Urban heat islands in South Africa: A case study of Cape Town

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ABBREVIATIONS

AUHI	Atmospheric Urban Heat Island
CE	Cooling Efficiency
CoCT	City of Cape Town
CTMSDF	Cape Town Municipal Spatial Development Framework
GHG	Greenhouse gases
GTI	GeoTerraImage
ICC	International Code Council
ISA	Impervious Surface Area
IUDF	Integrated Urban Development Framework
LC	Land Cover
LST	Land Surface Temperature
MSDF	Municipal Spatial Development Framework
NDP	National Development Plan
SUHI	Surface Urban Heat Island
SUHII	Surface Urban Heat Island Intensity
SDF	Spatial Development Framework
UCI	Urban Cool Island
UHI	Urban Heat Island
UHII	Urban Heat Island Intensity

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CHAPTER 1 INTRODUCTION

Modern urban spaces are at odds with the natural environment, absorbing heat and repelling water as they disrupt the natural weather processes creating distinct climates within cities. A prominent feature of urban areas is that of Urban Heat Islands (UHI). UHI are areas in cities in which the atmospheric and surface temperatures are noticeably higher in comparison to the surrounding areas. These UHI are a result of a combination of the built infrastructure - size, shape, material and grouping of buildings and transport infrastructure – the increased energy use in urban areas and the lack of adequate green spaces. This effect is negatively influencing the habitability of these spaces, leading to adverse impacts on urban environments including human health. Major negative impacts of the UHI phenomenon are further increases in energy consumption, higher emissions of pollutants and greenhouse gases as well as reductions in human health and thermal comfort (Estoque, Murayama & Myint 2017).

The City of Cape Town (CoCT) is the second largest city in South Africa with a total population of just over 4 million people in 2016 (Statistics South Africa 2018a). Over the last few years, population growth figures have declined slightly from an average of 2.57% p.a. between 2001 and 2011 to 1.6% p.a. between the 2011 census and the community survey in 2016 (Statistics South Africa 2018a,b). Since the turn of the century, the population of Cape Town has increased just shy of 40% with the number of households increasing by almost 70% and adding over half a million people over 15 years (Statistics South Africa 2018a). In-migration to the CoCT is driven by two different motivations. There is a distinct migration pattern favouring environmentalism, where highly skilled and affluent migrants choose to migrate from other metropolitan cities in South Africa to Cape Town and its surrounding coastal municipalities. The dominant migration stream, however, originates from the poorer communities in the Eastern Cape, with young, unmarried, low-income as the common denominator of migrants. These people, driven mainly by productionism, the hope for economic opportunity and social upliftment, mainly end up in informal settlements in the CoCT and thus increase the demand of housing and the burden of employment creation for the municipality (Jacobs & Du Plessis 2016). The influx of people from a variety of origins, social status and skill-level, coupled with a reduction in average household size leads to stresses on the built environment, increasing the need for new housing, infrastructure and service development and continuously changes the existing land cover. For the fiscal period of 2017/2018 alone, 28% (R2.4 billion) of the Western Cape Governments infrastructure budget will be spent within the Cape Metro area, R621 million of which is to be used for the development of human settlement, illustrating the need for development (Western Cape Government 2017)

In addition to the influx of people and the demand for housing and infrastructure, the climate of the CoCT is changing as part of a global trend. Over the past decades, hot days have become more frequent and increased in intensity, indicative of significant warming trends. Projections forecast a drying trend for the whole of the Western Cape, including an incremental rise of mean, minimum and maximum temperatures. This trend could exacerbate the UHI-phenomenon in the future, alongside trapping more pollutants in the air, increasing heat stress and increasing the possibility of flooding (Midgley, Chapman, Hewitson, Johnston, De Wit, Ziervogel, Mukheibir, Van Niekerk, Tadross, Van Wilgen, Kgope, Morant, Theron, Scholes & Forsyth 2005).

With an increase in urbanisation, an understanding of the causes, effects and spatial distribution of UHI is important for the successful implementation of adaptation and mitigation measures (Li, Zhou, Asrar, Imhoff & Li 2017). As such the study of UHIs has developed into a prominent research topic in urban climatology, urban ecology, urban planning and urban geography and a significant number of papers have been put forward on the topic. Many of these studies are emphasizing that the heating effect can be mitigated and climate change effects can be managed through urban greening and smart building techniques. The overall consensus of these papers is clear, the UHI is a prominent phenomenon that occurs in every part of the world, at different stages of urbanisation and in different climates and urban management systems. The extent of the UHI-effect differs between varying externalities with the UHI Intensity, the difference between rural and urban temperatures, reaching upwards of 6°C in some regions. (Du, Cai, Xu, Wang, Wang & Cai 2017; Estoque *et al.* 2017; dos Santos, de Oliveira, da Silva, Gleriani, Gonçalves, Moreira, Silva, Branco, Moura, da Silva, Juvanhol, de Souza, Ribeiro, de Queiroz, Costa, Lorenzon, Domingues, Marcatti, de Castro, Resende, Gonzales, de Almeida Telles, Teixeira, dos Santos & Mota 2017; Yu, Guo, Jørgensen & Vejre 2017).

1.1 PROBLEM STATEMENT

Cities disrupt the natural ecosystem and microclimate as built-up areas consist of non-permeable surfaces such as tar and concrete. The resulting lack of vegetation and the form and structure of the urban built environment lead to the build-up of heat in most parts of the modern city. Some areas show an above average increase in temperature. This increase can be related back to a variety of factors, part of which are the structure, materials and positioning of the buildings and infrastructure, the overall morphology of the land and the lack of green spaces. This increase in temperature increases energy consumption exacerbates the pollution of the urban environment and proliferates heat stress and other potential health hazards, whose impacts will be exacerbated in the face of a changing climate.

The CoCT has seen a significant increase in population over the past decades and the city is predicted to continue this pattern of growth. The constant influx of people significantly changes the urban landscape, alters the existing land cover and leads to a higher ratio of the impervious surface area while simultaneously diminishing green spaces. With its Mediterranean climate, the city is already vulnerable to droughts and heatwaves, which are exacerbated by the rapid growth of the last years (Sorensen 2017). As recent as 2018, the city almost ran out of freshwater three years into a severe drought, diminishing close to critical capacity levels of 13.5% (Maxmen 2018). Part of the problem was the lack of supply reserves for the city, with six reservoirs holding less than two years' supply that was not extended due to short-sighted planning and hesitation regarding significant capital investments in infrastructure. This resulted in direct losses of about R2.5 billion in agriculture, tourism and other related economies as a direct result of the water crisis which could have been avoided with more futureproof planning (Muller 2018). Estimates conclude that climate change exacerbates this phenomenon, tripling the risk of severe droughts in the Western Cape (Le Page 2018). All of this points to an urgent need to invest resources in monitoring and modelling of the current and future risks of increases in temperatures, extreme weather events and periods of drought so to inform both political and private actions (Muller 2018). So far, the absence of publicly available documentation of the UHI effect within the city boundary indicates the absence of relevant data on its UHI phenomenon. The CoCT is thus currently ill-equipped to adequately address the phenomenon within its city boundaries

Analysis and visualization of the location and size of UHI in the CoCT will assist with the identification of areas in need for interventions as well as the most vulnerable populations. In terms of immediate relief and potential climate change mitigation, an assessment of both existing UHI and cool islands throughout the city can potentially inform both current urban management and future urban planning. This includes the possibility of encouraging the continued greening of urban spaces, increasing the albedo of built structures and changing the layout of new and existing developments to alleviate immediate and future heat stress in these spaces. In the CoCT especially, the coexistence of both formal and informal development is prone to the promulgation of inefficient human habitats with a large part of the population deemed especially vulnerable to extreme weather events. As heat waves and droughts are a natural part of the Mediterranean climate, it is of utmost importance to create a more sustainable and livable city for all its inhabitants going forward.

1.2 RESEARCH QUESTIONS:

1. Which areas inside the CoCT boundary show statistically significant heat build-up attributed to the UHI effect and to what extent?
2. What can be done to alleviate the current extent of UHI in the CoCT and how can the City mitigate the increase in the extent and intensity of these UHI while still providing an environment conducive to the demands of economic growth?
3. What are the implications for the planning and design of future development in CoCT?

1.3 AIM AND OBJECTIVES

1.3.1 Aim

The aim of this research project is to assess the current state of UHI and the cooling effect of green spaces in the City of Cape Town. This will assist with the identification of areas in need of intervention by both public and private entities to positively influence the urban microclimate, reduce energy consumption, curb increases in pollution and alleviate adverse health effects of increased urban temperatures such as heat-related mortality and heat stress.

1.3.2 Objectives

1. To establish the main trends, concepts and methodologies concerning UHI, green cities and urban greening concepts and their possible effects on climate change mitigation, globally and regionally, in order to confirm popular theory for testing.
2. To consider international, regional, national and local legislation, assess the awareness of the UHI phenomenon and its integration into development frameworks and action plans to indicate shortfalls and possible alignment with existing documents.
3. To use openly available satellite imagery to calculate the extent and intensity of existing UHI in the CoCT today using the approach described as part of the methodology.
4. To assess the influence of different land cover categories on land surface temperature fluctuations and UHI generation using available land cover data for the year 2013/2014.
5. To apply both ordinary and spatial statistical tools in order to analyse influencing factors that lead to the development of UHI to inform current areas of contestation and future development of the CoCT.

CHAPTER 2 LITERATURE REVIEW

2.1 BACKGROUND

Over the past decade, the global population has increased by almost 1 billion people to a total of 7.6 billion in 2017. The global population is increasing steadily and projections by the United Nations Department of Economic and Social Affairs estimate that by 2050, the global population figures will increase by 2.2 billion people (United Nations 2017a). To date, about 60% of the world's population lives in Asia, but according to the development projections, more than half of the future population growth will take place on the African continent. The population of 47 least developed countries, 33 of which are located in Africa, will nearly double by 2050. This population increase will possibly escalate the difficulty African governments will have to reduce poverty and hunger as well as to provide access to and improve health and education systems (United Nations 2017a). Most of this population growth is expected to occur in urban areas and as such, a majority of urban development is going to take place in developing countries for the next decades (Cui, Xu, Dong & Qin 2016). In the year 1950, only 30% of the world's population lived in urban areas. In the year 2018, this share has increased to 55% and is expected to reach 68% by 2050 (United Nations 2018). Looking at the total number of city dwellers over time reveals the true scale of the development and its widespread implications. In the year 1950, around 750 million people lived in cities. Since then this number has increased sixfold to about 4.2 billion in the year 2018. Both the population increase and the overall drive towards urbanisation will add approximately 2.5 billion people to the urban population by 2050 (United Nations 2018). This underlines the fact that urbanization is one of the 21st centuries most transformative trends (United Nations 2017b). Developing nations like China showcase a scale of urbanisation processes that are unprecedented in human history, eventually drawing the focus to the least developed countries who’s development trends are expected to follow suit (Cui *et al.* 2016).

The African continent is predominantly rural with only 43% of inhabitants living in urban areas, as 90% of the expected global urban growth is located in Asia and Africa, the two continents are to face immense changes to their urban landscapes (United Nations 2018). In addition to the population increase, in 2008 sub-Saharan Africa was home to 31% of the world’s poor and was only exceeded by India which was home to 35% of the world’s poorest people (using 1,25$/day as reference for the poverty line). This extreme scale of poverty combined with the fact that a majority of the poorest live in what the OECD considers to be fragile states, puts emphasis on the fact that these populations are highly vulnerable to any kind of stresses such as health and economic development trajectories, increased pollution, climate change and related mitigation efforts as well as rapid urbanisation (Sumner 2012). The African continent specifically faces both existing and predicted sustainability challenges. The unprecedented growth of urban populations puts considerable social, economic and physical development pressures on the urban systems of today which emphasises the need to account for the growth and expansion of cities as part of a sustainable development agenda (Kotharkar, Ramesh & Bagade 2018). The following chapter introduces the concept of UHI, lists it's known drivers, negative effects, current and future mitigation and adaptation strategies in an effort to provide a summary of the latest research.

2.2 URBAN HEAT ISLANDS

2.2.1 Overview

As part of the expansion of urban areas due to urbanisation processes, today's cities have undergone dramatic build-up of residential areas and drastic increases in commercial and industrial activities. This development is accompanied by a heavy use of synthetic construction materials to help facilitate this growth. The growth process affects the balance of the natural environment and leads to, among other effects, cities developing a distinct urban climate noticeably different to their rural counterparts. It has been observed that large cities harbour areas of both noticeably higher temperatures, called Urban Heat Islands, and in some locations also lower temperatures, called Urban Cool Island (UCI), than their rural surroundings (Monama 2012; Roth 2012).

UHI can be classified into two broad types that are interconnected, the one being a result of the other: The Surface Urban Heat Island (SUHI) and the Atmospheric Urban Heat Island (AUHI) (Voogt & Oke 2003). For the purpose of this study, only the SUHI is analysed to gain a large-scale overview of the UHI phenomenon in the study area. The AUHI provides the opportunity for further research but is highly dependent on the availability of data (Monama 2012).

The SUHI describes the phenomenon of warmer surface temperatures of the urban surface compared to the surrounding rural surfaces. It varies in intensity relative to seasonal differences in the amount of solar energy, different types of land use, land cover as well as cloud cover, atmospheric water content and precipitation (Hardy & Nel 2015; Monama 2012). In winter, it can have positive effects, reducing heating costs and cold-related deaths. However, the positive benefits are clearly outweighed by the negative effects. As seen with heat-related illnesses and mortality, air pollution, energy demands for cooling and increased greenhouse gas emissions resulting from these increased urban temperatures (Roth 2012). A UHI occurs due to a change in the natural energy balance as urban spaces are built and expand. Urban structures, the materials used, changes in the land cover and a variety of human activity such as transportation systems and energy usage for lighting, heating and cooling, alter the energy balance and the atmospheric state of the city (Roth 2012). With all future projections pointing towards an increase in urbanisation, an understanding of the causes, effects and spatial distribution of UHI are important for the successful implementation of adaptation and mitigation measures (Li *et al.* 2017).

2.2.2 The field of Urban Climatology

Ever since the advent of cities, their visual, physical and social impact have been analysed and discussed. It is only since the invention of meteorological instruments such as the thermometer, that these analyses gained more complexity and scientific significance. At the start of the 19th century, Luke Howard published two volumes of *The climate of London* (Howard 1818). He is since regarded as the father of urban climatology, being the first person to formally describe the distinct urban climate and the phenomenon underlying the UHI (Oke 1991). Howard is regarded as one of the first people to accurately measure differences in temperature between the city and the surrounding rural areas, even though the term Urban Heat Island was not used until 1958. Gordon Manley, an English climatologist that studied the urban climates of his home country, coined the phrase in his publications, marking the beginning of the official UHI research (Manley 1958).

2.2.3 Measuring UHI in the present

Since its humble beginnings, UHI research has undergone an extensive transformation. Computerisation and the increasing availability of satellite-based land remote sensing data through constellations like Landsat revolutionised the field. A review of UHI studies in the South Asian region revealed that the largest body of recent research on UHI used satellite-based analyses as their main research method, accompanied in a significant share by the use of fixed weather stations (Kotharkar *et al.* 2018). Mainly concerned with surface UHI, using satellite imagery is the preferred option for researchers. Converting the thermal infrared band measurements to gain temperature results is well documented with a variety of approaches, allowing the accurate assessment of land surface temperature (LST) and land cover (LC). Using satellite imagery to calculate LST has proven one of the most efficient ways of assessing surface temperatures on a regional scale, offering the ability to deduct relationships between land use, land cover changes and variations in temperatures (Monama 2012). Due to a high spatial resolution of modern satellites, a remote sensing approach is a method that allows for large-scale research of the UHI effect with relative ease compared to the traditional method which uses surface-based measurements with uneven distributions and a limited amount of locations (Liu & Zhang 2011). Studies found the LST method to serve as a reliable indicator for UHI and that there is a strong correlation between LST and atmospheric temperatures (Arrau & Pena, 2010 in: Monama 2012). There is, however, some variance in the relationship of LST and near-surface atmospheric temperatures. This variance is mainly exhibited during daytime due to short-term fluctuations in surface temperature depending on solar input when compared to the more consistent atmospheric temperature that results from the mixing of air in the atmosphere (USA Environmental Protection Agency 2012a).

2.2.4 Causes of urban heat islands

UHI involve a variety of factors that influence their generation and intensity. Higher urban temperatures are predominantly caused by the complexity and variety of urban structures that comprise cities and the diverse range of artificial materials that are used. In general, urban structures have a higher thermal capacity to store and radiate heat originating from both anthropogenic and natural sources (Rizwan, Dennis & Liu 2008). If a surface is dry, just under 50% of the absorbed energy is transferred to the surrounding air, heating it up in the process (Oke & Cleugh 1987). The intensity of solar radiation plays a major role in the amount of heat stored in urban buildings and infrastructure. The operation of vehicles, power plants, air conditioners and a host of other heat sources amplify the heating effect (Rizwan *et al.* 2008). In addition to the increase in thermal capacity, urban areas also typically feature less vegetation than their rural counterparts. This amplifies the local heat intensity due to a reduction in evapotranspiration, which would usually counteract excessive heat build-up to an extent (Rizwan *et al.* 2008). Urban areas are also very disparate in their internal structure among themselves and in comparison to rural areas. The high roughness that results from the way cities are shaped additionally limits natural convective heat removal, further amplifying the heating effect (Rizwan *et al.* 2008). A higher built-up intensity is recognised to potentially increase the amount of heat that is trapped by street canyons, increases the amount of heat emitted by human activities, exacerbates the amount of heat stored by artificial building materials and decreases the heat loss due to decreased and impaired vertical flux (Zhou, Zhao, Liu, Zhang & Zhu 2014)

2.2.4.1 Urban area and population growth

Although the size of an urban area is not considered a direct driving factor for an increase in the UHI-effect, it is an important proxy to these factors (Li *et al.* 2017) Previous research on 5000 urban areas in the USA revealed a statistically significant relationship between the size of urban areas and the SUHI. Doubling the size of the urban area results in a temperature increase of 0.7°C on average with results differing between different climatic and temporal particulars. Urban size alone explains up to 87% of the variance of SUHI in the USA, thus it can be concluded that larger cities face more problems with UHI (Li *et al.* 2017).

The population figures and individual demographics also have an effect on the UHI generation. Regions of high population growth exhibit a higher potential for the increase of UHI. The regions most affected by this trend are the Middle East, the Indian Subcontinent and East Africa (McCarthy, Best & Betts 2010). An assessment of UHI in a number of global cities found population numbers to have a more significant influence on the SUHI intensity in early urbanisation stages, with increases in GDP exerting a more significant influence on SUHI intensity in later development stages (Cui *et al.* 2016). It should be noted that research results on the influence of population densities on UHI build-up differ depending on the climatic, political and social context. Data on population densities influence on the SUHI intensities that were collected as part of a study of 70 European cities indicates no significant correlation between surface UHI intensity and population density (Ward, Lauf, Kleinschmit & Endlicher 2016). This demands further investigation in a variety of environments from urban areas in developed countries to developing countries. The African continent could be of specific interest due to the expected population growth and the expected influx of people to urban areas herein which exceeds that of every other continent over the next century (Cui *et al.* 2016; United Nations 2017a).

2.2.4.2 Land Cover Change

Urban growth drastically transforms the land surface characteristics including that of land cover and leads to an increase in the share of impervious surfaces (Li, Zhang & Kainz 2012). A case study of Berlin in Germany shows a significant correlation between the spatial pattern for land surface temperatures and impervious surface areas (ISA). This relationship can be reproduced for cities in biomes dominated by forests and grasslands. In the case of Berlin, the Surface Urban Heat Island Intensity (SUHII), the maximum temperature difference between urban and non-urban surfaces, reached temperature differences of between 4-6°C (Li, Zhou, Li, Meng, Wang, Wu & Sodoudi 2018). Studies in other parts of the world reveal a similar pattern. In the case in Vila Velha in Brazil the SUHI ranged between 2.3°C and 7.1°C, with the maximum intensity recorded in areas with a higher built-up index (dos Santos *et al.* 2017). An analysis of the city of Lucknow in central India revealed an increase in temperature over a decade of 0.75°C. This increase was linked to increased urbanisation and the resulting land cover changes, especially in areas with high building densities (Singh, Kikon & Verma 2017). Meanwhile, cities in arid or desert environments around the world react differently to an increase in impervious surface areas and show no or small UHI effects (Imhoff, Zhang, Wolfe & Bounoua 2010; Lazzarini, Molini, Marpu, Ouarda & Ghedira 2015; Li, Zhou, *et al.* 2018; Zhang, Imhoff, Wolfe & Bounoua 2010). An example of such a city is Las Vegas, which instead of exhibiting a distinct UHI effect acts as a heat sink in comparison to the surrounding environment (Imhoff *et al.* 2010). Often, hot desert cities exhibit an urban cool island effect during the day and a classical UHI effect at night, indicating diurnal temperature fluctuations. In the most extreme cases, the SUHII was measured at up to -5.3°C (Abu Dhabi summer – April to September) (Lazzarini *et al.* 2015). The differences in UHI between biomes have mainly been attributed to differential roles of vegetation during precipitation, evaporation and photosynthesis (Imhoff *et al.* 2010). Innovative urban developments such as Masdar City in the United Arab Emirates showcase that the cooling phenomenon can not only be amplified with vegetation but also through the application of thoughtful urban design such as shaded walkways and wind-towers to maximise shading and airflow and create sustainable human habitats (Masdar 2015, 2018).

2.2.4.3 Pollution

A higher built-up intensity and an increase in human activity generally lead to increases in the levels of polluting aerosols in the urban environment. This is mainly the result of increased energy use for cooling, heating and other uses as well as the proliferation of urban transport, both private and public. The increase in polluting aerosols alone has been proven to increase nighttime temperatures by about 12% due to heat being trapped inside the city. Pollution-induced higher aerosol concentrations near the surface, albeit slightly decreasing the amount of solar radiation received on the surface during daytime due to scattering effects, lead to a higher reflection and absorption of radiation during the night, thus increasing the temperature of the surface and atmospheric UHI (Li, Meier, Lee, Chakraborty, Liu, Schaap & Sodoudi 2018).

2.2.4.4 Climate change

An analysis of European cities established that urban areas in colder climates are overall more vulnerable to heat waves and increases in UHI intensities when compared to cities in the Mediterranean or more arid climates. Cities in temperate regions are often less adapted to heat than their counterparts in hotter more arid environments (Ward *et al.* 2016). The USA show the same trend, with the cities in the colder climates of the northern states exhibiting a stronger SUHI effect with an increase in urban area size compared to that of cities in the southern states (Li *et al.* 2017). A comparative analysis of UHI in the different climates of the African continent or individual countries thereof is lacking.

Second only to urbanisation, the possible implications of climate change are amongst the most transformative trends of our time. The current and predicted changes raise a host of issues. While not strictly a main cause, increases in temperature have a high probability to increase in the number and extent of UHI in both the near and far future (Ward *et al.* 2016). There is vast potential to exacerbate the negative effects attributed to UHI dramatically, with their intensity expected to increase by up to 30% in some regions, considering a doubling of atmospheric CO^2 concentrations. While the global average temperature increase resulting of a doubling of atmospheric CO^2 are expected to fall between 2.3°C and 3.4°C, urban surfaces could face a potential temperature increase of up to 6.2°C on average (at its extreme end in the Middle East) (McCarthy *et al.* 2010). Especially the night-time UHI will be affected, with the number of hot nights expected to increase significantly. This could aggravate urban populations vulnerability to heat stress and deteriorate human health and well-being (McCarthy *et al.* 2010; Oleson 2012). Although these figures represent the extreme end of the spectrum of scenarios, the impact of climate change on urban climates is highly relevant for the planning of sustainable cities and mitigating adverse effects of the warming in the future.

Some studies suggest that while the UHI effect will increase significantly in its occurrence and extent, the SUHI intensity will only increase slightly over the course of this century. This counterintuitive phenomenon can be related to rural areas being expected to experience a greater increase in average temperature than urban areas. This can mainly be linked to changes in evapotranspiration. An increase in average temperatures reduces the liquid water content of the soil matrix, resulting in a lower heat capacity and thus slowly increase rural temperatures relative to the city. Notwithstanding, this only reduces the UHI intensity, not their occurrence nor adverse effects. If anything, this effect might exacerbate the problem (McCarthy *et al.* 2010; Oleson 2012; Roberge & Sushama 2018).

Around the globe, researchers are trying to predict the effects of climate change on the urban sphere using a variety of models to estimate urban growth and local and regional climate trends. In South East Asia a regional climate model was used to predict the UHI influences of planned urban expansion of Ho Chi Minh City, the largest city in Vietnam. While the study's outlook covered a mere three years into the future, the predictions show a surface air temperature increase of 0.22°C in pre-existing urbanized areas and 0.41°C in new highly urbanized areas (Doan, Kusaka & Ho 2016). Their data did not, however, reveal a short-term influence on thermal comfort in these areas. Their study explained the intense temperature increase in newly established areas by linking the accompanying decrease in evapotranspiration. This decrease manifests in a reduction of relative humidity of between 1.3-3%, in turn increasing the atmospheric temperatures (Doan *et al.* 2016). The implications of reduced humidity and a more intense UHI effect in newly developed suburbs, as well as its influence on urban thermal comfort in humid climates such as the subtropics, offers the chance for future research.

2.2.4.5 Summary

Overall, global SUHI shows significant heterogeneity which can be related back to different geographical, climatic and socioeconomic disparities between cities globally. A study of global SUHI distribution and variance showed a significant correlation between SUHI, population numbers and GDP figures in global cities around the world indicating a significant increase of SUHII in cities with more economic activity and population (Cui *et al.* 2016). This notion repeats in a variety of papers, with the underlying data demonstrating that higher Land Surface

Temperatures are usually correlated with the rise of fractional or absent vegetation cover, higher population densities and road densities (Li *et al.* 2012). During the day, SUHI intensity correlates strongly with vegetation activity and anthropogenic heat emission in the summer months, and with the local climate in winter. During the night, SUHI intensity correlates strongest with surface albedo, anthropogenic heat emission, built-up intensity and the local climate both during winter and summer. The local climate seems to have the most control over the SUHI spatial variability, but common consensus is that more complex mechanisms are involved, especially for daytime SUHI (Zhou *et al.* 2014). Pollution is also deemed an important factor, mainly because it increases temperatures at night time.

The inherent heterogeneity of UHI emphasises the need to look at different urban environments, especially in developing countries with the aim to assess the common factors influencing UHI occurrence and increases in SUHI intensity. This can inform the development of mitigation strategies adapted to the individual regional context.

2.2.5 Effects and mitigation of UHI

Urbanisation carries a variety of effects on the cities of today. Increases in urban populations can have distinct advantages, especially in a developing country context. The process of urbanisation is closely linked with economic development. Urbanisation level and per capita income are positively correlated, especially in countries with a GDP per capita of below 10 000 US$. Urban growth can thus be seen as a strong indicator of productivity growth and cities play a major role in the national economies of developing countries. With an increase in urban populations the economy can take advantage of the establishment of large and diversified labour pools, locational advantages in terms of proximity of suppliers and consumers, horizontal and vertical spillover effects and the incubation of new ideas and technologies in a creative milieu. Additionally, cities act as agents of social, political and cultural advancements and can thus be conducive to the advancement of societies (Zhang 2016). However, even though urbanisation can have a range of distinct advantages the process is also accompanied by a range of potential negative effects and developments. From intensified energy consumption to congestion, from air and water pollution to toxic waste disposal, from social inequality to a decrease in public health. Urbanisation increases the strain on urban systems in general (Bibri & Krogstie 2017). UHI exacerbate many of these negative effects of urbanisation. The number, extent and intensity of UHI can have a variety of effects on the urban environment and its inhabitants. Increases in energy consumption, economic losses and adverse health effects are only a glimpse of the potential effects (Du *et al.* 2017; Ng, Chen, Wang & Yuan 2012).

