34 % of the country's GDP (Gross Domestic Product) and has been the fastest growing economy in the country (Statssa.gov.za, 2017). All this wealth is in stark contrast to areas like Katlehong, Thokoza and Vosloorus (collectively named, Kathorus) which are also found in Gauteng. Kathorus is characterised by having high unemployment rates even though it is surrounded by industrial areas. Low-cost housing options (RDPs, shacks and matchbox houses) are a norm, housing more than 60 % of the Kathorus population (Turok and Borel-Saladin, 2016).

This collective group of townships are located east of Johannesburg (Gauteng) in the Ekurhuleni Metropolitan Municipality. The study will be specifically looking at the communities of Thokoza and Katlehong (with a combined area of 64.79 km^2 and population of nearly 60 thousand). Interestingly, even though the South African government's main objective for implementing low-cost housing policies was to encourage and facilitate "home ownership" it has inadvertently increased the popularity of backyard shacks (Lemanski, 2009), this is particularly true for the Kathorus area. All of the shacks sampled were located in backyards of RDP and matchbox houses.

3.2.2 Wakkerstroom (eSizameleni)

The second study site is located in the second-smallest province, Mpumalanga, located north-easterly covering an area of 76 495 km^2 with a population of about 4.3 million, it is the 6th most populated province and accounts for about 7.9 % of the country's population. Mpumalanga is loosely translated as "the place of the rising sun", which is paradoxical to the low winter temperatures experienced in Wakkerstroom. It is divided by the Drakensberg escarpment into the Highveld (westerly) and the Lowveld (easterly). This study location is situated in the Highveld.

The province is well-known for its coal mining, approximately 83% of the total coal (in tonnes) produced in the country is mined in Mpumalanga (Dabrowski *et al.*, 2008). Additionally, the province is internationally recognized as being home to the scenic Kruger National Park, a major tourism destination. Mpumalanga accounts for only about 7% of the GDP of the country, having a relatively large portion of so-called "homeland" areas (49%).

This study took place in Wakkerstroom, specifically in a township known as eSizameleni, literally translating to "assist us". The Wakkerstroom township, mostly had low cost housing options, with an overwhelming majority of township dwellers reliant on those housing types. Wakkerstroom is a sleepy settlement overlooked by the Ossewakop Mountain. This Highveld wetland region is home to about 7 thousand residents, covering an area of about 87.68 km^2.

3.3 Data Analysis

3.3.1 Long term trends in monthly minimum, maximum and mean temperatures

It's well established that South Africa has been plagued with incomplete or sometimes even completely missing temperature data records; consequently, the issue of processing data with missing values is an important one. Many methods have been used to solve this problem (Joly *et al*., 2011) with some being more accurate than others. The methods used are for the most part dependent on the percentage of missing data (for a given weather station), and on the type of investigation being performed. For the purpose of this study data were sourced from the South African Weather Services (SAWS) where the weather stations selected were within 25 km's of the study sites. Monthly average temperature data (maximum and minimum) for the Kathorus, were sourced from SAWS from 1960 to 2017. To supplement for missing data, which accounted for approximately 2% of the long-term data record in Wakkerstroom, additional data were sourced from "The Wakkerstroom Bird Club". The Wakkerstroom Bird Club use private weather stations in order to record temperature readings. These data were used to avoid or minimise issues associated with interpolation methods that over or under estimated the likelihood of extreme events (Di Piazza *et al*., 2011), which is a known pitfall when making inferences based on incomplete datasets. Mean monthly temperature minimums (T_{min}) and maximums (T_{max}) were sourced from SAWS and Wakkerstroom Bird Club to construct a long-term temperature time series record from 1960 to 2017.

3.3.1. 1. Kathorus and Wakkerstroom long term temperature record

For the Kathorus areas, the long-term temperature data were sourced from Jan Smuts-WK weather station: 0476398A3 with the GPS coordinates -26.1330: 28.2330 and an altitude of 1694 masl. In mid-1989 this weather station was replaced with Johannesburg INT WO station number: 0476399 0, coordinates -26.430: 28.234 and an altitude of 1695 masl. The Jan Smuts and later the Johannesburg INT weather stations had a complete temperature record from 1960 to 2017.

Wakkerstoom temperature data were sourced from Volkrust weather station, station number: 0406682B0 with the coordinates Longitudinal:-27.3700 Latitudinal 29.8800, at 1652 masl altitude. The Wakkerstroom area had a complete temperature record from the years 1960 to 2015. The 2015-2017 temperature were sourced from private sources such as the Wakkerstroom Bird Club. Mappin*g* of the study sites was done using ArcGIS maps.

3.3.1. 2. Analysing long term temperature trends

The temperature records from both Kathorus and Wakkerstroom were analysed with the intention of identifying any significant long-term trends, using XLStat (2017) and Rstudio (2015).A Students paired T-test was performed to determine statistical differences (generating a p-value) in historical temperature maximums (T_{max}), minimum (T_{min}), of the Kathorus and Wakkestroom areas. These monthly averages were used in order to construct a seasonal (warmer and colder months) time-series, for Kathorus and Wakkerstroom (1960-2017).

3.3.2 Time-series generation and analysis

Many statistical tests are used to analyse trends, such as but not limited to, Spearman's rank correlation coefficient and Cramer’s test. For the purpose of this study a Mann Kendell trend test was used. The Mann Kendell test is largely considered to be the most effective in detecting climatic changes in a time-series, by determining the significance of the trend. The test and subsequent graphing of the two locations was done using XLStat (2017)

A simple liner regression was used to determine the changes in temperature overtime (with a 95% confidence level). The time series were done to compare the changes in temperature for warmer and colder months, in both areas. The line drawn represents the estimated slope of regression and the coefficient of determination (R^2). The line is represented by the equation: $y =$

$mx - c$ .Where m is the rate of increase of temperature per year. This does imply a linear increase which could be a limitation of the analysis.

3.3.2. 1. Defining warmer and colder months

For the purpose of this study, warmer and colder months were determined by comparing the mean temperature of each location. And a repeated measures ANOVA and Tukey's test of independence were used to determine which temperatures where more related to each other. The three (December, January and February) highest monthly temperatures (which were found to be similar in means) were then determined to be the warmer months. The two (June and July) lowest monthly temperatures where then determined to be the colder temperatures.

3.4 Daily and hourly temperature maximum and minimums

The daily T_{min} , T_{max} and hourly temperatures for Kathorus were sourced from SAWS for July 2017 to July 2018. These data records were used in order to determine the relationship between housing type and ambient temperature. Daily temperature data for Wakkerstroom were not possible to obtain from the Volkrust station, as such daily temperature maximums and minimums were retrieved from the Wakkerstroom Bird Club and an algorithm was used in order to infer hourly temperatures. The CIBSE method (1982) was used. This method was chosen because of its relative simplicity (as it required no previous experience with temperature interpolation methods). Additionally, the model is well recognized and respected (Chow and Levermore, 2007). The method used the same basic premises as the ASHRAE method (1993), which tactically allocates timeframes in which T_{max} and T_{min} happen daily.

Table 2: Presents the proposed times for Tmax and Tmin (CIBSE Guide, 1982), where tmax is the time of day temperatures are at their peak, and tmin is when they are at their lowest point.

Calendar Month	TMAX time (tmax)	TMIN time (tmin)
January	**14 h 00**	**6 h 00**
February	**14 h 00**	**6 h 00**
March	**14 h 00**	**5 h 00**
April	**15 h 00**	**5 h 00**
May	**15 h 00**	**4 h 00**
June	**16 h 00**	**4 h 00**
July	**15 h 00**	**4 h 00**
August	**15 h 00**	**5 h 00**
September	**15 h 00**	**5 h 00**
October	**14 h 00**	**6 h 00**
November	**14 h 00**	**6 h 00**
December	**14 h 00**	**7 h 00**

3.4.1 CIBSE method (1982)

This method allocates dualistic sinusoidal curves for data fitting. In order to determine hourly temperatures, T (t) (which is the temperature per time); is calculated by using the Equation (1): $T(t)=f_1*T_{min} + f_2*T_{max}$

- f_1 and f_2 are the standard factors given in a table guide provided in CIBSE method (1982).
- T_{min} and $T_{max;}$ are the daily temperature maximum and minimums respectively.

Since only the T_{max} and T_{min} values were available. The times of day in which maximum (tmax) and minimum (tmin) temperatures occurred (Table 2) were used to determine hourly temperature values.

The equation for calculating hourly temperature is given by:

$$T(t) = \left(\frac{Temp_{(next)} + \ Temp_{(prev)}}{2}\right) - \left[\left(\frac{Temp_{(next)} - Temp_{(prev)}}{2}\right) \times \cos(\frac{\pi(t - t_{(prev)})}{(t_{(next)} - t_{(prev)})}\right]$$

The times in the equations are represented in hours from 1h 00 to 24h 00. Where the $Temp_{(next)}$ is the next known temperature value, where either T_{max} or T_{min} values can be substituted. The $Temp_{(prev)}$ is the previous known temperature value, and it too can either be substituted with T_{max} or T_{min} values. Substitution is based on if the time of interest occurred before or after T_{max} or T_{min}. Furthermore, $t_{(next)}$ is the time the next known temperature (T_{max} or T_{min}) value occurred; $t_{(prev)}$ is the time where the previous known temperature (T_{max} or T_{min}) value occurred. For these ($t_{(next)}$ and $t_{(prev)}$) suggested times for either T_{max} or T_{min} are given in Table 2. The *t* represents the time of interest.

A more detailed explanation of the method is given in the CIBSE Guide A2 (1982).

3.5 Household temperature readings

The household temperature readings were collected for a period of a year, this covers the warmer and colder months. These readings were collected using temperature data loggers, namely: iButtons, which are enclosed in a plastic case in order to prevent moisture from entering. The data loggers were sourced from Fair Bridge technologies, as per the manufacturer’s specifications.

The data loggers were launched on the 29th of June 2017 (at 12 am) by inserting the iButtons into the data port which is connected to a USB cable, the cable is then connected to the USB port of the computer. A software program provided by the manufacturer was then used to extract the readings from the data loggers. Logging intervals were set to every three hours, as this was the maximum time for recording. When analysing the temperature, a six hour time interval was used, as these times corresponded to when ambient temperatures were at their highest and lowest points. The iButton data loggers contain an internal clock that syncs with the computer clock, thereby ensuring accurate readings. It is important to note that the data loggers can only log about 2000 readings before they expire. As such a second set of replacement data loggers had to be used; recording starting from the 9th of March 2018 (12 am).

In order to aid in the identification of different data loggers in the two study locations keys were used to name each data logger, for example, Wakkerstroom House 1: WH1 and Kathorus House 1: KH1. Thereafter the loggers were disconnected from the computer and placed in the field for a period of a year including the “replacement” data loggers. The same data logging software provided by Cold Chain thermodynamics was downloaded onto a portable laptop and results were collected first at the end of August 2017, then at the end of March 2018 and finally Mid July 2018.

3.5.1 Modeling of household temperature readings

Seasonal averages of each housing type's temperatures were used and then the data were combined to get an average per housing type for each area. Standard deviation's (SD) were used to determine the deviation from the mean temperature (at specified times) for each house, large deviations indicated larger variations in temperatures experienced by each housing type at the specified times.

A repeated measures ANOVA and pair-wise comparison was calculated in order to check between housing types, using the XLStat (2017).

3.5.2 Household temperature as a function of ambient temperature

A Pearson's coefficient (*r*) was used in order to calculate the strength of the relationship or apparent association between indoor household temperatures and the ambient temperatures. This relationship was then quantified using a simple linear regression with a confidence interval of 95%.

3.6 Constituents of housing material

Accessing information from the Department of Housing and Human Settlements on building materials used to construct low-cost government funded housing; in both the city of Ekurhuleni metropolitan municipality and the Pixley Ka Seme local municipality (situated in the Gert Sibande district municipality) proved difficult. However, an expert on housing from the municipality in the city of Ekurhuleni was consulted in order to provide information on housing material used in the construction of both old and new government funded houses. Information on informal housing (shacks) was provided by the dwellers and was supplemented by observations made by the researcher. Information such as wall (type of brick), floor and ceiling material was obtained from the municipal expert and the respondents. Additional expert validation of the information was provided by Professor David Root, specializing in Construction Economics and Management at the University of Witwatersrand.

3.6.1 Photographs of three housing types in the Kathorus and Wakkerstroom

3.6.1.1. Kathorus (Katlehong and Thokoza)

Figure 11 : A typical apartheid era matchbox house constructed in the early 1960s.

In the Kathorus area, matchbox houses were archetypically constructed with four rooms (two bedrooms, one kitchen and one living room). The houses were built with clay bricks (clays made mostly from kaolinite and chlorite, along with illite, quartz, resulting in a densely compacted product) and had asbestos or corrugated iron roofing. The houses generally had between one to six occupants, with a mean of two occupants. Typical apartheid era houses had no internal sanitation facilities, but instead had separate standalone sanitation facilities behind the home.

Figure 12: A distinctive RDP house in the Kathorus area, built in the mid- to- late 90s.

The houses were typically made from maxi bricks (with the dimensions 200 mm x 140 mm x 90 mm) made from cement, river sand and ash). These bricks were used on the external and internal walls. The house typically had four rooms and access to water and electricity. There were no internal sanitation facilities, they were commonly situated in a separate structure outside of the main building. The roofs were all made from asbestos. The houses had between two to 5 occupants.

Figure 13: A typical backyard informal house (shack) in the Kathorus area.

The shacks in the Kathorus were generally built in close proximity to each other. The houses were stereotypically made from iron sheets (corrugated or otherwise), cardboard and steel frames. The houses typically had one to two rooms. The homes had a range of one to three residents (mean of 2). Shack residents often shared sanitation facilities with the main house.

3.6.1.2. Wakkerstroom (*eSizameleni)*

Figure 14: Two sub-types of apartheid era (matchbox) houses found in Wakkerstroom

There were two sub-types of apartheid era (matchbox) houses in eSizameleni (Figure 14), one was partitioned in two, in order to allow for two families to live in “one home”. The other sub-type was the standalone house. The houses were made mostly with low grade clay bricks (similar clays to Kathorus), with corrugated or asbestos roofing material. There were between three and eight residents with a mean number of 5 occupants. The house consisted of two bedrooms, one kitchen and a living room. Sanitation facilities were commonly located outside the main house, in a standalone structure.

Figure 15: Typical RDP houses in Wakkerstroom; the houses on top were constructed in late 90's to early 2000s, and the house at the bottom is an example of earlier (1994) RDP constructions.

These low-cost houses (Figure 15) were typically made from maxi brick (200 mm x 140 mm x 90 mm) on the external and internal walls, with corrugated or asbestos roofing. The houses were typically four rooms (2 bedrooms, one kitchen and a living room). Most houses had access to water and electricity. There were between two to nine residents per house, with a mean number of 5. Sanitation facilities were commonly located outside the main house, in a standalone structure.

Figure 16: On the left is a typical shack in the Wakkerstroom. On the right the informal house was deconstructed shortly after the temperature monitoring device was installed.

Informal housing (shacks) in this area was typically found in enclosed yards, as a temporary solution (to housing) while the owners constructed traditional mud houses. These shacks were typically made from a mixture of materials including corrugated galvanized iron sheets, wood and cardboard cladding. The houses normally comprised of one large room, and at most one room partitioned in three. Most houses had no access to electricity or sanitation. The number of shack occupants in Wakkerstroom were between one and four, with a mean of two dwellers.

The houses were grouped according to area and housing type. Features such as number of doors, windows, floor material as well as presences or absence of ceilings were observed. In order to measure the effect of ancillary housing features such as ceilings, a regression model between mean indoor temperature and outdoor temperature was performed. Wakkerstoom was the only area with enough houses that had ceilings to compare their effect on indoor temperature.

3.7 Household thermal comfort interviews

Interviews present a great opportunity to collect more detailed and nuanced sets of qualitative data, allowing for participants' experiences and perspectives to be fully expressed and engaged. For this reason, a semi-structured interview approach was used, where 20 closed and open-ended questions were asked allowing for unprompted responses. See a copy of the questionnaire in Appendix 1. It must also be mentioned that interviews present their own unique set of challenges, by creating artificial conditions there is a chance that participants could offer disingenuous responses (for this reason responses where compared to temperature readings). The semi-structured interviews were divided into warmer and colder months. Community buy-in is an essential aspect to conducting household interviews because Kathorus and eSizameleni (Wakkerstroom) are for the most part Zulu Speaking areas, the interviews were predominately conducted in isiZulu, furthermore being acquainted with or travelling with someone who is acquainted with the community, aided in gaining community buy-in.

3.8 Thermal comfort investigation

The investigation into thermal comfort was divided into two parts: (i.) household temperature readings and (ii.) guided semi-structured interviews.

The study was initiated on the 29th of June 2017, corresponding to the colder months in South Africa. It was terminated a complete year after inception on the 20th of July 2018, also during the colder months. A sample of thirty-six households were used, where at least one member of the household was above the age of 18. Either written or verbal consent was given to participate in the study. Participation included consenting to answering interview questions as well as having the temperature data logging sensors placed in their homes.

A total of 129 individuals occupied the houses of interest, eSizameleni (in Wakkerstroom) having a 62% share of the occupants and Kathorus having the remaining 38%. The temperature data loggers were placed in the houses “living area” away from direct sunlight, windows or external heat source. The data loggers had the capability of recording temperatures from -20 °C to +85 °C, at an accuracy of about 0.5 °C.

Chapter 4: Results

Introduction

The results chapter will be arranged as follows: at the outset, the long-term temperature trends will be presented; followed by an indoor temperature analysis (across and between housing types as well as across locations); subsequently, the housing materials as well as their thermal properties will be presented and lastly, the semi-structured interview questions will be placed in context.

4.1 Long term temperature time series analysis

4.1.1 Comparison of long-term temperature trends of the Kathorus and Wakkerstroom areas

Contrasting and comparing warmer and colder indices is a useful way to understand the relative annual changes in temperatures of a given area. A comparison of long-term (1960-2017) temperature maximum and minimum (T_{max} and T_{min}, respectively) was made in the Kathorus and Wakkerstroom areas.