2.2.5.1 Energy consumption

Urban areas are the most energy demanding areas on the planet. They already account for between 75% and 90% of the world energy use and have a dramatic impact on the environment (Akbari & Kolokotsa 2016; Bretzke 2013). An increase in temperature is accompanied by an increase in electricity use for cooling. A host of studies throughout the world prove a significant relationship between UHI intensity and increased energy consumption. In both Brazil and Thailand, an increase in UHI intensity is also correlated with an increase in energy consumption in the same area (Arifwidodo & Chandrasiri 2015; Souza, Postigo, Oliveira & Nakata 2009). In Rome, the current UHI has attributed a 10% increase in cooling demand in institutional buildings, while simultaneously decreasing the need for heating in winter by 5%. This effect was especially prominent in buildings with a low thermal mass (Calice, Clemente, Salvati, Palme & Inostroza 2017). Modelling building performance (a building's response to external and internal stimuli – in this case, focused on heating and cooling demand), the incorporation of UHI effects into the mathematical model resulted in an increase in energy demand of between 15% and 200% (Palme, Inostroza, Villacreses, Lobato-Cordero & Carrasco 2017). Even if the extent of the increase in energy consumption due to the UHI phenomenon differs between cities in different climates, different urban policies and different economies, the overall trend is clear: the UHI phenomenon results in a significant increase in energy consumption.

2.2.5.2 Economic impacts

It has already been established that UHI can have serious implications for energy consumption within cities. While an assessment of the economic impact is a complex endeavour, some studies have tried to quantify the effect with concerning results. In an assessment of 1692 cities, it was found that climate change and UHI impacts combined could cost cities as much as 10.9% of their GDP. While this figure represents the extreme outliers, the average loss in GDP due to the combined costs of climate change and UHI is still as high as 5.6 %. However, it should be considered that climate change drives most of these costs, but the estimations are on average 30% higher due to UHI effects, even under low emission scenarios (Estrada, Botzen & Tol 2017). In a study of a range of global cities, the annual cost of the current UHI was calculated to be as high as 0.28% of the cities GDP (Phoenix, USA) – only looking at increases in cooling degree days and the related increasing electricity and repair costs of AC equipment. The additional electricity and maintenance costs for operating AC equipment in Phoenix alone was estimated at almost 500 million dollars a year based on a UHI intensity of 3°C. Considering that the calculation is based only on increased AC usage and as such is very limited in scope, overall costs might be much higher, albeit difficult to assess. These costs vary between cities in different political and atmospheric climates. Additionally, the model works under the assumption of universal access to AC units in all countries under study, which cannot be substantiated in some cases. Notwithstanding, the UHI effect is a cost factor for any city which should be taken into consideration to avoid unintended consequences of urbanisation(Miner, Taylor, Jones & Phelan 2017). Looking at South Africa in particular, its economy is heavily reliant on its strong human capital, especially the labour force. Direct exposure to UHI in the form of increases in temperature might result in diminished labour capacity. Indirect exposures can have a similar if not more extreme effect due to the faster distribution of diseases with increases in temperature (Department of Environmental Affairs 2017).

2.2.5.3 Health and lifestyle effects

Higher urban temperatures in general and UHI especially have a significant impact on human health, thermal comfort, heat-related mortality and mortality risk (Curriero, Heiner, Samet, Zeger, Strug & Patz 2002; Hondula, Davis & Georgescu 2018). A case study of Ho Chi Minh, the Capital of Vietnam, revealed that UHI lead to an overall increase in mortality risk. As part of the analysis, the attributable fraction of heat deaths resulting from all heat categories is higher in central areas of cities compared to that of the outer areas. The attributable fraction of deaths in the central areas of Ho Chi Minh was 0.42% higher than the outer areas (1.42% and 1% of all deaths respectively), implying a link to the UHI phenomenon (Dang, Van, Kusaka, Seposo & Honda 2017). In a study of nine US cities around the turn of the century, a 5.5°C increase in temperature was found to increase mortality by 1.8% overall. Cities in the warmer climates of California were found to undergo a mortality increase of between 2-3%, emphasizing a linear relationship between higher temperature and mortality (Zanobetti & Schwartz 2008) Both cardiovascular and respiratory diseases are the most prominent cause for the increase in mortality. This is mainly linked to the fact that a large percentage of deaths involved old and frail people, parts of the population that are deemed most vulnerable overall (Baccini, Kosatsky & Biggeri 2013; Curriero *et al.* 2002; Leone, D'Ippoliti, De Sario, Analitis, Menne, Katsouyanni, De'Donato, Basagana, Salah, Casimiro, Dörtbudak, Iñiguez, Peretz, Wolf & Michelozzi 2013; Zanobetti & Schwartz 2008).

Another USA based study of 11 cities in the eastern part of the United States revealed that while mortality is increasing with additional heat, northern cities located in more temperate environments are the most vulnerable to the increase in temperature. The risk increase for the southern cities eventually levelled off, which was attributed to the high percentage of air-conditioning ownership in the homes (e.g. 96% in Miami). As such, mortality risk levelling off can be attributed to the economic status of the population (Curriero *et al.* 2002). Their study also revealed that people without a high school education and people in poverty exhibit the highest vulnerability to the effects of warmer temperatures, throughout every latitude. In the case of hot-weather events, mortality increases almost instantaneous, with effects statistically proven to be noticeable within a single day (Curriero *et al.* 2002). Similar conclusions have been drawn on the European continent. A study of 15 European cities in the 1990s revealed that up to 2300 deaths could be attributed to summer heat in that decade. Aside the total number of deaths, an estimated 23000 years of life were lost due to the negative effects of heat in these cities with over half of that effect felt by population groups younger than 75 (Baccini *et al.* 2013). Leaving the more temperate climates, the Mediterranean climates of Istanbul and Tunis result in a higher mortality increase for the younger age groups between 0-14 and 15-65 while cities in more temperate climates show a higher increase in the vulnerability of older population groups (65+) (Leone *et al.* 2013). The increased vulnerability of younger populations showcases an especially severe public health issue, considering urban development trajectories in the countries under study (Leone *et al.* 2013). Considering their results, it is equally if not more important to assess and address the future of heat stress in cities like Cape Town, that hold similar climates.

The urban climate also influences the way people use the urban environment. A healthy climate is more conducive to active usage of public spaces such as parks, squares as well as residential and shopping streets, making UHI mitigation even more attractive to facilitate the creation of sustainable human settlements (Kleerekoper, Van Esch & Salcedo 2012).

2.2.5.4 Summary

The UHI phenomenon is associated with a wide and serious range of implications for current and future urban spaces. The increase in temperature is proven to significantly increase energy consumption, mainly as additional demand for cooling. The economic impact of this increased energy use (including that of diminished labour capacity) is deemed dramatic, with climate change and UHI effect leading to significant losses in GDP. The UHI phenomenon also significantly influences the health of the population, with an increase of cardiovascular and respiratory diseases as well as increased mortality and years of life lost, particularly for vulnerable populations.

2.2.6 Current and future mitigation and adaptation strategies

A variety of UHI mitigation and climate change adaptation strategies can be used to limit the effects, scale and intensity of the UHI. Over the last decades, two prominent clusters of mitigation strategies have been identified, increasing evapotranspiration and increasing solar reflectance. The latter is mainly concerned with minimising the absorption of solar radiation in the urban environment by development and use of materials with a high reflectance. The former aims to increase evapotranspiration, cooling the surrounding air with an increase in the number and extent of vegetated areas such as parks, green roofs, facades and walls (Akbari & Kolokotsa 2016). The subsequent sections provide an overview of the potential methods and efficiencies of these methods in an attempt to evaluate the options available for the City of Cape Town. Overall, effective landscape planning is known for its potential to have drastic effects on the urban thermal environment and can even lead to a reversal of the heating trends by actively facilitating the construction of Urban Cool Islands (Du *et al.* 2017)

2.2.6.1 Increasing evapotranspiration

i. Green spaces (Parks, street planting and more)

A host of research papers have assessed the benefits of a variety of urban green spaces as part of UHI mitigation strategies. The increased evapotranspiration and shading mechanisms provided by green vegetation have a distinct positive influence in keeping urban temperatures in check and reducing the UHI effect (Santamouris 2014; Yu, Guo, Zeng, Koga & Vejre 2018; Žuvela-Aloise, Koch, Buchholz & Früh 2016). As such, green spaces can be seen as fulfilling an important ecosystem service (Estoque *et al.* 2017). Their cooling effect varies depending on their spatial characteristics, landscape composition and vertical structure (Akbari & Kolokotsa 2016; Bowler, Buyung-Ali, Knight & Pullin 2010; Vaz Monteiro, Doick, Handley & Peace 2016; Xiao, Dong, Yan, Yang & Xiong 2018). In a meta-analysis of 51 studies on urban greening and the cooling effect of different types of green sites, it was found that the size of parks plays a major role in the cooling efficiency with larger parks usually exhibiting cooler temperatures and a further reaching cooling effect as proven in Taipei and Mexico City. In terms of spatial characteristics, green spaces with a higher percentage of tree and shrub cover yield the highest cooling efficiencies while grass surfaces indicate the lowest cooling effect (Bowler *et al.* 2010). Similarly, a study on London manages to show a linear connection between cooling distance and area of green space, tree canopy and grass coverage. Cooling distance herein is most strongly related to increases in tree canopy (Vaz Monteiro *et al.* 2016). Similarly, in Suzhou in China, green area perimeter is correlated with maximising cooling and humidifying effects of green spaces. Smaller parks were found to sometimes counteract the cooling effect by preserving heat instead of cooling the air. The study found that an increase in complexity of the vegetation community structures yields a significant cooling effect (Xiao *et al.* 2018). This goes to show that the planning and provision of effective green space for cooling purposes is highly complex. In order to optimise green space cooling efficiencies current and proposed green spaces will need to undergo a range of assessments from optimum canopy density, local climate and vegetation and localised circulation patterns (Hondula *et al.* 2018).

The relationship between LST and urban green spaces has been approached by a variety of researchers in recent years (Asgarian, Amiri & Sakieh 2015; Ren, Deng, Zuo, Song, Liao, Xu, Chen, Hua & Li 2016; Yu *et al.* 2018). Quantifying the cooling extent and cooling intensity of green spaces has yielded a wide variety of results. While all the studies considered did prove a cooling effect of green spaces, the degree of cooling efficiency differed between the different cities under analysis. A comprehensive meta-analysis of this research concluded that the average reduction of green space temperature is 0.94°C and 1.15°C during the day and night respectively (Bowler *et al.* 2010). A study of different megacities in Southeast Asia reported a 3°C difference between LST of impervious surface and green space on average, indicating the importance of green space in UHI mitigation (Estoque *et al.* 2017). Meanwhile, a study in Lisbon established that green spaces can result in a temperature reduction of up to 6.9°C on a summers day emphasizing the dependence of cooling efficiencies on local climate and built environment (Oliveira, Andrade & Vaz 2011). Reducing atmospheric temperatures can have more implications than simple thermal comfort. An analysis of Ho Chi Minh City and heat-related deaths suggests that every increase of green space by 1 km^2 can prevent 7.4 deaths caused by heat-related stresses and illnesses (Dang *et al.* 2017).

The cooling extent is additionally more than just a micro phenomenon, with its effect reaching further than the green space boundary. A study from Japan suggests, that while the cooling extent can exceed 300m, it did not extend beyond 500m (Hamada & Ohta 2010). With temperature ranges, there are vast differences between high and low latitude cities with a study in Gothenburg, Sweden showing a maximum temperature difference of 5.9°C and a cooling extent of over 1km from the respective park's borders (Upmanis, Eliasson & Lindqvist 1998). Results from Mexico suggest that the cooling extent can exceed 2km (Jauregui 1990). A meta-analysis of cooling extent puts the average cooling extent at 500m (Bowler *et al.* 2010). A more recent study in China suggests an optimal green space size of 4.55 hectare (± 0.5) to reap maximum cooling efficiency (Yu *et al.* 2018). This value would obviously differ on the geographic location based on local climate, built environment, patterns of human behaviour and activities and more (Zhao, Lee, Smith & Oleson 2014). An individually calculated threshold value of cooling efficiency for every province or city could prove to be a relevant tool for urban planning and management. These results stress the fact that there is a drastic need to increase the ratio of green space to the impervious surface area as cities grow. Ideally, green space should hold a higher share than impervious surfaces overall (Estoque *et al.* 2017; Zhang, Estoque & Murayama 2017). An important element of future urban planning would thus be the use of green spaces to maximise its cooling effect as part of the effort to build more sustainable cities (Yu *et al.* 2018). Large parts of UHI mitigation efforts are based on optimizing the spatial configuration of existing and all future urban spaces, including green spaces (Cui *et al.* 2016). The optimization of green space to built-up area ratio to maximise cooling effects is a predominantly cited method. Methods and efficiencies of countermeasures differ according to the local context, data availability and the researcher's focus. In addition to reductions in temperature and reduced mortality, urban green parks and green zones have a variety of benefits attributed to their aesthetic value, their role as an amenity as well as cost savings related to electricity and water regulation (Song, Tan, Edwards & Richards 2018).

Despite the positive influence of green spaces on the urban climate, health, wellbeing and monetary savings it remains the single most significantly changed and diminished land cover type during the process of urbanisation and urban growth (Yu *et al.* 2018). It is thus of utmost importance for urban governments to realise and actualise the potential of existing green spaces as well as facilitate efficient integration into the urban framework and the protection of existing areas and improve on their distribution, variety and extent.

ii. Green roofs

Green roofs are roof surfaces that are fully or partially covered with vegetation and form an important part of UHI mitigation methods (USA Environmental Protection Agency 2012b). As with street level green spaces, green roofs provide cooling by shading low-albedo materials from absorbing short-wave radiation and convert heat from the air due to evapotranspiration from both plant and soil. This effect cools down both the surface of the roof and the ambient air and further insulates the building, keeping indoor temperature fluctuations low (Kleerekoper *et al.* 2012; USA Environmental Protection Agency 2012b). Roofs make up between 20-25% of the overall landcover in urban areas. Even though not all roof surfaces are able to support the installation of a green roof, there is vast potential for retrofitting and implementing green roofs into new developments (USA Environmental Protection Agency 2012b). The resultant temperature decrease of green roofs varies between different urban contexts and climate zones but different studies found temperature decreases of 25-55°C in comparison to traditional roofing materials. Green roof surfaces also consistently keep below ambient atmospheric temperatures (Amt für Umweltschutz Stuttgart 2010; Theodosiou, Aravantinos & Tsikaloudaki 2014). A synthesis of different modelling approaches throughout the world indicated a potential temperature reduction of the widespread use of green roofs on a city scale of between 0.3 and 3°C (Santamouris 2014). In addition to the temperature reduction, green roof strategies also reduce the material wear on the roof construction, thereby reducing costs. They also have the potential to relieve strain on the stormwater infrastructure and reducing the risk of flooding (Amt für Umweltschutz Stuttgart 2010). However, the green roofs ability to reduce ambient temperature has also been met with criticism. Some research suggests that while green roofs might reduce the surface temperature, they have a negligible direct effect on the surrounding atmospheric temperature with benefits mostly related to energy savings, noise reductions and air quality instead of thermal comfort. This holds especially true for green roofs on medium and high rise buildings (Kim, Gu & Kim 2018).

iii. Green facades and walls

Greening walls and facades is not a revolutionary concept but one that has gained in importance over the last decades. Long known for their aesthetic value, they have gained renewed significance as part of a host of nature-based solutions for climate change mitigation due to temperature reduction and energy savings (Akbari & Kolokotsa 2016; European Commission 2015; Naumann, Kaphengst, McFarland & Stadtler 2014). Although impact studies for urban greening mainly focus on parks, street-level greenery and green roof concepts, there have been select studies assessing the impact of green walls over the course of the years. In Singapore, green walls under study measured a surface temperature reduction of up to 12°C (Wong, Kwang Tan, Chen, Sekar, Tan, Chan, Chiang & Wong 2010). A similar study in Hong Kong revealed temperature reductions of up to 8.4°C, emphasizing the efficiency of green walls in urban canyons (Alexandri & Jones 2008). A mathematical model developed and tested in Chicago revealed that a plant layer on a vertical surface can result in surface temperature decreases of 0.7-13°C depending on wall orientation, leaf area index and intensity of solar radiation (Susorova, Angulo, Bahrami & Brent Stephens 2013). In addition to direct differences, the temperature fluctuations are also halved on a greened surface, reducing heat stress on building materials and increasing energy efficiency (Wong, Kwang Tan, *et al.* 2010). In terms of placement, dark walls and facades should be prioritised when implementing green walls or facades. Poorly oriented walls that are angled too far towards maximum solar radiation benefit the most, as green walls make up for poor passive design. Green walls and facades thus offer an enticing option for building retrofitting (Kontoleon & Eumorfopoulou 2010). With a greater attention to detail, new case studies and more efficient configurations, irrigation methods and maintenance schemes are expected to increase the efficiency of these spaces over years to come (Akbari & Kolokotsa 2016).

2.2.6.2 Increasing solar reflectance

i. Cool Roofs

As previously mentioned, roof surfaces offer vast potential for UHI mitigation. Traditional roofs can reach peak temperatures of up to 85°C during the summer in the US, heating up the surrounding air dramatically (USA Environmental Protection Agency 2012c). A cool roof works on the principle of increasing reflectance or albedo of traditional roofing materials, scattering or deflecting heat radiation instead of absorbing it. Thus, the amount of light that is converted into heat is minimized. Generally speaking, lighter coloured roofs have a higher reflectance and stay cooler (Global Cool Cities Alliance 2012). With the inclusion of higher reflectance and emissivity, cool roofs can remain up to 36°C cooler than regular roofing materials depending on their reflectance value and age (Global Cool Cities Alliance 2012; USA Environmental Protection Agency 2012c). Modelling increases in albedo on a city scale returned potential cooling of between 0,5 and 1,5°C with an only moderate increase in albedo. Extreme increases would yield temperature reductions of between 1°C and 2,2°C (Synnefa, Dandou, Santamouris, Tombrou & Soulakellis 2008). With the implementation of cool roofs alone, the average urban ambient temperature would be reduced by close to 0,2°C per 0,1 increase in albedo, showcasing a massive potential for UHI mitigation (Santamouris 2014).

Many of the common roofing materials already have a more reflective counterpart that is available today, sometimes at no or only incremental cost increase (Akbari & Levinson 2008). Since the advent of cool surface technology, new and more efficient cool-coatings that maximise the reflectance of near-infra-red rays, which make up over 50% of the solar radiation reaching the planet but are outside of the visible spectrum, have been developed. There is still vast potential for new technologies such as thermochromic materials (that increase reflectance with increases in temperature), directionally reflective materials (that reflect rays at a certain angle only), and retroreflective materials (that reflect light into the direction of the incoming radiation) limiting diffusion into urban canyons (Akbari & Kolokotsa 2016).

Cool roofs are often very competitive in pricing compared to traditional roofs. Energy savings alone alleviate the price differences in most cases. Provisions for cool roofs in energy efficiency standards would be a simple way to affect change on a city scale, mitigate the UHI effect and reduce the life-cycle cost of buildings (Akbari & Levinson 2008)

ii. Cool pavements

Urban spaces are dominated by different kinds of pavement. The types vary but range from roads, driveways, sidewalks, parking lots and runways to public plazas and playgrounds. Due to their diversity in application and use they can make up between 30%-45% of the land cover in densely populated urban areas in countries like the USA (USA Environmental Protection Agency 2012d). Conventional paving materials are usually very dense and boast a low reflectance, absorbing large parts of the solar radiation received by the surfaces. Pavements in the US have been proven to reach surface temperatures of up to 67°C in summer, leading to an increase in atmospheric temperatures above (USA Environmental Protection Agency

2012d). Increasing reflectance of these surfaces by using different materials or coating conventional surfaces has been proven to reduce the surface temperatures dramatically, facilitating temperature reductions in all urban areas (Global Cool Cities Alliance 2012). As an added benefit, pavements with a higher reflectance usually have a higher service life and can reduce the cost of lighting fixtures and electricity as their increased reflectance reduces the need for lanterns by 30% (Pomerantz, Akbari & Harvey 2000a,b) Permeable pavement surfaces have also gained academic interest as they allow for evapotranspiration, in turn keeping the surfaces cooler than conventional pavements (USA Environmental Protection Agency 2012d).

2.2.6.3 Fresh air corridors – utilising natural ventilation

Often neglected in mitigation strategies are methods of utilising existing and building new fresh air corridors or ventilation paths to assist with natural ventilation, reducing air temperatures and facilitating a cooler and healthier thermal environment. By facilitating increased ventilation the total surface heat flux is redistributed across a larger area and potentially away from the city into the countryside. Ventilation paths are dependent on the dominant wind direction and the roughness of the urban surface layer. If planned correctly, they draw in cool and fresh air from the countryside to reduce the UHI effect (Hsieh & Huang 2016). The establishment of these green corridors has to be planned and assisted by urban policies to include all stakeholders. Connecting existing parks, rivers and other areas attributing to a cooling route has to be taken into consideration. In order for a cooling effect to take place, undeveloped fresh air corridors, including areas with high green and water coverage, have to be increased on a city-wide scale (Amt für Umweltschutz Stuttgart 2010; Hsieh & Huang 2016). Ventilation paths can thus be seen as an accompanying mitigation method amplifying urban greening strategies. Keeping ventilation corridors open has to be balanced against housing and development needs, but looking at climate change projections ventilation corridors might prove more valuable in the long run (Amt für Umweltschutz Stuttgart 2010).

2.2.6.4 Summary:

This section considered the variety of mitigation strategies available to mitigate the UHI phenomenon. Urban spaces today are underutilising their UHI mitigation and climate change adaptation potential. Green spaces specifically can make cities more resilient to climate change and extreme weather events. In addition to their UHI mitigation potential, they also have the potential to reduce potential losses of life due to heat-related diseases, lower aerosol and noise pollution levels and are conducive to improved mental health, physical activity and stress relief (Akbari & Kolokotsa 2016; World Health Organization 2016). Additionally, greening buildings can compensate for an originally poor passive design, reduce cooling and heating loads and as such increase energy efficiency of the built environment (Kontoleon &

Eumorfopoulou 2010). The combined benefits of urban greening can potentially justify the extension of green spaces in urban areas (Song *et al.* 2018). Nature-based solutions, in general, offer different synergies and multiple beneficiaries. Different political goals like emission reduction, ecosystem protection, health implications and energy efficiency can be pursued at once, often at lower costs than comparable traditional methods. In a European context, local communities were found to prefer adaptation methods that create healthy and green surroundings simultaneously (Naumann *et al.* 2014). The attitudes of communities in African cities have however not been established.

Merely proving the existence, severity and the extent of the cooling effect of green spaces, green roofs and cool surfaces are not sufficient to guarantee their success as a heat mitigation strategy. Often the successful adaptation mitigation strategies are hindered by the lack of formal instruments and financing models for the provision as part of urban planning and management (Sun & Chen 2012; Yu *et al.* 2017). Early adoption of new technology is always difficult. In the case of green technology such as green roofs and walls, active support from governments can play a significant role in promoting the development and market entry of these systems. Current market conditions are more and more conducive to the diffusion of green technology with populations increasingly aware of climate change processes and the importance of sustainable development. A 2010 perception study in Singapore showcased that raising awareness, technical assistance and guidelines, policy, financial and program support as well as the support from building professionals can help create this conducive environment and help with a faster adoption (Wong, Tan, Tan, Sia & Wong 2010). Due to their nature as dynamic environments, urban areas are in a constant flux. Buildings are constantly being re-roofed and maintained, pavements have to be upgraded and replaced and new developments are changing the urban landscape (Akbari & Kolokotsa 2016). Integrating cool roofs and pavements can together affect more than 50% of urban land cover, emphasising the mitigation potential of these solutions. Depending on the urban environment, the establishment of ventilation corridors might provide additional mitigation capacity. Overall, actively integrating all manner of UHI mitigation into development policy and building codes thus allows for a gradual and sustainable upgrading of the urban structures, increasing resilience and facilitating the creation of healthy human settlements along the way.

2.2.7 UHI in Africa

The African continent has not received much attention of mainstream UHI related research so far. There are a few selected studies that have been put forward in a variety of different countries, but the number is low when compared to other regions around the globe.

Examples of previous research in Sub-Saharan Africa include multiple analyses of Johannesburg, South Africa. Efforts were made to develop a predictive UHI model for the city (Hardy & Nel 2015) and different methodologies from a very complex atmospheric UHI analysis using a mobile data collection method and rudimentary satellite analysis (Goldreich 1992), to a more modern approach comparing land surface temperatures and land cover change derived from satellite imagery with ground-based weather stations (Monama 2012) were used to analyse Johannesburg's UHI occurrence. As part of this study, a negative relationship of higher normalised vegetation index and LST was found. Higher LST additionally correlated with a higher normalised built-up index. Possible mitigation methods were mainly found in increasing strategic deployment of resources during heat waves and the establishment of new green spaces such as parks, planting fast-growing indigenous trees in close proximity to the hot-spots identified (Monama 2012). Other work includes the evaluation of green infrastructure as mitigation technique in Burkina Faso (Di Leo, Escobedo & Dubbeling 2016), an observation of UHI characteristics in Nigeria using ground-based weather stations as reference (Balogun 2012) and an analysis of the urban geometries influence on cooling and warming rates in Nairobi City, Kenya (Makokha & Shisanya 2010). In northern Africa, the focus of research has been mostly on Cairo, Egypt where remote sensing was used to assess the UHI effect (Abutaleb, Ngie, Darwish, Ahmed, Arafat & Ahmed 2015).

The lack of research on UHI in an African context emphasizes the importance of increasing African governments, research institutions and individuals attention to this field of study. Sub-Saharan Africa showcases similarities in its urbanisation process, offering similar geographies and climate types across international borders and could benefit from collaborative multi-disciplinary research efforts on the topic. A similar situation is applicable to the South Asian research community on this topic and knowledge sharing could help governments and planners to forecast, respond to and mitigate the adverse effects of UHI, especially in the face of a changing climate (Kotharkar *et al.* 2018).

2.2.8 Research going forward

One of the most influential developments for UHI research is the advancement of predictive modelling approaches. Due to the complexity of factors influencing UHI effects, future models would have to include a variety of factors, including but not limited to, wind-generation, anthropogenic heat release, shading, evapotranspiration and urban geometry. The development of integrated modelling approaches will allow a more accurate and contextualised analysis of the phenomenon in different urban areas throughout the world, possibly highlighting the variety of mitigation methods for different regions (Hien 2016).

Current predictive models, such as the urban canopy model (UCM) and computational fluid dynamics (CFD), fail to capture the complexity of the urban spaces and the abundance of factors influencing the thermal household of these spaces (Mirzaei & Haghighat 2010). Additionally, the high computational cost of simulations of usable resolutions and scale is an important issue. Building and microclimate models especially cannot be extended further than very localised simulations because of the computational power required with mesoscale simulations lacking usable levels of accuracy (Mirzaei 2015). Current models also lack the ability of vertical integration going back to the different scales of the urban climate. Further effort is thus required towards the further development and integration of different predictive models to inform planning, urban design and thermal comfort (Mirzaei & Haghighat 2010).

UHI research has gained considerable traction over the past years. Newly established NGO bodies like the Global Cool Cities Alliance or the US focused bipartisan GO of Climate Mayors are driving the conversation, funding research, educating and putting plans into action ("Climate Mayors" 2018; "Global Cool Cities Alliance" 2017).

2.3 LEGISLATION

The following chapter presents a basic overview of international, regional, national and local legislation and their relation and recognition of the UHI phenomenon. Even though the UHI effect is not necessarily specifically mentioned in all of the documents, nuances and related topics can be found.

2.3.1 International

2.3.1.1 Sustainable Development Goals

The 2030 Agenda for Sustainable Development is a blueprint document to achieve a better and more sustainable future for all of humanity. It is comprised of a set of 17 goals that were set by the UN General Assembly in 2015, building on the content of the Millennium Development Goals. Most importantly in the UHI context, they seek to realize the human rights of all by 2030 and aim to achieve sustainable development in three dimensions: economic, social and environmental. The most important goals in relation to climate change, urban development and UHI are goals 3, 11 and 13. Goal 3 aims to ensure good health and well-being for everyone. It is formulated to ensure healthy lives and well-being at all ages. Although it mainly regards life expectancy and common issues for mortality, it does not include heat-related mortality. Goal 11 is the goal to create sustainable cities and communities. Most important in this context is the goal to achieve safe and affordable housing and to reduce the slum population worldwide. Goal 13 concerns climate action and is meant to facilitate climate change mitigation and adaptation. However, it does not mention adverse effects or regulation of heat, instead focussing on the regulation of emissions and the promotion of renewable energy and other green technology (United Nations 2015)

2.3.1.2 New Urban Agenda - Habitat III

As part of its global mandate, the 2016 United Nations Conference on Housing and Sustainable Development (Habitat III) resulted in a new declaration on sustainable cities and human settlements. The 'New Urban Agenda', also known as the *'Quito Declaration on Sustainable Cities and Human Settlements for all'*, was established as a guideline document to make current and future cities as well as human settlements more inclusive, safer, more resilient and more sustainable. The overall role of the document is to provide guidance for national urban policies, assist the continued process of strengthening urban governance and it's institutions as well as support a stricter focus on long-term and integrated urban and territorial planning as well as that of design. Additionally, it surmises a host of proposals on sustainable financing frameworks to guarantee this inclusive urban development (United Nations 2017b).

UHI are not specifically mentioned in the more general remarks of the declaration. However, the shared vision and commitment to improving urban resilience, reducing disaster risk, combatting and mitigating adverse effects of climate change present opportunities for its potential integration. Among others, section (g) of the shared vision highlights the ideal to "build resilience and responsiveness to natural and *human-made hazards*" (ibid. 2017b: 7), which UHI can be attributed to.

UHI themselves are only mentioned once, as part of the commitment to '*sustainable and inclusive urban prosperity and opportunities for all'*. Article 54 mentions the need to reduce the UHI effect as caused by inefficient mobility. In order to combat congestion, air pollution, UHI and noise it propagates the switch to renewable and affordable energy, with a focus in providing for the poor and people living in informality, as well as the push for sustainable, efficient transport infrastructure (ibid. 2017b: 17). The framing of the UHI effect is based on inefficient mobility instead of inefficient human settlements.

Large parts of the document focus on environmental sustainability by not only promoting clean energy but also through the promotion of sustainable use of land and resources in the urban sphere. It specifically mentions the need to adopt "(…)healthy lifestyles in harmony with nature" as part of the principles (ibid. 2017b: 8). The reduction and mitigation of the UHI effect could form part of this harmonious relationship with nature, increasing public health in the process.

Also mentioned are issues of social justice and equitable and affordable access to sustainable basic physical and social infrastructure. Article 34 of the commitment for social inclusion and ending poverty lays out the basic question of equity, takes note of the access to land, housing, sanitation, healthcare but excludes the relationship with the right to a healthy environment (ibid. 2017b: 12). Even though a specific right to a healthy environment is excluded from the commitments, health plays a major role in Habitat III, with the goal being to inhabit and produce "(…) just, safe, healthy, accessible, affordable, resilient and sustainable cities (…) fostering prosperity and quality of life for all" (ibid. 2017b: 4).

It is recognized that urban centres have certain characteristics increasing the vulnerability of citizens to both climate change effects and other natural and human-made hazards. These include, among other things, extreme weather events, heat waves and air pollution. Cities in developing countries are deemed especially vulnerable to these effects emphasizing the need to focus efforts of increasing resilience in these spaces (ibid. 2017b: 18).

Further related to the UHI effect, especially towards the aspect of mitigating its adverse impact, is Article 67 of the agenda. It entails the commitment to create and maintain open, inclusive, green and public spaces. As a consequence this should improve resilience to, amongst other hazards, heat waves, increasing physical and mental health as well as to promote ambient air quality. A keyword mentioned herein is the creation of 'liveable' cities, which is of considerable importance when assessing the current and future impact of UHI. (ibid. 2017b: 19)

Climate change adaptation and mitigation form a large part of the recommended actions included in the guideline document. Article 79 includes conformity of the guideline document to the goals of the Paris Agreement which encompasses, among others, limiting the increase in global average temperature to below 2°C above pre-industrial levels. Building resilience and reducing emissions of greenhouse gases (GHG) in an inclusive process involving all local stakeholders should be included in these efforts (ibid. 2017b). Reducing the UHI effect can work alongside this process.

Within the document, special mention is made to developing adequate, enforceable building codes, standards, land-use by-laws and ensuring the aforementioned trajectory towards resilience, sustainability, energy as well as resource efficiency and health (ibid. 2017b). These could have dramatic implications for the mitigation and reduction of UHI.

2.3.1.3 The Future We Want.

In 2012, following the United Nations Conference on Sustainable Development (UNCSD) in Rio, a document called "The Future We Want" was signed by the 192 heads of state in attendance renewing their commitment to sustainable development. Even though UHI are not mentioned specifically, some of the articles speak towards the future development of UHI and the need for collective action (United Nations 2012). Future iterations should include a mention of UHI.

Article 128 mentions the need to increase energy efficiency in order to mitigate climate change and facilitate sustainable development. This could indicate a need to facilitate the creation for more effective heating and cooling solutions so to mitigate UHI effects. This is further explored in article 135 which includes the commitment to the promotion of safe and healthy living environments for all, the protection and restoration of green urban spaces and a healthy air quality, which are all related to the UHI effect – either exacerbating or mitigating the consequences. Effective building management and the development of sustainable, locally appropriate transport systems as mentioned in article 136 could also influence the mitigation of UHI, among other effects. (ibid. 2012)

Article 136 also reaffirms the increased probability of extreme weather events and persistent droughts as part of climate change effects and formulates a commitment towards limiting global temperature increases in articles 190 and 191 respectively. (ibid. 2012)

As previously established, the health of the population is affected by the UHI effect. Accordingly, any commitment regarding an increase of resilience, a decrease of mortality and related effects are relevant in this context. Article 138 speaks to the importance of creating inclusive, equitable, economically productive and healthy societies. According to the commitment it is of utmost importance to facilitate the establishment of the highest standard of physical and mental health possible for a population. In article 141, the connection of positive health effects and the reduction of air pollution are drawn. This potentially promotes an interrogation of the UHI effect and its influences on the urban pollution island but neglects mortality and health effects as established in other documents (ibid. 2012).

2.3.1.4 Paris Agreement

Adopted as part of the United Nations Framework Convention on Climate Change, the Paris Agreement was a major step for climate change recognition and mitigation efforts. The document itself does not provide any recommendations on how to mitigate climate change but does offer a platform in the form of a non-binding agreement for national governments to reduce emissions on their own terms. It does not include any mentions of the UHI phenomenon, but there is alignment with the issue. Relevant to the UHI phenomenon are two main aspects. Firstly, the emphasis on the right to health and the rights of people in vulnerable situations. Secondly, the main goal of the agreement, which is to limit the increase of global average temperature to below 2°C above the pre-industrial level, ideally limiting the increase to 1.5°C and acknowledging the risks and impacts of climate change. A realisation that the UHI effect could exacerbate the impact of climate change is missing (UN-FCCC 2015).

2.3.1.5 Sendai Framework on Disaster Risk Reduction

The Sendai Framework on Disaster Risk Reduction was endorsed by the UN at the start of 2015 as part of the UN World Conference on Disaster Risk Reduction in Sendai City, Japan. Like most UN Frameworks it is a voluntary, non-binding agreement that serves as a guideline for methods on how to reduce disaster risk, focusing on the different and overlapping responsibilities of states and other stakeholders. It does not specifically mention UHI but its inclusion should be facilitated on the basis of one of the most important goals of the framework is the planned reduction in disaster mortality by 2030. It includes difficulties specifically concerning different regions and assesses their respective risk foci (UNISDR 2015).

The framework does, however, offer insights of a different value. One of the most relevant means of implementing the disaster risk reduction goals is the aim to enhance cross-country and cross-sector coordination as well as continued international support for disaster risk reduction. The African continent especially needs more support through bilateral and multilateral channels to strengthen existing capacities as mentioned in Article 43 of the framework. It calls for innovation in all sectors related to poverty reduction, sustainable development, natural resource management, the environment, urban development and adaptation to climate change (UNISDR 2015).

2.3.2 Regional

2.3.2.1 Johannesburg Declaration as part of the 10th BRICS summit.

The Johannesburg Declaration is the outcome document of the 10th BRICS summit of 2018. It does not mention UHI directly. Heat-related topics in the Johannesburg declaration are mainly found in the pledge to advance the development and implementation of sustainable energy systems and the transformation from traditional energy production towards renewables. The language used indicates the main goal to be aligned with international sustainable development processes, economic growth and the socio-economic well-being of BRICS citizens. No mention of physical well-being or health related to heat or pollution is made. In terms of the energy transition, the document mentions transportation, heating and industry uses as the main benefactors. It also speaks of alignment to the Paris Agreement and the need for developing countries support in enhancing mitigation and adaptation capabilities (BRICS 2018).

2.3.2.2 Africa 2063

In 2013, the African Union Commission agreed on a common strategic framework for the socio-economic transformation of the continent until the year 2063. The overall goal is for further growth and sustainable development and in this context, offers a few elements which are noteworthy for this research project. Like the other documents, it does not specifically address the issue of UHI, but the connection can be noted as part of the sustainable development goals, in the effort for political integration and the furthering of ideas related to pan Africanism (African Union Commission 2015).

In its aspiration for a prosperous Africa based on inclusive growth and sustainable development, a handful of goals are mentioned. Most important for this specific context are the ambitions to increase the overall quality of life and well-being of African citizens which includes modern and liveable habitats, basic services as well as increased health and nourishment. It also includes the goal to create more environmentally sustainable and climate change resilient economies and communities. This is supposed to be attained by a host of methods and most relevant in this context are the promulgation of climate resilience and natural disaster preparedness and prevention, the use of renewable energy as well as the introduction of sustainable consumption and production patterns (ibid. 2015).

Political integration in this instance plays a major role due to the aim of uniting the continent politically under the umbrella of Pan Africanism. Inner African cooperation with common frameworks and institutions are mentioned, which also implies cooperation in research relevant to the continent such as the challenges facing urban Africa (ibid. 2015).

2.3.3 National

Article 24 of the Bill of Rights of the South African Constitution reserves every person the right to an environment that is not harmful to their health or well-being (The Constitution of the Republic of South Africa 1996). The phenomenon of UHI and its related impact impedes this right, effectively establishing its reduction and mitigation as a matter of public concern. The following is an overview of the national development frameworks and policies on urban development with a focus on the implementation of the UHI phenomenon and related policy instruments.

2.3.3.1 Integrated Urban Development Framework

While neither the Integrated Urban Development Framework (IUDF) implementation plan nor the general framework contains any mention of UHI or heat effects, the general framework comments on related topics (COGTA 2016a,b). As part of the subsection on resilience, the phenomenon of droughts is mentioned. The authors also concede that South Africa needs to strengthen the resilience of the poor and those in vulnerable situations. In order to do that, the pledge is made to undertake the systematic reduction of their exposure to extreme climate-related events as well as other economic, social and environmental shocks and disasters. This includes an assessment of the opportunities urban disasters pose, the analysis of the anticipated impacts of climate change and the long-term protection of ecosystems and resources. As cities gain in importance for the development trajectories of a nation they need to take concrete actions for climate change adaptation. A reduction of disaster risk has the ability to secure assets and enables societies to accumulate wealth (COGTA 2016a). Integrating the UHI effect would assist that goal and help inform concrete action.

2.3.3.2 National Climate Change Response White Paper

The National Climate Change Response White Paper outlines the government's vision for building resilience to climate change as well as the options for mitigation and responses throughout all sectors. Even though it doesn't mention the UHI phenomenon directly it does specifically mention both the inefficiencies of the urban environment as well as the detrimental health effects resulting from overall intense heat (Government of the Republic of South Africa 2011).

The White Paper acknowledges that direct physical temperature facilitates an increase in mortality and pose risks especially for children, the elderly and socioeconomically vulnerable communities. While heat itself is seen to pose risks for the population of South Africa, the document also makes mention of air quality and its influence on health particularly that of stagnant air episodes in urban areas. To solve these issues, tackling air quality and implementing awareness campaigns on health risks of high temperatures are suggested. Instead of looking at inefficiencies in the environment that might cause or exacerbate high temperatures or stagnant air episodes respectively, it presents avoidance behaviour such as minimising exposure as well as increasing preparedness of emergency services as the solution to the problem. It is thus not acknowledging the fact that a vast amount of people don't have the access to avoidance mechanisms such as temperature controlled environments and neglects to talk about an efficiency rationale of these avoidance mechanisms (ibid. 2011).

Looking at urban areas specifically, the effective management of the interface between residents and their natural environment is emphasized, acknowledging the need to further develop the climate resilience of urban socio-ecological systems. The white paper reconciles this with the fact that thermal efficiency and climate-resilient technologies need to be implemented into the designs of housing developments in general and especially low-cost housing (ibid. 2011).

It calls for assurances that land-use zoning regulations are enforced with consideration of climate change impacts and ecosystem services, both for settlement and infrastructure developments. It also noted the distinct lack of available data to assist urban planners in identifying priorities with regards to climate change responses. The main limitation is found to be the scale of climate modelling, calling for down-scaling of predictive models on provincial, metropolitan and district levels and their incorporation into Geographical Information Systems (GIS) (ibid. 2011).

Without mentioning specific mitigation methods, the goal is set to reach peak emissions between 2020 and 2025, with emissions hopefully declining from 2035. Mitigation methods are meant to curb the pre-2009 trajectory by 34-42%. Green technology is deemed to form a big part of this decrease and the white paper cites the commercial sense of resource efficiency, the potential of a growing green economy and as a way to build up resilient infrastructure (ibid. 2011). With specific regards to the UHI, their acknowledgement and mitigation should technically be part of the establishment of sustainable human settlements and an improved quality of household life as set out in desired outcome 8 of the document (ibid. 2011).

2.3.3.3 South Africa National Adaptation Strategy 1st and 2nd draft

The national adaptation strategy is a legal document which acts as a focal point for all climate change adaptation efforts in South Africa. It serves as a platform to articulate national objectives as well as to provide guidance for the different sectors of the economy. The first draft of the adaptation strategy has multiple points of alignment with the UHI phenomenon. It recognises the fact that heat-related mortality is on the rise due to an increased likelihood for heat waves. The elderly, chronically sick, children and poor are overall most vulnerable to the increase in heat intensities. In addition to the effects on humans, the document also stresses the need to develop measures to deal with heat-stress for livestock. It is one of the few documents in the South African context explicitly naming the UHI effect, which is said to gain in intensity due to climate change. Unfortunately, there is no further explanation of the concept, its origins, effects or specific adaptation strategies (Department of Environmental Affairs 2016).

Overall health, with a focus on human health, plays a big part in the adaptation strategies with climate-change related health concerns being attributed to local disaster management mandates. A focus should lie on identifying communities that are the most vulnerable to climate change health impacts. Risk reduction is supposed to be facilitated through ecosystem and community-based approaches, without going into detail on what these might entail. An important shift in the rhetoric from previous guideline documents is the direct mention of correlations between environmental quality and human health, based on analyses within the City of Johannesburg. A study found extreme heat and air pollution events to have a significant and direct impact on communities, affecting physical as well as mental health, another first mention and change of rhetoric from mitigating long-term effects to recognising an immediate problem present in the urban areas of today (ibid. 2016).

The second draft, released for public comment in 2017emphasized the need to increase investments in mitigation strategies and the identification of present and future risk areas. It also outlined the inevitability of average temperature increases in South Africa of between 2.5°C and 4°C. These figures are most likely to become reality even when taking extreme mitigation focused scenarios into consideration. Another first is the recognition that stresses related to climate change might decrease labour productivity and health, either through direct (increases in temperature) or indirect (distribution of diseases) exposure to its effects. Pre-existing cardiovascular diseases especially increase peoples vulnerability with an increase in heat stress (Department of Environmental Affairs 2017).

2.3.3.4 Let’s respond – A guide to integrating climate change risks and opportunities into municipal planning

Let’s respond is a joint effort between the Department of Environmental Affairs and the Department of Cooperative Governance to guide municipalities on the integration of climate change risks and opportunities in their respective development frameworks and other planning processes. While the UHI effect is not mentioned, they emphasise the need to redress outdated building code requirements to include greater efficiency in lighting, heating, cooling and water heating services. The main aim is the reduction of GHG emissions as well as the development of grid independence. However, these measures, if adapted correctly, could also help to address prominent issues related to UHI. The document specifically mentions the need to improve the thermal quality of housing in low-income areas to increase resilience to disease and boost the efficiency of heating and cooling. This thereby can increase the quality and reduce the cost of living (Department of Environmental Affairs & Department of Cooperative Governance 2012).

2.3.3.5 Guidelines for human settlement planning and design: The Red Book

The two volumes of the Guidelines for human settlement planning and design are documents aiming to establish the qualities desired in human settlements as well as providing guidance on how to achieve these qualities. It was compiled by CSIR Building and Construction Technology under the patronage of the Department of Housing (CSIR 2000a). The red book was released in 2000 and a new green book, looking specifically to provide a variety of stakeholders from municipalities to the private sector with guidelines for adaptation of existing and future South African settlements to climate change, is expected to be released in March 2019 (Van Niekerk 2016).

While UHI is not specifically mentioned within the guideline document, frequent mention of the potential for excessive heating in urban spaces is apparent, including that of potential pathways to mitigate this heat build-up. Their relevant considerations can be grouped in both general considerations for the external environments such as roads and soft space as well as for individual buildings (ibid. 2000a).

In terms of external spaces, it does clearly recognise the need to look at horizontal surfaces such as streets, which do show potential for excessive heating. The document doesn't specify solutions and merely suggests being mindful about the specific conditions of surfaces. More important herein is the role of soft open spaces. Soft open spaces are deemed essential contributors to the settlement metabolism, enabling natural ecological processes to occur sustainably and safely within a human-made environment. These soft open spaces play an important role in breaking up, absorbing and processing by-products of urban metabolic processes such as heat, liquid and gaseous waste. They facilitate the purification of these waste products by cleansing and filtering water and cleaning the air. As such, they should be appropriately located, sufficiently large, interconnected and vegetated. The guideline document leaves the exact amounts up to question and makes vague statements. It goes so far as to stipulate a balance that needs to exist between the natural and built environment without giving direct suggestions on how to enable this balance. It does call for the reduction in the share of concrete and asphalt, in turn scaling up the share of vegetation and open water surfaces in our human settlements. This is accurately depicted as increasing volumetric heat capacities and greater rates of latent heat flux and as such, lower air temperatures. In this sense, the red book is describing the UHI phenomenon without naming it directly as urbanisation is established to create and change the distinctive urban climate (ibid. 2000a). In addition, increasing the urban canopy has the potential to limit the reflection of heat from paved surfaces on to walls and windows, lowering the temperature of both the external and internal environment (CSIR 2000b).

In addition to soft open spaces, wind direction is also taken into consideration as one of the factors potentially able to dramatically alter the urban climate. Special consideration is to be taken with orienting developments to optimise ventilation, cooling and removal of pollutants while not creating wind-tunnels and negating the positive impacts (CSIR 2000a).

Heat build-up and pollution are also mentioned in the guidelines so to managing indoor environments. A focus should lie on increasing energy efficiency, preventing heat loss in winter and heat build-up in summer. To achieve this the document mainly tackles the heat loss of roofs and walls, where simple modifications are able to have dramatic impacts on the energy balance of a home. Simply adding a ceiling could reduce space heating energy bills by more than half and that is before any insulation measures are considered. Similarly, the addition of ceilings and insulation has the dramatic potential to keep spaces cool and facilitate a more balanced living environment. According to the red book, adding ceiling insulation is deemed to be the most cost-effective intervention in South Africa. Additionally, the red book recommends limiting heat gain from roofs by painting them in a light colour (CSIR 2000b).

2.3.3.6 Western Cape Spatial Development Framework

The Western Cape Spatial Development Framework of 2014 makes no mention of UHI, temperature or heat, especially in relation to the need to adapt to current and future climate change related risks. Adaptation and mitigation responses are to be informed by specialist studies commissioned by the Western Cape Government, the focus areas of which are mainly the risk analysis of rising sea level. In terms of mitigation, the document is more inclusive, integrating matters of energy efficiency, demand management in settlement making and upgrading as well as renewable energy. Most applicable to the UHI phenomenon are two of the focus areas for adaptation: built environment adaptation and social resilience. One of the fundamental challenges implied is the general lack of awareness and acceptance of the reality of climate change and its general implications throughout the province. Educating the public and informing a more inclusive provincial SDF should be the goal for the next renewal periods going forward as well as translating goals to municipal level SDF's (Western Cape Government 2014).

2.3.3.7 Cape Town Municipal Spatial Development Framework

The current Cape Town Municipal Spatial Development Framework (CTMSDF) was originally approved by the city council in 2012. In its 10 year lifespan, it has undergone adaptation and transformation as part of its 5-year review which was approved in April 2018. Overall it aims to curb urban sprawl, promote densification and mixed land use, transform transportation and bring people closer to their jobs as well as jobs closer to the people. It does not include any mentions of the UHI phenomenon specifically as a short-term risk and only mentions the need to accommodate for changes in climate such as higher temperatures in the long-term as part of general climate change mitigation. Herein lies the most potential for the CTMSDF to include elements of assessment and mitigation of the UHI phenomenon. The CTMSDF recognises the need to accommodate for a changing climate and has identified it as one of the biggest challenges of our time. It also stresses the need to view it as an ongoing process instead of a once-off disaster event with change happening slowly and incrementally implying the need for proactive behaviour and constant adaptation. Carbon-intensive development patterns, the deterioration of ecosystem services and inefficient use of resources by the population provide motivation to commit to action and policy. The CTMSDF recognises the need to change spatial planning and building standards to increase the adaptive capacity of both communities and our economy. Naturally, it is mainly concerned with the long-term effects but also mentions opportunities arising from a stronger investment into the green economy (TDA 2018).

The energy sector especially is deemed unsustainable in its current form and development trajectory, stressing the need to relieve the economy from unsustainable cost burdens by increasing efficiencies and addressing vulnerabilities. Instead of settlement upgrading, the CTMSDF sees the most potential in a focus on transport upgrading and transforming energy supply and generation. Usage patterns or existing inefficiencies in our built environment are not mentioned as part of the mitigation effort (ibid. 2018).

In addition to efforts revolutionizing transport and energy generation, the CTMSDF mentions the importance of the cities biophysical assets to mitigate climate change impacts. These assets play a major role in shaping urban form and quality of life of the citizens as well as in sustaining a natural balance of ecological processes. Thus, urban development must incorporate these natural assets, maximising the possible benefits the cities citizens and visitors can derive from them. The benefits are left without proper definition but link to quality of life, climate change mitigation and increases in food security. The cooling effect of these assets should be thoroughly investigated and recognized in the MSDF (ibid. 2018).

Looking at specific policies within the document, policy numbers 22,23 and 24 are worth mentioning in the context of the UHI effect with possible implications towards the amendment of their wording and scope (ibid. 2018).

Policy Nr. 22: Discourage urban growth in areas at risk from natural hazards/coastal processes which are expected to be amplified by climate change impacts – Implying the potential to include UHI into risk areas, discouraging development in these areas and limiting an unnecessary increase in UHI intensity.

Policy Nr. 23: Increase efforts to protect and enhance biodiversity networks at all levels of government – Protecting biodiversity networks should also include a provision to assess and uphold existing cooling effects.

Policy Nr. 24: Reduce the impact of urban development on river systems, wetlands, aquifers, aquifer recharge areas and discharge areas. – Which should include mention of the assessment and preservation of cooling effects.

2.3.3.8 Moving Mountains, Cape Town's Action Plan for Energy and Climate change

Formally released at the end of 2011, the Cape Town Action Plan for Energy and Climate change underlines 11 objectives including targets and implementation plans. Although some of the objectives are already past their deadline, most of them are still relevant and can be expanded on. The action plan mentions the potential to implement measures of resource-efficiency in the planning and development of new and refurbished residential and commercial properties. It additionally stresses the need to adopt updated building regulations according to new national standards addressing matters of energy efficiency. Retrofitting properties owned and operated by the city itself are meant to deliver data on the savings and effects of both physical changes and behavioural changes. Retrofitting herein seems to have a very narrow definition as simple measures such as control of air-conditioner operating hours and thermostat control and do not entail any major construction work on the built structures themselves. The action plan establishes that low-income households can spend up to 25% of their income on meeting their energy needs (for both cooking and heating). Thus, the action plan mentions specific projects of settlement upgrading such as adding ceilings to pre-2005 housing units and public-private partnership projects using clean development mechanisms such as the Kuyasa CDM, which installed insulated ceilings, solar water heaters and energy-efficient lighting in over 2300 houses in Khayelitsha. Some, but not all new housing projects include measures on energy efficiency, which would sometimes also increase thermal comfort in homes (e.g. insulated ceilings) (City of Cape Town 2010).

2.3.3.9 City of Cape Town smart Building Handbook

As part of the continued effort on climate change mitigation and adaptation, the City of Cape Town released a smart building handbook in 2012. The handbook contains a host of recommendations, not actual policy, to educate and change developers and the behaviour of citizens. This includes a host of relevant suggestions related to UHI. It is one of the first official documents in Cape Town to mention the UHI effect overall albeit not going into sufficient detail on it. The city advocates for green buildings mainly from both a capital cost and operational cost reduction point of view. Green buildings should mainly maximise the efficiency of energy, water and resource use. In addition, developers should focus on creating healthy environments for people to live, work and play. Indoor environments specifically are recognised to have a strong effect on the well-being and productivity of the occupant. Special consideration should be given to air quality, light and the visual and thermal comfort in the built environment (City of Cape Town 2012).

Overheating is mentioned as one of the most prominent issues in the South African summers and multiple design aspects are drawn to combat overheating of buildings. The green book advocates that architects should include passive solar designs to heat and cool buildings naturally, reducing running costs and creating a more comfortable and healthy indoor environment. Buildings and windows should be angled appropriately towards the sun to maximise sun exposure in winter to reduce heating costs while reducing exposure to the summer sun, as it follows a higher angle in the sky. While insulation is deemed the most effective overall to attain comfortable temperature levels throughout the year, adding ceilings is the most cost-effective measure due to the amount of heat gained and lost through the roof. Due to the drastic differences between night and day, the handbook advocates the creation of heat sinks with a high thermal mass. These could store heat during the day and radiate it in the evenings, keeping buildings cold during the day and temperate at night. According to the document, a reduction of UHI is mainly attributable to integrating plants with buildings, shading and insulating the structure from temperature changes. Rooftop gardens and living walls are mentioned yet the handbook leaves out further information on how to implement these structures (ibid. 2012).

2.3.3.10 City of Cape Town – Climate Change policy

Realising that previous policies towards curbing climate vulnerability which include emission reductions were not efficient enough to address the pace at which climate change impacts Cape Town, the need for action arose. Thus, the specific policy was devised to redress the cities management of the issue, culminating in the approval of the Climate Change Policy (policy number 46824). Like the smart building handbook, the Climate Change policy is one of the only official documents in Cape Town to mention the concept of UHI and the necessity to reduce their impact. It is also aligned with goal 8, 9, 10 and 13 of the UN sustainable development goals (City of Cape Town 2017).

Improved resource efficiency is at the core of the policy. Innovation and certain minimum requirements for developments are mentioned, without specifically going into detail or discussing enforcement. City Planning and building development policies, as well as by-laws, are supposed to be reviewed to facilitate the inclusion of climate considerations. This can be seen as a major step in the right direction. Energy efficient design and construction of all new buildings, additions and renovations are to be encouraged in both the private and public sectors. The document also mentions the creation of incentives for development that promotes climate change mitigation and adaptation efforts. Additionally, the document highlights the individual responsibility to adopt efficient practices and promote energy conservation within all economic sectors, especially among high users, pushing the agenda on the involvement of the public. Educating citizens on the importance of climate change mitigation is clearly outlined in the policy document. The policy focuses on the importance of inducing behavioural change in all citizens. Leading by example should encourage citizens sense for individual responsibility. As such, the city is addressing their own responsibility by recognising the need to include the impact of climate change on human health in the design, maintenance, improvement and development of recreational spaces as well as public transport and healthcare facilities, with special consideration of reducing the heat island effect. Encouraging developers to act sustainably might not be the most efficient way to proceed, but it is a step in the right direction (ibid. 2017).

Further, green spaces are gaining traction as part of the inward growth strategy. The potential for parks and other urban recreational spaces to act as a buffer for increased temperatures is underutilized, not well-maintained and or not suitable for the specific needs of the neighbouring communities (ibid. 2017).