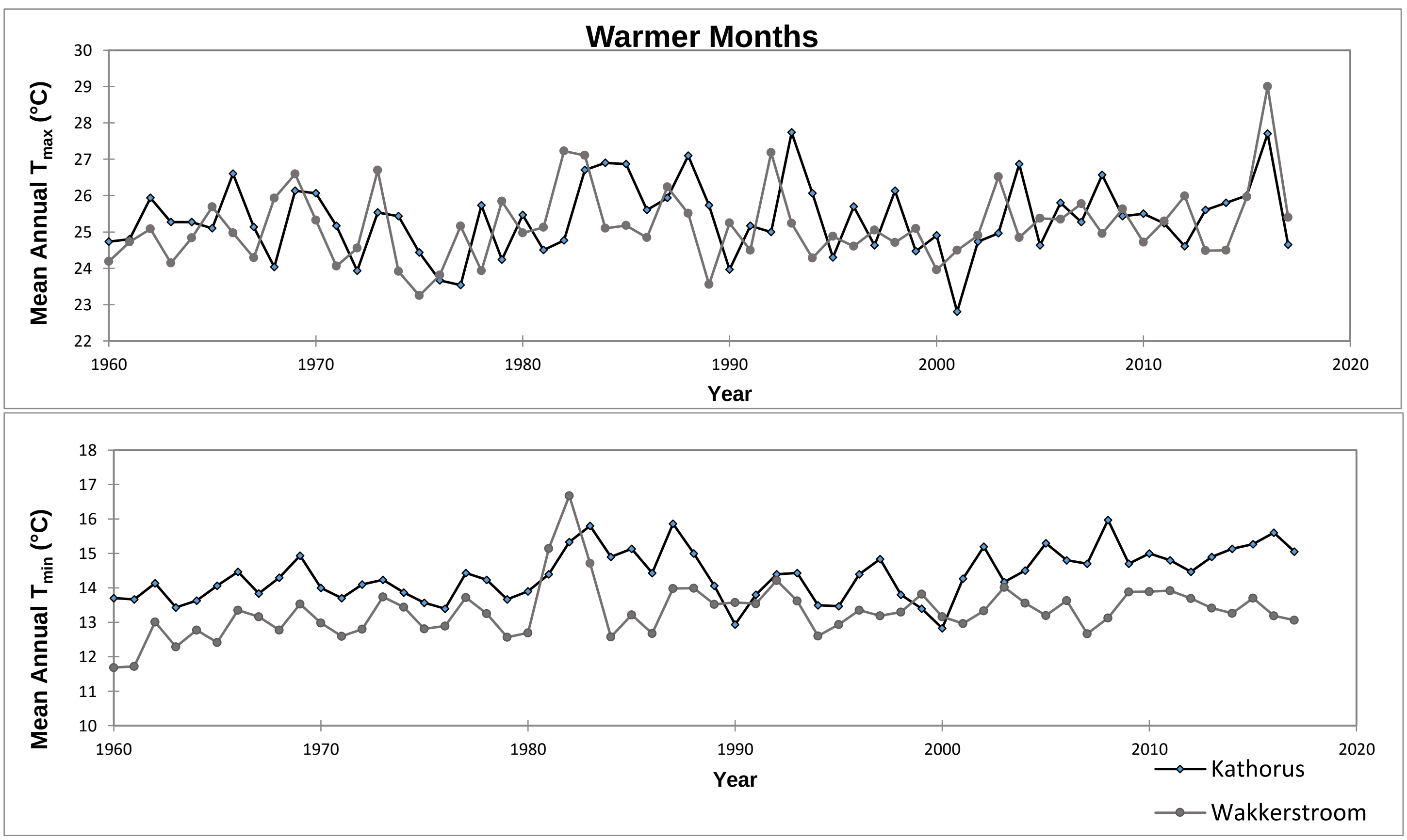


Figure 17: Time series of the long-term variations of the warmer month's annual mean temperature (maximums and minimums) from 1960 to 2017, in Kathorus and Wakkerstroom.

Long-term temperature trends were measured during the warmer and colder months (defined as December to February and June to July, respectively). When comparing the two areas, no statistically significant differences ($p > 0.5$, d.f. =114) were found in either the mean T_{max} or T_{min} of the warmer months between the years 1960-2017. From the mean T_{min} time-series given in Figure 17, there is an indication that Kathorus had higher temperatures than those experienced in Wakkerstroom. The only temperature anomaly occurred in the year 1982, where Wakkerstroom was 0.9 °C higher than the Kathorus. The year 1982 is of particular importance because it falls within a recorded ENSO (El Niño- Southern Oscillation) event. Another notable aspect of the Wakkerstroom temperature record can be found from the year 2000 to 2017 (Figure 17). In those 17 years, T_{min} (of the warmer months) had been showing a significant decreasing trend (Kendall's tau= -0.088; $p<0.05$). Which means that for those years T_{min} temperatures in Wakkerstroom have been getting colder but only during the warmer months.

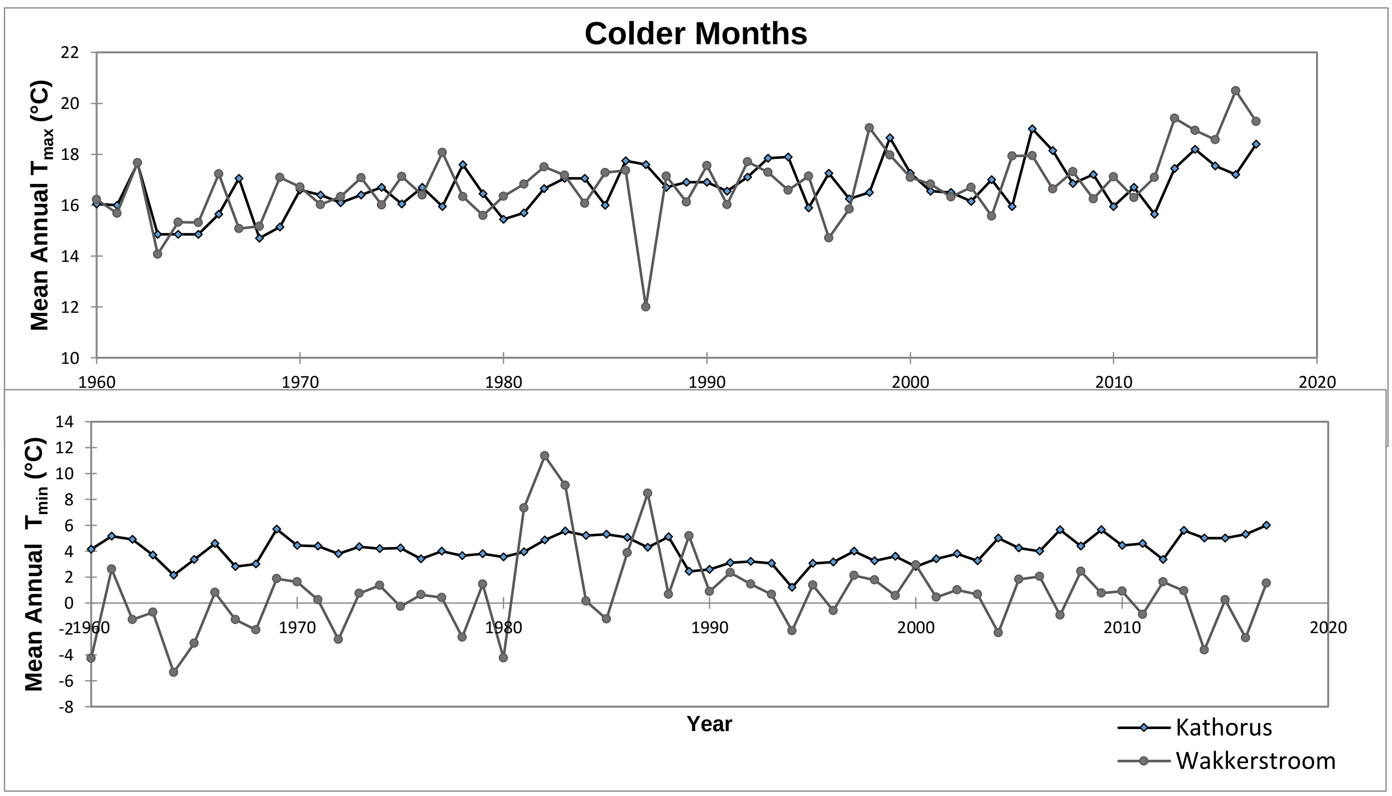


Figure 18: Time series of the long-term variations of colder month's annual mean temperature (maximum and minimum) from 1960 to 2017, Kathorus and Wakkerstroom.

When comparing the mean annual T_{max} for the Kathorus and Wakkerstroom during colder months, for the 1960 to 2017 period, no statistical difference ($p > 0.5$, d.f. =114) was calculated. However, during the same period, there had been a statistical difference ($p<0.001$, d.f. =114) between the mean T_{min} (of the colder months). We can then conclude that minimum temperatures experienced in the Kathorus and Wakkerstroom, during the colder months were not alike (Figure 18). This relationship is defined by Wakkerstroom having a consistently lower annual T_{min} than that of the Kathorus. Simply put, during colder months, Wakkerstroom experienced exceedingly lower temperatures than those in the Kathorus.

From the time series (Figure 18) we again see that in 1982 (colder months; T_{min}), Wakkerstroom (11.35 °C) had higher temperatures than the Kathorus (4.85 °C). Another noteworthy feature to the Wakkerstroom T_{min} time series (Figure 18) can be found from the years 2000 to 2017 (colder months) during this period a decreasing trend (Kendall's tau= -0.33) can be identified. However, this trend was not determined to be of any significance ($p>0.5$). From Figure 18 we see that in the colder months T_{max} in both Kathorus and Wakkerstroom displayed a similar trend, except for Wakkerstroom in 1987. In the year 1987 colder T_{max} temperatures in Wakkerstroom of 12 °C were measured ,which is approximately 2 °C lower than the average colder month temperatures (from 1960- 2017) in Wakkerstroom.

Table 3: Seasonal Mann-Kendall and two-tailed t-test at Kathorus and Wakkerstroom (1960-2017)

		Warmer Months		**Colder Months**	
		T_{min}	T_{max}	T_{min}	T_{max}
Kathorus	Kendall's tau	0.182	0.014	-0.028	0.451
	p-value (Two-tailed)	0.237	0.769	0.922	0.002144
Wakkerstroom	Kendall's tau	0.222	0.056	0.306	0.278
	p-value (Two-tailed)	0.141	0.769	0.039	0.024477

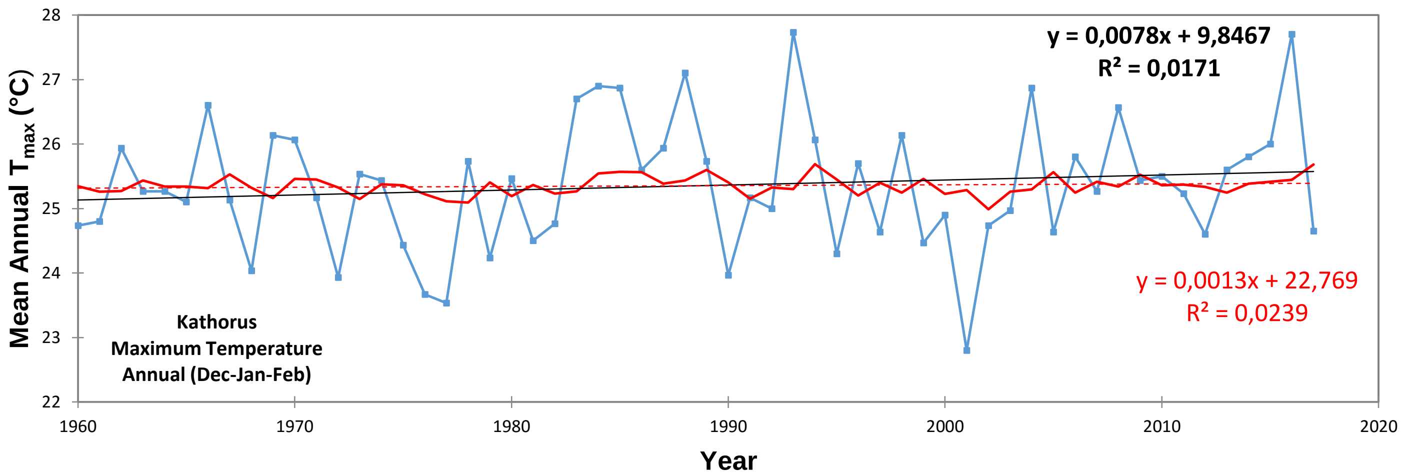
Overall from the years 1960 to 2017 there has been a trend of rising temperatures in the Kathorus and Wakkerstroom areas. The only exception being the T_{min} of the Kathorus during colder months (Table 3). This trend was not found to possess any statistical significance, for the sampled timeframe (1960-2017), except for during the colder months in Wakkerstroom (T_{min} and

T_{max}, $p<0.05$) and Kathorus (T_{max}, $p<0.05$), no statistical significance could be found in any of the temperature indices.

4.2 Time series comparison of warmer and colder months

4.2.1. Warmer months

During the 57-year reference period there has generally been an increasing trend in temperatures across both studied locations. Less than 40% of the weather station records from the Kathorus (during the colder months) show a statistically insignificant decrease. For the most part, temperatures across Wakkerstroom and the Kathorus have been increasing, at a largely insignificant rate. For almost six decades, temperatures during the warmer months (Figure 19) have increased in the Kathorus in both T_{max} and T_{min} (0.45 °C - 1.07 °C respectively). When comparing these data to the annual Wakkerstroom record (Figure 20), warmer temperatures, T_{min} and T_{max} have been rising at a relatively slower rate 0.71 °C for T_{min} and 0.75 °C for T_{max}.



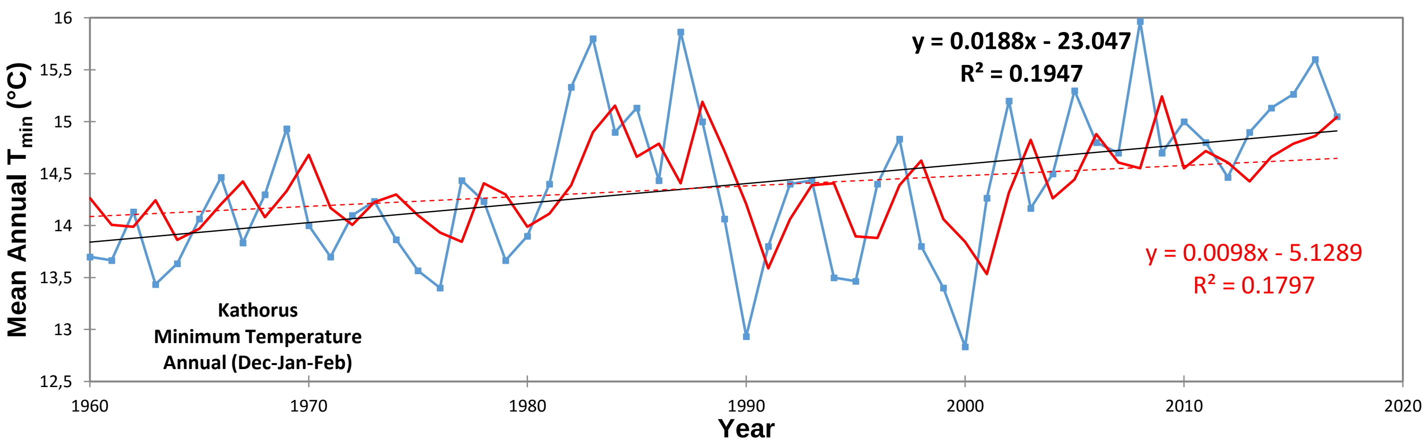
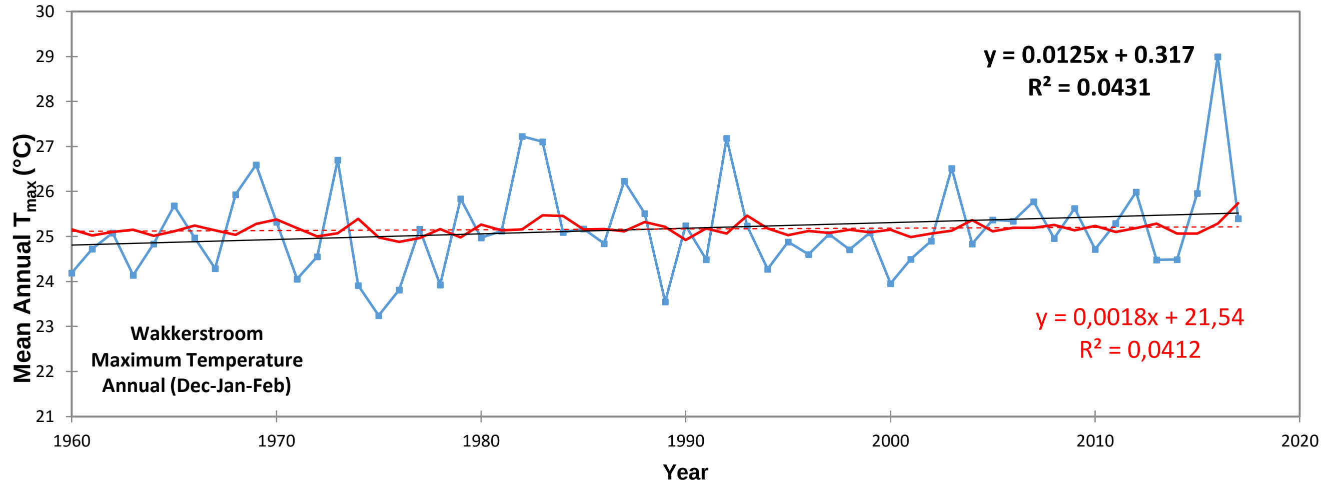


Figure 19: Time series and trend lines of observed warmer weather (Dec to Feb) mean temperatures (blue) and the moving average (red) in Kathorus area. The black trend line is drawn for the observed temperatures and the broken red line for the moving average

During the warmer months in Kathorus, temperature maximums were at their highest in 1993 and 2016 (27.7 °C, respectively) and at their lowest in 2001 (22.8 °C). The highest T_{min} (15.8 °C) occurred in 1983 and 1987, and again in 2008 (16 °C). Conversely, the lowest T_{min} (12.9 and 12.8 °C) happed in the years 1990 and 2000 (respectively).