Again, poor communities are deemed to be among the most vulnerable to climate change impacts, both due to their marginal locations and their inability to invest in mitigation and adaptation measures. Within the Climate Change Policy, the city reconciles with the fact that informality is likely to be an ongoing problem, indicating a need to develop more climate resilient informal housing to actively involve residents in long-term resilience build-up. It also recognises the historical perspective that initially led to the climate and resource-inefficient ways that parts of the urban framework of today were built, especially due to the legacy of Apartheid. In addition, the policy reconciles with the fact that the climate change response within the city was mostly based on hard engineering instead of soft, green engineering approaches. The new policy recognises the potential of building resilience with the help of ecological infrastructures such as parks and other soft open spaces. Urban greening, both by tending to existing infrastructure and establishing new artificial ecological infrastructure, is acknowledged to reduce the negative effects of the UHI phenomenon as well as improving environmental quality and ecosystem health (ibid. 2017). What is missing most noticeably from the climate change policy is the enforcement of actual adaptation and mitigation efforts as action stays mostly in theoretical terms.

2.3.3.11 SANS 10400 XA and SANS 204

In 2011, the South African Bureau of Standards (SABS) updated the national building codes writing a voluntary standard into law. Some of the most significant changes were made regarding energy efficiency in buildings, directly creating a link to an increase in Energy Efficiency and thus a decrease of the UHI effect. SANS 10400-XA imposed new maximum energy usage values in buildings while SANS 204 deals with energy efficiency. As part of the new regulations, new commercial and industrial developments must adhere to a maximum annual energy demand and consumption. The maximum values are not imposed for residential buildings. The building codes also suggest an optimisation of the orientation of the building towards the point of lowest net energy use. The document is much more concerned with heating demands in winter as these are calculated to be much higher than cooling demands in summer. The building codes do mention the inclusion of cool roof strategies, but only as part of the informative annexe. They do list the common solar absorptance values of different roofing materials but do not provide reference towards the importance of the energy efficiency of the building or the thermal environment (SABS 2011). The inclusion of UHI mitigation strategies such as the mandatory use of cool roofing materials should be a straightforward inclusion in the building codes, but until this point they are inadequate. SABS estimates that by installing appropriate ceiling insulation and high-performance window systems, 3500MW of electricity could be saved by 2020 (SABS n.d.).

2.4 APPLICATION OF UHI MITIGATION STRATEGIES WORLDWIDE

In contrast to the City of Cape Town, a host of cities around the globe have sufficiently acknowledged the phenomenon of the UHI and have pledged to actively minimize and mitigate its negative effects through conscious urban planning and collective action as well as specific action. An overview of some progressive policy and planning initiatives is outlined in the subsequent sections. The selection covers some of the changes and shifts in UHI related urban development policy over the past ten to twenty years.

2.4.1 Chicago

In 2001, the City of Chicago adopted the Chicago Energy Conservation Code. This building code was based on the International Code Councils (ICC) 2000 International Energy Conservation Code (IECC) and was adapted to the local environment of Chicago. One of the most prominent additions is the inclusion of the UHI Effect into the code, emphasising the city’s desire to both conserve energy and minimise the heat island effect. In order to facilitate this reduction, the roofing systems of new developments and rebuilds have to conform to certain reflectance standards which in turn lowered the amount of heat radiation absorbed by roof surfaces, lowering roof and ambient temperatures. Since its implementation in 2002, the code has undergone minor changes but the provisions still stand as part of chapter 18-13, energy conservation, section C402.3 (City of Chicago 2018).

In addition to the implementation of cool roof standards into the municipal building code, Chicago is also leading the United States cities in the implementation of cool roofs and green streets. Almost 400 green roofs had been completed by 2008, moderating roof temperature, providing shade and insulating the building reducing energy requirements to cool or heat the buildings. The city’s goal is to reach 6000 rooftop gardens by 2020. In terms of retrofitting, the city is successfully applying a new mindset and green technology. Their industrial rebuild program managed to accumulate a 28% rate of return on investment on average, while dramatically reducing emissions. As a mechanism for change, the city offers special incentives, technical help and access to financing for both citizens and businesses alike. In addition to building specific mitigation methods, the city also implemented a large-scale tree-planting program which is expected to see more than a million trees planted in total. The city’s climate action plan recognises the improvements of quality of living, beautification, temperature decrease and climate change mitigation from the combined efforts and the dual purpose of many adaptation methods that also increase mitigation efforts. Cool roofs lower temperatures and retain rainwater, but also increase a buildings energy efficiency (Chicago Climate Task Force 2008).

2.4.2 Los Angeles

In 2015, the City of Los Angeles, California, released a sustainable city action plan that looks to transform the city towards a more equitable and sustainable future. Instead of only recognising the UHI effect, the document sets out specific targets for UHII reduction. The urban-rural temperature differential is aimed to be reduced by 1.7°C by 2025 and 3.0°C by 2035, based on the 2012 differential of 5.58°C. By 2017, the city aimed to install 10000 cool roofs. The plan includes the identification of neighbourhoods with the highest temperatures and individual buildings with the highest heat loss (City of Los Angeles 2015). In addition to pushing for the implementation of cool roofs, the City of Los Angeles also pilots other cool surface programs such as applying high reflectance coating to pavements around the city (Berg 2017). They further actively pursued the softening of typical city hardscapes like alleys and parking lots by adding green spaces and planting trees (City of Los Angeles 2015).

In 2014, applying cool roofing materials to new buildings as well as rebuilds was made mandatory as part of the cool roof ordinance, changing the Los Angeles Municipal Code. The purpose as stated was to reduce the heat island effect and so the code imposed a minimum solar reflectance value for the construction of roofs in the city (LACityClerk 2014).

2.4.3 Toronto

Toronto has made a name for itself as one of the most progressive cities worldwide to actively and aggressively pursue climate change mitigation and adaptation methods. The city has realised the potential negative effects of UHI and has imposed one of the most advanced green roof requirements into their municipal building codes. Since January 2010, article 492-2 of the code imposes that every new building with a gross floor area of 2000 m² or more must include a green roof covering a set minimum percentage of the available roof space. Starting at 20% of the roof area for smaller developments the mandatory percentage cover peaks at 60% for buildings with more than 20000m² gross floor area. The only exception from the green roof standard is industrial buildings, which can substitute the roof greening by using cool roofing materials for the entire roof surface. Article 492-2 goes into detail on the statics requirements, drainage and vegetation recommendations including maintenance plans so that developers can easily apply the new standard (City Council Toronto 2017). In addition to the inclusion of green roofs into the municipal building code, the Toronto Green Development Standard suggests that 50% of all hardscape within the city should be light in colour with a minimum reflectance of 0.3, further building capacity for UHI mitigation (City of Toronto 2018).

2.4.4 UHI-mitigation going forward

The term cool city has been introduced as part of the sustainable development trajectory for urban areas around the globe over recent years. Urban heat management is one of the key factors for future climate change mitigation. Modifying the thermal properties of new and old buildings as well as applying green city concepts and positive environmental management in urban areas has the potential to create sustainable, healthy and livable environments for the future (Rehan 2016). City governments play a major role in facilitating a move towards sustainable and cool city development. They have the potential to encourage individual action and responsibility through educating citizens and incentivising futureproof development. As most of the urban surfaces around the globe are privately owned, this approach could drastically transform cities (Kleerekoper *et al.* 2012). More and more governments accept their role in this critical transformation process towards the establishment of cool surfaces. An additional incentive to the beneficial effects of cool city concepts on UHI and climate change mitigation are electricity savings (costs of cooling and heating respectively) and economic opportunities. A 2015 study on Washington D.C. revealed that a city-wide adoption of smart surface technologies such as cool roofs, green roofs and porous pavements could result in savings of up to 5 billion US dollars, all the while reducing temperatures and creating a healthier, more livable environment (Kats & Glassbrook 2016).

In South Africa, the establishment of the South African Cool Surfaces Association in 2014 can be seen as a first step in amplifying the public voice in the adoption of cool surface strategies on a wider scale. In collaboration with the United States Department of Energy the non-profit association aims to educate stakeholders as well as implement a credible rating system for roofs and other surfaces in the country (SACSA n.d.)

2.5 LITERATURE REVIEW SUMMARY CONCLUSION

The global population is increasing fast, both in total numbers and in its share of urban population. Urbanisation was established as one of the 21st century's most transformative trends and the African continent is expected to see a majority of it's population increase in this century. This raises questions on how to deal with increased vulnerability to stresses to African nations due to uncertain economic trajectories, climate change, pollution, migration and health status. Expanding urban areas and the respective increase of human activity and urban structures greatly alters the energy balance and the atmospheric state of the city. Due to this alteration, large cities harbour areas of noticeably higher temperatures, the so called urban heat islands (UHI). The UHI effect can be related back to a variety of factors from land cover change in terms of high built up intensities and the loss of vegetation to increased pollution and related aerosol concentrations in the atmosphere as well as the effects of climate change. UHI are believed to increase the intensity of climate change impacts in urban areas by up to 30%, emphasizing the importance of the inclusion of UHI in urban planning and futureproofing development. The UHI effect was established to significantly influence increases in energy consumption, create economic losses and have adverse health effects. Urban areas consume the most energy worldwide, having a dramatic impact on the environment. The UHI effect increases the cooling demand in buildings and thus increases the energy consumption greatly. In economic terms it was established that the UHI effect can have significant costs in both day to day and total life-cycle costs of urban structures and lifestyles. Its health effects reach from diminished labour capacity to the increase in cardiovescular as well as respiratory dieseases and the faster spread of diseases; mainly affecting already vulnerable populations such as the young and the frail. In terms of mitigating these effects, two main avenues have been established: increasing evapotranspiration and increasing solar reflectance, both issues of effective urban and landscape planning. Increasing evapotranspiratio includes increasing the number and share of vegetated surfaces such as parks, green roofs, facades and walls. This was established to dramatically decrease surface temperatures and have knock-on effects on the surrounding areas decreasing temperatures. Increasing solar reflectance is based on minimizing the absorption of solar radiation by the use of materials with high reflectance, creating cool roofs, cool pavements. Additionally, the use of natural ventilation by extending fresh air corridors was shown to mitigate the UHI effect. Overall, altering a city’s roofs and pavements can together affect more than 50% of urban land cover and thus, the efficiencies of these surfaces should be looked at in detail. It was further established that the African continent severely lacks UHI research. A handful of studies was conducted over the years but the phenomenon is comparatively untouched in an environment that is both currently and in the foreseable future exibiting intensive urbanisation and population growth. This calls for an increase in collaborative, multi disciplinary research efforts and the uptake of predictive modelling for UHI effects. The literature review further provided an overview of international, regional and local legislation and its uptake and recognition of the UHI phenomenon. On all levels, from the UN’s New Urban Agenda to national, regional and local development frameworks, UHI are barely mentioned. If they are mentioned, the concept is not used consistently, is not further or inadequately explained and or it is misaligned. Most of the documents, however, show the potential to integrate the concept and thus increase awareness and adaptation of mitigation strategies; this holds especially true in the face of an increasing recognition of vulnerabilities to climate change impacts and the aim of creating sustainable human habitats throughout all spheres. On local level, both the CoCTs smart Building Handbook and CoCT Climate change policy specifically demonstrate local governments basic awareness on the UHI effect but also fail to provide enough detail on the causes and necessary mitigation efforts. Binding measures to combat the UHI, such as a specific provision in the city’s building codes, are still missing. Further, an examplary collection of the application of UHI mitigation strategies worldwide was provided. The CoCT and other urban areas can potentially learn from other cities’ experiences in integrating UHI mitigation in energy conservation and building codes by implementing cool and or green roof standards and limiting the energy consumption of buildings. The benefits of UHI mitigation and cool city proliferation are increasingly recognised and there is a growing body of research as well as international cooperation on the topic.

CHAPTER 3 METHODOLOGY

3.1 STUDY AREA

Located on the South Western tip of the Western Cape, the CoCT Metropolitan city area spans an area of almost 250000ha (2445km^2). It extends close to 100km on its widest from north to south and just over 60km from east to west. The Metropolitan City boundary borders with the Swartland Local Municipality in the North and the Drakenstein Local Municipality, Stellenbosch Local Municipality, Theewaterskloof Local Municipality as well as the Overstrand Local Municipalities towards the East (see figure 3.1).

Within the CoCT Metropolitan City boundary lies the urban edge. The urban edge is the area within the Metropolitan City boundary which is specifically defined to demarcate and limit the area of urban development. It marks the formal transition between rural and urban land use. The urban edge directs urban growth and promotes urban and environmental efficiency. The area within the urban edge is made up of the urban inner core and incremental growth and consolidation areas, the areas in which the city is and will be able to efficiently supply urban services such as roads, sewers, water, stormwater systems and street lights. The Urban Edge is reviewed as part of the municipal spatial development framework to update development edges, urban growth management strategies and adopt policies and guidelines to the development trends (Department of Environmental Affairs and Development Planning 2005; TDA 2018). Of the 99000 ha of land that falls within the 2015/2016 urban edge, just over 60% have been developed, roughly half of the remaining 36000ha remain as developable land, with the other half constrained due to location or regulations (TDA 2018).

For the further analysis, the focus was directed on the urban edge boundary. This study specifically looks at temperature variations within the urban framework, as such the extended municipal area would skew the temperature results and the resulting hot-spot and regression analysis.

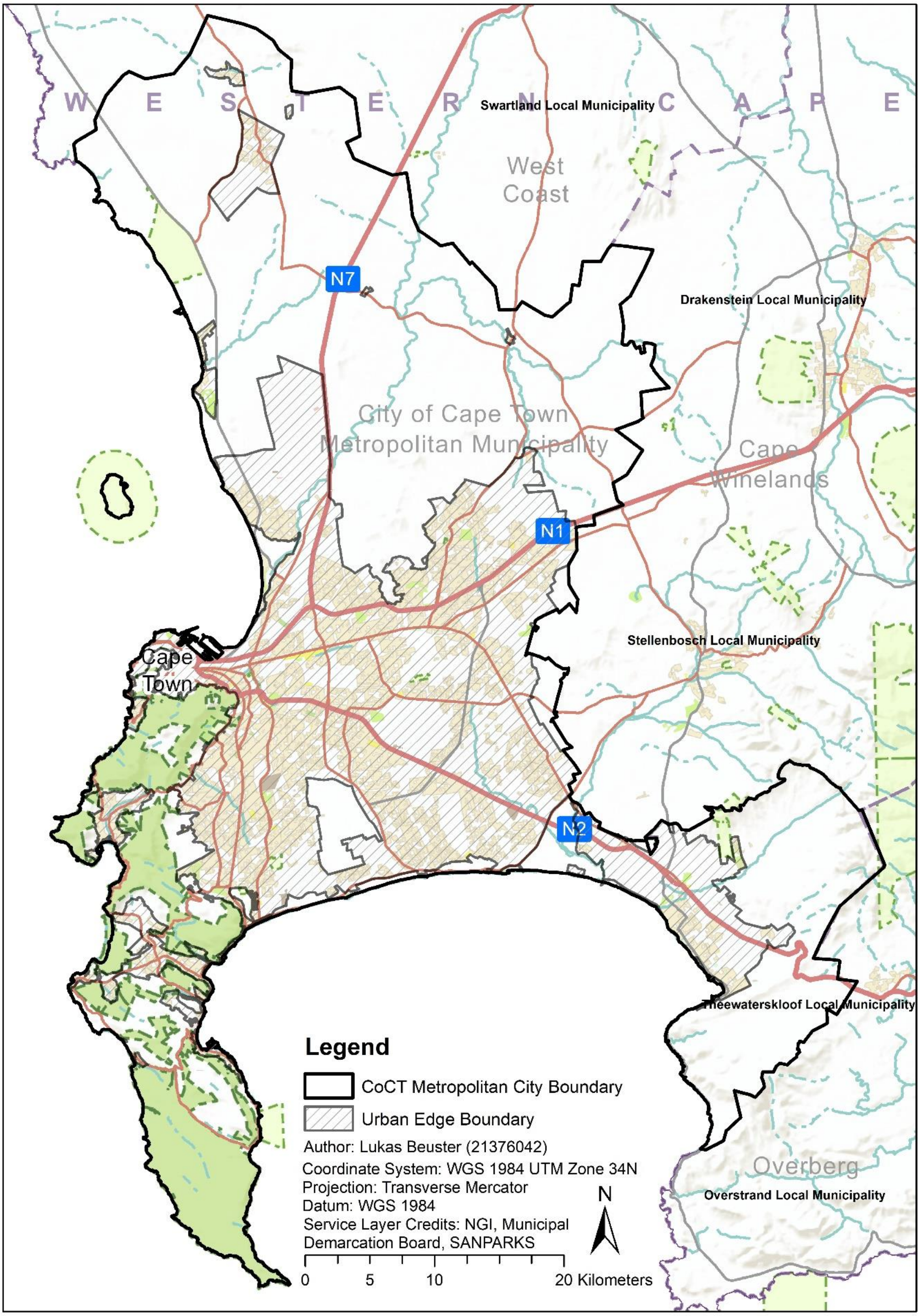

Figure 3.1 Overview CoCT - study area

3.2 DERIVING LAND SURFACE TEMPERATURE

Since the 1960s, the amount of high-resolution satellite imagery available for researchers increased. In conjunction with an increase in computational power the data obtained was increasingly used to analyse land cover change and surface temperature observations (Liu & Zhang 2011). Beginning in the early 2000s, satellite data became abundant and often openly available to researchers around the globe, making remote sensing methodologies a cost- and time-efficient methodology (Kotharkar *et al.* 2018). In the case of developing countries or more remote regions of the world, one has to deal with certain limitations in the availability of data-packets as imagery is dependent on the timing and interval of a satellites overpass, of the cloud cover during that time and of the geometry of the sensors viewing angle (Roth 2012). Over time, different datasets were used for the study of UHI. The most prominent of these were NOAA AVHRR, Landsat TM/ETM+/TIRS, MODIS and ASTER. They differ in resolution, return time and data availability. Most widely used is that of Landsat TM/ETM+/TIRS data because of its high resolution of 30mx30m and open availability of datasets through the USGS (dos Santos *et al.* 2017; U.S. Geological Survery 2018). For large scale regional, national or international assessments such as the EU, USA, China or global analyses, MODIS data has been used (Cui *et al.* 2016; Li *et al.* 2017; McCarthy *et al.* 2010; Ward *et al.* 2016; Zhou *et al.* 2014). Smaller scale projects utilizing MODIS data are often supplemented by measurements of atmospheric temperature on the ground or regional climate model simulations which make up for the relatively low resolution of MODIS data (1km in comparison Landsat-7/8s 30m resolution) (Li, Meier, *et al.* 2018; Roberge & Sushama 2018).

Even though satellite analysis is a reliable method and data is easily accessible there are its own set of limitations. Using satellite data only allows the extraction of surface temperatures and as such that of the surface UHI. The surface UHI can differ from the atmospheric UHI due to the lack of turbulence and air velocity close to the ground. Filtering different sources of noise and countering the effects of the distance between the satellites instruments and the objects under study is constantly evolving as methods become more reliable and accurate measurements are available (Mirzaei & Haghighat 2010). A further consideration is that the urban landscape is three dimensional, which is not reflected in the measurements derived from the bird's eye point of view that satellite images are taken at (Mirzaei & Haghighat 2010).

3.2.1 Deriving land surface temperatures

The temperature data used in this study was acquired through the latest addition to the Landsat satellite constellation, Landsat-8. Both Landsat-8 and its predecessor Landsat-7 are located in a near-polar, sun-synchronous orbit. They each orbit in 99-minute intervals completing over 14 orbits a day. This yields a total coverage of the planet for each satellite every 16 days, with both satellites being offset by 8 days (U.S. Geological Survey 2016).

Landsat-8, the newest of the constellation, is equipped with a sophisticated Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). The United States Geological Survey (USGS) and NASA run Landsat project data is openly available for download and comes as both unprocessed and pre-processed datasets (U.S. Geological Survey 2016). Landsat- 8 OLI/TIRS images are made up of eleven bands, eight of them multispectral (1-7 and 9), one panchromatic (Band 8) and finally the two thermal bands of the TIRS module (Bands 10, 11). In the case of this research, pre-processed datasets were used which already contain converted 'surface reflectance' values for the multispectral bands and 'top of atmosphere brightness temperature' for the thermal bands (U.S. Geological Survery 2018). An advantage of using the pre-processed data is that the L8SR algorithm that is used to calculate the surface reflectance already includes necessary atmospheric corrections and compensates for solar zenith and view zenith angles (Estoque *et al.* 2017). To increase accuracy, only images with 10% or less land cloud cover are selected. As of October 2018, five years after the launch of Landsat 8, 99 images fit the criterion. Due to the fact that the extent of the City of Cape Town covers two separate satellite images, between 40-50 different dates are available as full datasets for the entirety of the City of Cape Town since 2013 which equates to almost half of the time the satellite's sensors covered the area.

As the pre-processed atmosphere brightness is output in Kelvin, a conversion of these data-values into degrees Celsius is the first part of the LST retrieval process. The data is then corrected for land surface emissivity (both soil emissivity and vegetation emissivity) and the normalised difference vegetation index (NDVI) (Artis & Carnahan 1982; Estoque *et al.* 2017; Weng, Lu & Schubring 2004)

$$LST\ (°C) = \frac{T_B}{1 + \left(\lambda \times \frac{T_B}{\rho}\right)\ln(\varepsilon)}$$

Where T_B = Landsat-8 Band 10 brightness temperature, λ = wavelength of emitted radiance ($\lambda = 10.8\mu m$, the centre wavelength of Landsat-8 Band 10), $\rho = h \times c/\sigma$ $(1.438\ x\ 10^{-2}\ m\ K)$.

To calculate ρ one uses the Planck's constant: $h = 6.626\ x\ 10^{-34}\ Js$, the velocity/speed of light: $c = 2.998\ x\ 10^{8}\ m/s$ and the Boltzmann constant: $\sigma = (1.38\ x\ 10^{-23}\ J/K)$. The last element, the land surface emissivity: ε is estimated using the formula postulated by (Sobrino, Jiménez-Muñoz & Paolini 2004):

$$\varepsilon = m\,P_v + n$$

where $m = (\varepsilon_v - \varepsilon_s) - (1 - \varepsilon_s)F\varepsilon_v$ and $n = \ \varepsilon_s + (1 - \varepsilon_s)F\varepsilon_v$

For this equation ε_s represents the soil emissivity and ε_v represents the vegetation emissivity. As part of this study, the figures stated by Sobrino *et al.* are used - $m = 0.004$ and $n = 0.986$.

At last, P_v is the vegetation proportion , derived by:

$$P_v = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2$$

The NDVI is the normalized difference vegetation index, which is established using the surface reflectance of Landsat-8 Bands 4 (Red) and 5 (near-infrared (NIR)) (Rouse, Hass, Schell & Deering 1973).

$$NDVI = \frac{(\rho_{NIR} - \rho_{Red})}{(\rho_{NIR} + \rho_{Red})}$$

The inspiration for this approach was drawn from the work of (Estoque *et al.* 2017) on the UHI in megacities in South-east Asia in 2017.

3.3 LAND COVER MAPPING

In order to assess the relationship between LST and land cover, data availability can generally be seen as a concern because of the complexity involved. Instead of generating new land cover data, this research project used previously existing land cover data for the years 2013/2014 prepared by GeoTerraImage (GTI). GTI generated the land cover dataset from multi-seasonal, 30-metre resolution Landsat-8 imagery using semi-automated data modelling procedures. The dataset incorporates an average of 7 images acquired for different dates encompassing one annual, seasonal cycle (GeoTerraImage 2014). Their LC-categories are established with a minimum of 45% coverage per tile to qualify and are available close to standard Landsat resolution of 30m. LST data had to be resampled to the cell size of the land cover dataset of 34,46052917. After resampling, both the LST and Land Cover data were converted from raster data to polygons using the ‘raster to polygon’ tool in ArcGIS. Thereafter, the different shapefiles were collated using the ‘union’ tool to return a single file containing the land cover data and the corresponding LST of January, April, July, October and November of 2014.

3.4 SPATIAL ANALYSIS

After the collection and preparation period, all data collected underwent thorough quantitative analysis. Analysis of spatial data was exclusively executed using the ArcGIS geographic information system. This includes data manipulation, descriptive and inferential statistics (both spatial and non-spatial) as well as the final preparation of different maps visualising the results. The techniques used encompassed hot spot analysis/Getis-Ord Gi* (Section 4.2) and cluster and outlier analysis/Anselin Local Moran's I (4.2.1) to map clusters of high and low values and show statistically significant outliers respectively. Additionally, both local and global regression tools such as ordinary least squares/OLS (Section 4.3.4.1) and geographically weighted regression (GWR) (Section 4.3.4.2) were used to model spatial relationships and test expected against measured temperature values. To validate the results of the OLS and the GWR, the residuals were subjected to a spatial autocorrelation/Moran's I. Throughout the analysis, special emphasis was placed on the seasonal variation of LST, hot- and cold spots and the relationship between LST and LC within the study area.

CHAPTER 4 RESULTS

4.1 LAND SURFACE TEMPERATURE

As part of this research undertaking a set of 5 dates in the year 2014 was analysed. The dates were chosen based on the availability of satellite imagery with minimal cloud cover over the land. Taking into account the Landsat satellites recurrence time of 16 days, the amount of imagery available fitting the criteria was limited. Care was taken to select different dates representative of the different seasons with two images taken into consideration for the CoCT summer. The dates that were selected were the 3rd of January, the 25th of April, the 14th of July, the 2nd of October and the 19th of November 2014.

The results of the satellite analysis show distinct patterns of land surface temperatures in the CoCT. While the temperature ranges seem to be in line with expected temperatures during these dates there was no verification of temperature results with atmospheric measurements as the number of meteorological stations within the CoCT boundary is not sufficient[1] to allow for meaningful interpolation and comparison of data. Previous research suggests a high accuracy of the single channel approach used and as such, the results are deemed to be correct with a reasonable level of confidence (Estoque *et al.* 2017).

Overall, the LST analysis reveals relatively high temperatures throughout the urban areas, whereas lower temperature values are mainly recorded in the elevated areas around Table Mountain National Park, along the mountains that cover the eastern border of the CoCT boundary in the Somerset West and Gordons Bay areas, in close proximity to the coastline and alongside waterbodies such as lakes, ponds and rivers. Areas that feature natural or artificial vegetation also seem to exhibit lower temperatures (See figure 4.1). The highest range of temperatures recorded was in November with a difference of 30,6°C between the coldest and hottest surfaces within the urban edge (See table 4.1).

03rd January '14		25th April '14		14th July '14		02nd October '14		19th November '14	
Min.:	17,1	Min.:	7,4	Min.:	-0,6	Min.:	10,7	Min.:	9,7
Max.:	43,7	Max.:	29,4	Max.:	19,1	Max.:	35,8	Max.:	40,2
Mean:	33,3	Mean:	21,1	Mean:	13,5	Mean:	25,9	Mean:	29,2
Std Dev.:	2,5	Std Dev.:	1,5	Std. Dev.:	1,0	Std. Dev.:	2,2	Std. Dev.:	2,8
Range:	26,6	Range:	22,0	Range:	19,7	Range:	25,1	Range:	30,5

Table 4.1 LST recorded throughout 2014

[1] The South African Weather Service makes use of 6 Stations within the CoCT Urban Edge: 00208053 (Royal Cape Yacht Club), 00207466 (Molteno Reservoir), 00208669 (SA Astronomical Observatory), 00207804 (Kirstenbosch Botanical Gardens), 0021178A3 (Cape Town International Airport), 00056088 (Strand). Other stations are not centrally organised and would have to be manually obtained and compared.

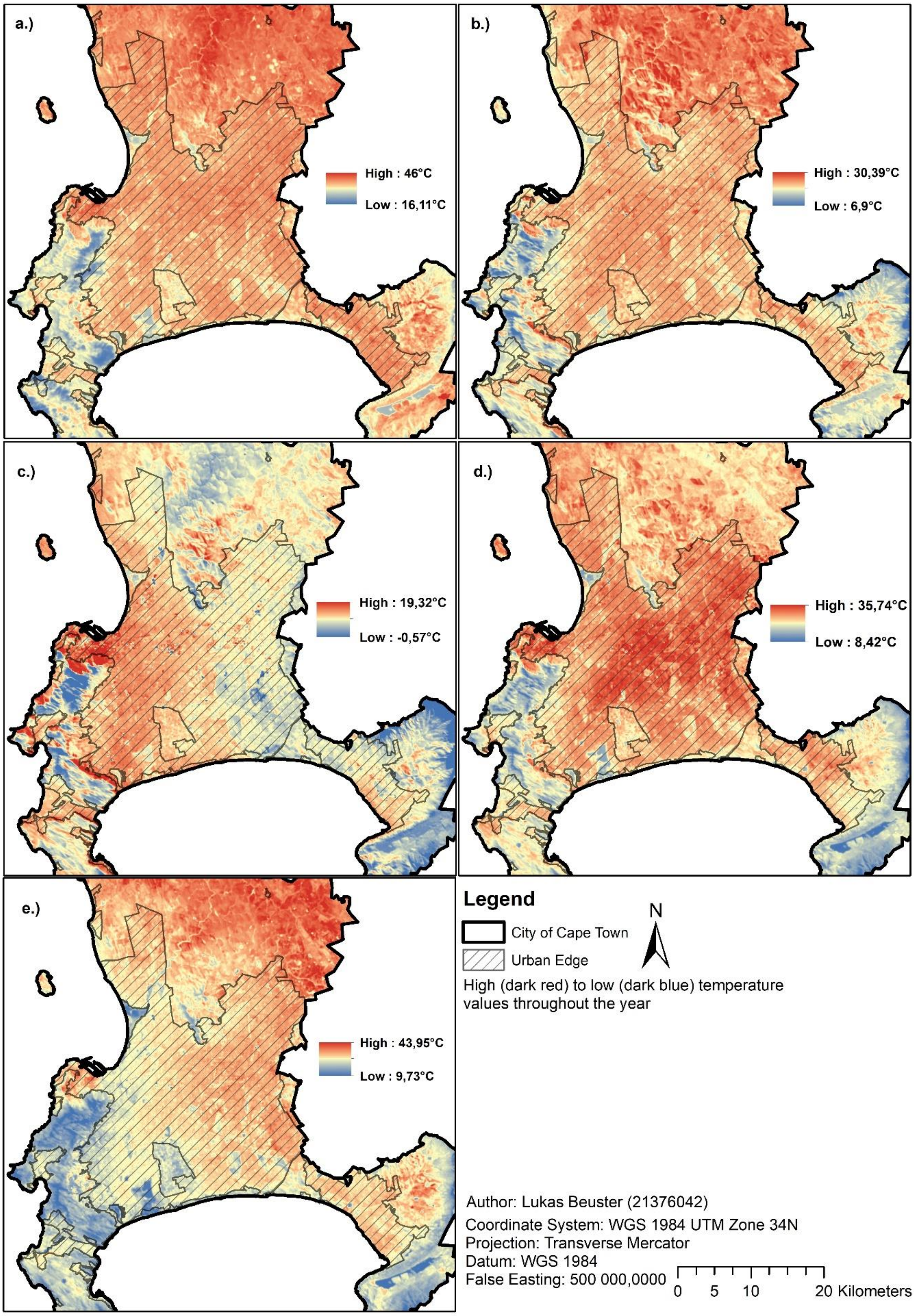

Figure 4.1 Raw LST data throughout the year 2014. a.) January, b.) April, c.) July, d.) October, e.) November

On average, the range of temperatures was 24,8°C. The hottest temperatures were recorded in the middle of summer in January, with an average of 33,3°C and a maximum recorded surface temperature of 43,7°C. Not surprisingly, the lowest temperatures were recorded in the middle of winter in July, with an average temperature of 13,5 and a maximum of 19,1°C. The range of temperatures recorded was at a minimum (19,7°C in July) around the same time due to the angle of the sun, the resulting diffusion of solar radiation in the atmosphere and the reduced daylight hours when compared to the summer months (30,5°C in November).

The raw data was then subjected to both global and local statistical tools to identify statistically significant local hot and cold spots (using the Getis-Ord GI* statistic), global clustering of high/low values (Getis-Ord General G) and concentrations of low or high values and spatial outliers (Anselin Local Moran's I). In order to focus the analysis on hot and cold spots within the urban framework, both global and local statistical tools were applied to the temperature measurements within the urban edge boundaries instead of the whole administrative zone.

4.2 HOT AND COLD SPOTS (GETIS-ORD GI*)

Overall, the results show both a large amount of hot and cold spots throughout the study area. Large concentrations of significantly warmer temperatures can be found in the densely built-up commercial and residential areas around the city bowl and suburbs around the inner urban core as well as towards the northeast (See figure 4.2). The red demarcated areas within the map hereby indicate a statistically significant clustering of high temperature values (hot spots) while the blue demarcated areas signify a statistically significant clustering of low temperature values (cold spots).

The analysis reveals a notable influence of the Atlantic ocean on the temperatures in areas adjacent to the coastline, as these areas consistently exhibit significantly cooler land surface temperatures than areas that are further removed from it. It additionally reveals that areas in close proximity to areas of natural or artificial vegetation alongside the fringes of the urban edge such as the Phillipi Horticultural Area, as well as within the remaining wetlands and naturally vegetated areas located in the Cape Flats, both remain significantly cooler than heavily built-up areas. Close proximity to the elevated surfaces of the Cape Peninsula Mountain range also negatively influences temperature and surfaces are often colder, exhibiting statistically significant cold spots almost consistently throughout the year with the exception of July. Noteworthy are also the cold spots in the densely vegetated shadow of table mountain towards the east which are mainly affluent peri-urban spaces. Additionally, the cool island around the company gardens park close to the parliament in the city centre is a prominent feature throughout the year. The cooling effect of the Swartrivier close to the city centre and the significantly colder temperatures within most of the golf courses, stadiums and vegetated areas are noticeable as well. Overall, the hot spot analysis reveals significantly higher temperatures in the built-up areas, with a special focus on the densely populated areas in the city centre and suburbs like Parow, Belhar, Century City and Brackenfell. Cooler temperatures are mainly recorded in vegetated areas or close to waterbodies as well as the more affluent suburbs. A High/Low Clustering Analysis (Getis-Ord General G) confirmed the visual assessment that there is an overwhelming concentration of high values in January, April, October and November. The July value is missing due to the inability of the Getis-Ord General G statistic to work with negative values – the lowest recorded surface temperature in July was -0.57°C.

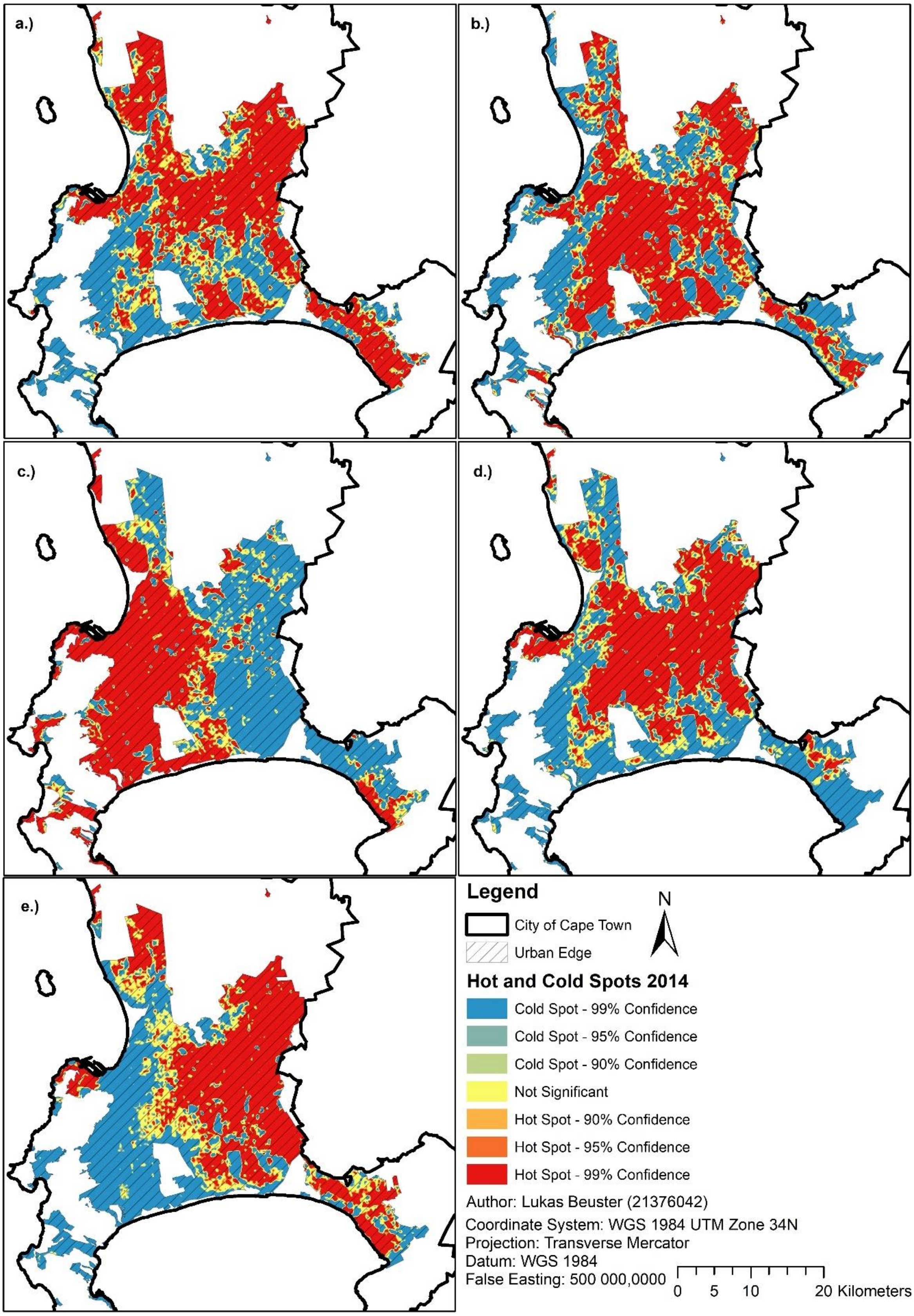

Figure 4.2 Hot spot analysis within the urban edge a.) January, b.) April, c.) July, d.) October, e.) November 2014

Looking at the results of the local Hot Spot Analysis (Getis-Ord GI*), the overall pattern of hot, temperate and cold areas change throughout the year (see figure 4.2). While the CBD area, including most of the surrounding residential suburbs, exhibits statistically significant hot spots throughout the year, the overall pattern throughout the urban edge shifted and changed with the different seasons.

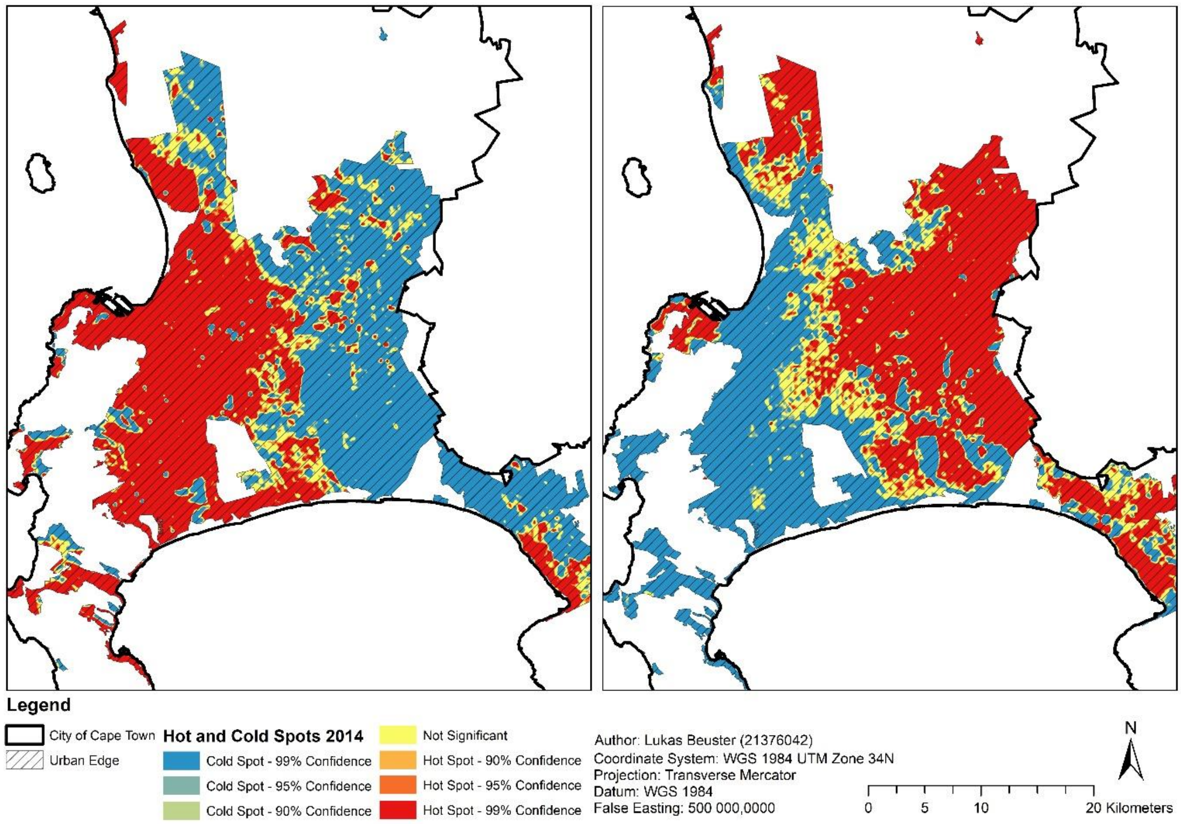

Figure 4.3 Hot and cold spots July (left) and November (right) 2014

Most noticeably are the differences between July and November which show an almost completely inverse pattern of LST which can be considered an outlier phenomenon (See figure 4.3). In July, most of the western urban edge and the more affluent suburbs show statistically significant hot spots while the more removed areas towards the east can all be deemed cold spots. This phenomenon might partially be explained by two dominating factors: wind and land cover. In the summer months, a predominant south easterly wind brings in cold air from False Bay which could have a distinct cooling effect on the southern suburbs and all areas towards Table Mountain. The Cape Doctor, as the predominantly south easterly wind is affectionately called, is usually present between October and March, amplifying the dispersion of vertical heat flux. The predominant wind-direction might also explain the extension of the cold spots towards the north where the cold air is deflected by the increase in elevation resulting in possible cooling effects in the areas towards the north-north-east (Observatory, Woodstock, Milnerton and Table View) as well as over the mountain in the south-east extent of the City

Bowl (Oranjezicht, Vredehoek). Towards the east of the urban edge, the Hottentots-Holland Mountain Catchment Area might act as a physical barrier, decreasing the cooling effect of the South-Easter. An additional explanation might be the increase in vegetation density towards the West and the increase in non-irrigated grassland towards the east. In the summer months like November, large areas fall dry, decreasing evapotranspiration and increasing heat build-up. In July, these areas are generally more lush and green, increasing their cooling effect. As to why the areas around table mountain show significant hot spots in July, no substantiated theory could be formulated. The milder temperatures could possibly be the result of increases in vegetation canopy retaining heat as well as a higher thermal capacity of the buildings in the affluent Southern Suburbs in combination with higher built-up densities. Landsat images are acquired around 10:00 am mean local time on each pass, so the sun angle and shading should not play a significant role (U.S. Geological Survey 2016).

Other than this anomaly, the pattern remains more or less consistent throughout the year. However, the colder months exhibit a more equalized distribution across the urban footprint, with a focus around the suburbs of Parow, Elsies Rivier, Belhar and Brackenfell as well as towards Ottery, Mitchells Plain and the CBD areas. The cooling effect of parks and vegetated areas are clearly visible throughout the year with cold spots corresponding to areas that are either vegetated, in close proximity to green spaces or close to water bodies. A prominent example of this cooling effect of green spaces is that of the company gardens within the City Bowl. Close to parliament, the surrounding area including the adjacent city blocks towards the harbour are visible cooler than the rest of the CBD throughout the year (see figure 4.4 – the cross demarcates the park). Although the cooling effect is less pronounced in summer, the temperatures are still visibly lower than in the rest of the city bowl. Noteworthy is the apparent directional behaviour of the cooling extent which resembles a fresh air corridor. This cooling extent seems to follow elevation decreases and predominant wind directions towards Cape Town Harbour throughout the year. Furthermore, figure 4.4 reveals the cooling effect of the cold ocean surfaces which is visible in adjacent residential and commercial areas such as Sea Point and Green Point, especially during the summer and until April.

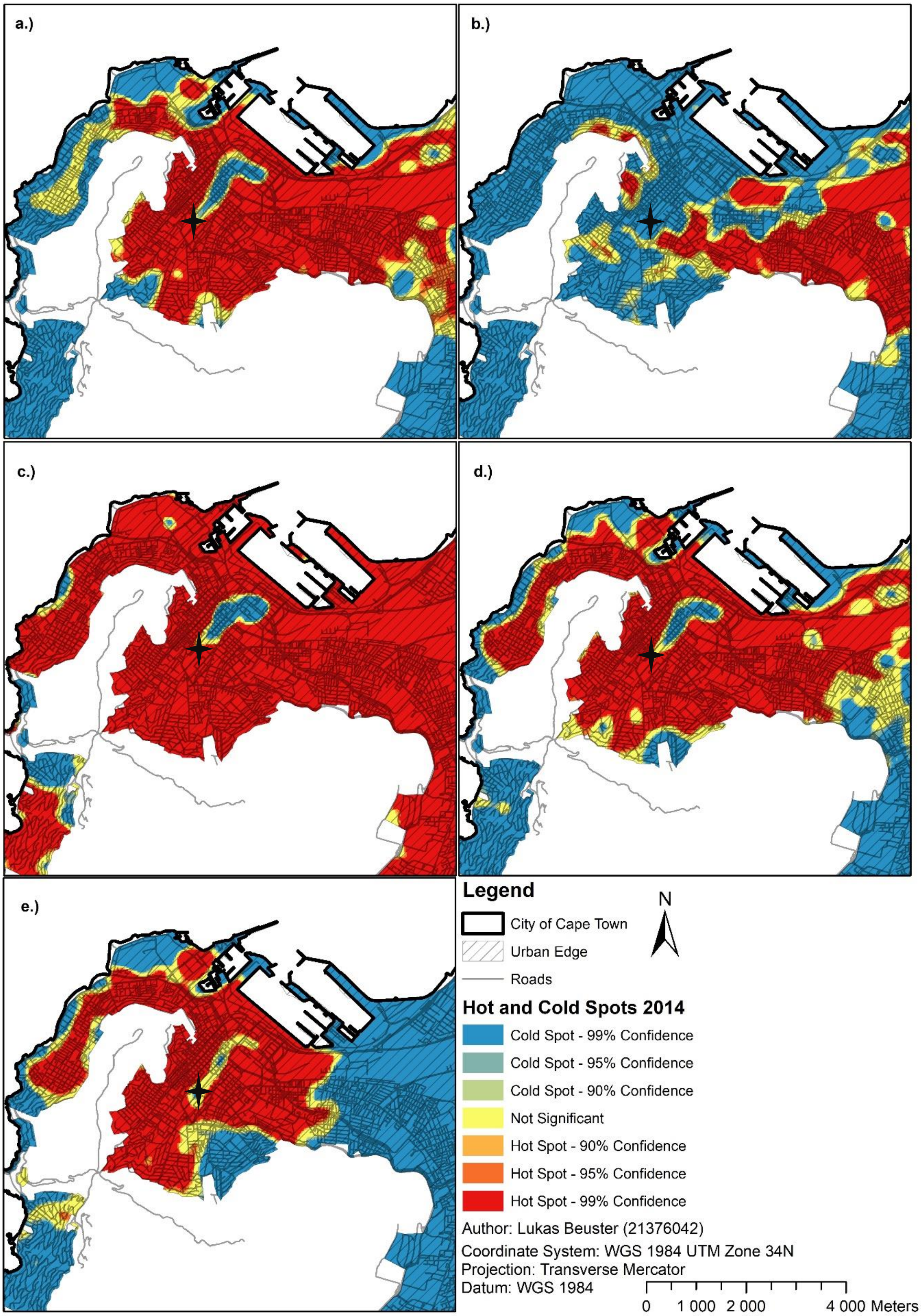

Figure 4.4 Hot and cold spots around the CBD - a.) January, b.) April, c.) July, d.) October, e.) November 2014

In order to further investigate the temporal and seasonal occurrence and intensity of these hot and cold spots, factors such as wind speed and direction, building materials and spatial configuration as well as the intensity of human activities of these areas should be taken into account. It also has to be taken into consideration that this analysis is only based on these 5 dates. To make a more accurate account of the seasonal intensity of the UHI phenomenon, a larger set of dates over multiple time periods will be necessary to paint a more accurate picture of the long-term local climate.

4.2.1 Cluster and outlier analysis

Overall, the cluster and outlier analysis (Anselin Local Moran's I) revealed similar patterns to the hot spot analysis, especially in terms of the trajectory and the changes throughout the year 2014 (See figure 4.5). As such, a detailed roundup of the different dates in question does not yield significantly different results. The orange demarcated areas within the map hereby indicate a statistically significant concentration of high temperature values while the blue demarcated areas signify a statistically significant concentration of low temperatures. The advantage of the Anselin Local Moran's I, however, is its capacity to not only reveal clusters of similar values but also spatial outliers which are demarcated in red where high values are surrounded by low values and purple where low values are surrounded by high values. In regard to the underlying LST values, this reveals areas where low-temperature values lie adjacent to high values and high-temperature values are located close to low values. Throughout the year, high-low clustering seems to occur in areas with industrial activities, around large intersections due to the tarred surfaces with a higher thermal capacity than surrounding greenery, and where land cover changes from vegetated surfaces to bare or built up surfaces. Also highly affected are parking lots and certain high-density configurations of street canyons. Low-high clusters mostly occur where buildings have highly reflective roofs (visible in some commercial and industrial areas). They also occur where densely vegetated parks are present close to built-up land, in the vicinity of lakes and ponds surrounded by bare land or built-up areas as well as alongside rivers. Some of the more prominent examples of low-high clusters in Cape Town is that of the Company Gardens close to the CBD and parliament, which exhibit much cooler temperatures compared to that of its surroundings.

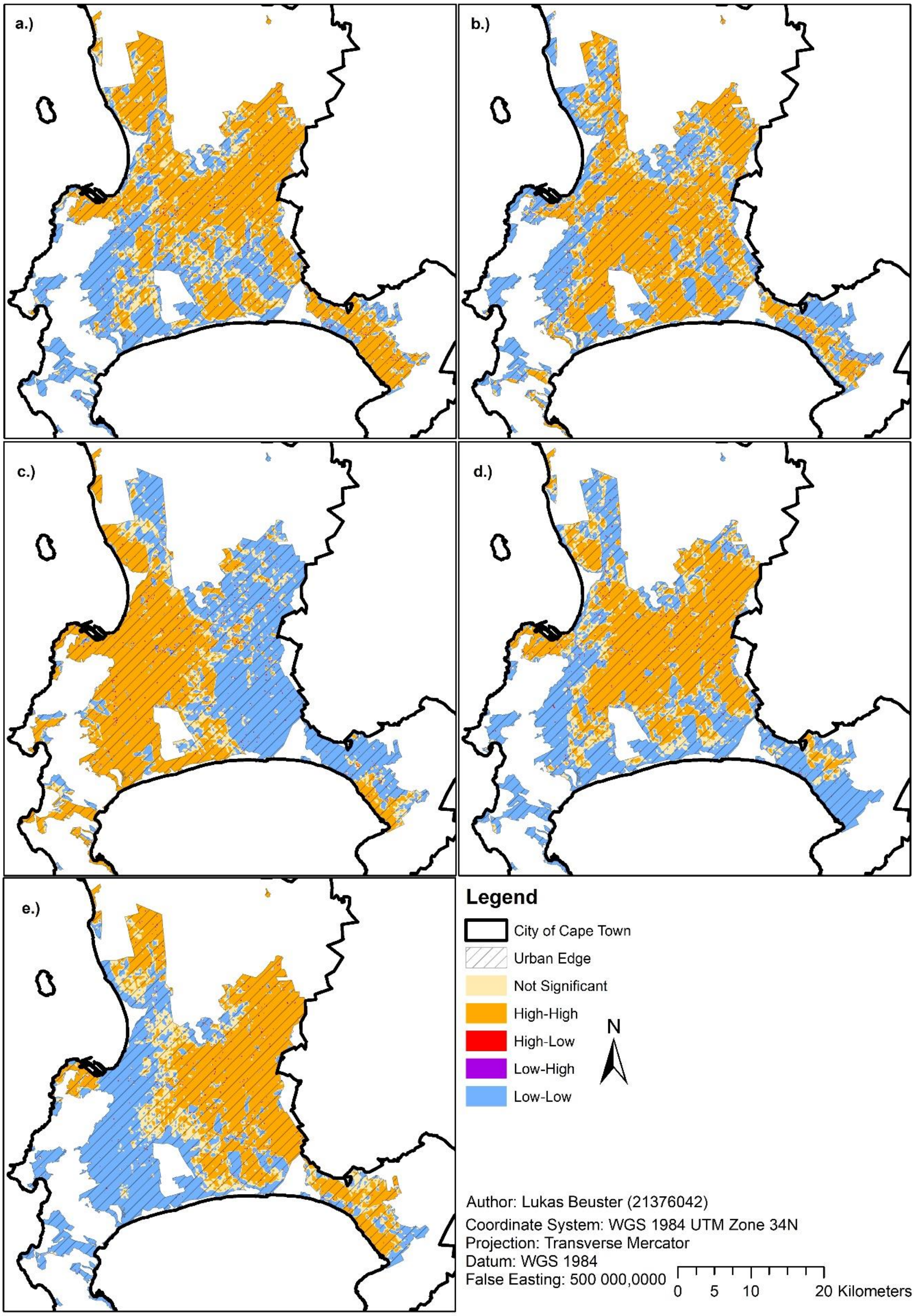

Figure 4.5 Cluster and outlier analysis - a.) January, b.) April, c.) July, d.) October, e.) November 2014

4.3 LAND COVER AND LST – CONSISTENT HOT SPOTS AND REGRESSION

4.3.1 Overall analysis

While looking at the LST data and Hot Spot Analysis data, a relationship with social status and hot/cold environments seemed to emerge. Thus the differentiation between regular urban areas and townships/informal settlements and their temperature performance was highlighted and given special consideration. After using the union tool to collate the pre-existing land cover data and the LST data the 57 LC categories present within the CoCT were aggregated into 14 different land cover classes to ease the display of data. The land cover data that was used differentiates between urban areas not only in terms of its dominant use such as commercial and industrial but also between respective vegetation density of each pixel. The land cover data in the urban areas generally differentiated between commercial, industrial, regular urban spaces (mainly residential), townships and informal settlements. Regular urban spaces, townships and informal settlements are divided into four distinct vegetation density categories each, high, medium, low and bare. For the purpose of this study, informal settlements and townships have been amalgamated as they showed similar LST trajectories.

Over a third of the land within the urban edge is covered by natural vegetation (see figure 4.6). Urban areas are the second largest category covering just shy of two-thirds of the area broken down into different urban activities and vegetation density. Noteworthy is the equal share of densely vegetated urban spaces to low density vegetated urban spaces both covering around 15% of the land within the urban edge. Additionally noteworthy is the general lack of vegetation within informal settlements and townships with almost a 50/50 split between low density vegetated spaces and bare spaces. The amount of medium density vegetated regular urban as well as informal/township LC is negligible. Waterbodies only make up less than 5% of land cover within the urban edge, agricultural use even less.