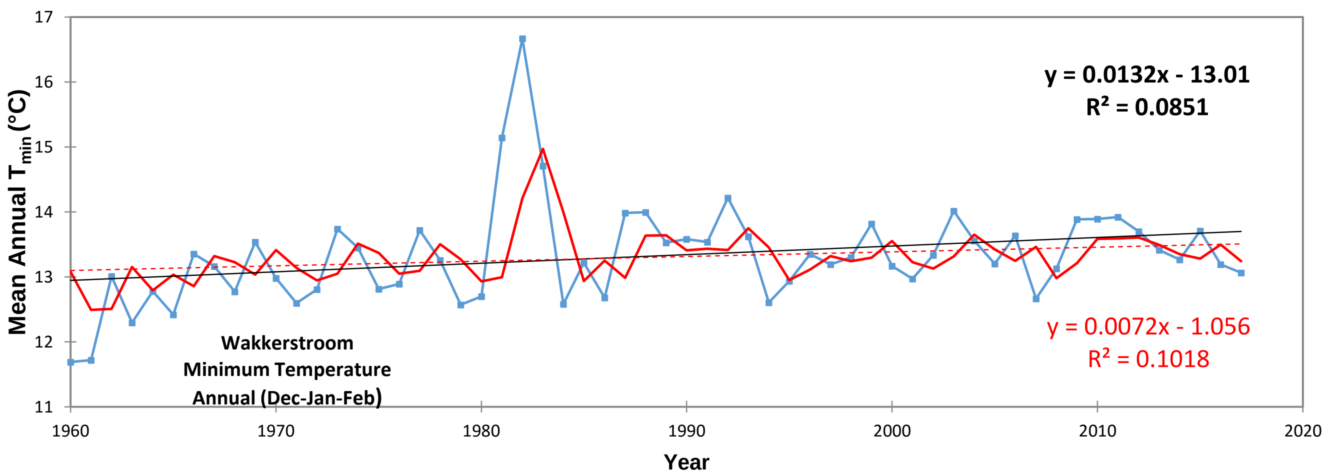
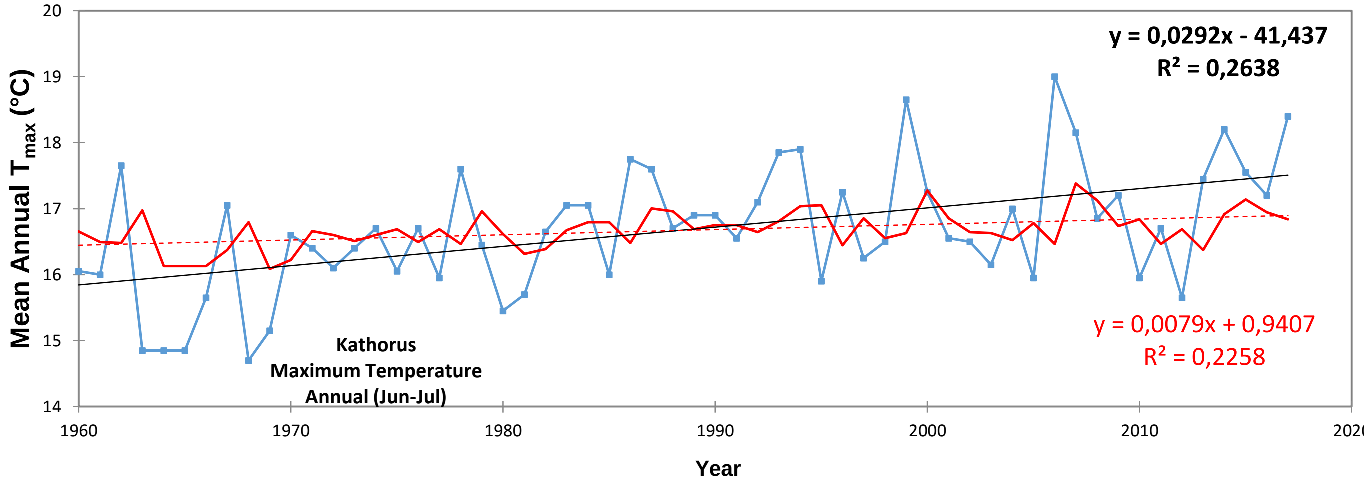


Figure 20: Time series and trend lines of observed warmer weather (Dec to Feb) mean temperatures (blue) and the moving average (red) in the Wakkerstroom area. The black trend line is drawn for the observed temperatures and the broken red line for the moving average.

Temperature maximums in Wakkerstroom were at their peak in 2016 also, reaching highs of 29 °C (1.3 °C higher than the highest recorded temperatures in Kathorus). Temperature maximums in the area, did not go below 23 °C, through the reference period (Figure 20). The mean annual $T_{min,}$ generally remained below 14 °C, except for 1982 were there was an almost 3 °C (16. 7 °C) increase.

4.2.2 Colder months

Colder days have generally decreased from the year 1960 to 2017. In Kathorus (Figure 21) T_{min} has risen by 0.6 °C /decade and T_{max} by 1.66 °C. In the same reference period, Wakkerstroom (Figure 22) has also shown a trend of increasing (colder month) temperature 0.99 °C and 2.18 °C (T_{min} and T_{max} respectively). Minimum temperatures have been rising at a noticeably elevated rate in Kathorus for the last two decades. From 1997-2017 there has been a 2.07 °C increase.



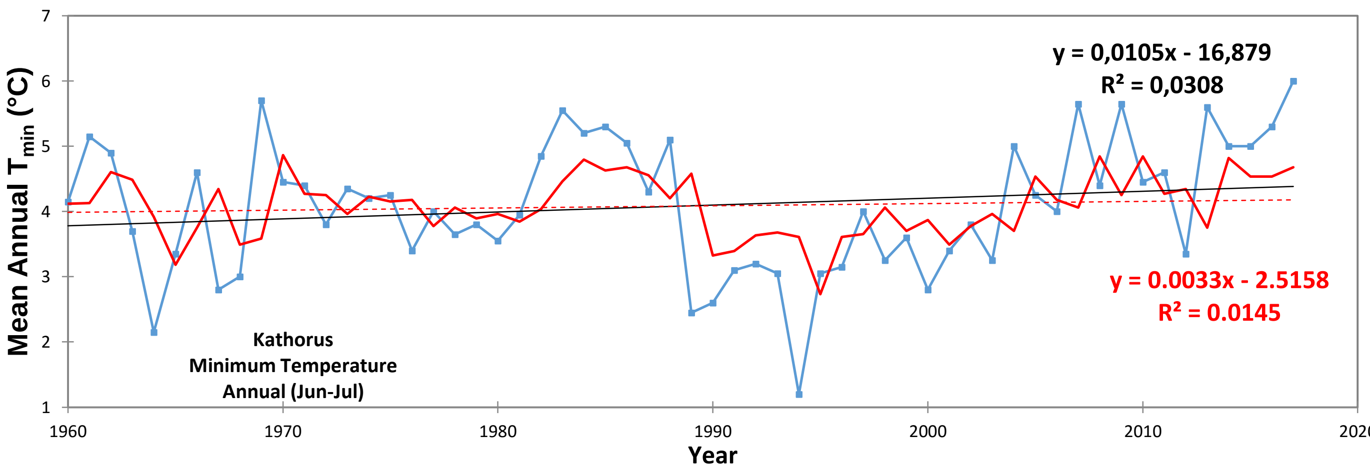
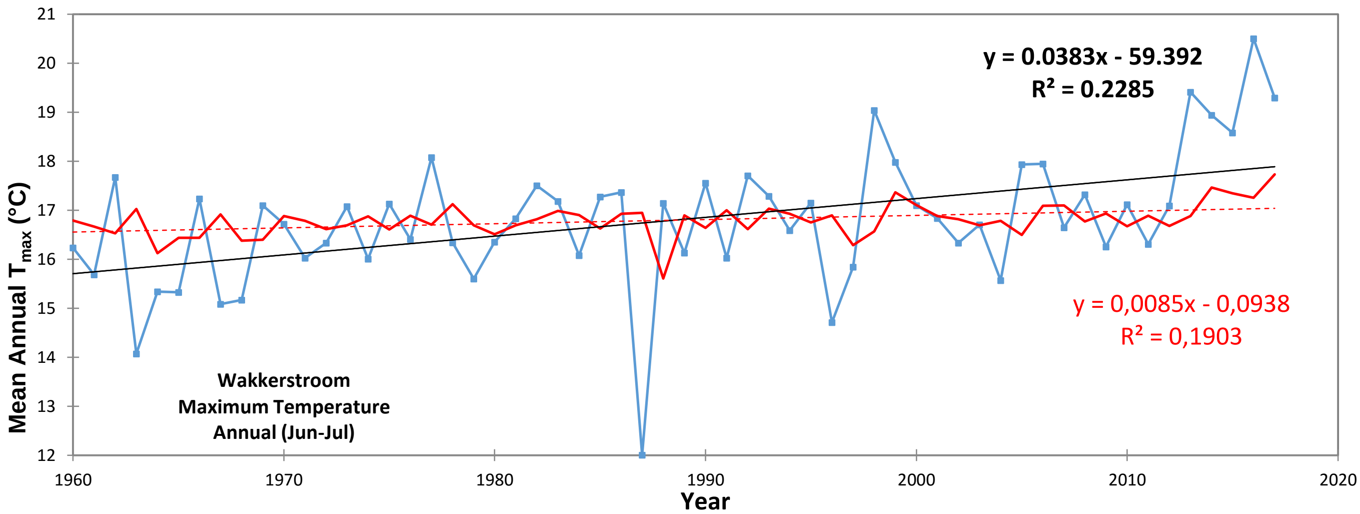


Figure 21: Time series and trend lines of observed colder weather (Jun and Jul) mean temperatures (blue) and the moving average (red) in the Kathorus area. The black trend line is drawn for the observed temperatures and the broken red line for the moving average.

In Wakkerstroom, in the same period, minimum temperatures have shown a slight decrease (-0.2 °C /decade). While maximum temperatures have shown a substantial increase in Wakkerstroom (2.9 °C), and a relatively more moderate increase (0.9 °C) in Kathorus.

A noteworthy feature of the mean annual T_{min} in the Kathorus, can be found in the year 1994 (Figure 21), the only time colder month temperatures reached below 2 °C. Minimum temperatures in Kathorus have been showing a steady increase, reaching their peak recently in 2017 at 6 °C.



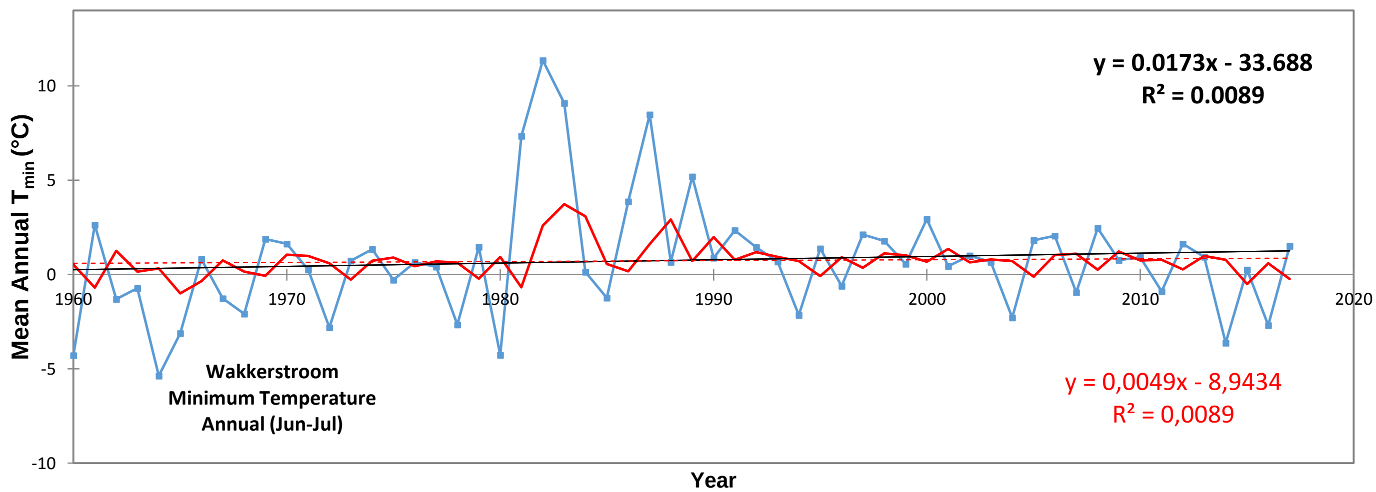


Figure 22: Time series and trend lines of observed colder weather (Jun-Jul) mean temperatures (blue) and the moving average (red) in the Wakkerstroom area. The black trend line is drawn for the observed temperatures and the broken red line for the moving average.

Remarkably 1994 was not the coldest year in Wakkerstroom. The coldest year in Wakkerstroom can be traced back 30 years earlier, in 1964, where average T_{min} colder weather (June-July) temperatures went as low - 5.4 °C. During colder seasons in Wakkerstroom, minimum temperatures characteristically remained below 2 °C but above - 4 °C.

4.3 Indoor temperatures of the three housing types

4.3.1 Warmer temperatures (Dec-Jan-Feb)

As outdoor temperatures warmed up, in the Kathorus and Wakkerstroom areas, indoor temperatures of matchbox, RDP and informal (shack) houses also increased. Daily indoor temperatures fluctuated by between 5 °C - 15 °C, with matchbox houses fluctuating the least and shacks the most.

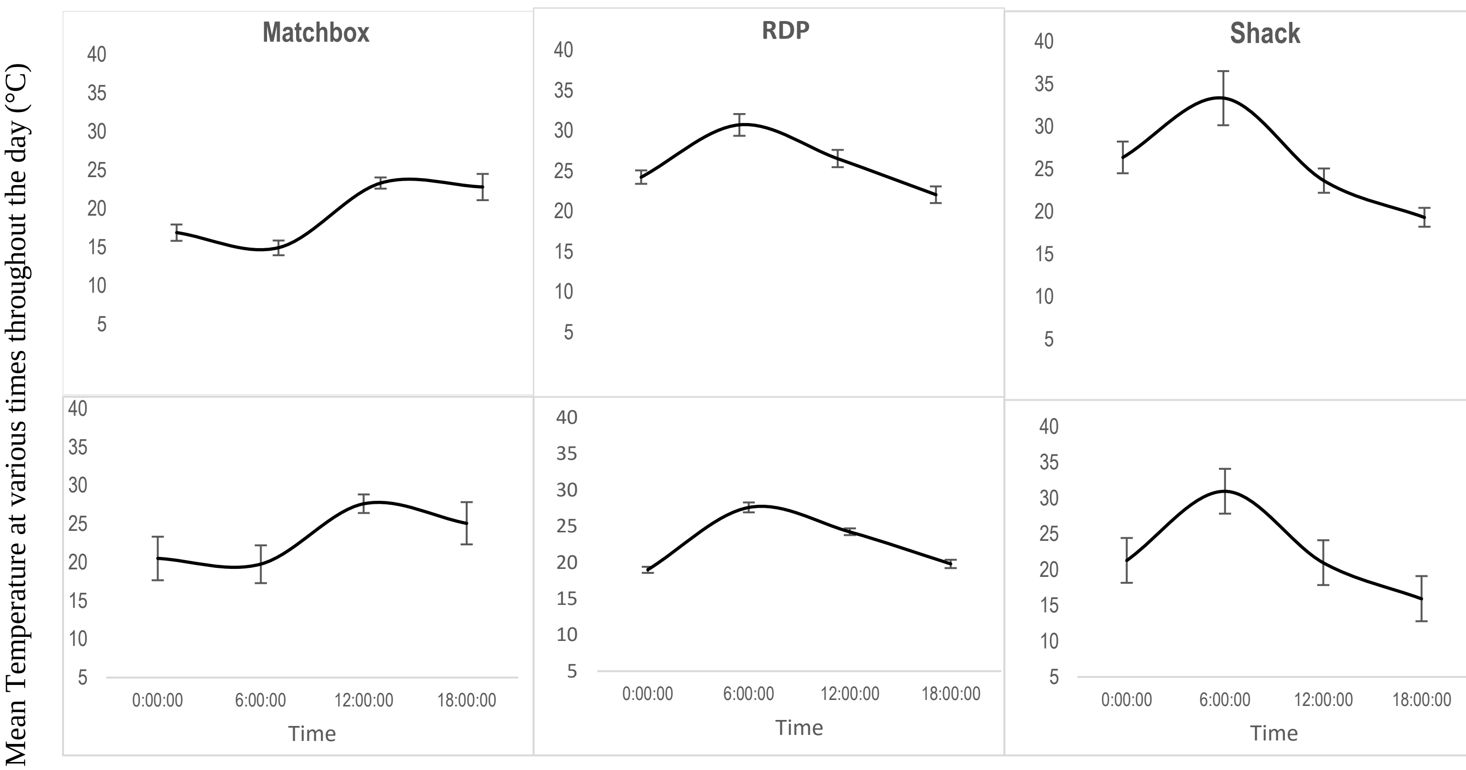


Figure 23: Mean temperature readings at selected times throughout the day, during warmer months in the Kathorus (top row) and Wakkerstroom areas (bottom row)

The lowest daily temperatures took place at 6 am for matchbox houses in both the Kathorus and Wakkerstroom areas (Figure 23). Apartheid era matchbox houses in both areas reached their daily peaks just after 12 pm, whereas, newer RDP houses in both the Kathorus and the Wakkerstroom, were at their warmest at around 6 am. They steadily declined thereafter until they reached their lowest point at around midnight. When ambient temperatures were at their lowest, temperatures inside informal houses (shacks) were at their highest. Temperatures inside shacks were measured to be consistently higher than those of the other two housing types (and ambient temperatures). For shacks, the highest recorded temperatures in both areas happened at approximately 6 am and the lowest recorded temperatures in the evening (6 pm).

Household temperatures of RDP and informal houses in both areas, followed a similar distribution (to each other), having their daily peaks at approximately 6 am. Throughout the hours in which the houses were sampled, very limited indoor temperature variability could be measured.

The greatest variability was found in shacks, during the morning hours (6 am) and matchbox houses closer to midnight. Household temperatures ranges (in both areas), deviated a substantial amount throughout the day. There was an 8 °C, 9 °C and 14 °C deviation between daily indoor highs and lows in matchbox, RDP and shacks (respectively) in both areas.

4.3.2 Colder temperatures (Jun-Jul)

When comparing temperatures at specified hours during the day (Figure 24), of the three housing types in the Kathorus and Wakkerstroom areas, it is evident that houses in Wakkerstroom had higher indoor temperatures than those in Kathorus. In both areas (Figure 24), matchbox houses had indoor temperatures that reached their daily peaks at about 12 pm and were at their most variable (household temperature deviated from median markedly at this time) at 6 am. The indoor temperatures of RDP houses in the Kathorus and Wakkerstroom, followed a similar distribution (to each other), having daily lows at about 6 am and reaching daily highs at about 12 pm. In both areas RDPs indoor temperatures were most variable at 6 am.

Indoor temperatures of informal houses (shacks), in the Kathorus and the Wakkerstroom, had a distinct pattern. The houses had temperatures that reached their daily peak at 6 am, corresponding to times when they were at their most variable. Informal houses in the Kathorus had their lowest (daily) temperatures at about 6 pm, and at midnight in Wakkerstroom.