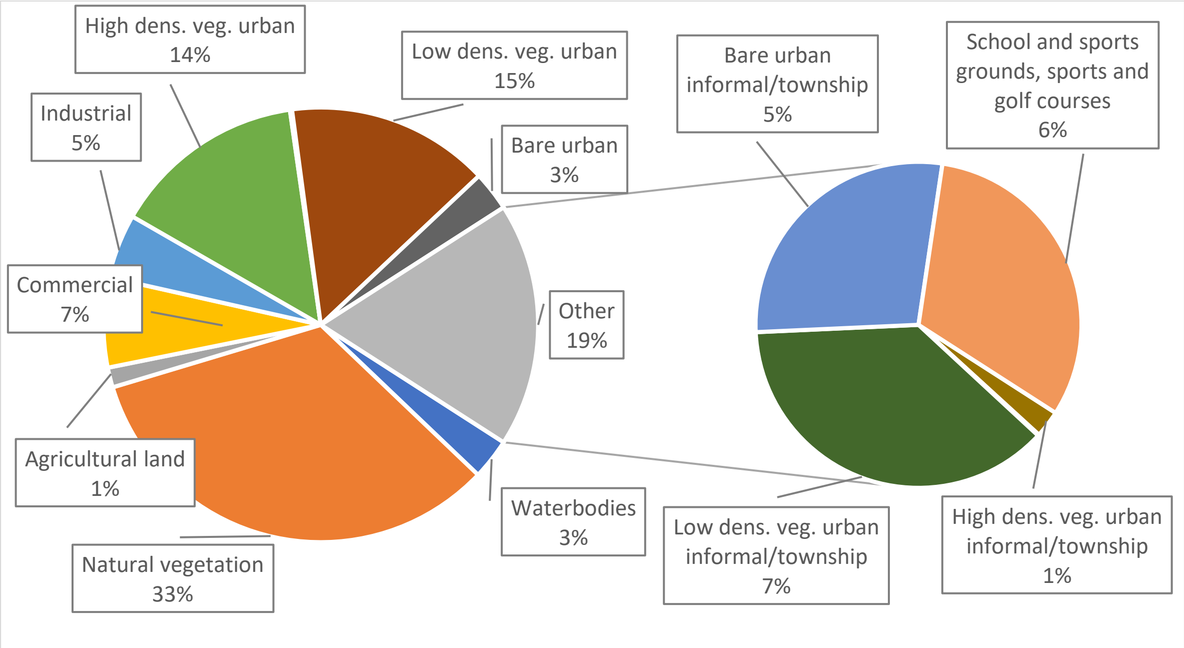

Figure 4.6 Land cover share within the CoCT urban edge

4.3.2 Differences between LC Categories

Most important for the underlying research are the differences between natural vegetation and urban spaces and the differences of temperatures between different urban land cover categories. Three categories are evaluated: the differences between minimum temperatures, the differences between the maxima and lastly between the average temperatures. The following graph represents the temperature differences between the different land category categories and is a result of subtraction of the first-mentioned category from the latter.

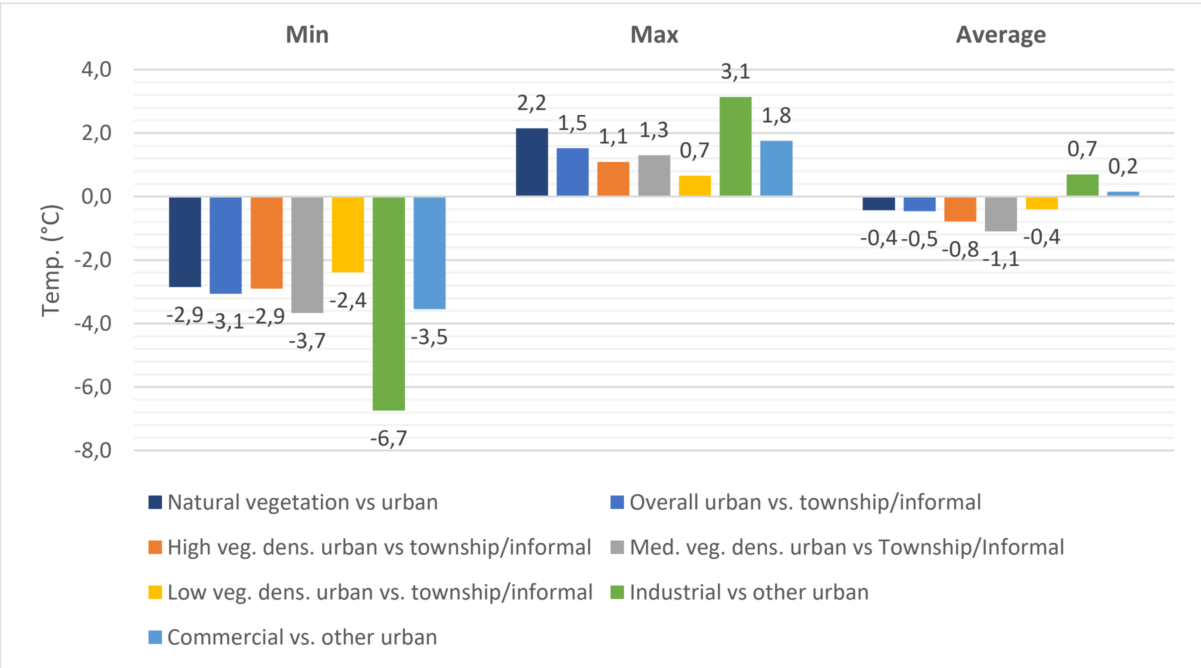

Figure 4.7 Temperature differences between LC categories

i. Minimum temperatures

In comparison to urban spaces, naturally vegetated areas are up to 2.9°C cooler overall indicating different thermal capacities between the land cover categories and a certain cooling effect of the natural environment (see Figure 4.7).

Regular urban spaces (for the purpose of this comparison all urban areas except for townships, informal settlements and industrial areas) show much lower minimum temperatures than township/informal spaces throughout the year. On average they have a minimum temperature that is 2.6°C lower than their informal/township counterparts. This phenomenon is clearly exacerbated in the summer months when the average differences in minimum temperatures reach between 4-6°C throughout the different categories of regular urban and townships/informal settlements. These areas not only show the highest difference in minimum temperatures in summer but also the highest differences throughout the year, with regular urban spaces exhibiting temperatures of up to 3.7°C cooler than townships/informal areas throughout the year.

Further, commercial properties show minimum temperatures of up to 3.5°C lower than regular urban temperatures throughout the year. A similar phenomenon is visible in industrial areas, which exhibit a minimum temperature up to 6.7°C colder than regular urban areas.

ii. Maximum temperatures

Even though regular urban spaces show lower temperature values on the low end, they reach temperatures of up to 2.2°C warmer than their township/informal counterparts. This phenomenon lacks a substantiated explanation but could be related to the higher thermal mass of elements of the regular urban such as parking lots and pavements. Looking at the different spaces from a vegetation density perspective they exhibit a similar phenomenon with surface temperatures between 0.7°C and 1.5°C higher than their respective counterparts. Industrial areas also show a higher maximum temperature than the rest of the urban sphere with maxima up to 3.1°C above the rest. The same goes for natural vegetation, which is up to 2.2°C warmer than the urban spaces, which is to be explained by the inclusion of bare land in the category as per GeoTerraImage classification.

iii. Average temperatures

Throughout the time of the study, regular urban spaces are consistently cooler than townships/informal settlements by at least 0.5°C. Looking at vegetation density within the urban, the highest differences can be found between the medium densely vegetated category which exhibits the highest difference throughout the year: -1.1°C. In addition, natural vegetation is consistently about 0.4°C cooler than regular urban spaces.

Overall the data reveals that informal/township areas are generally hotter than other urban areas throughout the study period. Additionally, there is a noticeable decrease in mean temperature with an increase in vegetation density for regular urban spaces which is not as prevalent in the informal/township areas.

4.3.3 Consistent hot and cold spots

In order to derive the areas that show consistent statistically significant hot and cold spots throughout the year, the Getis-Ord Gi* results obtained throughout the study period were intersected to reveal areas of overlap. The resultant figure 4.7 shows the consistent hot and cold spots within the urban edge throughout the study period. Of the ~990km² inside the urban edge, 54km² (5.5%) are consistent hot spots and 62km² (6.3%) exhibit consistent cold spots.

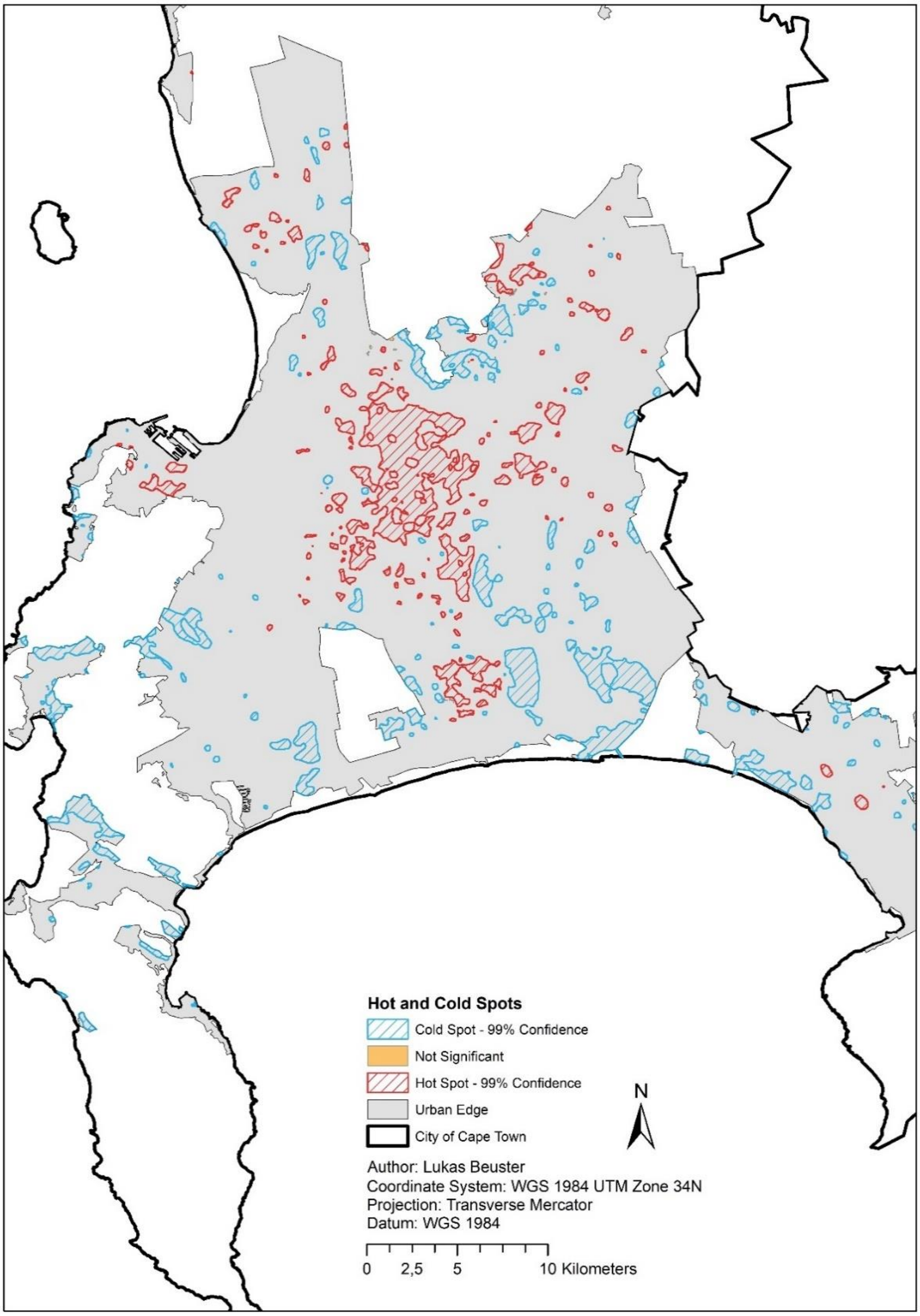

Figure 4.8 Consistent hot and cold spots throughout 2014

i. Regular urban spaces and commercial

Looking at the distribution of regular urban residential spaces as well as commercial areas distinct patterns emerge (see figure 4.9). These areas are mainly found around the more affluent areas around City Bowl and towards the northern and southern suburb extensions towards the northeast and the south respectively. While high density vegetated urban spaces can also show consistent UHI, the share of these spaces is relatively low overall and accounts for only about 7% of the identified consistent hot spots overall (see figure 4.13). Densely vegetated urban areas are more likely to exhibit consistent urban cool islands with about 13% of all UCI attributed to this category. Low density vegetated urban spaces are among the most prominent areas to exhibit the UHI phenomenon throughout the year. Almost 1/5 of the consistent hot spots are located on this land cover category. The main areas that are affected by the UHI effect are Parow as well as parts of Hanover Park and Vanguard. An additional 5% of hot-spots are found in bare urban areas.

Further, commercial areas cover over 11% of the consistent hot spots. This is clearly visible in the town centres of Parow, Durbanville and towards large commercial complexes like CapeGate Mall, Mitchell's Plain District Hospital as well as the Western Cape Rehabilitation Centre. Looking at the figure it becomes obvious that most consistent hot spots are located around the central parts of Cape Town. The commercial areas and low density vegetated urban spaces towards Table Mountain and the CBD seem to be less affected, some even exhibiting consistent cold spots as is the case around Cavendish Square in Newlands.

ii. Informal settlements and townships

There is a distinct area of overlap with the consistent hot spots in close proximity to Elsies Rivier. Mitchell’s plain also shows significant overlap with the consistent hot spots (see Figure 4.10). Overall, informal settlements and townships with a low vegetation density make up about 10% of the consistent hot spots within the urban edge (see figure 4.13). They are, however, not consistently hot as they also make up about 3% of cold spots. A similar trend is visible with the bare informal/township areas. While these areas make up 3% of the consistent hot-spots they have a share of close to 5% of the consistent cold spots. This might be attributed to the fact that some of the townships are in close proximity to wetlands and large, vegetated areas which would have extended cooling effects.

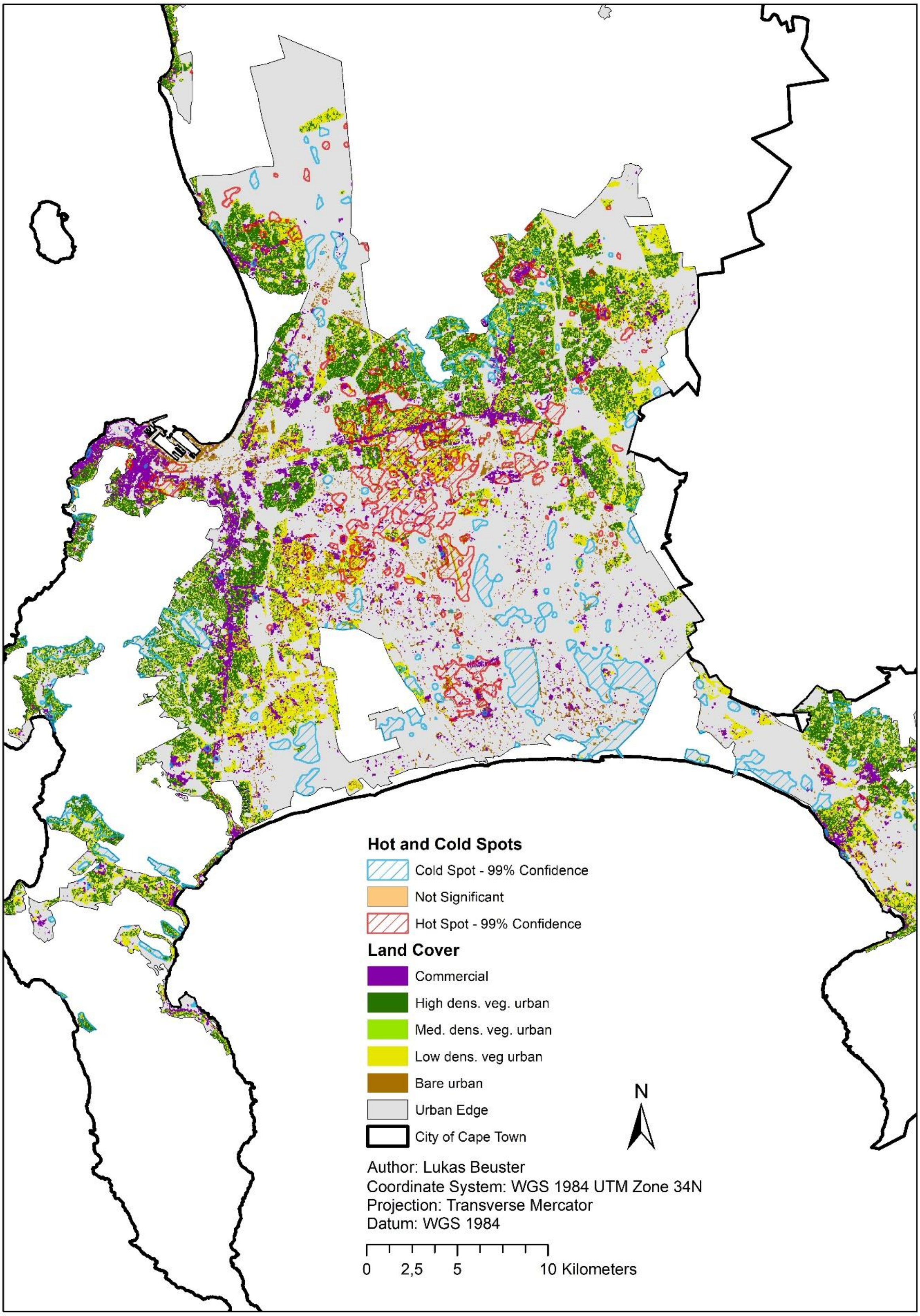

Figure 4.9 Consistent hot and cold spots - commercial and regular urban areas

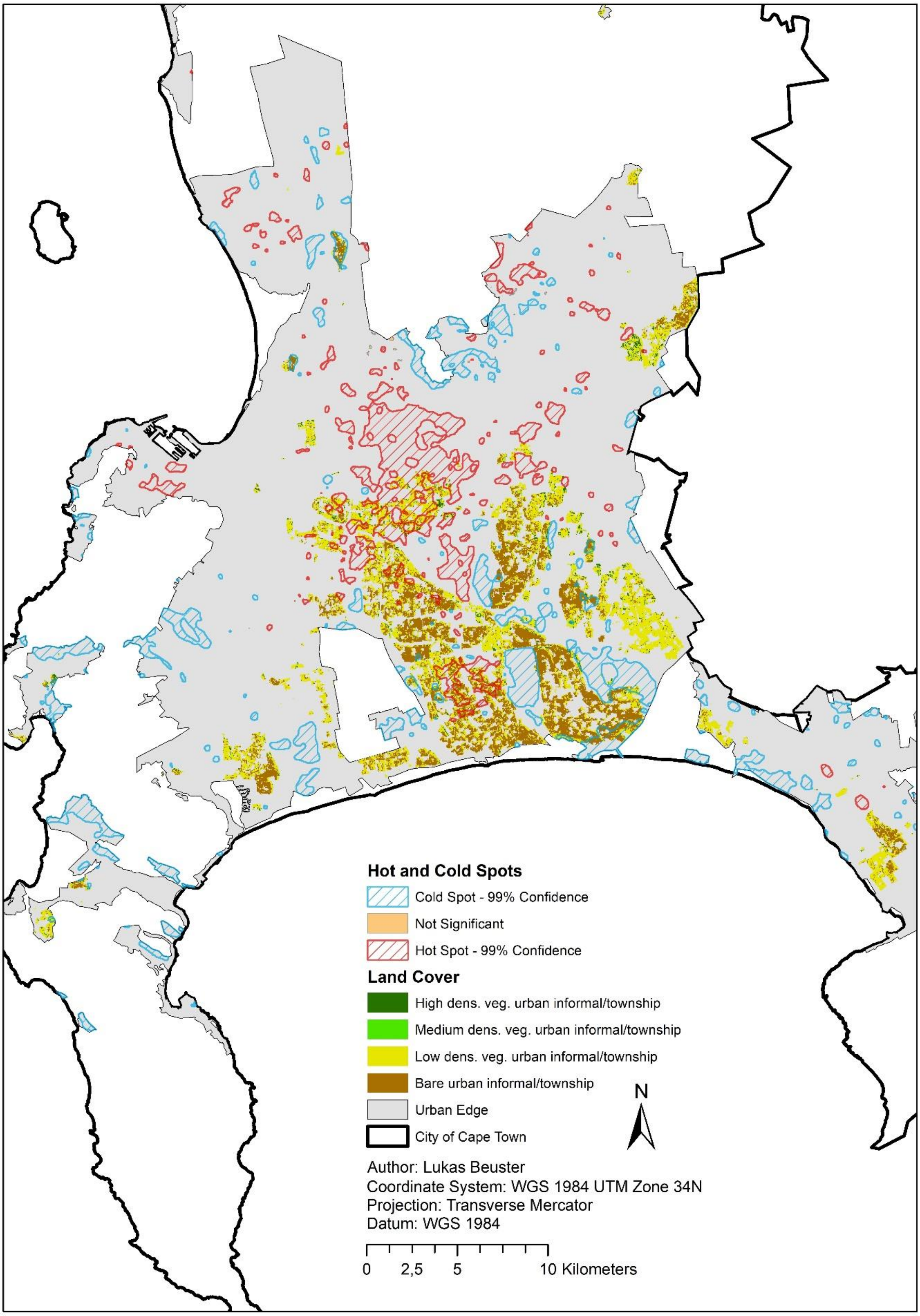

Figure 4.10 Consistent hot and cold spots - Informal settlements and townships

iii. Industrial

Looking at the distribution of industrial areas within the urban edge it becomes apparent that they are mostly located in close proximity to major infrastructure nodes such as highways and more prominently located towards the northern suburbs (see figure 4.11). Industrial areas make up almost a fifth of the consistent hot spots, making it the second highest share of all land cover categories (see figure 4.13). Even though industrial areas can also exhibit consistent cold spots (1.6% of cold spots) throughout the year its share in the identified UHI indicates the overall inefficiency of these spaces in terms of their thermal environment. These inefficiencies make industrial areas a possible focus area to implement UHI mitigation measures in order to lower temperatures along these targets.

iv. Agricultural land, natural vegetation and waterbodies

In the case of the CoCT, the highest share of consistent hot-spots within the urban edge is covered by natural vegetation. Over 20% of the consistent hot spots are made up of natural vegetation (see figure 4.13). Looking at the location of these hot spots it becomes apparent that the vegetation type herein is mainly dominated by grass instead of lush vegetation. The implications of this phenomenon will be discussed at further stages. The most visible examples of the heating effect of vegetation can be seen around the Cape Town International airport as well as inside the City Bowl around District 6, both of which are dominated by grass surfaces. Although natural vegetation makes up a large part of the consistent hot spots (22.8%), it also represents the dominant majority of land cover within the identified consistent cold spots within the urban edge (41.8% of land cover within consistent cold spots). This effect is more noticeable in the densely vegetated areas towards table mountain and in the wetlands in the Cape Flats and shows the duality of green spaces featuring both UHI and UCI.

Second to natural vegetation waterbodies make up just under a fifth of the consistent cold spots. This is easily visible throughout the map. Many of the larger cold spots towards the southern end of the urban edge are either waterbodies or wetlands, indicating the local cooling potential of water-surfaces

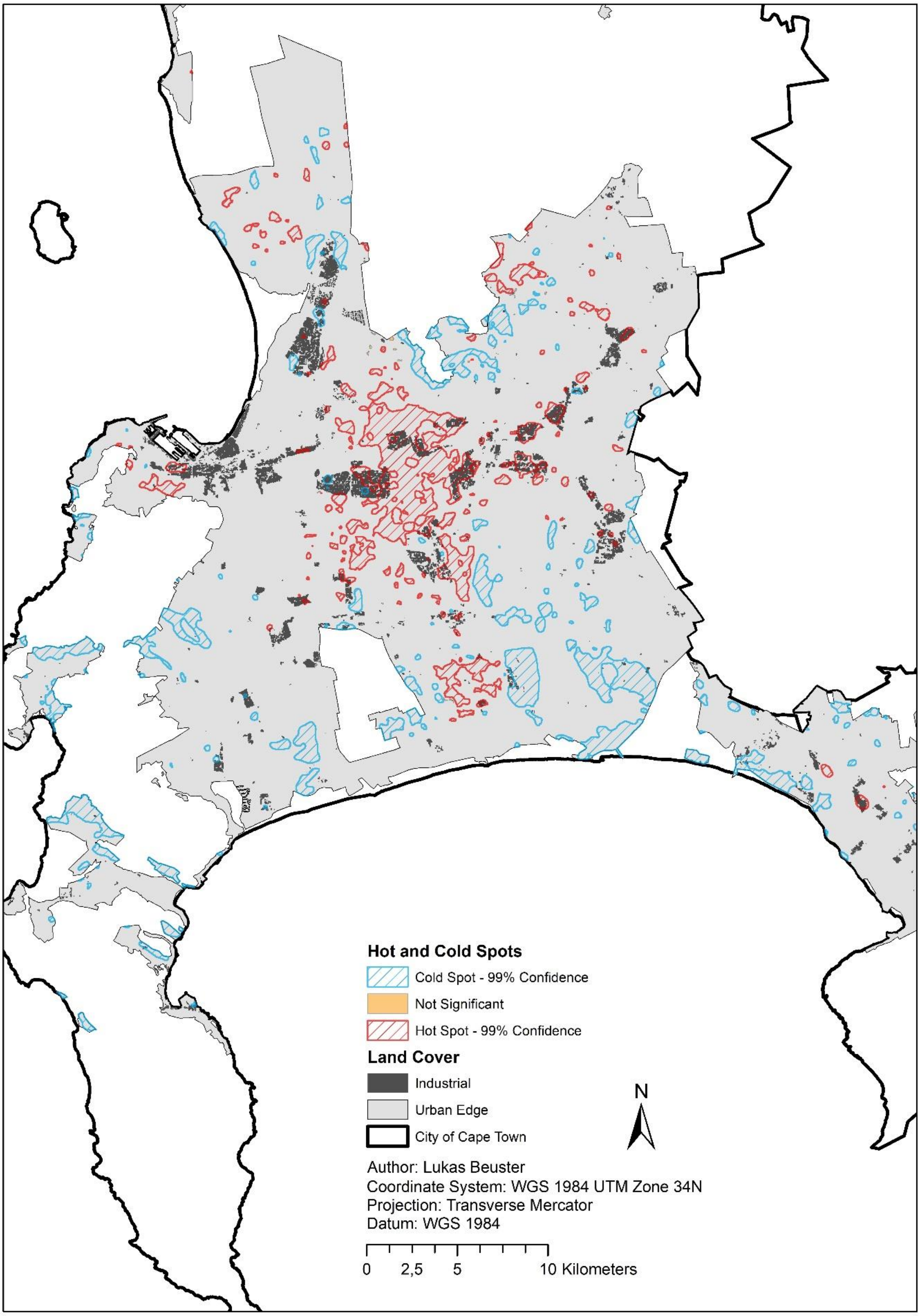

Figure 4.11 Consistent hot and cold spots - Industrial areas

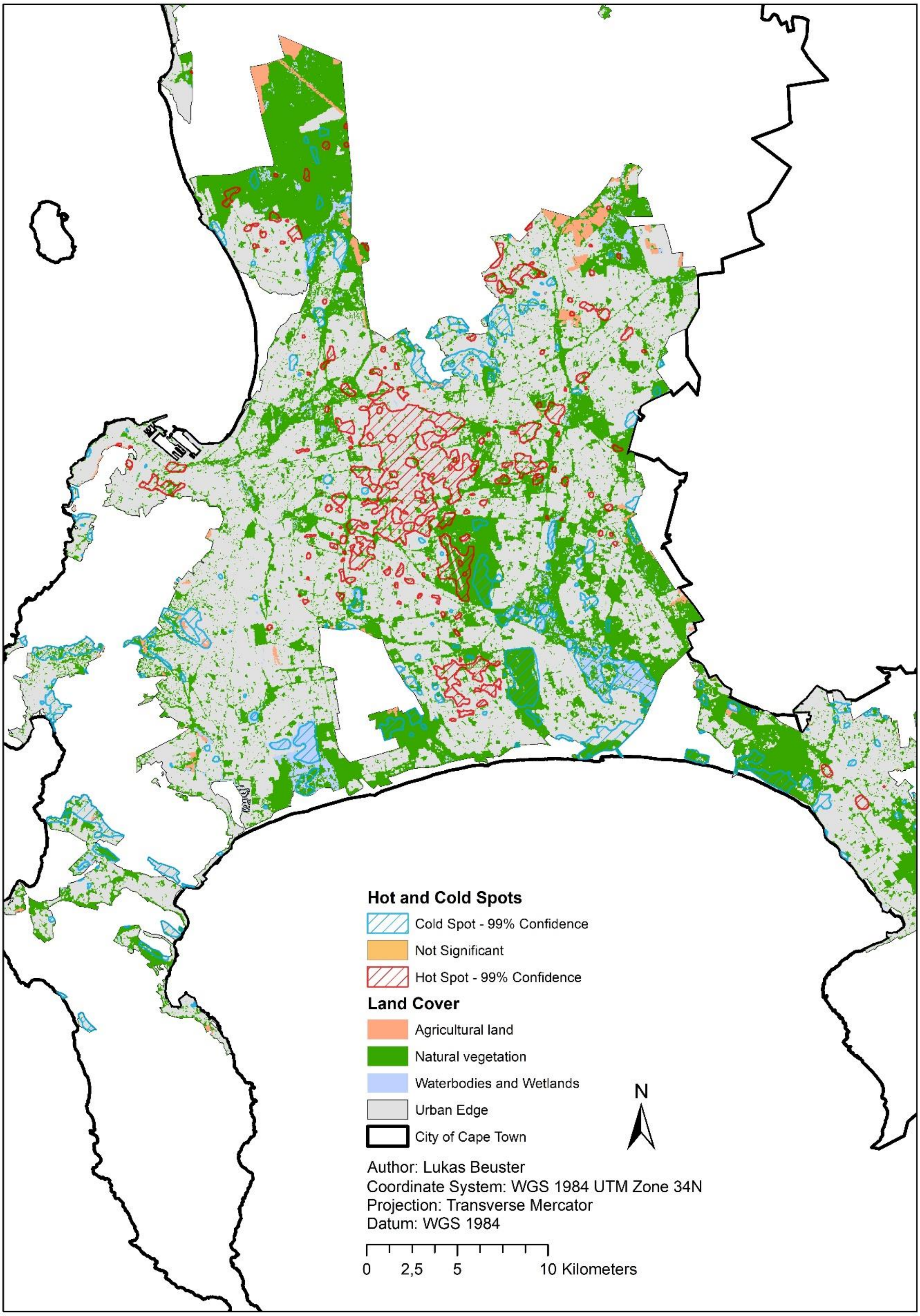

Figure 4.12 Consistent hot and cold spots - Agriculture, natural vegetation and waterbodies

Below, a summary graph of the different land cover categories provides an overview of the aforementioned data.

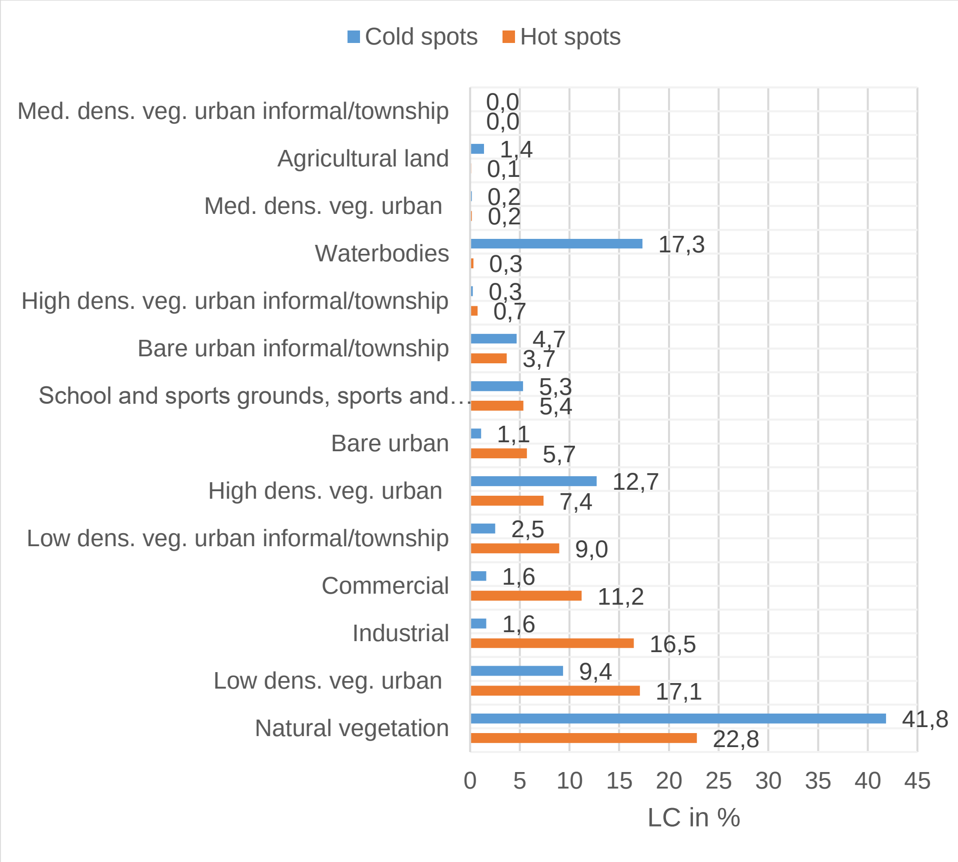

Figure 4.13 Land cover share of consistent hot and cold spots within the urban edge

4.3.4 Regression analysis

In order to explain temperature variations across the study area, the selected land cover categories were aligned with the LST values to compute the relationship between the values. After using the individual LST values for each of the five dates to calculate the average temperature for each individual of the 2 million cells in the study area, a union tool was used to collate the land cover categories with their respective temperature values. After using the union tool to combine the LC and LST data, the dataset was dissolved according to the LC category, all the while establishing the mean LST for each of the newly established polygons. Dissolving the dataset resulted in a simplification of the dataset to just over 60.000 polygons. Using this dataset, both a local and global regression analysis, ordinary least squares (OLS) and geographically weighted regression (GWR), was computed.

4.3.4.1 OLS

As part of the OLS, LST was analysed for its relationship with the different land cover categories overall. The results of the OLS showed that the model was able to explain 50.8% of the variation in the dependent value (LST) throughout the study area over the year. Thus it can be concluded, that the different land cover categories have a distinct influence on the temperature values throughout the year as the model is a relatively good fit. Due to the complexity of urban spaces, the diversity of materials used, the spatial configurations, different usage patterns as well as intensities and local climate influences (wind direction, - speed, precipitation), not all temperature variations can be explained by the model. The results of the OLS analysis are statistically significant.

Looking at the spatial distribution of standard residuals, the OLS results clearly show a mixture of over- and underprediction in specific areas, indicating missing variables to the model (see figure 4.14). The red areas in the map show an underprediction of values of varying intensity (where temperature values are up to <2.5 std. deviations higher than expected). Respectively, the blue areas show areas where values are overpredicted (where temperature values are up to <-2,5 std. deviations lower than expected). The yellow demarcations showcase areas where expected and measured values fall within 0,5 std. deviations from each other, indicating that the variable is a good fit. Overall, the model fairly accurately predicts the temperature values in the naturally vegetated areas – most likely due to their relatively homogenous makeup due to the dominant vegetation type surrounding Cape Town. The urban spaces show higher deviations from the expected temperatures, indicative of their heterogeneous nature. Densely vegetated urban areas also show little variation from the model. Prominent outliers in the urban areas are densely built-up commercial and residential areas within the City Bowl/CBD of cape town, equally densely built-up parts of Green Point and Sea Point and the neighbourhoods alongside the transport axes towards the North (N7), east-northeast (N1) and towards the southern suburbs (M5) – all of which show warmer temperatures than predicted. The effect is not as visible alongside the east-south-east axis (N2) towards Somerset West where a variety of areas show an overprediction of temperatures, with real values lying below what's expected. In the urban spaces, industrial areas seem to be significantly underpredicted and showcase significantly higher temperature values than the model predicts, many of them by more than 2.5 Std. deviations. Overall, areas of high commercial activity, as well as areas close to critical infrastructure, show warmer temperatures than the model expected indicating that land cover alone is not sufficient a variable to explain the temperature variations in these areas.

The OLS analysis also shows cooler values than expected in areas close to water bodies and towards the Cape Peninsula Mountain Range and close to both small and large parks as well as golf courses. This is likely explained due to the influences of higher wind speeds, as well as the shadow of the mountain limiting daylight hours as well as the overall increased evapotranspiration of green spaces. Additionally, many of the informal settlements and townships towards the south-east show slight overprediction with real values lower than expected throughout large parts of Mitchells Plain, Khayelitsha and Blue Downs.

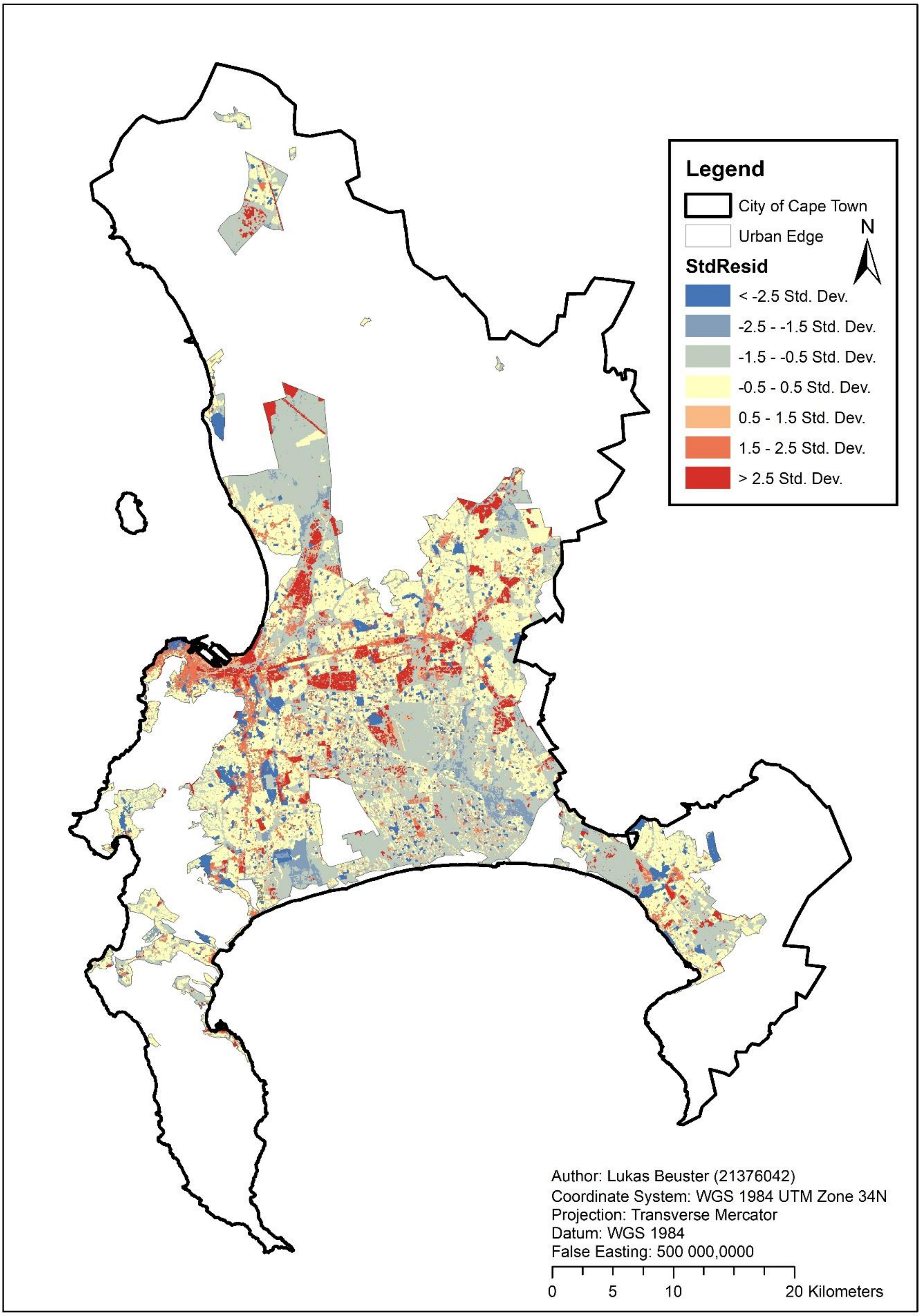

Figure 4.14 OLS Residuals - LST LC

4.3.4.2 GWR

The GWR was computed using the same dependent and independent variables as the OLS. The results of the GWR accentuate the outcome of the OLS and, due to it being a local statistic, manage to paint an even more localised picture (see figure 4.15). In the local model land cover explains 58% of the temperature variation within the study area and as such is a slightly better fit than the OLS. A sigma-value of 0.49 indicates the estimated standard deviation of the residuals. Smaller values are preferable, the sigma of 0.49 is indicative of the fact that there are variables missing from the model. Looking at the visual output, an interpretation is equal to the aforementioned interpretation of the OLS. The GWR clearly showcases a more differentiated picture of the cooling effect of green spaces with green spaces closer to the north and the east of the urban edge exhibiting stronger overprediction than in the south-east. The underprediction along the aforementioned transportation axes out of the city are still visible, as is the intense heat build-up in the industrial zones and the densely built-up areas within the City Bowl as well as the suburbs of Green Point and Sea Point. The development axis towards the south-east showcases a weaker overprediction of temperature values than the OLS with large parts of the areas exhibiting temperatures close to the model predictions. Only dense urban centres and other areas of commercial activity showcase higher values than expected in this direction. The GWR manages to underline the importance of green spaces such as natural wetlands and parks. Throughout the study are, the vegetated areas show a clear overprediction of values with real measurements below the expected temperatures.

To validate the results of the OLS and the GWR, the computed residuals were analysed using the Spatial Autocorrelation (Moran's I) Tool. The OLS yielded a Moran's I index of 0.024720 and a Z-score of 54.49. The GWR generated a Moran's I index of 0,001416 and a Z-score of 3.16. This indicates a clustering of residuals, indicating that important predictive variables are missing. This does not come as a surprise as the land cover is obviously only one of the factors influencing the LST of the study area. Mapping the residuals revealed that largest anomalies were caused by the land classified as industrial and agricultural. The most extreme deviations in the urban areas seem to occur in the highly dense areas around important infrastructure and in commercial areas. Overprediction of values mostly occurs around green spaces and especially green neighbourhoods. Both tests were statistically significant, indicating that the relationship between land cover categories and their respective temperature ranges is not a product of random chance. With careful planning, the variables responsible for the temperature differences can be controlled and allow to plan for a cooler environment.

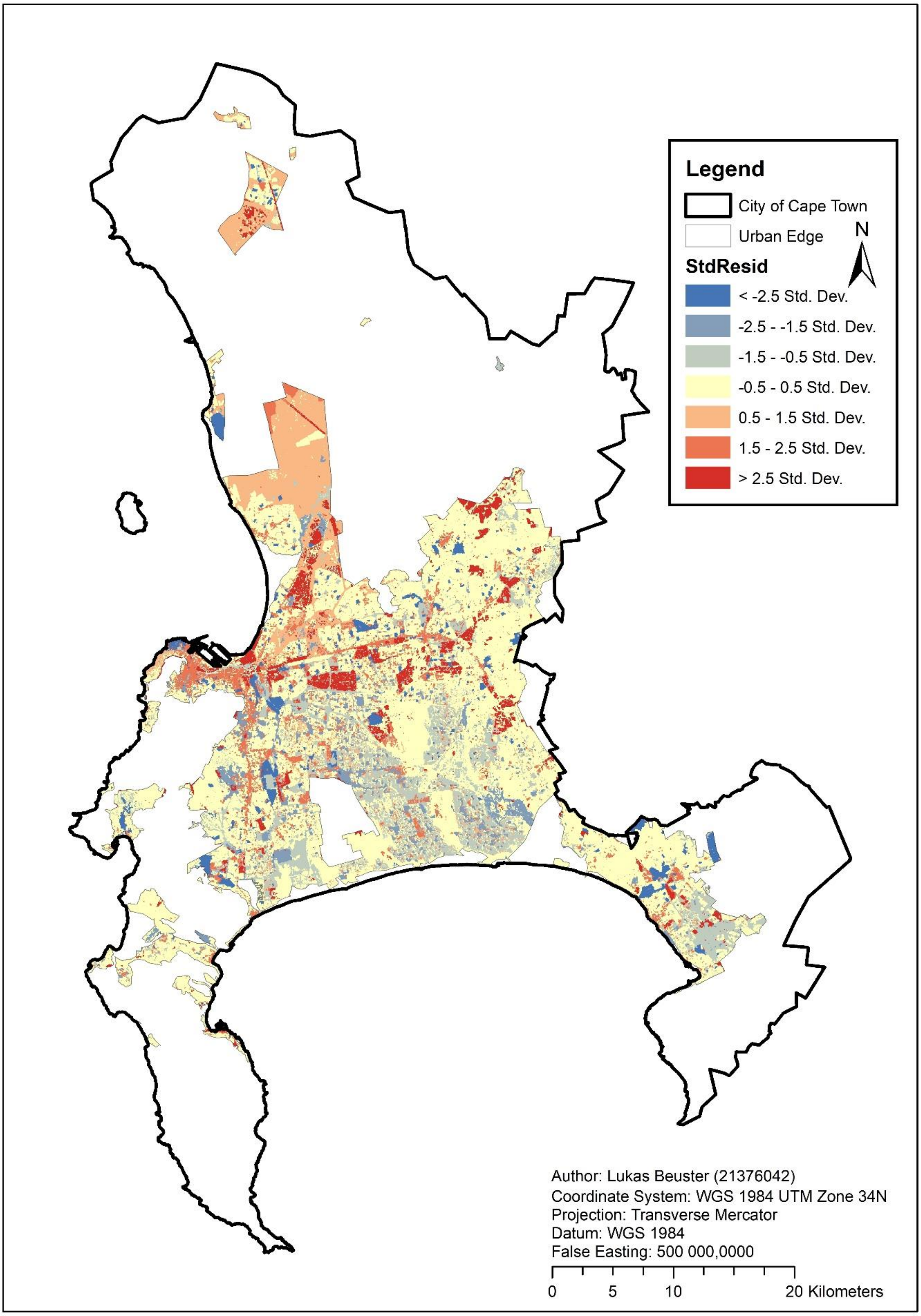

Figure 4.15 GWR Residuals - LST LC

Although the results of the regression analysis are statistically significant and the results indicate a relatively good fit of the model, not all temperature variations can be explained by the model. Due to the complexity of urban spaces, the diversity of materials used, the spatial configurations, different usage patterns as well as intensities and local climate influences (wind direction, - speed, precipitation), are all factors that could potentially also be considered as independent variables in the model. Urban spaces are very rarely homogenously built. Many cities grow organically over time and thus incorporate a variety of different building types, sizes, orientations and predominant building materials. As established in the guidelines for human settlement planning and design, these factors can dramatically alter the thermal efficiency of buildings and thus alter the surface temperature exhibited in this analysis (CSIR 2000a). Moreover, the land cover analysis also can’t predict the underlying morphology of the spaces. The city of Cape Town is not located on a perfect plane, as such, there are many different slopes to consider influencing an areas exposure to solar radiation and wind. Due to data availability and computational resources required, it is however extremely difficult to accurately model all variables influencing surface temperatures within urban environments, especially if detailed modelling is required on city scale (Mirzaei 2015).

CHAPTER 5 SUMMARY AND CONCLUSIONS

The following is a discussion of the main trends concerning UHI, including that of relevant legislation as well as the implications and intricacies of UHI in the CoCT.

5.1 MAIN TRENDS

As part of the wider field of urban climatology and climate change research, the field is of urgent importance for the creation of sustainable and livable cities for the future. The UHI phenomenon is set out to have significant consequences for urban areas around the globe. Looking at the available literature, one of the most obvious discrepancies to date is the severe disparity between available data on the UHI effect between regions. While the phenomenon is reasonably well documented in Europe, North America and Asia, the effect of UHI on African cities are almost non-existent with only a select few studies available in the region. African cities face tremendous changes over the coming decades with a host of their own unique problems including that of informality, poverty reduction and infrastructure provision. Thus, it is of the utmost importance to encourage further studies of UHI on the continent. The need for data on climate change impacts and sustainable urban development is pressing. The focus should thus lie on increasing international cooperation of governments, research institutions, the private sector and individuals to build regional as well as local knowledge and capacities to face future issues pertaining the development of our cities. While the lack of data and the need for cooperation is illustrated on different levels from the UNs Sendai Framework for Disaster Risk Reduction 2015-2030, the African Commissions Agenda 2063 and the South African National Climate Change Response White Paper, little is said on how to facilitate progress in this regard (African Union Commission 2015; Government of the Republic of South Africa 2011; UNISDR 2015)

Only recently have researchers come to the widespread realisation that the costs associated with UHIs ability to amplify climate change effects are significant. Meanwhile, the possible savings of implementing UHI mitigation strategies and investing in the green economy offer attractive alternatives and a reason to invest in a better future. The long-term benefits, both to the economy as well as the population, far outweigh the short-term costs of adaptation as case studies of different urban environments worldwide manage to prove (Kats & Glassbrook 2016; Miner *et al.* 2017). The existing research also shows that UHI mitigation does not have to be incredibly complex. The integration of basic cool surface provisions into national and municipal building codes can affect a vast part of the surface area of cities and make a noticeable impact in thermal comfort, health benefits and energy efficiency.

5.2 A QUESTION OF POLICY AND LEGISLATION?

The analysis of international, regional, national and local legislation on climate change mitigation and urban as well as sustainable development, yielded mixed results. Although frameworks like the UN's Future We Want and the New Urban Agenda, as well as the African Unions Agenda 2063, are committed to the promotion of safe and healthy living environments, cities and habitats, they fail to mention the UHI effect and its influence on attaining said goals (African Union Commission 2015; United Nations 2012, 2017b). The majority of documents under review don't specifically mention the UHI phenomenon at all. Thereafter, the documents that do mention the UHI effect generally don't go into specific detail but rather mention the term without giving sufficient context. There is no guideline or value attached to the phenomenon and thus remains a relatively abstract concept. The mentioned causes of the UHI are mostly incomplete and inadequately phrased with the New Urban Agenda attributing UHI to inefficient mobility and the South African National Adaptation Strategy simply phrasing UHI as gaining in intensity due to climate change (Department of Environmental Affairs 2016; United Nations 2017b). Mitigation methods are identified but are equally non-inclusive with the CoCT Smart Building Handbook mentioning a reduction of the effect mainly with the integration of plants and buildings, increasing shading and insulating buildings. Many documents frame a narrative of inefficient human settlements and a need to increase energy efficiencies. The creation of healthy environments is also identified repeatedly either as the duty of the government or as the prerogative of developers (City of Cape Town 2012).

Few documents on national level, such as the South African Climate Change White Paper as well as the guide to integrating climate change risks and opportunities into municipal planning: Let's respond, reconcile with the fact that new developments should implement thermal efficiency and climate-resilient technologies. They also note that measures have to be taken to integrate climate change risks into municipal planning. However, little has been done about actual mitigation (Department of Environmental Affairs & Department of Cooperative Governance 2012; Government of the Republic of South Africa 2011). On a local level, the Cape Town Action Plan for Energy and Climate Change argued for updated building regulations in 2010 (City of Cape Town 2010). Even though building regulations on energy efficiency and use in buildings were adapted in 2011, the changes were limited and concepts such as cool surfaces were only mentioned in the informative annexe (SABS 2011).

The most progressive document is the 2017 CoCT Climate Change Policy (City of Cape Town 2017). It recognises the inefficiencies of climate change mitigation efforts to date, stressing the need to review by-laws, city planning and building development policies. The language of the document does not indicate binding commitments as of yet, instead wanting to encourage both the private and the public sector to include energy efficiency into all new buildings and upgrades. It also establishes the need for incentives to promote development facilitating climate change mitigation and adaptation, so far without publicly available results. The need to educate and push for individual responsibility has been met with talk of leading by example to induce behavioural change. According to the Western Cape Spatial Development Framework, awareness of issues like climate change still pose a massive hurdle within the population (Western Cape Government 2014) Educating the public and informing a more inclusive SDF should be emphasised in upcoming reviews.

In addition to enforcing new building regulations and educating the public, the city's urban management and planning division themselves should be better informed about the extent and occurrence of UHI within the city boundaries. The National Climate Adaptation Strategy specifically calls for the identification of areas at risk from climate change impacts (Department of Environmental Affairs 2017). Considering the possibly detrimental effect to the CoCT, UHI should be directly implemented into the development directives on precautionary areas of the city's SDF. UHI should be included in the current areas of risk alongside issues such as aviation, utility services buffers, safety zones as well as areas of increased flood and fire hazards. This would allow for alignment to policy number 22, which discourages urban growth in areas at risk from natural hazards. The inclusion of UHI as risk areas would further allow for the sub-policies to take effect. These sub-policies would allow the CoCT to officially discourage development in areas of known risk and encourage adaptation and risk reduction where the existing property is at risk (Policy 22.1 and 22.2 of the MSDF respectively). The risk areas are currently informed broadly by specialist studies commissioned by the CoCT or Western Cape Government (TDA 2018). The result of this research can contribute to the identification of these areas of risk to inform further research and ensure a more accurate delineation. Tackling the issue also seems to be a problem of responsibility and mandate between the departments of urban planning and management as well as the departments of disaster risk which are both deemed responsible parties. Awareness should facilitate the integration and holistic view according to the IUDF ideals of cooperation, alignment and efficiency (COGTA 2016a).

Even though progress is visible, South African legislation is far behind with regards to acknowledging, assessing and mitigating UHI effects. Development frameworks in other cities around the world like Chicago, Los Angeles, Toronto, London and Stuttgart have realised the importance and possible impact of the phenomenon, adjusting development frameworks and building codes accordingly. Adoption into legislation takes different shapes and forms. While some cities commit to specific temperature reduction targets, other cities adapt building codes to include provisions for reflective surfaces, insulation and or greening, educating and incentivising citizens and triggering behavioural changes (Chicago Climate Task Force 2008;

City Council Toronto 2017; City of Chicago 2018; City of Los Angeles 2015). Looking at different cities around the world, the methods, guideline documents and amendments of building codes have already proven effective. South Africa and the CoCT should take note and implement not only recommendations but make provisions like the inclusion of cool surfaces and urban greening in new developments as well as for upgrades mandatory as part of the national and municipal building codes. Both the City of Cape Town's Smart Building Handbook of 2010 and the CSIRs Guidelines for Human Settlement Planning and Design include elements of building efficiencies and mitigation of intense heat build-up (City of Cape Town 2012; CSIR 2000a). Adding on and writing voluntary guidelines into law should be considered. It has been established that information, awareness and incentives are the first steps in integrating UHI mitigation strategies in any city. This process clearly needs improving in the CoCT.

The UHI phenomenon, its effects and mitigation rationale should form an integral part of international, regional, national as well as local development frameworks. The short and long-term effects, as well as mitigation methods as discussed at length, should inform development trajectories as well as the everyday work of urban management and planning around the world, with a particular focus on Africa. Adoption of new concepts can prove slow when implementing so the new iteration of urban development frameworks in the CoCT should include more advanced plans on how to deal with future heat build-up within the city.

5.3 URBAN HEAT ISLANDS IN THE CITY OF CAPE TOWN

The results of the satellite analysis have shown that UHI are a wide-spread phenomenon within the City of Cape Town. Large parts of the urban inner core of the CoCT show significantly higher temperatures than the rest of the City. As part of the discussion, four different phenomena will be highlighted, the possible correlation between poverty, heat and mortality, the cooling effect of green spaces, agriculture and heat stress and cool roof technologies within the city.

5.3.1 Poverty, informality and heat

Article 43 of the new urban agenda mentions that *"human settlements should be places of equal opportunities, allowing people to live healthy, productive, prosperous and fulfilling lives"*(United Nations 2017b: 14). In Cape Town, inequalities are pronounced. As the research shows, there is a distinct social justice issue pertaining to the build-up of heat in the City. Poorer areas show higher surface temperatures on average as well as higher minimum temperatures compared to that than in the more affluent urban areas. While there are exceptions to this, townships and informal settlements are on average 0.4°C warmer throughout the year. In October and November, this difference increases to 0.8°C and 1.1°C respectively (see figure 5.1). Most notable are the differences in plot sizes (considerably larger in Constantia Heights), building density (low in Constantia Heights) and vegetation (more lush and prevalent in Constantia Heights whereas Elsies Rivier is either bare or sparsely vegetated). Especially in the summer months, this difference could increase mortality due to heat stress, exacerbating cardiovascular and respiratory diseases. Previous research has shown that cities in more temperate environments exhibit a higher increase in mortality risk than their counterparts in warmer climates (in a developed country context). This is mainly attributed to the widespread availability and use of air conditioning in warmer cities. It was also proven that people in absolute or relative poverty show the highest mortality increase throughout all latitudes due to heat effects (Curriero *et al.* 2002). Even though no data was available, it can be assumed that a large share of South Africans don't have access to and can't afford to maintain and run air conditioning systems. As established, heat mortality is closely linked to economic status. Mortality increases almost instantaneously after an extreme weather event and temperature increases can lead to years of life lost, especially for already vulnerable populations like children and the elderly (Baccini *et al.* 2013). In Mediterranean climates, this effect seems to affect the younger generations even more than the old (Leone *et al.* 2013). Overall, 30% of Cape Town's population can be deemed vulnerable to heat stress due to their age groups alone, disregarding the vulnerability effects of poverty.