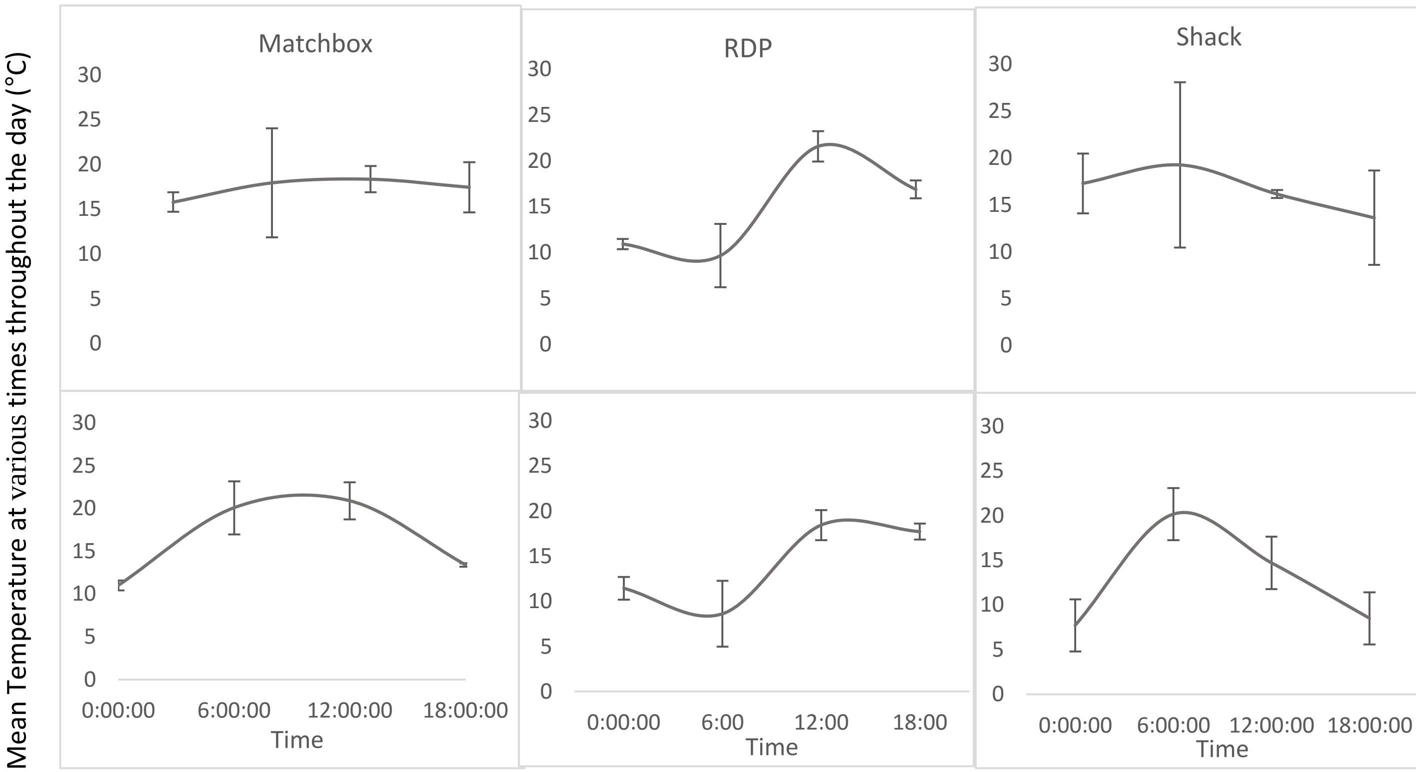


Figure 24: Mean temperature readings at selected times throughout the day, during colder months in the Kathorus (top row) and Wakkerstroom areas (bottom row)

Indoor temperatures in Kathorus (Figure 24), for matchbox and shacks remained at a narrow range, this is especially true for matchbox houses which remained in the range (15.8 - 18.4 °C). Conversely, shacks in Wakkerstroom had the greatest temperature deviation throughout the day (7.7 - 20.16 °C).

When comparing the houses thermal patterns seasonally, it was found that shacks (in both areas), followed a similar distribution. Consistently reaching their daily highs just after 6 am (Figures 23 and 24). RDP houses reached daily temperature highs around 6 am in the warmer months and were at their lowest during colder months at those times (and where highly variable at 6 am). Daily temperatures of matchbox houses in both areas, were consistently at their highest just after 12 pm during warmer and colder weather. In the colder months, midnight was when the houses (matchbox) were at their lowest and during the warmer months, 6 am. Additionally, during warmer months temperature variation was limited, but during colder months there was a substantial amount of fluctuation.

4.4 Comparison of daily indoor temperatures between housing types

When assessing the relationship of the three housing types, a better picture can be painted with regards to the living conditions experienced in each type of house, by making side by side comparisons of mean temperatures experienced in each.

4.4.1 Warmer temperatures (Dec-Jan-Feb)

During the warmer months, mean indoor temperatures of matchbox houses in both Kathorus and Wakkerstroom were not statistically different ($p>0.05$) to RDP houses in the same area (Figure 25). This was also true for mean indoor temperatures of RDP houses and shacks (in the same area; $p> 0.05$). However, the mean indoor temperature of shacks, in both Kathorus and Wakkerstroom, were found to be significantly different to those of matchbox houses ($p<0.05$). Daily mean indoor temperatures of RDP houses in Kathorus showed minimal variation, on average during the warmer months, households in the Kathorus had a higher indoor temperature than those experienced in the Wakkerstroom (Figure 25).

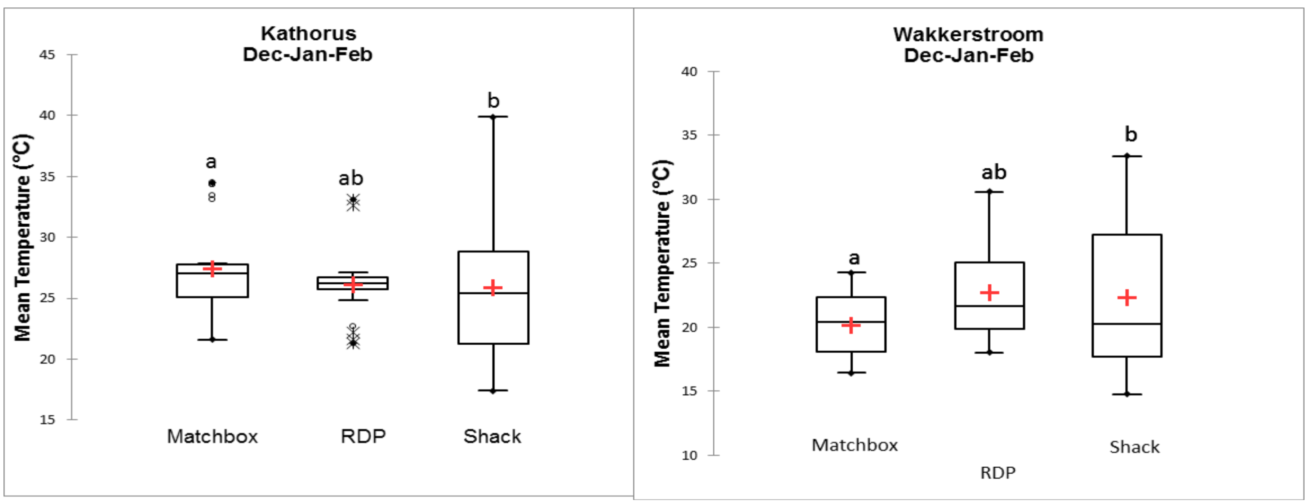


Figure 25: Box plot representing mean (warmer) indoor temperature per housing type. The top whisker represents the highest value not including outliers; the upper quartile represents that 25% of the data are greater than this value. The middle (median) represents that 50% of the data are greater than this value; the bottom whisker represents that 25% of the data are less than this value; the bottom whisker is the minimum value also without outliers.

4.4.2 Colder temperatures (Jun-Jul)

Mean indoor temperatures of matchbox houses were consistently higher than those of the other two housing types. This is evidenced in the box plot representations in Figure 26. In Kathorus there was no significant difference ($p>0.05$) between mean indoor temperature of RDP houses and shacks (Figure 26). However, there was a significant difference found between, matchbox houses and RDP houses ($p<0.05$) and matchbox houses and shacks ($p<0.0001$). During colder months, matchbox houses experienced different indoor temperatures than RDPs and shacks. All the investigated housing types in the Wakkerstroom were significantly different from each other (Figure 26). Notably shacks were found to have the lowest and matchbox houses the highest, mean indoor temperature throughout the colder months. With shacks having indoor temperatures reaching below 5 °C (Figure 26), and matchbox houses reaching about 30 °C.

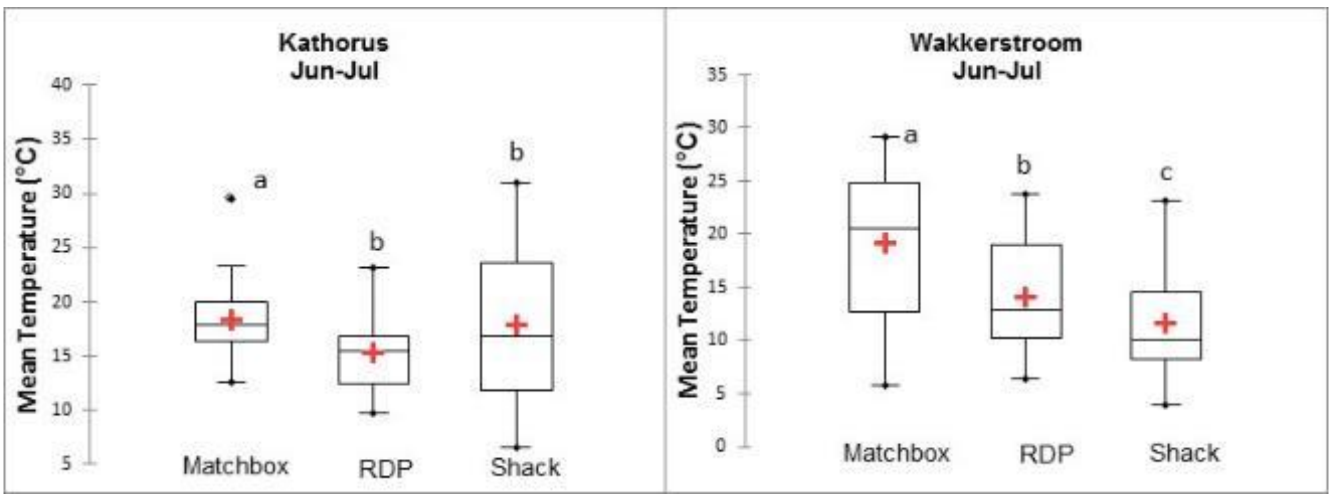


Figure 26: Box plot representing mean (colder) indoor temperature per housing type. The top whisker represents the highest value not including outliers; the upper quartile represents that 25% of the data are greater than this value. The middle (median) represents that 50% of the data are greater than this value; the bottom whisker represents that 25% of the data are less than this value; the bottom whisker is the minimum value also without outliers.

Temperatures of shacks (in the Kathorus) reached highs of about 40 °C, during the warmer months, and lows of 4 °C during the colder months (Figure 25 and 26). Whereas in Wakkerstroom temperatures inside shacks reached highs of about 33 °C and lows of 2 °C (Figure 25 and 26) during warmer and colder months (respectively). In the Wakkerstroom RDP houses on average, reached daily highs of approximately 30 °C during the warmer months, and lows of 7 °C during colder ones (Figure 25 and 26). About 250 km away in the Kathorus, RDP houses also showed a variation, between seasons. In the Kathorus matchbox houses remained at above 12 °C during the colder months and below 28 °C during the warmer ones. The same housing type in the Wakkerstroom (eSizameleni), fell between a temperature range of 23 °C to 7 °C in the warmer and colder months (respectively). Generally, indoor temperatures were higher in Kathorus than Wakkerstroom for both the warmer and colder months.

4.5 Indoor temperatures as a function of outdoor temperatures

Table 4 provides the Pearson's correlation and p-values for the indoor and outdoor temperatures experienced within each housing type for the warmer and colder months. For both areas during the warmer months, there was a statistically significant correlation between indoor and outdoor temperatures for matchbox, as well as RDP houses ($r = 0.74$, $p < 0.0001$) (each). While shack temperatures in Kathorus were not significantly correlated to ambient temperatures ($r = 0.05$, $p > 0.05$), in Wakkerstroom they were ($r \sim 0.6$, $p < 0.05$).

Correlation suggests that there is a relationship between indoor and outdoor temperatures, insofar as, when one increases so does the other (and vice versa). Throughout the colder months, in the Kathorus, there was no significant correlation ($p > 0.05$) between indoor and ambient temperatures of matchbox houses ($r = 0.15$) and shacks ($r = 0.03$). But there was a significant correlation during the same period for RDPs ($r = 0.75$, $p < 0.0001$). The indoor temperatures of matchbox houses ($r = 0.6$, $p < 0.05$), RDPs and shacks ($r = 0.75$, $p<0.001$ (each)) in Wakkerstroom, showed a significant correlation to outdoor temperatures in colder months.

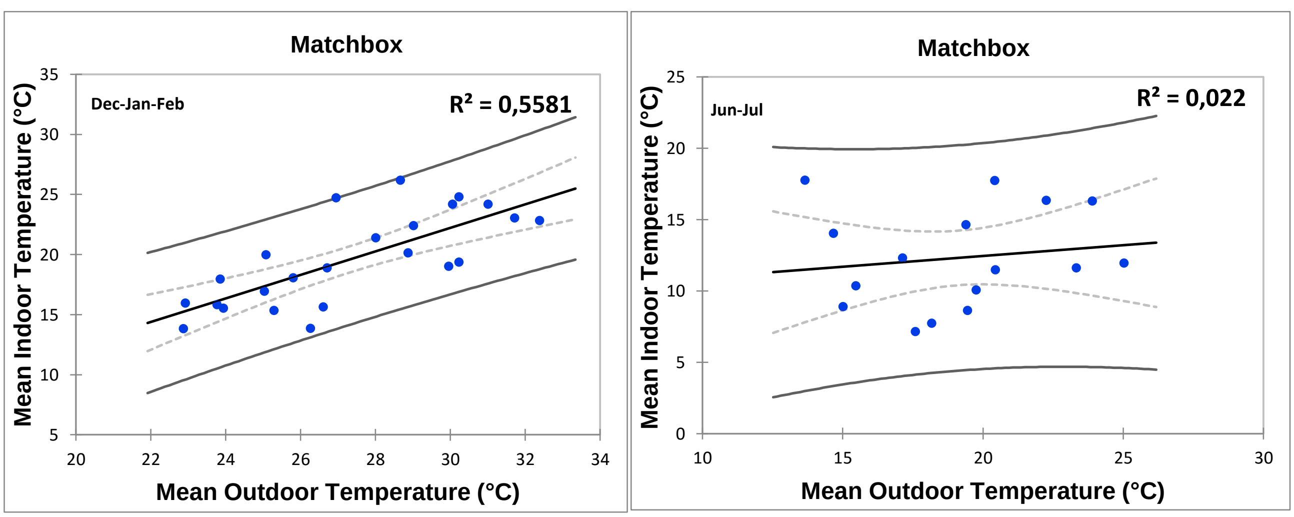


Figure 27: Regression models of matchbox houses in the Kathorus, during the warmer and colder months, with a confidence interval of 95 % (d.f.=1)

Figure 27 presents the regression models (R^2 model) of matchbox houses in the Kathorus in both warmer and colder months (R^2 =0.5581 and 0.022, respectively). The regression analysis illustrates the strength of relationship between indoor and ambient temperatures. It is evident that for matchbox houses, in the Kathorus during warmer months, ambient temperatures are an adequate indication of indoor temperatures. And a poor one during colder months.

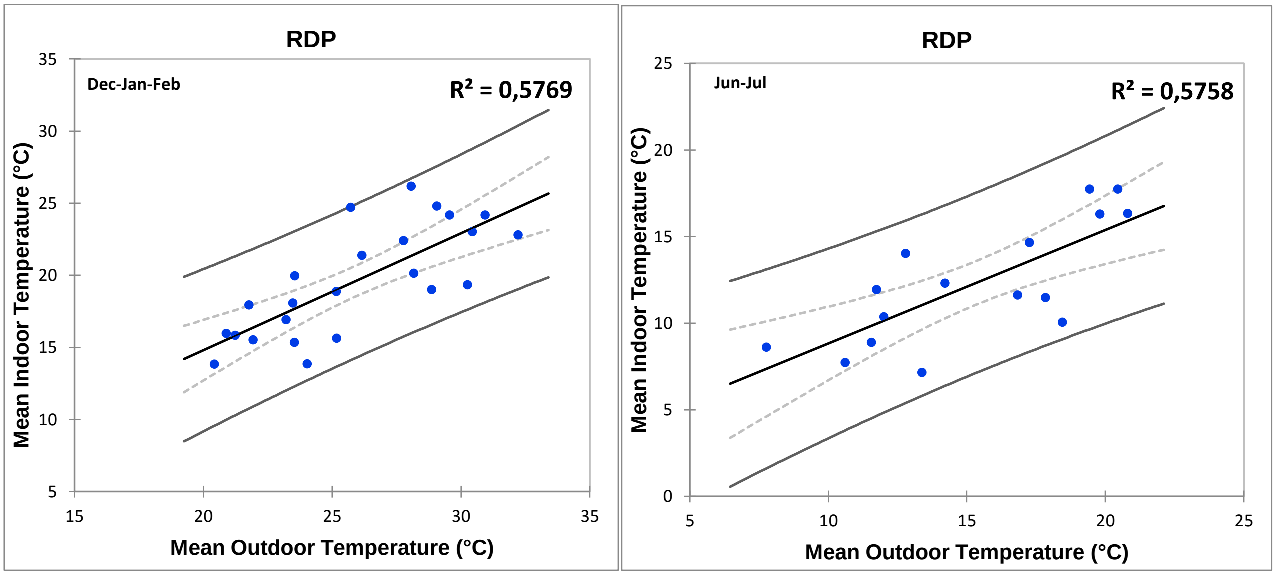


Figure 28: Regression models of RDP houses in the Kathorus during the warmer and colder months, with a confidence interval of 95 % (d.f.=1)

The regression models (R^2 model) presented above in Figure 28, of RDP houses in the Kathorus in both warmer and colder months (R^2 =0.5769 and 0.5758 respectively) illustrate that ambient temperatures are a moderate indicator of indoor temperatures. Indoor temperatures are regularly, lower than outdoor temperatures for both the colder and warmer seasons. The correlation analysis, suggests that when ambient temperatures increase, so do indoor temperatures.

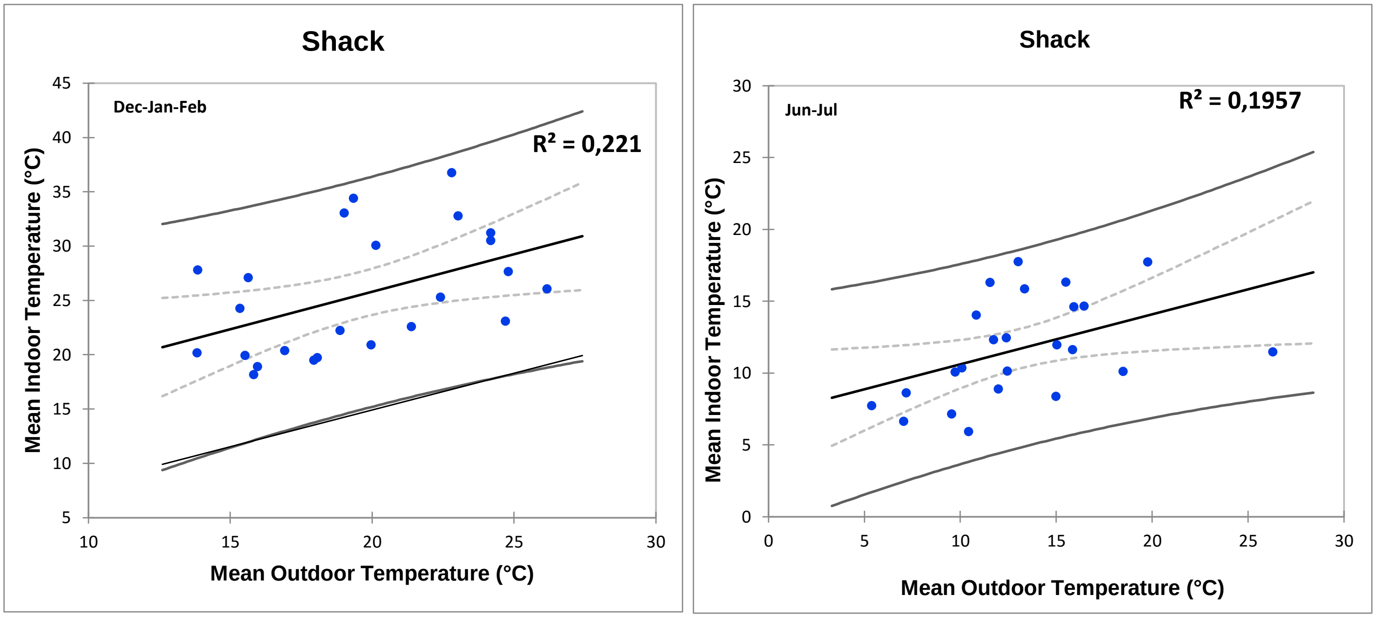


Figure 29: Regression models of informal houses (shacks) in the Kathorus during the warmer and colder months, with a confidence interval of 95 % (df= 1)

Temperatures in shacks, particularly in the Kathorus (Figure 29), are not a good indication of ambient temperatures. It appears from the regression models (R^2 model) in Figure 29 that for shacks, ambient temperatures in both the warmer and colder months (R^2 =0.221 and 0.1957, respectively) are not indicative of indoor temperatures.

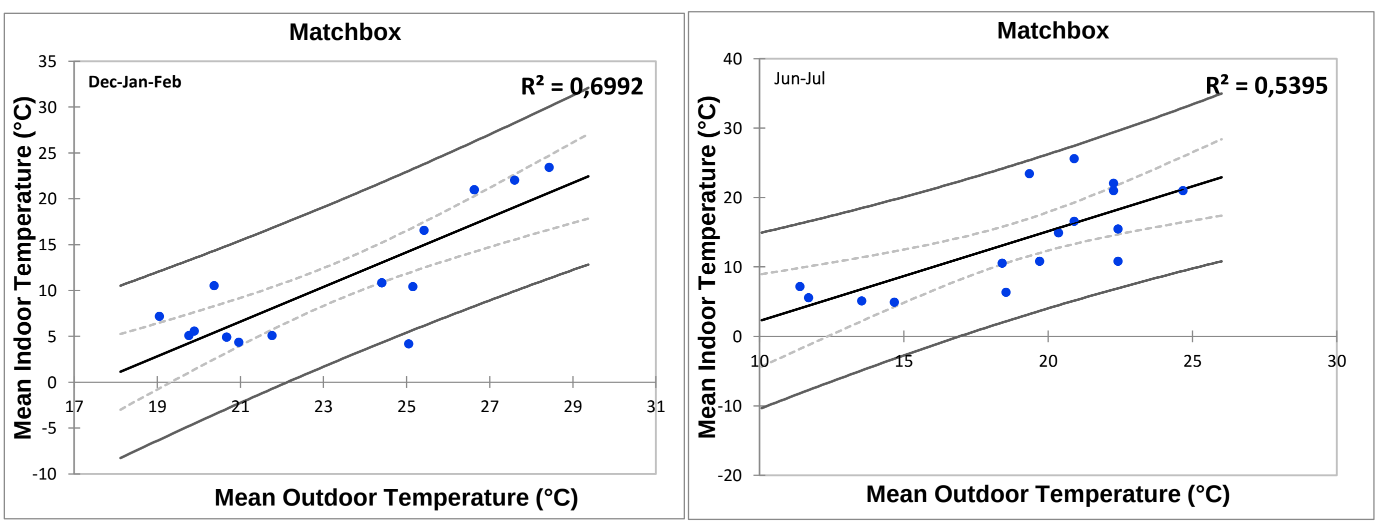


Figure 30: Regression models of matchbox houses in the Wakkerstroom during the warmer and colder months, with a confidence interval of 95% (d.f.=1)

In the Wakkerstroom during the warmer months (Figure 30), the indoor temperature of matchbox houses were relatively strongly associated to ambient temperatures (R^2 =0.6992) and only moderately associated in colder ones (R^2 =0.5395). The correlation (Table 4) and regression analyses (Figure 30) suggest a positive relationship between indoor and ambient temperatures during the warmer and colder months (as one increased so too did the other).

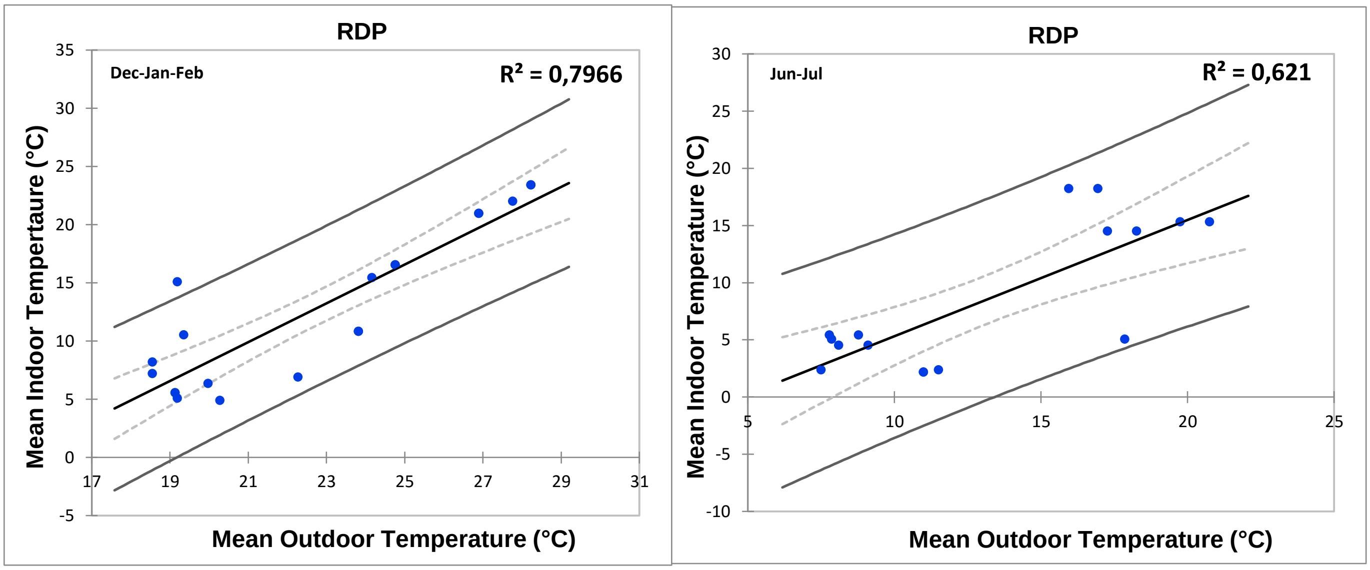


Figure 31: Regression models of RDP houses in the Wakkerstroom during the warmer and colder months, with a confidence interval of 95% (d.f.=1)

Ambient temperatures in Wakkerstroom, during the warmer months (Figure 31), give a strong indication of indoor temperatures of RDP houses (R^2 =0.7966). During the colder months this relationship is also good (R^2 =0.621). Additionally, using the correlation analysis, it is

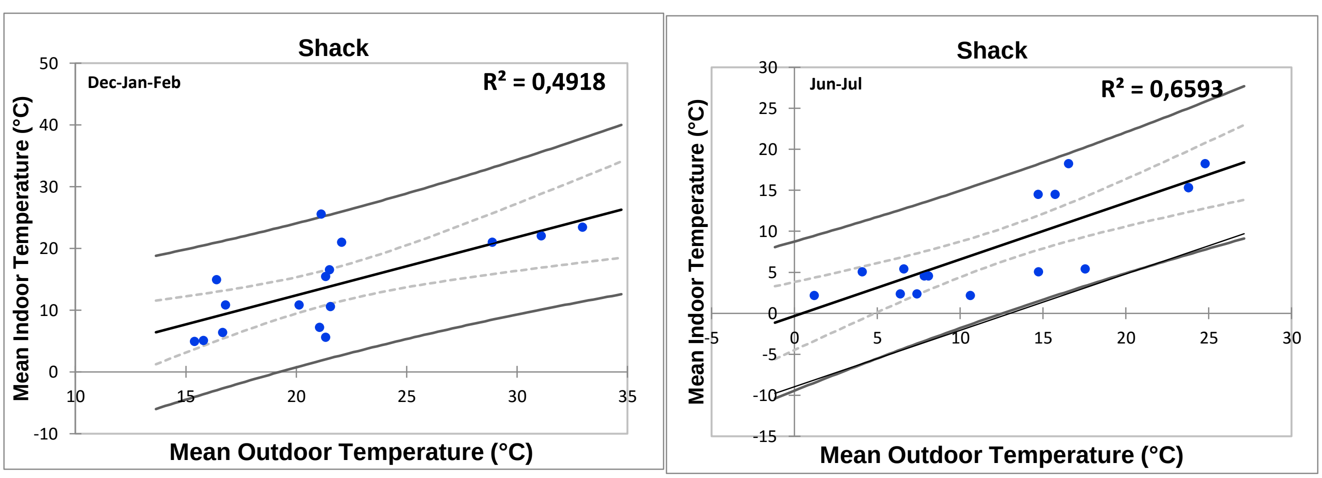


Figure 32: Regression models of Shack houses in the Wakkerstroom during the warmer and colder months, with a confidence interval of 95% (df=1)

evident that during the warmer and colder months, the relationship between indoor and outdoor temperatures is a significant one ($p>0.001$).

Ambient temperatures in Wakkerstroom are a slightly moderate ($R^2 = 0.4918$) to relatively good ($R^2 = 0.6593$) indicator of indoor temperatures of shacks, during the warmer and colder months (respectively) (Figure 32). The (correlation) relationship is moreover significant ($p<0.05$), throughout the warmer and colder months.

Table 4: Pearson's correlation of outdoor temperatures vs. indoor temperatures in the Kathorus and Wakkerstroom areas.

		Warmer Months	**Colder Months**
Kathorus	Matchbox	0.74 ($p < 0.0001$)	0.15($p > 0.05$)
	RDP	0.75 ($p < 0.0001$)	0.75($p < 0.0001$)
	Shack	0.05($p > 0.05$)	0.03($p > 0.05$)
Wakkerstroom	Matchbox	0.73($p < 0.0001$)	0.6($p < 0.05$)
	RDP	0.8($p < 0.0001$)	0.75($p < 0.001$)
	Shack	0.6($p < 0.05$)	0.75($p < 0.001$)

Overall, Figures 27 to 32 exhibit a common trend of indoor temperatures being most like outdoor temperatures during warmer months, barring from shacks in Kathorus. It is evident (from Figures 27 to 32) that Wakkerstroom's ambient temperatures even during colder months, were a good indication of indoor temperatures. Differences mainly arose in Kathorus during colder months, where ambient temperatures of matchbox houses and shacks, were not indicative of indoor ones. In these households, indoor temperatures were commonly higher than ambient temperatures.

4.5.1 Ceilings

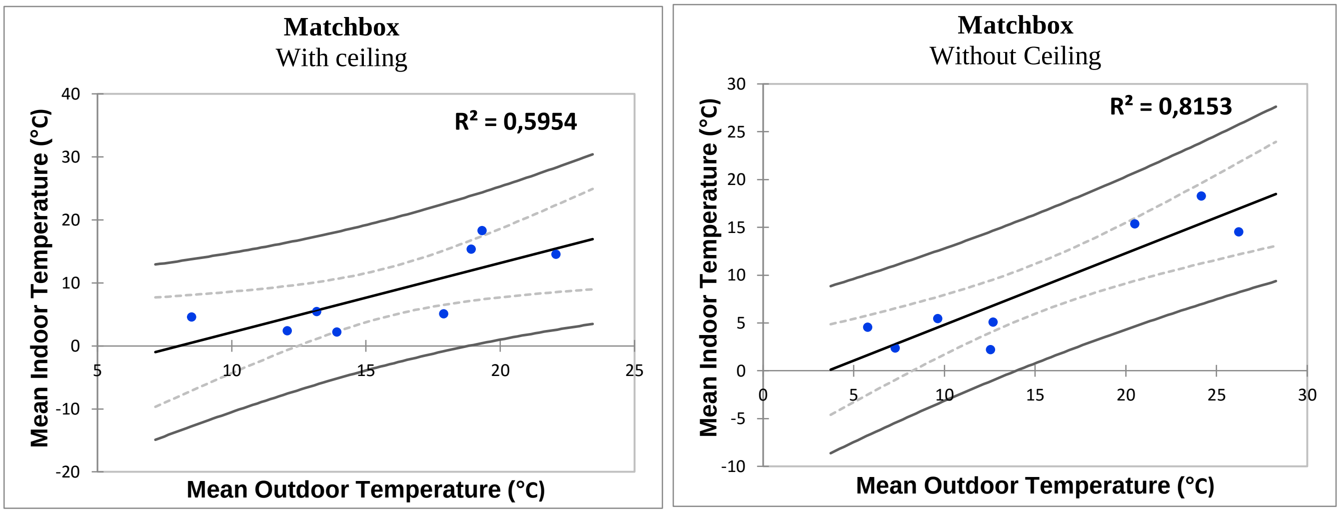


Figure 33: Regression model of matchbox houses in the Wakkerstroom, with and without ceilings (confidence interval: 95 %)(d.f.=1)

Building houses with or without ceilings, affects the thermal properties of homes. Ceilings offer a better than average indication of potential insulation. From Figure 33, it is evident that without ceilings, the mean indoor temperatures were strongly related (R^2= 0.8153) to outdoor temperature. With ceilings however, ambient and indoor temperatures of matchbox houses were approximately 25% less associated (R^2= 0.5954).

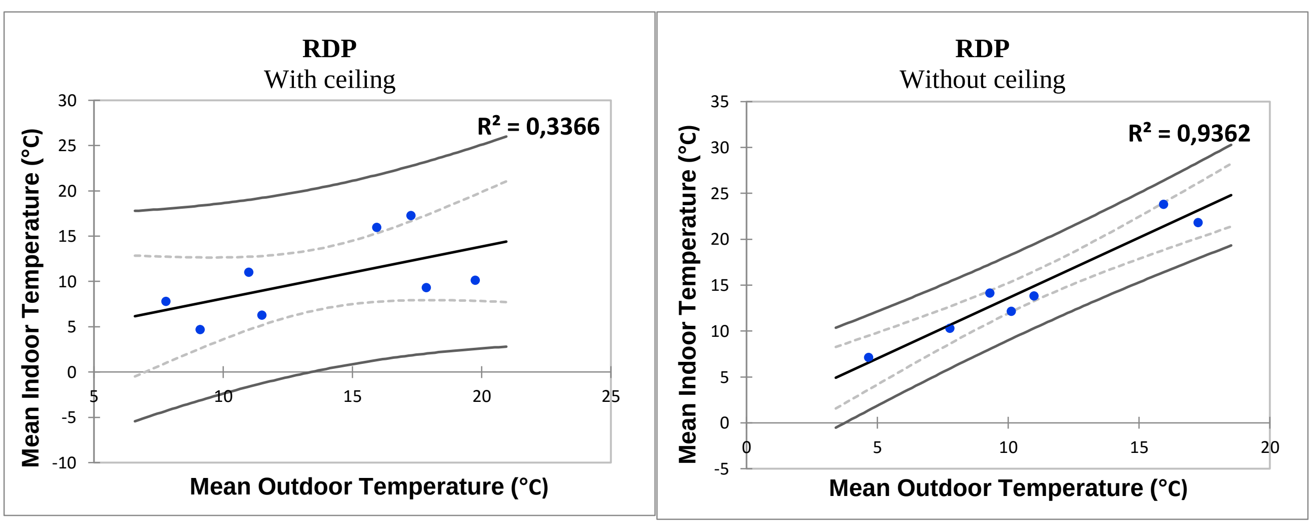


Figure 34: Regression model of RDP houses in the Wakkerstroom, with and without ceilings (confidence interval: 95 %)(df=1)

In the case of RDP houses, there was a striking difference between houses that had ceilings and those that did not. Figure 34 clearly shows that there is a weak relationship between ambient and indoor temperatures of houses with ceilings ($R^2 = 0.3366$). Without ceilings ($R^2 = 0.9362$) the relationship between ambient and indoor temperatures becomes very strong.

4.6 Construction material and household infrastructure

Information regarding construction material was inferred. Access to standardized construction guidelines was restricted and so could not be used. Nevertheless, information was gathered by means of interviews, which included occupant responses, experts on housing and the researchers own observations (this is especially true for informal houses).

Experts on low cost housing were also consulted namely; from The Department of Housing and Human Settlements (municipality of Ekurhuleni), and an academic specializing on construction from the University of the Witwatersrand. These consultations were done with the intention of determining the construction material used to construct these low-cost houses.

Table 5: Percentage of building material used to construct each housing type, as per expert opinion and self-reported accounts. The number of households which used a specific form of building material are quantified.

	Housing Type (n=6 per housing type)	Main construction material	Floor Material	Ceiling type	Roofing material	Mean age of houses
Kathorus	**Matchbox (Apartheid era)**	100% Bricks (low grade clay bricks) (n=6)	100% (Cement and Tiles) (n=4), 100% (Cement)(n=2)	-	100% (Corrugated iron) (n=6)	±60 years
	RDP (Post-1994)	100% Bricks (cement, ash/river sand) (n=6)	100% (Cement) (n=6)	-	100%(Asbestos)(n=4) 100% (Corrugated iron) (n=2)	±24 years
	Shacks (Informal Housing)	100% Galvanized Iron (80% Corrugated and 20% Other) (n=6)	100% (Vinyl and Cement) (n=6)	-	100% Galvanized iron (40% Corrugated and 60% other) (n=6)	±2.5 (Range:1-4) years
Wakkerstroom	**Matchbox (Apartheid era)**	100% Bricks (low grade clay bricks) (n=6)	100% (Cement)(n=5), 100% (Cement and Tiles) (n=1)	100% (Rhino-board) (n=1) 100%(Wood)(n=1)	100% (Asbestos)(n=4), 100% (Corrugated iron) (n=2)	±60 years
	RDP (Post-1994)	100% Bricks (cement, ash and river sand) (n=6)	100% (Cement)(n=6)	100%(Rhino -board) (n=2)	100% (Corrugated iron) (n=6)	±21.5 years
	Shack (Informal Housing)	100% Corrugated iron (n=6)	100% (Vinyl and Cement)	100%(Cardb oard)(n=1)	100% Galvanized iron (Corrugated iron) (n=6)	±9.25 (Range: 0.5-18) years

Table 5 presents a summary of the construction materials including floor material, ceiling material and roofing materials used to construct each type of low-cost house, as well as mean age of dwelling. It is evident from Table 5 that the use of ceilings is not common in Kathorus. On the contrary, in Wakkerstroom there were five households across all three housing types which made used of ceilings. The types of ceilings in Wakkerstroom differed, from the commonly used rhino-board type ceiling, to traditional wood ceilings and finally, self-constructed cardboard ceilings (which was only found in a single shack). Cement was a common feature used in the flooring of all housing types. In shacks vinyl was used to cover the raw cement in both Wakkerstroom and Kathorus. In Kathorus, the use of tiles was a popular choice for matchbox houses (n=5), and in Wakkerstroom only one home had this feature. Asbestos type roofing was primarily used in RDPs (in Kathorus) and in matchbox houses (in Wakkerstroom) (n=4 respectively).

All matchbox houses were reportedly built to be on average 60 years in age (and built in the late 1950s). The RDPs sampled in Kathorus were on average 24 years in age, and 21.5 years in Wakkerstroom (Table 5). Kathorus had newer shacks, generally no older than 4 years (mean ± 2.5 years), while Wakkerstroom was found to have the oldest shacks, averaging 9.25 years.