Possible increases in mortality due to increased temperatures and the resulting increase in the intensity of the UHI effect in the CoCT and in South Africa, in general, emphasize the need to mitigate this increase. UHI mitigation thus becomes a matter of upholding the constitutional right of every citizen to a healthy environment as the focus switches towards increases in well-being and productivity (Republic of South Africa 1996).

Projects such as the Kuyasa CDM showcased that in-situ upgrading of low-income housing projects can have a dramatic effect on energy efficiency, thermal comfort and the overall quality of life in low-income housing (UN-FCCC 2005). Simply adding ceilings and basic insulation can make tangible differences in the lives of vulnerable populations. There should be a broader effort to alleviate existing thermal loads for those that don't have access to, don't have knowledge of, and who can't afford insulation, cool roofs and other heat mitigation methods. In addition to low-income housing projects, there are is a large number of informal dwellings within the city boundaries. The CoCT has already reconciled with the fact that informality is going to be a constant feature of the urban landscape of the CoCT for years to come (City of Cape Town 2017). The prevalence of UHI in poorer areas with a high degree of informality stresses the importance to find appropriate solutions for people in these circumstances as well as to amend the building codes and shift responsibilities on to developers who won't alleviate this specific problem.

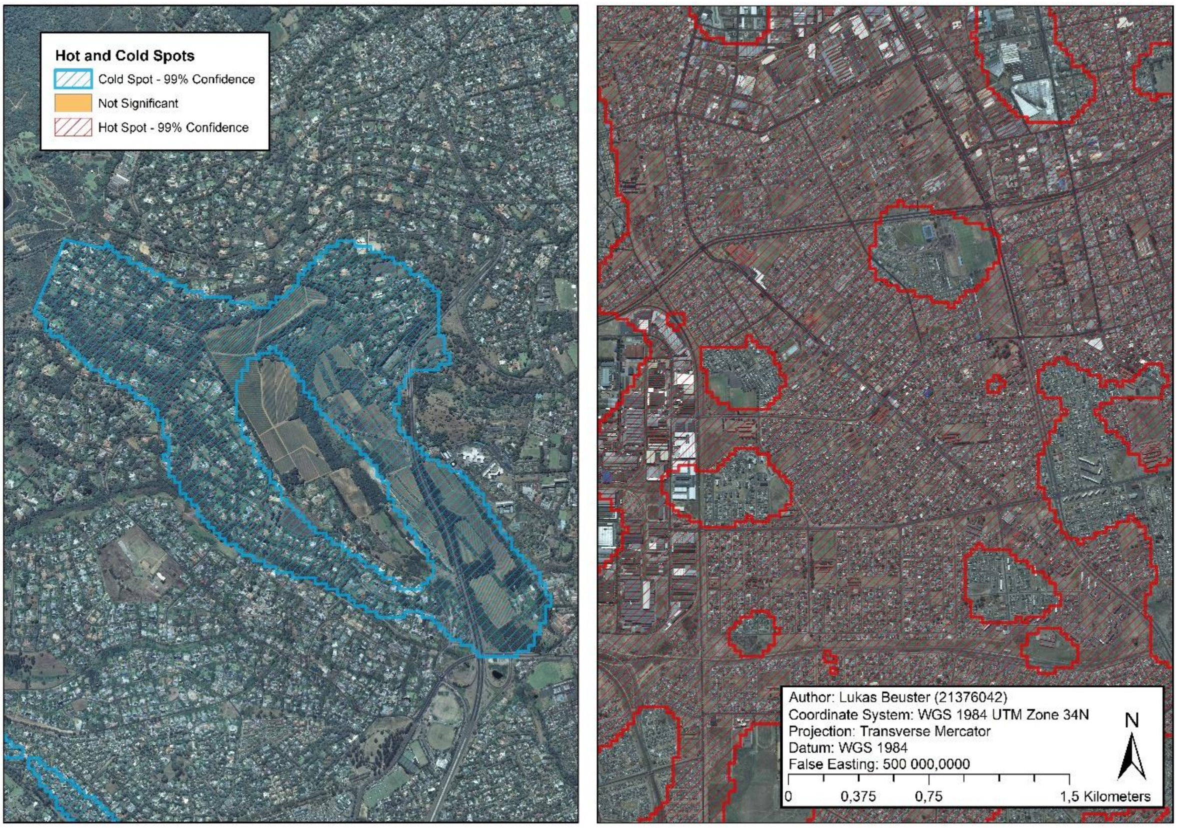

Figure 5.1 The differences between permanent cold and hot spots. Constantia Heights (left) and Elsies Rivier (right)

5.3.2 Green spaces for UHI mitigation within the urban edge

The data reveals that the natural vegetation inside the urban edge is on average -0.4°C cooler than the urban areas. This value is substantially smaller than the 0.94°C average calculated as part of a 2010 meta-analysis of green space temperature differentials during the day in 45 cities (Bowler *et al.* 2010). In comparison, while green spaces in the CoCT reveal wide-reaching cooling capacities and exhibit minimum temperatures of up to 3.9°C lower than all urban surfaces – a report in Lisbon showed a decrease of 6.9°C, almost doubling the reduction (Oliveira *et al.* 2011). The natural vegetation in the CoCT can reach surface temperatures that reach temperatures of up to 2.2°C higher than any urban surfaces on average. This is most likely to be explained by the dominant vegetation type in the study area. Most of the vegetation in and around the CoCT is very light and naturally vegetated areas are mostly bush and shrub-dominated, which falls dry during the summer – increasing the heat build up. Despite some exceptions, the CoCT lacks wide-spread lush thick vegetation to facilitate a cooling effect on a large scale. About 20% of the consistent hot spots throughout the urban edge are categorised as natural vegetation, indicating the widespread prevalence of sparsely vegetated grassland. As previously established, increases in temperature change the soil matrix and heat capacity of the land. These changes in capacity for evapotranspiration have the potential to transform previously cool environments into heat islands, especially during summer (McCarthy *et al.* 2010; Oleson 2012). In the CoCT, these open spaces with a low vegetation density show this phenomenon. While green spaces dominated by grass might exhibit insignificant temperature differences or even a cooling effect during the rainy season in winter, they transform into dry areas of excessive heating during the summer months. Some of these grassy areas are significantly hotter throughout the year, increasing atmospheric temperatures in the surrounding areas. The vacant land within District Six in the city bowl is a prominent example of this phenomenon (See figure 7.2). The increased exposure due to the north-facing slope of the district might contribute to the heating effect as well. Emphasizing the importance of taking evapotranspiration into account is the fact that over the course of the next decades, solar radiation is expected to increase between 5-10% as increases in temperature lower overall humidity. This underlines the fact that irrigation schemes on a large scale seem unreasonable in a drought-prone environment such as the CoCT. Instead of extending green spaces for cooling purposes the immediate focus should be on preserving existing parks, wetlands and the remaining indigenous forest. In order to facilitate the extension of green spaces as part of thermal management, the city would first have to impose new efficiencies in regards to its water management. Re-evaluating a combination of thermal and water management and culminating in sponge-city approaches (retaining rainwater within the city bounds, used to irrigate vegetation and to keep groundwater levels high) could be looked at further (Chan, Griffiths, Higgitt, Xu, Zhu, Tang, Xu & Thorne 2018; Jiang, Zevenbergen & Ma 2018; Liu & Jensen 2018)

Related to this, previous studies established that the UHI effect might be exacerbated for new developments as changes in the soil matrix reduce the local humidity, in turn, exacerbating the effect of changes in the thermal capacity of the land due to the use of artificial building materials. Integrating a formal process for heat assessments into environmental impact studies of developments might be a sensible choice for governments to keep unwanted heating in check. Sensible densification mostly yields lower increases in temperatures, especially with the inclusion of cool surfaces like green or cool roofs in the development process (Doan *et al.* 2016)

Figure 5.2 Permanent hot spots in the city bowl. Bo-Kaap, District 6, Foreshore

5.3.3 Agriculture and heat stress

The LST derived from the Landsat images revealed that agricultural surfaces within the CoCT have the potential to increase in temperature to an extreme extent. With surface temperatures reaching a maximum of 43,3°C in January and the highest average surface temperatures throughout the year except for July, the agricultural surfaces exhibit a distinct temperature anomaly. The intense heat build-up can most likely be explained by the reduction in evaporation during the warmer months and the reduced heat capacity of the heavily farmed land surrounding the Urban Edge. The first draft of the National Climate Adaptation Strategy points to a lack in capacity and data not only to mitigate the heat stress for human recipients but also for ways to alleviate heat stress for livestock (Department of Environmental Affairs 2016). The surface temperatures recorded in the agricultural areas of the CoCT emphasise the need to urgently assess the heat stress conditions of livestock within the city boundaries and have to be mentioned herein even if most of the agricultural surfaces lie outside the urban edge.

5.3.4 Cool surfaces

As discussed previously, industrial areas are among the hottest within the CoCT boundaries overall. However, small portions of these industrial areas stand in contrast to this heat build-up and exhibit minimum temperatures that are up to 6.7°C lower than the rest of the urban area combined. Looking at some of the industrial areas the reason for this apparent discrepancy can be found in the usage (whether purposeful or accidental) of highly reflective roofing materials. The Cape Town Market in Epping Industria 1 is one of the most prominent examples of the efficiency of cool surface technology within the CoCT (See figure 5.3). The surface temperature of the roof of the wholesale market is consistently cooler than the surrounding areas. While large parts of Epping Industria show significant hot spots, the market stays cool.

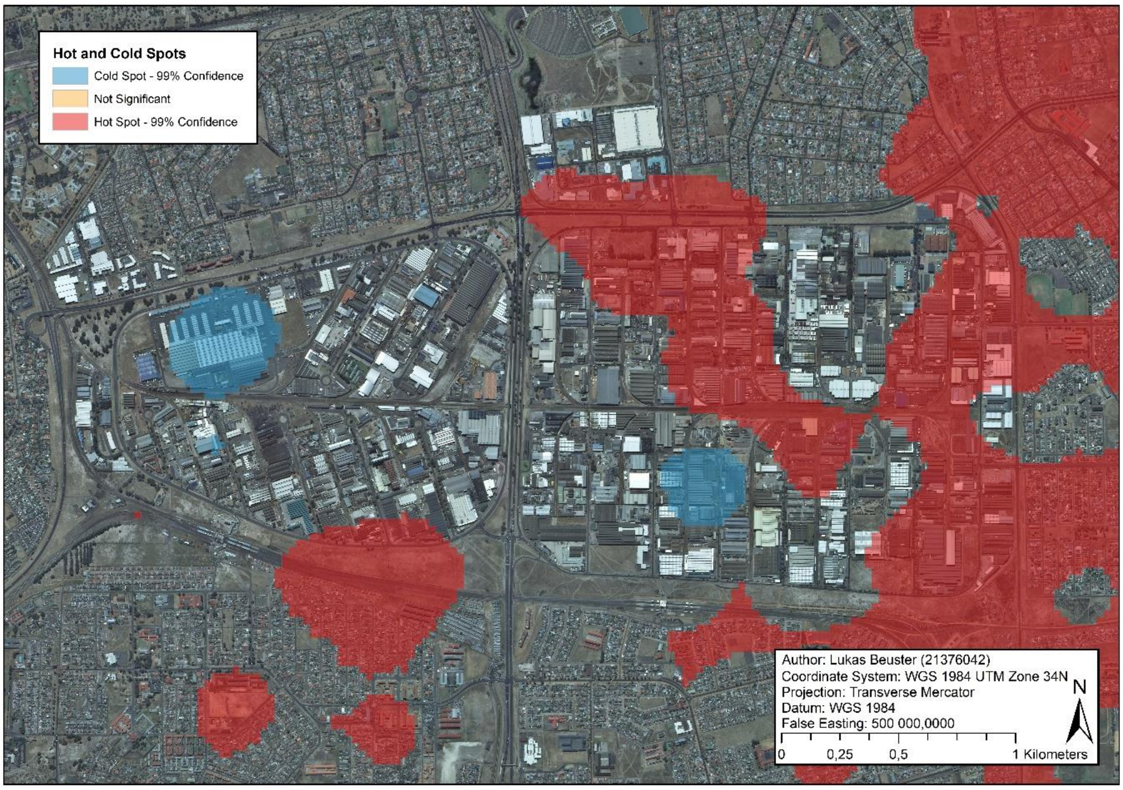

Figure 5.3 Permanent hot and cold spots in Epping Industria

According to the Environmental Protection Agency of the USA, an average of 20%-25% of a city's area is covered by roofs (USA Environmental Protection Agency 2012c). Implementing cool roof provisions according to the examples set by Los Angeles, Chicago and or Toronto could yield dramatic increases in the overall albedo of the city. Similarly, many of the UHI within the city boundaries are located around major intersections and other transportation infrastructure. The Citywide application of cool surfaces could theoretically increase the albedo of between 55-70% of the cities land cover (on average 25% of overall landcover in urban areas are roofs, 30-45% are pavement (USA Environmental Protection Agency 2012c,d)) dramatically altering the temperature experienced within the city. Only slight increases in albedo could yield temperature reductions of 0.5 to 1.5°C overall, extreme increases between 1°C and 2.2°C – as shown in a modelling approach for Athens, a city with a similar climate to the CoCT (Santamouris 2014). This goes to show that the CoCTs roofs and pavements offer vast potential for UHI mitigation. The adaptation of cool surface strategies into the building codes is heavily reliant on public will and the availability of cool paving solutions in the country. While some reports suggest that cool surface products are easily obtainable without additional cost to the end user other reports suggest the need to formally prepare the roofing industry for a change in policy. One needs to make sure that the roofing industry is ready for such a change. In Chicago, new building codes were held off for a year because of pushback from the roofing industry. According to some, adopting cool roof standards severely limits the choices of roofing systems, so the expertise, supply of materials and the cost efficiency for the switch must be evaluated. In Cape Town, a combined approach of redressing surfaces of both industrial and commercial areas alone could positively influence almost a third of the consistent hot spots exhibited within the urban edge. Addressing reflectance in both low density vegetated regular urban surfaces, as well as their informal/township equivalent, could potentially increase this number to over 50%. Applying cool surface strategies in these areas should thus gain priority status in UHI mitigation.

5.4 POSSIBLE RECOMMENDATIONS

In order to holistically approach the UHI phenomenon and its successful mitigation, a variety of methods could be discussed. To assess the current situation of UHI and give recommendations on how to move forward an adaptation of the 5A's framework used to localise the New Urban Agenda is proposed (SACities Network 2016). The 5 A's of localisation were derived from the SACities discussion document, the key findings and recommendations were developed as part of the study.

5 A's of localisation	Key findings of research	Recommendations
Awareness **-** Based on understanding the issue at hand and knowledge of the related consequences and policy options.	- There is a trend of increasing awareness of UHI both globally and locally, but only in recent years. - The processes are not fully understood as is revealed by a lack of engagement. - Even though certain levels of government are aware of the issue, general social awareness is lacking - limited ownership. - Cape Town exhibits the UHI phenomenon and its severity will most likely increase in the future. - Already vulnerable populations might suffer the most from current extents and future increases in UHI. - A variety of factors influence the extent and intensity of UHI. Land cover was established as an important variable.	- Awareness of the positive effects of UHI mitigation has to be more widely understood. - It was established that decreasing temperatures increases thermal comfort and reduces heat stress resulting in health benefits for the population – especially already vulnerable population groups. - Additionally, UHI mitigation methods can extensively increase the energy efficiency of our built environment, leading to cost savings and reduced CO^2 emissions. - Further resources will have to be spent on investigating the complexities of the UHI phenomenon to assess the most important variables influencing the effect. These findings will have to translate into policies, become part of the overall development priorities as well as processes.
Alignment **-** Speaks to the need for Policy coherence and	- There is no wide-spread international and national recognition of the UHI phenomenon as part of major	- Supranational bodies, as well as national government, should include the UHI in their policy documents in order to facilitate wide-spread

intergovernmental collaboration. The roles of stakeholders and different spheres of government have to be defined to avoid confusion as well as policy fatigue.	development frameworks and urban agendas - There is no framework offering a consensus on the effects and mitigation methods. - As part of a bottom-up movement, metropolitan municipalities around the globe have taken the issue into their own hands. These cities have made resources available for research, mitigation and adaptation and have amended municipal building codes despite the prevalence of milder national agendas.	alignment of education on the topic as well as towards adaptation and mitigation methods. Looking at the specific policies of progressive cities around the globe could possibly inform the way forward. The City of Cape Town could establish itself in a leadership position in Africa in terms of UHI mitigation efforts. There is no reason to wait for national regulations to catch up.
Association - Aims at the importance of collaboration across sectors to empower actors enabling them to acknowledge their individual roles in the processes.	- Municipalities struggle with people's awareness on matters such as climate change, increasing the difficulty of prioritisation of issues related to the theme of sustainability . - Both public and private interest exist as exhibited in the existence of the South African Cool Surfaces Association and the inclusion of UHI into climate change policy in the CoCT. Combining such expertise or interests is currently lacking	- All levels of government, from international to national and local government should take a leading role in facilitating knowledge creation on UHI which includes support for research in terms of funding and finding ways to educate all stakeholders. - Assisting this diffusion could be the provision of a legal framework of building codes, guidelines and incentives around changing behaviours and facilitation of active engagement with the UHI phenomenon.
Actors - Implementation through all-of-society	It is not only the responsibility of the state to act on issues of the urban environment. Equipped with the right tools, large-scale developers and individuals can have a long-lasting effect on the thermal environment of cities.	- Develop and implement mechanisms to disseminate relevant UHI and related information, especially at municipal and community levels.

		- Vulnerable populations should be targeted in the information dissemination and capacity building programmes. - Promote shared ownership of the issue and of possible mitigation strategies and enabling shared political and developmental commitment. The inclusion of UHI and related issues in the municipal IDP and SDF processes could facilitate this process.
Activities **-** Formulation of clear, descriptive, available and realistic activities for the South African context.	Even though the CoCT acknowledges the existence of the UHI phenomenon and provides basic recommend-dations towards its mitigation, these methods are not strictly enforced and in the case of the CoCT might not even be enforceable.	- There needs to be a stronger emphasis on increasing building performance (its reaction to internal and external stimuli such as heat) overall, but specifically for industrial and commercial buildings as well as low density vegetated urban areas. - Informal settlements and existing social housing should be considered for the upgrading of cool roof surfaces, ceilings and insulation– These types of projects have been shown to yield positive results in terms of thermal environment as well as cost savings and increased quality of life. - Education on the efficiency of green buildings should be emphasised, from both a social responsibility and financial perspective. This could be accompanied by financial incentives such as tax rebates, lower rates and taxes as well as support in financing from government institutions.

5.5 POTENTIAL LIMITATIONS AND FURTHER RESEARCH RECOMMENDATIONS

One of the most profound limitations when it comes to the use of Landsat data to derive LST are the temporal and possible spatial discontinuities of the satellite data. Landsat 8 is operating on a recurrence time of 16 days (U.S. Geological Survey 2016). This makes it difficult to select images that represent the same or similar atmospheric and land surface conditions to compare the same urban areas. This would especially be detrimental for the analysis of time series data. Additionally, the low resolution of the available data makes it impossible to assess micro-level changes.

As established by the results of the regressions, land cover alone is not sufficient to explain temperature patterns and UHI generation. This study can thus only serve as a basic overview of the phenomenon within the CoCT. Other relevant variables, some of which were discussed as part of the literature review and regression analysis, will have to be established in future research.

Furthermore, as the topic of UHI has not been sufficiently dealt with in the African context, there are vast possibilities for further research. The following is a selection of possible avenues to pursue:

- Integrating the AUHI. It would be beneficial to prove the reliability of LST derived from satellite data by interpolating atmospheric temperature values throughout the study area. Problematic is the availability of data as there is an insufficient amount of connected atmospheric temperature measuring stations. There is, however, the possibility to find and amalgamate data from different sources throughout the city.
- As a time series analysis of the UHI phenomenon in a South African context is severely lacking, the CoCT and other major South African cities underwent drastic changes. In the past twenty years, there have been dramatic population and LC changes, impacting the distribution and severity of the UHI phenomenon. Looking at LST data over various time periods could provide clarity on the relationship between LC and LST.
- Adding on to the time series, an emerging hot spot analysis could prove useful in deducting areas of emerging hot spots as well as areas experiencing cooling. This could provide planners and developers with the tools to facilitate the development of cool cities for the future as well as to assess the efficiency of mitigation methods over time.
- The relationship between UHI and different variables of the urban framework would be of interest. Popular mentions include the relationship between UHI and poverty,

population density, building density, building materials, urban size, GDP, as well as that of heat-related diseases and mortality. An analysis including these variables could add to the international scholarship and further the creation of an African perspective.

- In order to facilitate a more accurate inclusion of optimum mitigation methods in a South African context, the cooling and economic efficiency of different mitigation methods should be considered with regards to the local climate, political and economic context. Of special interest would be UHI mitigation strategies in informal settlements as well as the availability of cool surface materials overall including cost-benefit rationales. Additionally, the cooling extent of different green spaces would prove useful as well as the establishment of a threshold value of cooling efficiency concerning area size.
- Considering the existence of predominant South Easterly winds throughout the summer months, the concept of fresh air corridors as UHI mitigation method could be of great value for the CoCT to increase latent heat flux away from the urban areas. The possibility of considering this aspect in urban planning and design should be further explored.

5.6 CONCLUSIONS

This thesis served to provide an overview over the UHI phenomenon, the legislative provisions of relevance, assess and mitigate its effects, and to provide an overview over the phenomenon's severity and extent of these risk areas within the CoCT. This discussion of UHI in the South African context in general and the context of Cape Town specifically, has shown that heat build-up in the form of the UHI is currently not given the attention it deserves in contemporary urban spaces. While governments, NGOs and researchers reluctantly acknowledge the long-term effects of the changing climate, heat build-up and its related effects on the urban population are still dismissed as a problem of the future. The information and data presented however indicate the need to more closely consider the urban thermal environment, not as a future activity but something to be acted upon in the short term. It's not only future heatwaves and climate change that pose risk for populations but also the current climate in combination with the inefficiencies of the built environment. There is a distinct need for international cooperation and capacity building on the topic of UHI, especially in an African context. The unprecedented scale of future urbanisation and population growth on this continent demand closer interrogation of current and future issues within the urban framework. Possible issues of social justice in terms of access to temperature controlled spaces, the increased vulnerability of children, the elderly and socioeconomically vulnerable populations to heat should trigger widespread recognition of the UHI effect and facilitate efforts to curb its effects. This would positively contribute to fulfilling the goals of building sustainable human settlements and improving the quality of household life as well as energy efficiency rationales, climate change mitigation and reduction of its effects. One of the major realisations for all stakeholders is that the mitigation of UHI does not have to be a costly endeavour. Instead, early adoption of mitigation methods could save urban governments and its citizen's significant costs whilst simultaneously increasing well-being and health.

Internationally, a variety of cities are leading the way and have included UHI mitigation into their development targets, as well as mitigation strategies such as cool surfaces into their respective building codes. The mandatory implementation of cool roofs can easily be implemented due to the widespread availability of materials improving the thermal reflectance of conventional roofing systems without significant additions in cost.

In the African continent in general, and the South African context specifically, informality poses a variety of additional problems that demand individual attention and solution. Instead of pushing for individual responsibility and behaviour change, societies should embrace their social responsibility towards vulnerable populations and focus on promoting basic human rights such as that of the right to a healthy environment for everyone, as set out in the Constitution.

Lack of planning and the hesitation to approve significant capital investments led to a loss of R2.5 billion as a result of the latest drought in the City of Cape Town (Muller 2018). Learning from these past experiences is essential. If the humanitarian and health impacts of UHI mitigation are not enough to persuade action, the increases in efficiency, monetary savings and the opportunities to build a resilient green economy might encourage proactive instead of reactive thinking.

CHAPTER 6 BIBLIOGRAPHY

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APPENDIX/APPENDICES

Appendix A - Land cover categories derived from the original GeoTerraImage classes

Nr.	Original LC Category	Aggregated Category
1	Water seasonal	Waterbodies
2	Water permanent	
3	Wetlands	
4	Indigenous Forest	Natural vegetation
5	Thicket /Dense bush	
6	Woodlan/Open bush	
7	Grassland	
8	Shrubland fynbos	
9	Low shrubland	
10	Mines 1 bare	
11	Mines 2 semi-bare	
12	Mines water seasonal	
13	Mines water permanent	
14	Mine buildings	
15	Bare none vegetated	
16	Cultivated comm fields (high)	Agricultural land
17	Cultivated comm fields (med)	
18	Cultivated comm fields (low)	
19	Cultivated comm pivots (high)	
20	Cultivated comm pivots (med)	
21	Cultivated comm pivots (low)	
22	Cultivated orchards (high)	
23	Cultivated orchards (med)	
24	Cultivated orchards (low)	
25	Cultivated vines (high)	
26	Cultivated vines (med)	
27	Cultivated vines (low)	
28	Plantations / Woodlots mature	
29	Plantation / Woodlots young	
30	Plantation / Woodlots clearfelled	
31	Urban commercial	Commercial
32	Urban Industrial	Industrial
33	Urban residential (dense trees / bush)	High density vegetated urban
34	Urban smallholding (dense trees / bush)	
35	Urban built-up (dense trees / bush)	
36	Urban residential (open trees / bush)	Medium density vegetated urban
37	Urban smallholding (open trees / bush)	
38	Urban built-up (open trees / bush)	
39	Urban residential (low veg / grass)	Low density vegetated urban

40	Urban smallholding (low veg / grass)	
41	Urban built-up (low veg / grass)	
42	Urban residential (bare)	Bare urban
43	Urban smallholding (bare)	
44	Urban built-up (bare)	
45	Urban informal (dense trees / bush)	High density vegetated urban informal/township
46	Urban township (dense trees / bush)	
47	Urban informal (open trees / bush)	Medium density vegetated urban informal/township
48	Urban township (open trees / bush)	
49	Urban informal (low veg / grass)	Low density vegetated urban informal/township
50	Urban township (low veg / grass)	
51	Urban informal (bare)	Bare urban informal/township
52	Urban township (bare)	
53	Urban school and sports ground	School and sports grounds, sports and golf courses
54	Urban sports and golf (dense tree / bush)	
55	Urban sports and golf (open tree / bush)	
56	Urban sports and golf (low veg / grass)	
57	Urban sports and golf (bare)	

Table A 1 Land cover categories used

Appendix B – Ethical Clearance exemption letter

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

PROJECT EXEMPT FROM ETHICS CLEARANCE

25 September 2018

Project number: GEO-BA-2018-8320

Project title: Urban heat islands and the cooling capacity of green spaces: A case study of Cape Town

Dear Mr Lukas Beuster

Your application received on **19 September 2018** was reviewed by the REC: Humanities.

You have confirmed in the proposal submitted for review that your project does not involve the participation of human participants or the use of their data. You also confirmed that you will collect data that is freely accessible in the public domain only.

The project is, therefore, exempt from ethics review and clearance. You may commence with research as set out in the submission to the Research Ethics Committee: Humanities.

If the research deviates from the application submitted for REC clearance, especially if there is an intention to involve human participants and/or the collection of data not in the public domain, the researcher must notify the DESC/FESC and REC of these changes well before data collection commences. In certain circumstances, a new application may be required for the project.

Please remember to use your **project number (GEO-BA-2018-8320)** on any documents or correspondence with the REC concerning your project.

Sincerely,

Clarissa Graham

REC Coordinator: Research Ethics Committee: Human Research (Humanities)