4.6.1 Expert consultation on building material
28/05/2018

Mr. George Kgasane

Mr Kgasane, a senior clerk of works from the city of Ekurhuleni metropolitan municipality, was interviewed. He shared his knowledge openly. He stated that, old apartheid matchbox houses were regularly built with low grade clay bricks having the dimensions 22 X 110 X 70mm, cement as well as river sand would commonly be mixed in with the clay. Nevertheless, clay was the primary ingredient because it formed tight lattice structures (making it less porous and denser). For RDP houses, the main building material was a cement brick (known as a maxi brick) these bricks as the name suggests are larger, having the dimensions 27 X 90 X 150 mm. According to Mr Kgasane houses were frequently built with similar material in Gauteng and Mpumalanga. Furthermore, Mr Kgasane reports that RDPs (using maxi-bricks) were (and are) commonly made with varying compositions of each key ingredient. Accounts suggest that the proportion of river sand to ash to cement (in RDP houses) was not standardized and differed according to contractor specifications. As the number of contractors increased post-1994, so did the variability in the proportion of each constituent material. These varying proportions of composite ingredients still met building regulations and therefore were permissible to use.

07/09/2018

Prof. David Root

Prof. Root is the current head of school in the Department of Construction Economics and Management at the University of the Witwatersrand. The professor reported on the thermal qualities of the applicable housing types. He stated that clay bricks (which have small amounts of cement and river sand) have a higher thermal mass than those of RDPs and shacks. The Professor further stated that the main construction material of RDPs brick houses which is a mixture of cement, river sand and/or ash was initially designed to form part of the internal structure of homes. The use of this type of brick externally, is permissible if plastering is also done to ensure that the porosity of the buildings is low. Nevertheless, the thermal mass of RDP houses is far higher than that of shacks. The thermal mass of matchbox houses is still however considered the highest of the three. Thermal mass as the name suggests takes the mass of the building into account, the heavier the building is the higher its thermal mass will be. The Professor detailed that buildings with a higher thermal mass are able to retain and store radiant energy for a longer duration of time, and conversely are able to release stored energy at a more sustained rate than those with a lesser thermal mass. Simply put, it would take a longer period for those buildings to heat up and cool down, keeping those buildings in a relatively "stable state". The thermal mass of buildings constructed with galvanized iron, is the lowest, subjecting occupants to shorter periods between heating and cooling events (experienced under ambient conditions). Prof. Root further stated that ceilings offer increased insulation by isolating the roof space from the living space, this adds what is called a convection effect. A convection effect effectively means that near the roof (or the highest point in the house) is where it is the hottest, and as you travel downwards there is a gradually less heat.

The Professor additionally indicated that during the apartheid regime the use of fewer contractors allowed for more standardisation of building materials. But when the post-apartheid government opened the construction industry, to emergent contractors, regulation and standardisation of construction materials was affected. To his knowledge, adequate monitoring and evaluation of numerous emergent construction companies is improbable.

4.7 Household and participant profile per housing type

4.7.1 Occupant profile

In order to determine the perceived thermal comfort experienced by occupants of low-cost housing in the Wakkerstroom and Kathorus areas; semi-structured interviews and some observational analyses were used. A total of thirty-six semi-structured interviews were analysed, representing 18 households in the Kathorus area as well as 18 households in the Wakkerstroom area (eSizameleni). Wakkerstroom was found to represent the largest number of occupants per household across housing types, having 80 residents in total. The Kathorus had approximately two-thirds of that with, 49 occupants across all three housing types. eSizameleni had more dwellers (Table 6) in matchbox houses than any other housing type, having on average 6 occupants per house. The majority of dwellers in Kathorus lived in RDPs (Table 6) with an average of 3 per household.

Table 6: Average number of occupants in the Wakkerstroom and Kathorus areas, per housing type

Area	Matchbox	Range	RDP	Range	Shacks	Range
Kathorus	3(n=16)	1-6	3 (n=20)	2-5	2 (n=13)	1-3
Wakkerstroom	6 (n=35)	1-7	5(n=30)	2-9	3(n=15)	1-4

The semi-structured interviews were only asked to those occupants above the ages of 18, where only one member in the household was required to respond. If their responses differed with other members, these were noted. Almost forty-eight percent of the sampled Wakkerstroom population was under the ages of 18, with only 12 % of the Kathorus sampled population falling into that age category. Matchbox and RDP homes (Table 6) in both the Kathorus and Wakkerstroom, had the largest range of occupants, having as little as one solitary occupant to as many as six (Kathorus: matchbox), seven (Wakkerstroom: matchbox) or nine (Wakkerstroom: RDP) occupants per household. In contrast to this, shacks typically had the smallest range of occupancy, having not more than three (Kathorus) or four (Wakkerstroom) dwellers.

Wakkerstroom represented the youngest average age of occupants, only 6 % of the sampled population was over the ages of 50. Kathorus represents a more heterogeneous mixture of ages, 1/3 of overall occupants being between the ages of 36-50, and 21% and 23% being between 26-35 years and over 50 (respectively).

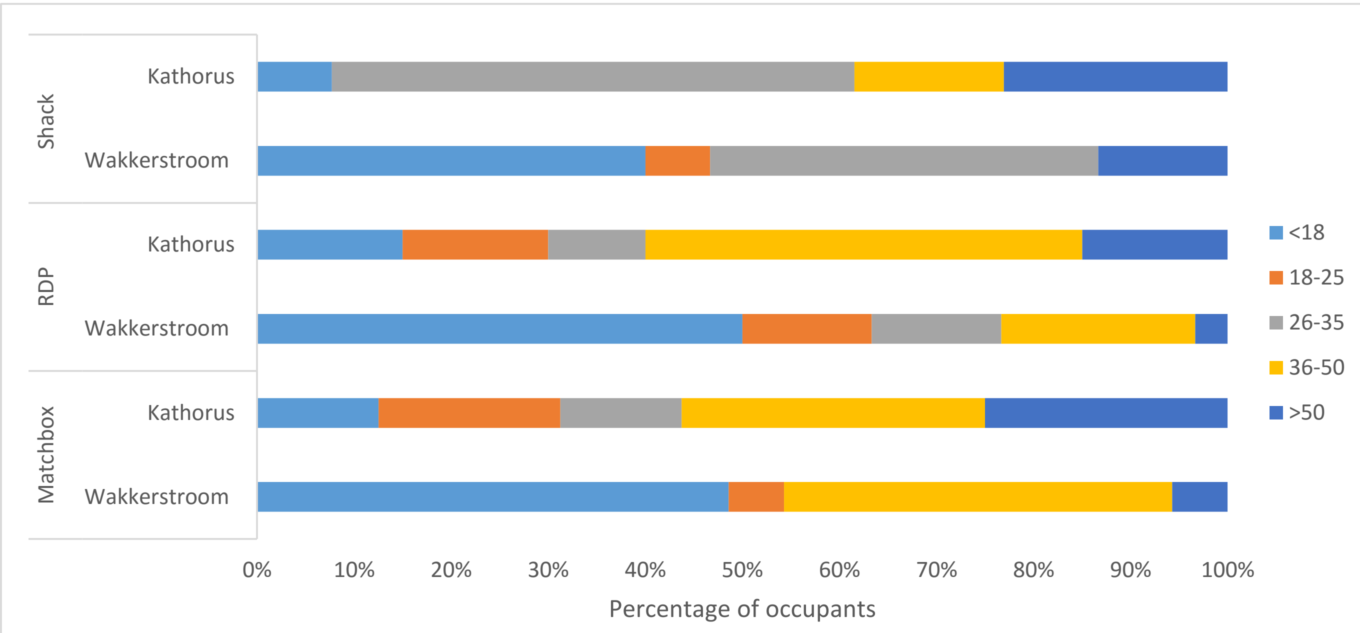


Figure 35: Age range of occupants as per location and housing type (n=36)

At a household level we see in Figure 35 that in Wakkerstroom 40% of shack dwellers where below the ages of 18, where in the Kathorus only 10% of dwellers were below this age group. A large percentage (50%) of shack dwellers in Kathorus were between the ages of 26 to 35. This is a noteworthy age group in the Wakkerstroom also, making up about 40% of sampled shack dwellers. Fifty percent of the sampled RDP dwellers in the Wakkerstroom were below 18, where only 15% of the Kathorus RDP population were minors. In the Kathorus a large percentage (45%) of RDP dwellers were over 36 but under 50 years. Keeping with the trend, only 10% of the matchbox population in the Kathorus was under the ages of 18 years. Where a sizeable percentage (50%) of Wakkerstroom RDP dwellers fell within this age group. Interestingly, of the sampled matchbox population in Wakkerstroom no dwellers fell into the "working" 26-35 (years) age group. And, only 10% of the matchbox population in the Kathorus were younger than 35 and older than 26 years.

Kathorus largely had the lengthiest years of occupation (Figure 36). The average years of tenancy in eSizameleni was 30 ± 19 years (mean ± SD) for matchbox houses, and 15 ± 7 years for RDPs. On the other hand, occupants of matchbox houses in Kathorus had on average lived in their homes for 49 ± 8.5 years and 17±7 years for RDP dwellers.

Wakkerstroom represented a younger population, and consequently represented the least years of residency (Figures 35 and 36). Shacks in Wakkerstroom however, had the highest mean years of occupancy (9 ± 6 years), compared to Kathorus (2.5 ± 0.9 years). Generally speaking, (the older) matchbox houses in both areas enjoyed the highest years of occupancy and occupants (Table 6), followed by RDP houses and lastly shacks.

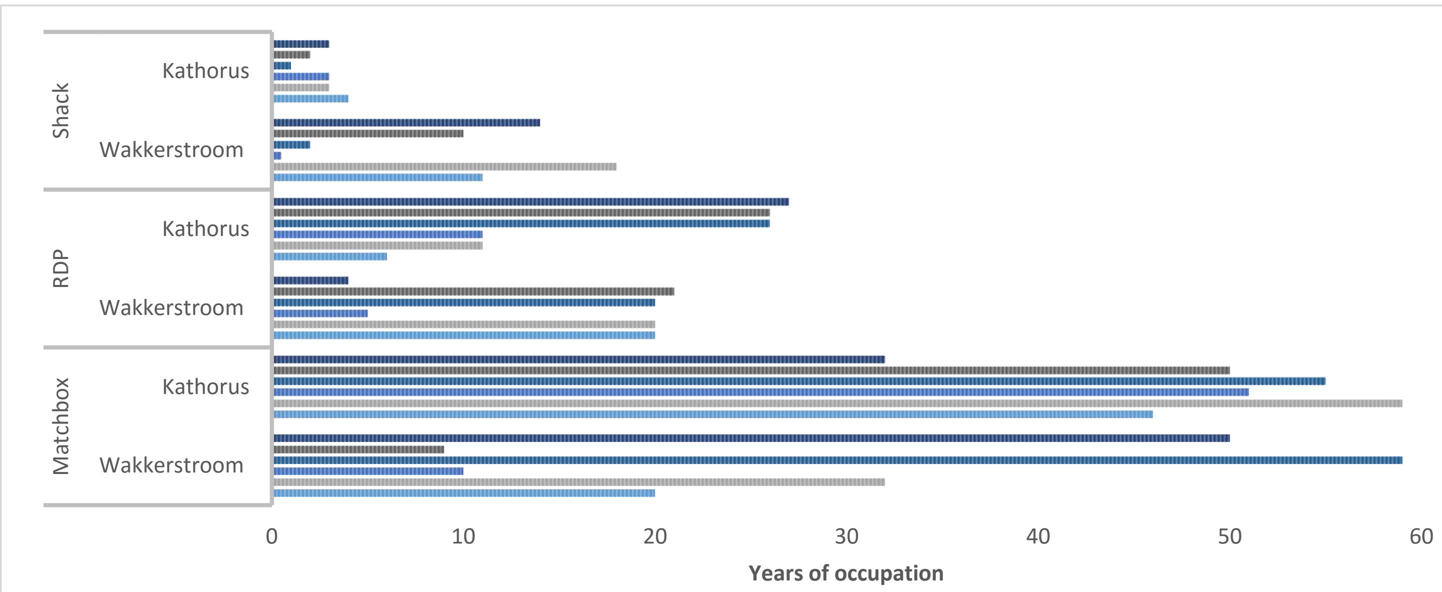


Figure 36: Self-reported years of occupation per housing type, per area (n=36), each bar represents a single household

4.7.2 Behavioural adaptation profile of occupants

Respondents were asked to communicate any adaptation strategy which they used, in both the warmer and colder months. The residents of Kathorus were found to be highly dependent on electricity, all the surveyed houses used electricity as their main source of energy throughout the year for cooking, and to heat their households during colder months (Table 7). If unforeseen events such as load-shedding (which is when power stations interrupt the supply of electricity in order avoid excessive load on the system) were to happen, most residents (65 %) in the Kathorus reported using gas stoves as an alternative. Residents of eSizameleni, relied heavily on wood as a primary source of energy (55%), for heating their homes as well as for the preparation of food. In eSizameleni dwellers largely avoided using electric heat sources, one respondent remarked "*Heaters do not warm up the whole house the way burning wood does… this is a cold place the whole house needs to be warm".* As such only 30% of RDP occupants and 16% of shack dwellers reported using electricity as their primary source of energy during the colder months.

Table 7: Self-reported adaptation methods used in Kathorus and Wakkerstroom during the colder and warmer months.

Housing Type (n=6 per housing type)		Additional energy consumption		Clothing Modifications		Behavioral Adaptations	
		Colder Months	**Warmer Months**	**Colder Months**	**Warmer Months**	**Colder Months**	**Warmer Months**
Kathorus	**Matchbox (Apartheid era)**	100% Electric Heaters	33 % Fans	100% Increasing clothing and add blankets	100% Decreasing clothing and blankets	*33% Sleep earlier 50% Open windows for circulation	100% Open windows and doors (67%-All day, 33%-2-4 hours)
	RDP (Post-1994)	100% Electric Heaters	-	50% Increasing clothing and blankets 50% Increase clothing only	100% Decreasing clothing and blankets	*50% Sleep earlier 0% opened windows and doors	100% Open windows and doors (All day)
	Shack (Informal Housing)	100% Electric Heaters	16 % Fans	67% Increase clothing and blankets 16% Blankets only 16% Nothing	100% Decreasing clothing and blankets	*67% Sleep earlier 33% Opened windows and doors	100% Open windows and doors (All day)
Wakkerstroom	**Matchbox (Apartheid era)**	67% Wood-fire 16% Coal fire	33% Fans	100% Increasing clothing and add blankets	100% Decreasing clothing and blankets	*50% Sleep earlier 67% Open windows for circulation	100% Open windows and doors (All day)
	RDP (Post-1994)	50% Wood-fire 30% Electric heater 20% Cow Dung	16% Fans	67% Increase clothing and blankets 16% Blankets only	100% Decreasing clothing and blankets	*50% Sleep earlier 67% Open windows for circulation	100% Open windows and doors (All day)
	Shack (Informal Housing)	50% Wood-fire 33% Gas stove 16% Electric heater	-	83% Increase clothing and blanket 16% Clothing only 16% Nothing	100% Decreasing clothing and blankets	*100% Sleep earlier 33% Open windows for circulation	100% Open windows and doors (All day)

**Sleeping earlier was found to be subjective, with average bedtimes in Wakkerstroom being 8pm and average bedtimes in Kathorus ranging from 10 pm -12 am daily.*

As seen in Table 7 during the colder months, increasing the amount of clothing worn and the number of blankets used was a popular adaptation strategy, used by almost 80 % of both the Kathorus and Wakkerstroom population, across all three housing types. Additionally, in Wakkerstroom, colder months resulted in earlier bedtimes, with 50 % of RDP and matchbox dwellers and an overwhelming 100 % of shack dwellers heading to bed earlier. Earlier bedtimes were also popular amongst the Kathorus population with 67 % of shacks dwellers and 50 % of RDPs choosing to sleep earlier. Half of the sampled matchbox population in eSizameleni and only 33 % in Kathorus reported to going to bed earlier during colder weather.

During colder months in Kathorus (Table 7), no RDP residents reported to opening either their doors or their windows. In eSizameleni more than 67 % of RDP residents reported to doing so. Fifty-percent of matchbox occupants in the Kathorus, and 67 % of matchbox occupants in eSizameleni reported to opening their windows and/or doors during the colder months. In both Kathorus and eSizameleni, only 33 % of shack dwellers reported to opening their windows during colder months. A common reason stated by a majority of shack dwellers for not opening windows during colder months was "*mechanical failure*", as the windows would fail to close properly after being opened. Additionally, all residents (across both locations) that reported to opening their windows and/or doors during colder months, reported doing so for less than 2 hours daily. During the warmer months, most residents (in both areas) communicated that they opened their windows and/or doors the entire day. Only 33 % of matchbox houses in Kathorus reported opening only their windows and doors for 2 - 4 hours per day. As a reason for this, they reported that they "*closed their homes windows and doors during working hours, and only opened them upon their return*". Ambient temperature seemed to play a large role on the duration occupants opened their windows and/or doors. During colder months windows and doors were commonly, opened for less than one hour, when asked the reason for this most occupants stated that "*opening windows or doors allowed for fresh air, but they didn't want the house to get cold"*.

During the warmer months in both Kathorus and eSizameleni (Table 7) very little was used to keep the house cool. In Kathorus and eSizameleni (during the warmer months), $^1/_3$ of matchbox brick houses reported to using electric fans to cool their homes. In the Kathorus only 16% of shack dwellers, and similarly 16 % of RDP dwellers in Wakkerstroom reported using this adaptation strategy. As anticipated, in the warmer months all respondents reported to have decreased the amount of clothing worn and the number of blankets used (on their beds).

4.8 Participant's thermal comfort perceptions

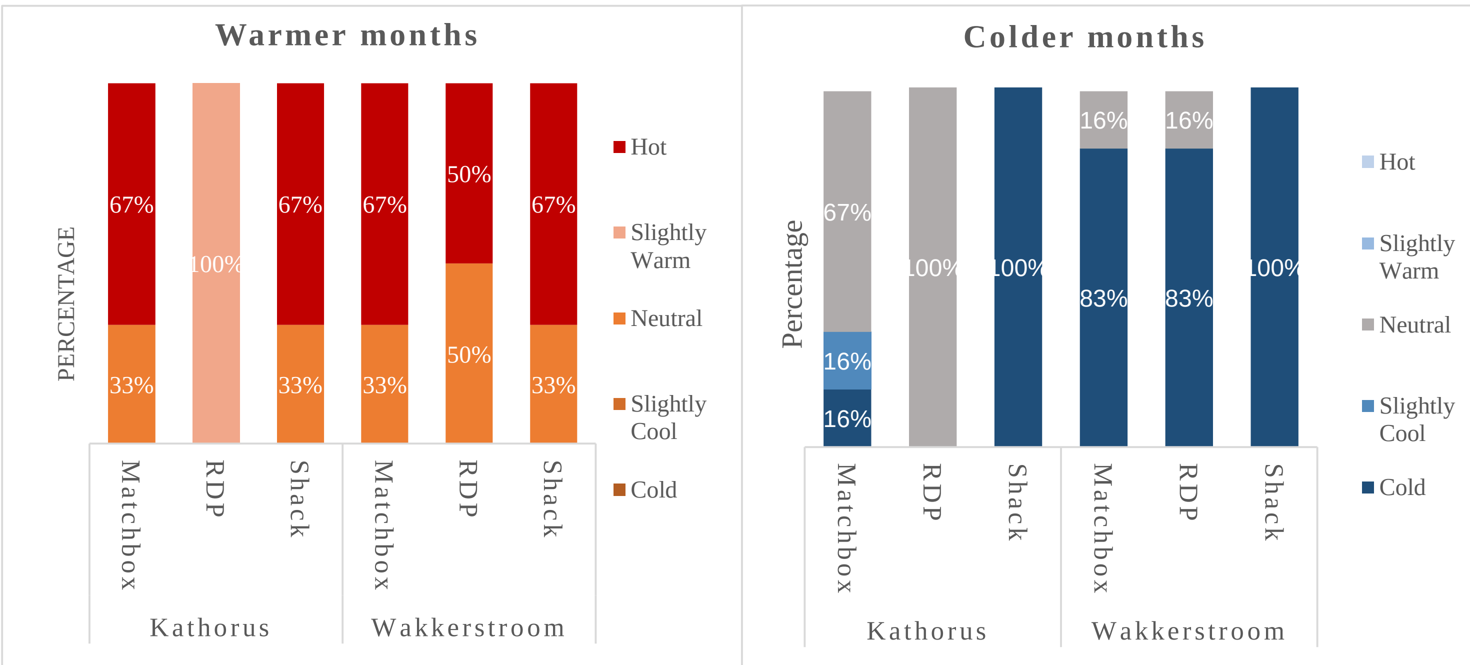


Figure 37: Self-reported perception of thermal comfort during warmer and colder months in Kathorus and Wakkerstroom area (n=35)

In order to understand the resident's perception of thermal comfort a three-point rating scale was used (too hot, neutral or too cold). However, many of the participants gave responses that did not quite fit into the scale. The scale was adjusted accordingly, where responses such as slightly warm and slightly cool were added as appropriate responses, and this is reflected in Figure 37.

In Kathorus (Figure 37), during warmer months, 67% of matchbox and shack (respectively) dwellers felt their homes were too hot, and only 33% felt thermally satisfied. All RDP dwellers in Kathorus, reported feeling that during warmer months their houses were slightly warm (but not intolerable). Following this trend, in Wakkerstroom 67% of matchbox and shacks dwellers (respectively) communicated feeling their homes were too hot during the warmer months. The remaining 33% of those occupants reported to having thermally satisfactory homes.

RDP Households in Wakkerstroom had an even mix (50%) of dwellers that felt their homes were too hot and those that reported feeling thermally satisfied.

During the colder months (Figure 37) in Kathorus, we see that a majority (67%) of matchbox house dwellers felt thermally comfortable, and 16% of residents felt the house was slightly cool and another 16% felt it was too cold. All Kathorus RDP dwellers felt that temperatures inside their homes were slightly cool (but not intolerable), while all the shack dwellers felt that their homes were too cold and offered little to no thermal comfort. In Wakkerstroom, during colder months, a large majority of dwellers (across housing types) felt their homes were too cold. For both matchbox and RDP houses, 83% of the occupants reported to having houses that were too cold, the remaining 16% (respectively) felt that their homes offered them thermal satisfaction. Interestingly, the homes that reported to feeling thermally satisfied were the homes with ceilings installed. All shack dwellers, in eSizameleni communicated that their homes were too cold during the colder months and offered them no thermal comfort.

Chapter 5: Discussion

Introduction

This discussion will address four interrelated subjects. Firstly, the range of indoor temperatures experienced in low cost housing will be discussed. Secondly, the apparent relationship between ambient and indoor temperatures, with special attention given to construction methods and materials used, will be placed into perspective. Thirdly, the overarching ambient conditions in which these houses exist in relation to their geographic locations will be discussed and, lastly the perceptions of house dwellers and factors which exist that determine satisfaction with one's surroundings will be reflected upon. The discussion will be organised so that it presents key research findings and relates them to the broader body of knowledge currently available.

5.1 The ranges of daily indoor temperatures experienced in low-cost houses

This study has provided much needed information on the thermal conditions experienced by residents of low-cost housing, during warmer (December –January) and colder (June- July) months, contributing to the fledgling field of thermal comfort studies in South Africa. The low-cost houses studied displayed significant levels of temperature variation between them, and between seasons, which supports similar studies conducted in Johannesburg (Gauteng) and Alice (Eastern Cape) by Naicker *et al.* (2017) and Makaka and Meyer (2006) (respectively). The Naicker *et al*. (2017) study was performed during relatively cooler months (February to May), which they hypothesized would not reveal as much indoor temperature variation as would warmer and colder months. Findings in this study were that during the colder months all three housing types showed greater amounts of indoor temperature variation than warmer months. Additionally, the study was able to demonstrate that the extent of tenants' vulnerability to indoor temperature extremes was largely dependent on where they lived, along with, which houses they occupied.

Naicker *et al*. (2017) showed that RDP houses as well as informal houses had the most variability and the highest temperature fluctuations throughout the day. This study however found that all three housing types displayed high temperature variability and daily fluctuations. Since this study recorded temperatures of the same three housing types in two different areas, which according to Kruger and Sekele (2013) had different climatological characteristics. It was able to further show that variability was to a great extent a function of season, location and housing type. Work by Nguyen *et al*., (2014) in Boston, in the United States of America, supported the concept of differing impacts that either warmer or colder weather had on indoor temperature variability. This study was able to build on those findings within the South African context using climatologically different areas. It was found, during the same season and geographical location, occupants of the three different low-cost housing types were not equally vulnerable.

Previous, South African based indoor thermal comfort studies did not look at which time of day the occupants of houses were at their most vulnerable to indoor temperature variations. Something which this study took into consideration. Indoor temperature variability in most of the houses studied (in both Kathorus and Wakkerstroom) was greatest in the early mornings (at 6 am). In China, Guo *et al.* (2014) found that people were most vulnerable to temperature variations when temperatures were at their lowest. According to SAWS's hourly indoor temperature readings, around 6 am was when ambient temperatures were at their lowest. Which simply put means, tenants of RDP low-cost housing types in Kathorus and Wakkerstroom were particularly vulnerable at 6 am (Figure 24), both during colder months.

5.2 Indoor temperature variability

5.2.1 Warmer months

During the warmer months even though temperature variability was low, daily temperature fluctuations were very high for all three housing types. In both areas indoor temperature fluctuations exceeded permissible ranges (of about 2 °C - 3 °C) given by ASHARE Standard 55 (2010) and Gaujena *et al*. (2015). Matchbox and RDP houses in both areas had approximately 8 °C of daily fluctuation each. Thermal studies suggest that such high thermal fluctuations cause thermal discomfort. As expected, the low thermal mass of shacks resulted in them exceeding the other two housing type's thermal fluctuations by almost double (at around 14 °C to 15 °C). This is more than quadruple the permissible range, adding to that increasingly high thermal fluctuations have been linked to numerous health issues (such as cardiovascular issues). Unlike the Naicker *et al.* (2017) study, which found that mainly RDP houses and informal houses displayed high temperature fluctuations. Our study found that high temperature fluctuations were common across all housing types and sites studied (particularly during warmer months).

Furthermore, the study found shack residents in Kathorus and Wakkerstroom were particularly vulnerable during the warmer months, due to exceedingly high indoor temperatures. The other types of housing (in both locations) largely had daily temperatures which fell within or near accepted South African thermal comfort standards (18 - 25 °C) suggested by Makaka and Meyer (2006). Even when temperatures in those households occasionally reached higher or lower values, while not ideal, were not life-threatening. Maximum temperatures inside shacks were found to be particularly high, reaching 33 °C in Wakkertstroom and 42 °C in Kathorus. The mean indoor temperatures measured in Kathorus shacks were consistently the highest (during warmer months) of any other housing type or site. According to Bröde *et al.* (2013), UTCI, and CIBSE (2015) temperatures above 35 °C, placed substantial physiological strain on the body, and could be life-threatening. The severity of risk however, is largely age related, very young and elderly people were of particular risk, this group accounted for about 30% of the shack dwellers in Kathorus.

5.2.2 Colder months

Colder month temperature variability was considerably high in both areas, across all housing types. Residents of low-cost houses in Wakkerstroom were particularly vulnerable to colder weather temperatures. The temperature clusters as defined by Kruger and Sekele (2013) placed Wakkerstroom in an area experiencing lower colder weather values than Kathorus. Mean temperatures in Wakkerstroom RDPs and shacks (at 6 am and midnight (respectively)), reached lows of about 8 °C, which according to UTCI could lead to slight cold stress.

The Guo *et al.* (2014) study linked increased risk of mortality to low early morning indoor temperatures when there was simultaneously high temperature variability. Residents of RDP houses in Wakkerstroom, were consequently identified as being at an increased risk to cold related physiological stress. High temperature variations, greater than 11 °C throughout the day, in all housing types Kathorus and the matchbox houses in Wakkerstroom, give reason for concern.

5.3 Relationship between indoor temperatures of low-cost houses and ambient temperatures

During the same season, indoor thermal conditions were different for each housing type occupying the same geographical location (Figures 25 and 26); but similar patterns did emerge.

In the warmer months, barring shacks, all other housing types' indoor temperatures were strongly associated and correlated with ambient temperatures. Warmer month indoor and ambient correlation is not unique to this study, work by Nguyen *et al*. (2014) also found this to be true. This study found that when dwellings were made from metal, not only was the correlation low in the warmer months, but temperatures often were several degrees Celsius higher than ambient temperatures. Shacks in Wakkerstroom had temperatures that were often 5 °C - 7 °C higher than ambient temperatures. The indoor thermal conditions in Kathorus were particularly noteworthy. Shack temperatures at times reached highs which were often 10 °C - 15 °C warmer than ambient temperatures. A study on indoor temperatures of shacks, by the Environmental and Geographical Science Department in UCT showed that having shack temperatures that were 10 °C higher than ambient conditions was not uncommon (UrbanAfrica.Net, 2018). This supports earlier indicators (temperature variability) that identified shack dwellers (particularly in the Kathorus) as being at increased health risk during warmer months.

Numerous international research studies (Gosling *et al*., 2009; Basu and Samet, 2002; Gouveia et al., 2003) have been conducted to show the association between highly elevated temperatures and increased mortality. This mortality is largely due to a range of cardiovascular diseases (such as ischemic heart disease, congestive heart failure etc.) which are prevalent during warmer months. Vulnerable subgroupings included, elderly people (over 65), young children, poorer people and the black racial group, which this study directly addresses

In Kathorus during the colder months, associations between indoor and ambient temperatures of shack and matchbox houses were low. There was a strong relationship between indoor and ambient temperatures of all housing types in Wakkerstroom, and RDP houses in Kathorus. The fact that during the colder months, particularly in Wakkerstroom such a strong relationship existed (with ambient temperatures) contradicts most literature on the topic which suggests that colder months have low indoor and ambient correlation. It appears that during the colder months, residents in eSizameleni were mainly vulnerable to low ambient temperature extremes. Even so, some occupants in Wakkerstroom were more vulnerable than others, due to the types of houses they lived in. Matchbox houses had indoor temperatures which were independent of the other two housing types, frequently having higher mean daily temperatures.

Which is to be expected, building on findings from Naicker *et al.* (2017) and Makaka and Meyer (2006). Studies (Makaka and Meyer (2006)) suggest that clay bricks used to construct matchbox houses have a higher thermal mass and lower thermal conductivity (than the other housing types), they more efficiently retained and stored solar energy. RDP and shack temperatures however, are buildings with low thermal mass and high thermal conductivity, and quickly responded to ambient changes. They had indoor temperatures which were closely associated with ambient temperatures $R^2 = 0.66$ (RDP) and $R^2 = 0.62$ (shack). Ambient temperatures often reached lows of 3 °C, the close ambient-indoor association should give reason for concern. Using the UTCI's scale, it is evident that very low temperatures, such as these could potentially lead to, slight to severe (age dependent) cold stress. This places RDP and shack dwellers (particularly in eSizameleni) at increased risk of cold related illnesses.

Keeping the house warm was of great importance to Wakkerstroom dwellers. They reported to predominantly using wood-fires to warm their homes (because it made the entire home warm), thereby exposing themselves to particulates in the air and to carbon monoxide poisoning. Occupants of RDPs and shacks in Wakkerstroom were identified to be at risk from not only cold related stress but perhaps from exposure to indoor pollution as well. Air quality and exposure to particulates while out of the scope of this study is an important risk factor to acknowledge, as it contributes to overall household satisfaction.

5.4 The choice of construction materials and its effect on ambient temperatures

The choice of construction materials should largely be climate dependent. This is true for developed countries where extreme seasonal variations, but low daily variations necessitate materials with good insulation properties. And climates with hot-dry extremes and high diurnal temperature range (DTR), necessitate materials with a high thermal mass. But because South Africa is a developing nation, the price and availability of building materials takes precedence over what is used to build low-cost houses. Ideally because of our climate, these materials would have an optimized balance between good insulation and high thermal mass. But this is often not the case.

In both Kathorus and Wakkerstroom matchbox houses were built with similar materials, for example, clay brick. According to the interview with Prof. Root this was because clay was so easily accessible in South Africa. Clay was found by Makaka and Meyer (2006) to have a good balance between insulation and thermal mass. During the warmer months homes built with clay brick had ambient temperature which were relatively strongly associated with indoor temperatures. It was not until the colder months that differences in indoor and ambient temperatures between the two locations could be more readily identified. Kathorus' matchbox houses were weakly associated with indoor temperatures where Wakkerstroom's weren't. Adding to that, matchbox houses in Kathorus had lower daily temperature fluctuations than in Wakkerstroom (3 °C and 10 °C, respectively). Since indoor temperatures (matchbox houses) were associated with ambient ones in Wakkerstroom, perhaps climatological differences displayed themselves in these high fluctuations. Furthermore, These findings support studies by Maoto and Worku (2018) that inadequate construction (even with adequate construction materials) lead to defects that display themselves in inadequate thermal regulation. Houses in the Wakkerstroom had on average more cracks (researcher observed) which is possibly the reason this strong association exists. Even so during the colder months, matchbox houses (in both areas) often retained heat better and had on average higher daily indoor temperatures than the other two housing types. Supporting research by Naicker *et al.* (2017) and Makaka and Meyer (2006) suggesting clay brick as being better than cement brick or metal sheets (used to construct the other two housing choices).

The RDP houses in both areas, had relatively high indoor and ambient temperature associations. In the Kathorus the association was about $R^2 = 0.57$ (both seasons). This association was higher still in Wakkerstroom, during both seasons studied ($R^2 = 0.7966$ (warmer) and R^2=0.621(colder)). As reported in interviews with Mr Kgasane and Prof. Root, RDP houses in Gauteng and Mpumalanga were made with similar brick materials, called maxi-bricks (composed of a large proportion of cement, and varying proportions of river sand and ash). As the name suggests these bricks were larger than conventional stock bricks (at least 25% larger), which means less of them could be used to build the same dimensions, making them the more cost-effective option. Makaka and Meyer (2006) stated that these bricks were highly thermally conductive (0.8 Watts per metre-Kelvin), less heavy, had a lower thermal mass and also had reduced insulation capacity than conventional stock bricks. The use of cement brick is not a poor choice of material, provided good plastering material is used. The RDP houses sampled were often not plastered which explains the relatively insufficient insulation offered.

The choice and ratio of each constituent building material (for example, what proportion of cement, to river sand to ash should be used) is largely contractor dependent. In both areas, during both seasons' the houses were not thermally ideal to inhabit. Even so, RDP houses in Kathorus were more thermally comfortable than those in Wakkerstroom, especially during the colder months. Quite probably differences in the level of skills, and experience of the various contractors used (in each municipality) and the variability of the construction materials markedly impacted the thermal properties RDP buildings. In addition, the open market procurement system (post-1994) resulted in an increase in poor quality control (Huchzermeyer, 2001). By increasing the number of small emergent contractors (according to Prof. Root) and not having an associated increase in the numbers of inspectors (for quality control), inconsistency in compliance with building standards increased. Analysis of actual building material was not within the scope of this study, it must be acknowledged that doing so would have aided in understanding how inconsistencies in contractor specifications either negatively or positively affected indoor thermal conditions. It appears from the results that the proportions of cement, river sand and ash in the maxi-bricks and contractors used in building RDP houses in Kathorus were better than Wakkerstroom. As recently as 2017 a Parliamentary Monitoring Group (PMG) determined that even though Gauteng's Department of Human Settlements had made some progress in addressing infrastructure issues, this progress had not been satisfactory (even with increasing funds). Interestingly, even with this poor performance Gauteng had outperformed Limpopo (Pmg.org.za, 2018). They identified that the main issues were inadequate infrastructure, choice and monitoring of contractors. The performance of the Department Human Settlements in the country is not satisfactory in some provinces and worst still in others, which often becomes apparent in the quality of low-cost homes given to the poor.

Adding ceilings (and plastering) could greatly improve the thermal quality of all housing types. The question arises, "*What is creating barriers to making necessary home improvements*?". For the occupant's, possible answers to this lie with the governmental system used to issue low-cost houses. The issuing of title deeds and home-ownership has been slow, and without ownership residents are often not motivated to make improvements to their houses. In the case of RDPs making alterations to homes means that occupants need to seek approval from the offices which issues said homes, which is often cumbersome. Adding to that, low-cost houses are inhabited by the poorest members of society who often cannot afford to add these structures post-occupation. The government cites monetary constraints, increased demand and inadequate capacity (municipal administrative issues) as reasons for issuing substandard housing (Marutlulle and Ijeoma, 2015). Even so ceilings (and additionally plastering) should be standard features in low-cost developments. Where ceilings were present, indoor temperatures of matchbox and RDP houses were about 25 % and 36 % (respectively) less associated with ambient temperatures, compared to similar households occupying the same geographical space. This marked disparity is as a result of the isolation (roof space from living space), stratification and convection effects offered by ceilings (Mathews and Weggelaar, 2017, Howden-Chapman *et al.*, 2007), which improved the thermal performance of the houses in question. Even with this knowledge, buildings with ceilings and/or plastering were in the minority in both areas, ceilings were only used in 33% of the matchbox and RDP houses in Wakkerstroom. Previous and existing low-cost housing regulations had/have not required ceilings or good plastering in order for building projects to be approved.

The Housing Development Agency (HDA) (2012) reports that the number of shacks is increasing particularly in Gauteng, as migrants (both international and national) seek accommodation close to their work. The use of metal and scavenged materials to construct shacks was based on availability and cost. For shack dwellers the thermal properties of their homes were not the major driver for choice of construction materials and the thermal properties of materials used to build shacks were particularly poor.

5.5 Long-term ambient temperatures in the context of housing

The 1960 to 2010 temperature record from the South African Department of Environmental Affairs (DEA, 2013) showed increasing annual T_{max} and T_{min} trends. The findings in this study are in support of general increasing temperature trends. Understanding historical ambient temperature trends can go a long way in understanding future indoor temperatures of low-cost houses.

Mean temperatures during the warmer months have increased at a more elevated rate in Kathorus. While warmer weather T_{max} (and not T_{min}) increases in the Kathorus have been more pronounced than those of Wakkerstroom. Kathorus has experienced a 1.07 °C increase in T_{min} since 1960 (Wakkerstroom has had 0.75 °C). Kathorus largely had warmer ambient temperatures than Wakkerstroom throughout the measured period. Elevated warmer month temperatures going into the future, in Kathorus are cause for concern as occupants in the area are already at an increased vulnerability to high temperatures. This is especially true for shack dwellers who live in homes where indoor temperatures are often several degrees Celsius higher than ambient temperatures.

For the most part temperature trends (from 1960 -2017) were not found to be significant, except for colder months. Both the T_{max} and T_{min} in Wakkerstroom, and only T_{min} in Kathorus were determined to be of statistical significance (during colder months). Overall temperatures (warmer and colder months) were increasing, however this increase was only statistically significant during colder months. Maximum temperatures during the colder months have been increasing at a relatively faster rate than other temperature values, 0.9 ˚C in Kathorus and 2.9 °C in Wakkerstroom. Which means that during the colder months, T_{max} temperatures were getting warmer, particularly in Wakkerstroom. The increase in mean (colder month) temperatures of Wakkerstroom can largely be attributed to the extremely high colder month temperatures experienced in 1982 (which will be discussed later). This significant warming T_{max} trend (in colder months) is in line with both regional and global warming trends (Kruger and Nxumalo, 2017; MacKellar *et al.*, 2014). When looking at temperature changes in southern Africa, cold extremes were more pronounced than warmer extremes (Tyson, 1990). Which is in support of this study's findings.

It is evident from the entire 57 year record (from 1960 to 2017) that there has been a general trend of increasing temperatures (T_{min} and T_{max}). However, T_{min} temperatures in Wakkerstroom from about 2000 have been showing a slight decrease during the warmer and colder months (getting colder), while T_{max} temperatures have been simultaneously getting warmer. Even though this is too short a period to make any conclusive findings on Wakkerstroom's general climatological trends, it is worthwhile to acknowledge. MacKeller *et al*. (2014) noted this apparent cooling trend (in the T_{min}) of the interior, but further stated that it was difficult to explain, he suggested more stability in ambient atmospheric conditions as a possible reason. Kruger and Nxumalo (2017) supported this, but additionally concluded that negative temperature trends in the interior were not of any significance and did not negate the general observed warming trend seen over the past 50 years.

5.5.1 Effect of ENSO on climate record

Several authors have shown the effect of the ENSO event (which is different to the observed long term interesting temperature trend) in 1982 to 1983, as having caused abrupt changes in mean annual temperatures. The effect of which is especially evident in Wakkerstroom, particularly with regards to minimum temperatures. During both the warmer and colder months, around 1982 to 1983, an abrupt increase (and disruption) of the general temperature trend of Wakkerstroom was obvious. However, the effect of the ENSO in Kathorus was not as clear. In fact, the T_{min} (and not T_{max}) of Kathorus slightly decreased (both warmer and colder weather) after 1982/83, when temperatures across the country were said to be at their highest. Interestingly, after the year 2000, temperatures in Kathorus have "recovered" from their slight decline and returned to their increasing trajectory. Which goes against what Kruger and Songwe (2004) had suggested. Moreover, the recent (insignificant) 17-year dip (starting in the year 2000) in T_{min} temperatures (warmer and colder months) experienced in Wakkertsroom could (speculatively) be a return to the earlier mean annual temperature trends experienced during 1960 to the early 1980s. At the same time, recorded T_{max} temperatures in Wakkerstroom (from 2000-2017) have shown an increase (getting warmer). It is unclear what occurred in the year 2000 which caused these temperature anomalies and consequently what led to this apparent "return" to pre-82 trajectories. But if this return to pre-82 trajectories is to continue then Kathorus inhabitants will experience higher warmer month temperatures and Wakkerstroom inhabitant's lower colder month lows (meaning that T_{min} temperatures will get even colder).

5.6 Perception of thermal comfort and its effect on resident's thermal satisfaction

The perception of thermal comfort was often not related with actual measured indoor temperature readings. Environmental factors (humidity and air velocity) and socio-economic factors (such as wealth status), while not within the scope of this research, which could perhaps offer some additional insight on thermal comfort and should be further investigated. This research did however focus on the key aspects which influenced perceptions of thermal comfort and satisfaction, of the two low-cost communities. The semi-structured interviews were structured in such a way as to encourage open dialog, respondent's thus shared additional information about their perceptions around housing, which included their perceived wealth status and mental state. Respondents reported to understanding what was being asked and were as a result candid with their responses (as there were no language barriers).

During the warmer months in both areas, matchbox house and shack residents reported having the same thermal experiences, 67 % reported to feeling hot and 33% reported to being thermally satisfied. These perceptions contrasted with the measured temperature, and ideal thermal comfort values given by ASHRAE Standard 55 (2010). Indoor temperatures in shacks were regularly much higher than matchbox houses (and ambient temperatures), so this similarity in satisfaction was unexpected. A reason for shack and matchbox dwellers having similar satisfaction rates could be the comparative number of occupants in each housing type, and the mental state of occupants. Because matchbox houses generally had more occupants than shacks, perhaps shack dwellers had a feeling of more control (Paciuk, 1990) of their thermal environments and therefore had a better outlook on their thermal comfort than expected. Additionally shack owners reported to being acclimated to their current homes, a number of shack dwellers reported to never having lived in a formal house (moving their shacks to different areas). The elevated percentage of thermal dissatisfaction reported, suggests that tenants are unhappy with their homes as a source of shelter in the warmer months. Housing according to Maslow's Hierarchy is at a similar level to other fundamental needs such as food.

All RDP dwellers in Kathorus reported to feeling slightly warm, but not to feeling high levels of discomfort, where only half of the RDP dwellers in Wakkerstroom reported to feeling hot. This largely positive response from RDP dwellers also does not coincide with the temperature readings. RDP houses' and shacks had similar daily temperatures. But for the most part RDP dwellers reported to feeling more positive about their homes. For shack, RDP and matchbox dwellers housing satisfaction and by extension thermal satisfaction seemed to be greatly associated with perceived wealth status. One RDP resident reported "*At least I don't live in a shack*" another commented on how old matchbox houses were. Suggesting that thermal satisfaction was as much a physiological phenomenon as a socio-economic one.

During the colder months in Kathorus a majority of matchbox (67%) and RDP (100%) occupants felt satisfied with their thermal environment. Their indoor temperatures were not too divergent from the suggested South African thermal standards (18 °C – 25 °C) (Makaka and Meyer, 2006). Contrastingly a vast majority (83%) of Wakkerstroom matchbox and RDP residents felt their homes were too cold and were therefore unhappy with their thermal environments. These findings corresponded with measured indoor temperatures, suggesting that during colder weather tenants were acutely aware of their thermal environments. As expected, all shack dwellers across locations felt thermally uncomfortable during the colder months. Even when the thermal conditions in Kathorus of shacks were slightly better than expected, respondents reported to feeling the least thermally satisfied. On the other hand, RDP dwellers (particularly in Kathorus) expressed the highest thermal satisfaction, which did not support thermal readings.

Conclusion

From the long-term record temperatures have generally increased, except for T_{min} temperatures in Kathorus during the colder months which have shown a largely insignificant decrease. Most temperature trends indices were statistically insignificant, barring from the colder months. Generally, Kathorus had temperatures which have been rising at a more elevated rate than Wakkerstroom. Mean indoor temperatures of all three housing types in Kathorus were higher than Wakkerstroom. During warmer months shacks had indoor temperatures which were exceedingly higher than any other housing type in both areas. During colder months RDP and shack temperatures in both areas were highly variable and insufficient at maintaining internal thermal conditions throughout the day. During the apartheid era, clay brick was used for low-cost houses because it was easily accessible. Maxi-brick's with unstandardized ingredients were used in post-apartheid tender based low-cost houses. Shacks mainly used cheap corrugated and scavenged material for builds. A lot of valuable information was gained from interviews, perception around thermal satisfaction and suggested guidelines on acceptable indoor temperatures often did not coincide. Confounding factors such as wealth status, perceived control over their environment seemed to greatly impact occupant's thermal satisfaction. In closing, and to answer the opening questions; it is unfortunate that the constitution does not explicitly define "adequacy", as a result the houses studied are technically constitutional, even though they are thermally inefficient.

Recommendations

Based on the findings in this study a few recommendations can be made, which could improve indoor temperatures of low-cost houses in order for them increase the standard of living of occupants . Firstly, features such as plastering, and ceilings should come standard with low-cost houses, as they are known to greatly improve indoor temperatures of low-cost houses. Secondly, because many people live in shacks for a number of years more research should be done by government in order to improve them and make them suitable for human inhabitation. And lastly, more long-term research should be done on the climate record in Wakkerstroom in order to understand the apparent temperature anomalies seen from the year 2000.

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Appendix 1: Semi-structured interview data

Title: A comparative study of indoor and ambient temperatures in three housing types in the Kathorus and Wakkerstroom areas, South Africa

School of Animal, Plant and Environmental Sciences

My name is Bongokuhle Mabuya and I invite you to participate in my MSc research project about the temperature inside and outside the house in warmer and colder months. I want to understand how comfortable you are living in the house during those times and if the materials used to build the house make any difference to your comfort level.
You have been chosen because you are a permanent occupant in one of the three common types of housing found in South Africa.

What is expected of you?
To allow me to place a small temperature monitoring tool in your living room. This tool only records the temperature. This tool will be placed where you decide and will be there for about 12 months. It will not affect your life. Answering 17 questions, 3 at the beginning of the study, I will then ask you 7 questions at the end of winter and 7 questions at the end of summer, which should take you no longer than 10 minutes to answer. Your answers will be recorded using an audio-recorder. The questions are about your experience living in the house. The questions will be about what you do inside the house to keep it warm when it is cold outside and cool when it is hot outside. You are under no obligation to participate and are free to withdraw at any time and you will not be penalised for doing so.

Promises made by researcher?
If you wish to participate, I will keep all your interview answers for this research project confidential, your privacy will be withheld at all times. Your answers to the questions will only be used for educational purposes and because of that there will be no payment offered to you for taking part.

What will happen to my answers?
Your answers will form part of my MSc dissertation, if you would like to see a summary of the project or have any questions you need answered feel free to contact me on bee.mabuya@gmail.com and my supervisor Prof. Mary Scholes on mary.scholes@wits.ac.za.

Thank You

Consent Form

I agree to participate in research entitled "A comparative study of indoor and ambient temperatures in three housing types in the Kathorus and Wakkerstroom areas, South Africa", conducted by Bongokuhle Mabuya. I will be participating of my own freewill and I understand that I have not been forced to do so. I also understand that at any point if I am uncomfortable or want to withdraw from participation, I will not be penalised in any way. I also know that this is a research project for academic purposes only and I will not get paid in any way for taking part. I am aware that my name and identity will stay private and my taking part is confidential. And my responses will remain private and confidential in the final research thesis and any resultant conferences and/or publications.

Are you willing to participate?	Yes	No
Are you willing to allow me to audio-record our interview?	Yes	No
Are you willing to allow me to use your answers for the purpose of my research (and resultant conferences and/or publications)?	Yes	No

I understand that the answers that I give will be stored electronically and will be used only for research now and at a later time.

X ______________________ X ______________________

Signature of participant Date

Isihloko: Siqhathanisa amazinga okushisa nokubanda ezinhlobeni ezintathu zezindlu, endaweni yase Kathorus naseWakkersrtoom eMzansi Afrika.

Mhlanganyeli/ Mbamb'iqhaza

Igama lami nginguBongokuhle Mabuya. Ngingajabula uma ungangisiza ukucubungula amazing okushisa nokubanda ngaphakathi nangaphandle kuhlobo lwendlu yakho.Ngezinkathi zokushisa nokubanda. Ngifisa ukwazi ukuthi uzizwa kanjani endlini yakho uma kubanda noma kushisa. Ngifuna nolwazi likuthi uhlobo lwematheriyali eyakheindlu yakho yenza mehluko muni uma kushisa noma kubanda.

Ukhethwe ukuthi ubambe iqhaza kulolucwaningo ngoba uhlala kwenye yezinhlobo zezindlu ezitholakala eMzansi Afrika.

Okulindeleke kuwe

Ukuphendula imibuzo engashumi nesikhombisa (17). Ngizokubuza imibuzo eyisikhombisa ukuphela kwehlobo neminye eyisikhombisa ekupheleni kobusika.Angeke yedlule emizuzwini engamashumi ukuyiphendula.Imibuzo izofuna ukwazi izimvo zakho ngokuhlala kulendlu yakho ngalezizinyanga. Imibuzo izofuna ukwazi ukuthi wenzani ukuthi ufudumale uma kubanda ngaphandle nokuthi wenzani uma kushisa ngaphandle ukuze uphole. Awuphoqelekile ukubamba iqhaza,ungayeka uma ungasafuniukuqhubeka.Angeke kwenzeke lutho oluzokubeka endaweni ebucayi. Lolucwaningo alunankokhelo ukusiza nje ukuthi ngikwazi ukuqoqa. Ulwazi ngamazinga okushisa nokubanda ezindlini ezinhlobonhlobo.

Okulindeleke kimi

Zonke izimpendulo zakhozizogcina phakathi kwami nawe.Isethembiso sami. Leso.Imfihlo yethu sobabili.Izimpendulo zakho zizosetshenziselwa ukuthola ulwazi oludingeka kwizifundo zami, yingakho kungenaholo.Isicelo sami ukuthola usizo lwakho ukuze ngikwazi ukuphothula lezifundo.

Kuzokwenzakalani ngezimpendulo zakho

Zizongisiza ukuhlaziya ekubhaleni izifundo zami zeziqu za masters.Uma ufuna. Iprojekthi ifingqiwe noma ufuna ulwazi ngayo ,khululeka ,ungithinte ngizochaza ngalokho ofuna ukukwazi. Ungangitinta bee.mabuya@gmail.com noma uthinte iSupervisor yami uMary Scholes ku mary.scholes@wits.ac.za

Ngiyabonga kakhulu

Ifomu lokuzibandakanya

Ngiyavumelana nokuzibandakanya , kanye nokubamba iqhaza kulomkhankaso wokucubungula ulwazi olumayelana namazinga okubanda nokushisa kwizinhlobo ezintathu zezindlu ezitholakala endaweni yaseKathorus nase Wakkerstroom e Mzansi Afrika.Ngizobamba iqhaza ngenhloso yokusiza , angiphoqiwe. Ngiyazi ukuthi uma ngifisa ukuqhela kulomkhankaso wokucubungula anginakujeziswa. Ngiyazwisisa ukuthi lolucubungulo luphathelene nezifundo akunaholo.Igama lami lizogodlwa lihlale liyimfihlo .

Uyavuma'uku nokuzibandakanya?	Yebo	Cha
Uyavuma uku'recodwa?	Yebo	Cha
Ungiphaimvume ukusebenzisa ipendulu zakho kuwi research (nama kwikomfa?)	Yebo	Cha

Ngivumelana nesiphakamiso sokuthi konke okuqukethwe kulolucwaningo kuzoqoqwa nge Computer ukuze izohlolisiswa.

________________________ ________________________

Ukusayina kobambe iqhaza Usuku

Interviewee Name: ____________________

Housing Type: ____________________

Location of Interview: ____________________

Date of Interview: ____________________

Gender: | M | F |

Age Range: | 18-25 | 26-35 | 36-50 | 51- |

Number of Occupants: ____________________

How long have you lived in the house?
Are you happy with how your windows and doors work?
If not what do you do to address this?

Colder Months Questions (From June to August)

1. Did you use anything to keep your house warm this winter?
2. If so what did you use to warm the house?
3. How do you decide when to warm the house?
4. What else did you do to keep warm this winter?
5. In winter do you go to bed earlier because it is cold outside?
6. Did you open your windows and doors this winter?
7. Indicate which answers corresponds most closely to your experience:

-In winter the house gets
- Too hot ☐
- Too cold ☐
- None of the above ☐

Warmer Months Questions (From December to February)

1. What did you do to keep the house cool this summer?
2. Did you open your windows and doors this summer?
3. If so for how long were the windows left open?
4. Did you do something else this summer to keep your house cool?
5. If so what did you use?
6. Indicate which answer corresponds most closely to your experiences:

- In summer the house gets
- Too hot ☐
- Too cold ☐
- None of the above ☐

7. Do you feel the house offers you enough shelter from the weather outside?

Igama Iobobzwayo: ______________________________

Uhlobo lwendlu: ______________________________

Indowo owakhe kuye: ______________________________

Usuku Iokuvavanywa: ______________________________

Ubulili: M F

Iminyaka: 18-25 26-35 36-50 51- above

Inani labantu endlini: ________________________

Uyangivumela yini ukhuthi ngifake ithulusi lokuhlola izinga lokushisa nokubanda emzini wakho? Yebo Cha

Sowuhale isikhathi esingakanani endlini?

Ujabulile ngokhusebenza kwama fastile nomunyango?

Uwenzani ukulungisa loko?

Imibuzo emyelana nezinga zasebusika

1. Kukhona yini okusebenzi-say ukufudumeza indlu kulobusika?
2. Usebenzisa ini ukufudumeza indlu yakho?
3. Uphoqwa yini ukuthi uyifudumeza?
4. Ukubanda kunomthelelo yini emananini ezingubo ozigqokayo?
5. Ingabe ukubanda kuyakuphoqa yini ukuthi ulale ngokushesha?
6. Uwavulile yini amafastile nomunyango kulobusika?
7. Khetha impendulo esondelene nokwenzeka kuwe endlini yakho:

-Ebusika indlu ithola

Ukushisa ngokwqile ☐

Ukubanda ngokweqile ☐

Ayikho okuhambelana nokungenhla ☐

Imibuzo ehambelana nehlobo

1. Ingabe uyavula amafastiela nomunyango la ehlobo ukuza kungene umayo opholile?
2. Uwashya isikhathi esingakanani amafestile evuliwe?
3. Kungabe kukhona yini okwenzayo ehlobo ukugcina indlu ipholile?
4. Usebenzisani?
5. Kukona okunye okuyenzayo ukuyenzayo ukugcina indlu ipholile?
6. Khetha impendulo esondelene nokwenzeka kuwe endlini yakho:

- -Ebusika indlu ithola

Ukushisa ngokwqile ☐

Ukubanda ngokweqile ☐

Ayikho okuhambelana nokungenhla ☐

7. Uma usendlini ingabe uthola ukuphepha kwisimo sezulu?

Appendix 2: Ethics Certificate

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Mabuya

CLEARANCE CERTIFICATE	PROTOCOL NUMBER: H17/06/06
PROJECT TITLE	A comparative study of indoor and ambient temperatures in three housing types in the Kathorus and Wakkerstroom areas, South Africa
INVESTIGATOR(S)	Ms B Mabuya
SCHOOL/DEPARTMENT	Animal, Plant and Environmental Sciences/
DATE CONSIDERED	23 June 2017
DECISION OF THE COMMITTEE	Approved
EXPIRY DATE	12 July 2020

DATE 13 July 2017 CHAIRPERSON ______________ (Professor J Knight)

cc: Supervisor : Professor M Scholes

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and ONE COPY returned to the Secretary at Room 10004, 10th Floor, Senate House, University. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to completion of a yearly progress report.**

Signature ______________ 20 / 07 / 2017 Date

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES