The Spatial and Temporal Characteristics of the Urban Thermal Environment in East Africa: Implications for Sustainable Urban Development

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Abstract

Targeting cities in East Africa, where urbanisation and climate change are posing unprecedented threats to livelihoods and ecosystems, this thesis focuses on the combined effects of rapid urbanisation and climate change on Land Surface Temperature (LST), Surface Urban Heat Island (SUHI) effects and the role of Blue Green infrastructure (BGI) and vegetation dynamics. The aim of this thesis is to advance understanding of the urban thermal environment and the role of factors such as climate, vegetation and urbanisation patterns that add to its complexity.

Through the use of satellite and remote sensing data (e.g., Google Earth Engine), spatial and statistical analyses, conducted in ArcGIS, Geoda and R, this thesis provides analyses of temporal trends between 2003 and 2017, and spatial differences in LST and SUHI in five East African cities (Khartoum, Addis Ababa, Kampala, Nairobi, Dar es Salaam). It advances understanding of how the configuration of urban areas affects the urban thermal environment, the amount of vegetation and surface water, and demonstrates the influence of urban density on the changes in SUHI intensity in both space and time.

By linking the findings from the three results chapters and placing this in the context of the broader literature, corresponding policy implications and solutions are presented. The urgent need to provide a more detailed understanding of urban thermal environments, including macroclimate differences, seasonal variation and urban morphological characteristics, is highlighted. Recommendations emphasise the use of cloud-based analysis methods to overcome data scarcity, while the results point towards the utility of nature-based solutions for urban sustainable development. The methods and lessons emerging from this study can also be applied in other rapidly urbanising cities, where climate change is posing an unprecedented threat to livelihoods and ecosystems, and where resources are limited.

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List of Acronyms

AUHI	Air Urban Heat Island
CMIP5	Five GCMS in The Coupled Model Intercomparison Project
DESA	Department Of Economic and Social Affairs
DSM	Down-Scaling Model
ECHO	European Community Humanitarian Office
ENSO	El Nino/La Nina Southern Oscillation
ESA CCI	European Space Agency Climate Change Initiative
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organisation of the United Nations
FEWS NET	Famine Early Warning Systems Network
GCMs	Global Climate Models
GDP	Gross Domestic Product
GEE	Google Earth Engine
GWL	Global Warming Level
IPBES	Intergovernmental Platform on Biodiversity and Ecosystems Services
IPCC	Intergovernmental Panel on Climate Change
ISC	Impervious Surface Coverage
ITCZ	Inter-Tropical Convergence Zone
KD	Kernel Density
LST	Land Surface Temperature
LULC	Land Use and Land Cover
MODIS	Moderate Resolution Imaging Spectroradiometer
OECD	Organisation For Economic Co-Operation and Development
NUA	New Urban Agenda
RCPs	Representative Concentration Pathway
SDGF	Sustainable Development Goals Fund
SDGs	Sustainable Development Goals
SSP	Shared Socio-economic Pathways
SUE	Simplified Urban-Extent
SUHI	Surface Urban Heat Island
UHI	Urban Heat Island
UN	United Nations
UNECA	United Nations Economic Commission for Africa
UN-Habitat	United Nations Human Settlements Programme

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Declaration

I declare that this research and its presentation is my original work and I am the sole author. To my knowledge, this work has not been presented for an award at this, or any other, university. All sources used in support of the points being made are acknowledged within text and as references.

I was responsible for developing the idea, articulating the theoretical framing, designing the methodology, carrying out all data collection and analysis, and writing and revising the manuscript. Lindsay Stringer, Martin Dallimer and Sarah Chapmen provided feedback and advice on the research design, contributed to the writing of the manuscripts, and gave final approval for publication.

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The publications mentioned above made up my thesis. As the lead author of these works, I developed the methodology, data gathering, and analysis procedures. They were written in cooperation with my supervisors, who had the role of suggesting modifications and enhancements to the manuscript.

Chapter 1: Introduction

1.1. Background

1.1.1. Urbanisation and climate change

Urbanisation is a global phenomenon. The proportion of the world's population living in urban areas was only 30% in 1950 but reached 55% in 2018, and is projected to be 68% by 2050 (DESA, 2018). These dramatic shifts have substantial impacts on people, the environment and development (Li et al., 2021), across local, regional and global scales (Grimm et al., 2008; Nagendra et al., 2018). Changes include air and water pollution (Hoekstra et al., 2018; Lin & Zhu, 2018), land use (Song et al., 2018), biodiversity loss (Newbold et al., 2015), and ecosystem degradation (DeFries et al., 2010; Haddad et al., 2015; Seto et al., 2012), while carbon emissions from cities and associated land use changes are becoming an important driver of climate change (Wigginton et al., 2016). This urban growth dynamic is not homogeneous, and urban expansion patterns differ markedly across developing countries (Gollin et al., 2016). By 2050, the number of urban dwellers will increase by 2.5 billion, with nearly 90% of this growth happening in Asia and Africa (DESA, 2018).

Africa is experiencing rapid population growth (Figure 1.1), especially in the East (Figure 1.2) (coding is presented in Appendix 1). Cities in these countries are undergoing dramatic spatial, social, economic and environmental transformations (Lall et al., 2017; Ryan, 2016), due to a combination of multiple factors such as resource availability (While & Whitehead, 2013), technological innovation processes (Castells, 2010), the circulation of global capital (Kundu, 2020), and the impact of climate change on primary production activities (Adams & Klobodu, 2017; Bazrkar et al., 2015). This has meant that as people have moved from rural to urban areas, many cities in Africa have grown in an unplanned manner, with a mix of commercial centres, industrial areas, residential communities, informal settlements and agricultural lands (Lwasa et al., 2018; Thorn et al., 2021).

Three major urban forms were detected for African cities in 2015: first, the transitional urban

form, characterised by built-up sprawling urbanisation and a decrease in open space, as seen in Accra, Addis Ababa, Bamako, Cairo, Gombe, Ibadan, Khartoum. Kigali, Luanda, Marrakesh and Port Elizabeth. The second type of urban form is the compact-grey form. This kind of city has become even more compact and simple in shape, and includes cities such as Alexandria, Kairouan, Oyo, Tebessa. The third type is the ragged-small form, which is less irregular and complex in shape, with examples including Arusha, Beira, Nakuru and Ndola (Lemoine-Rodríguez et al., 2020). Cities under these different urban forms are projected to experience various changes as they expand further, offering the opportunity for more sustainable planning, but also presenting a challenge (DESA, 2018). Data from the World Bank shows African cities are growing at a rate that is out of sync to real economic growth (Tsai et al., 2018). Due to rapid rural-urban transformation and the continuous influx of rural-urban migrants, the situation limits cities' ability to reduce poverty and provide improved standards of living (Anderson et al., 2013). Despite the economic gains made for many who moved to urban centres, millions of people in the cities of Africa lack access to resources and facilities to meet their essential needs, such as shelter, water, food, health, and education (ECHO, 2018). Over 59% of the urban population in sub-Saharan Africa is estimated to be living in informal settlements (UN-Habitat, 2016). While the fact that cities are perceived to offer more economic opportunities still pulls many people to live in cities. However, doing so increases their exposure to climate impacts (IPCC, 2022).

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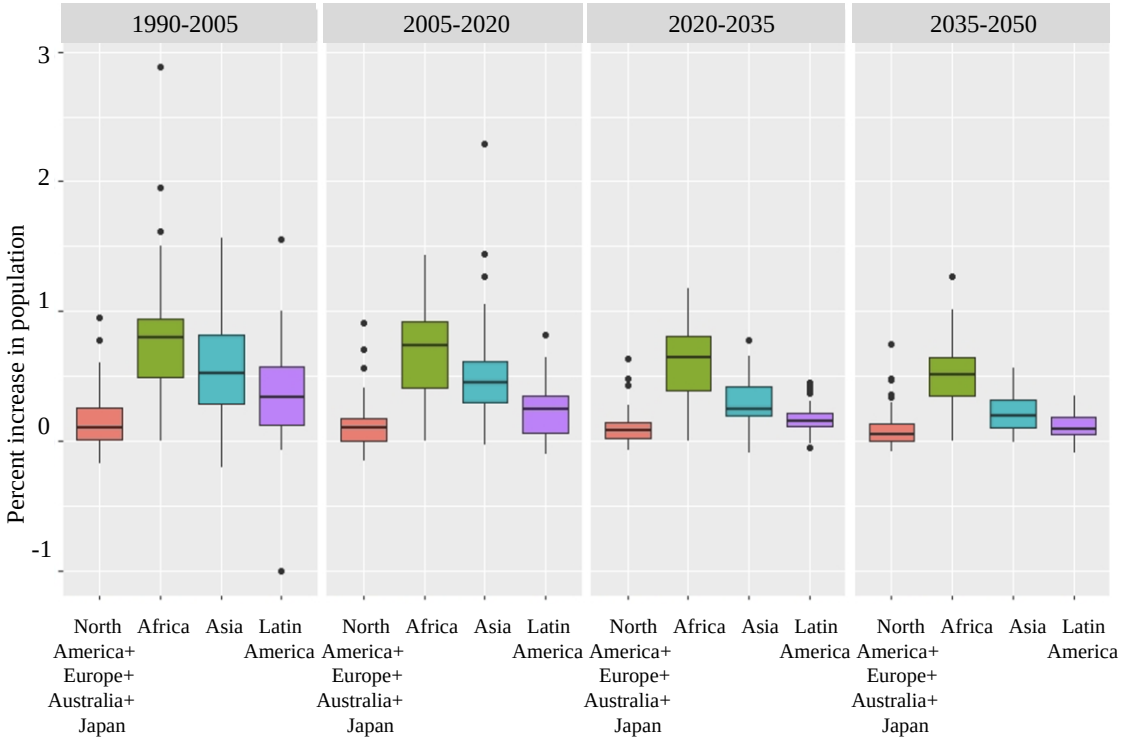

Figure 1.1 Inter- regional comparison of urban population growth 1990-2050 (a), 2005-2020 (b), 2020-2035 (c), 2035-2050 (d).

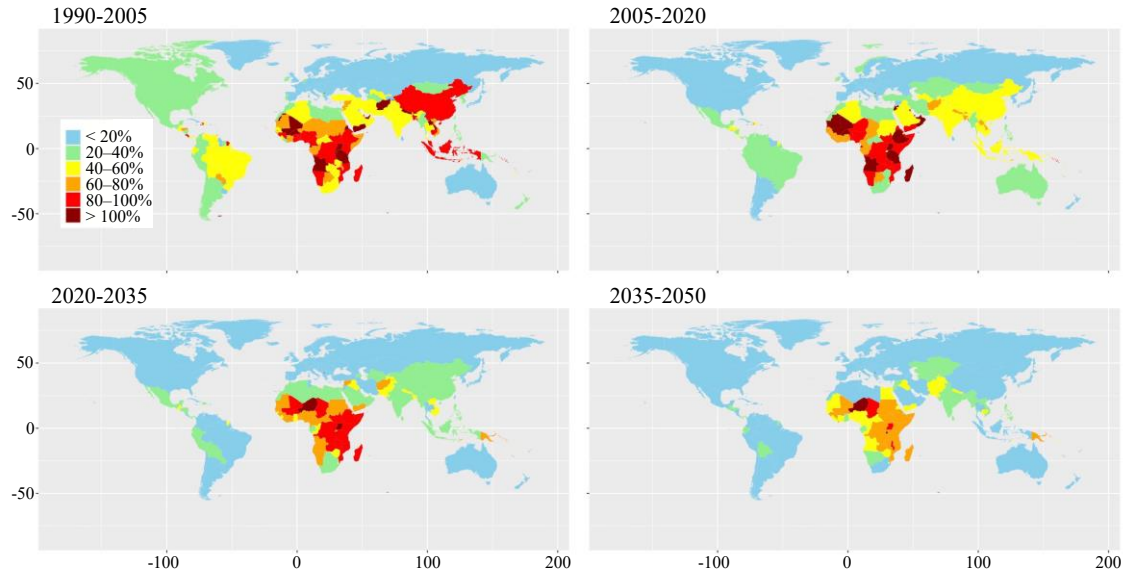

Figure 1.2 Global urban population growth, 1990-2005, 2005-2020, 2020-2035, 2035-2050.

Africa is particularly vulnerable to climate change (IPCC, 2022) and extreme temperature increases have been recorded in most of the continent. The rising rate of temperature increases is higher than at the global level, and even double that of some areas (Seneviratne et al., 2012). Africa's climate is highly diverse and variable (Conway & Schipper, 2011; Henderson et al., 2017; Seneviratne et al., 2012). Patterns of temperatures and precipitation are being altered by climate change (Henderson et al., 2014), with increased probability and magnitude of extreme events, such as floods, heatwaves, droughts and storms. Changes in annual temperature and precipitation patterns have been nuanced and variable (Almazroui et al., 2020), with increasing and decreasing trends in different subregions. Lower precipitation and higher temperatures will likely reduce crop productivity in large parts of the continent (Arneth et al., 2019). In West Africa, particularly in the Sahel, prolonged dry seasons, shorter wet seasons, and less regular rainfall are contributing to an increase in migration and displacement (Band, 2020; De Haan, 2016). Lack of structural transformation in Africa's agriculture inhibits responses to climate change (Mukasa et al., 2017). Events such as the intense outbreak of desert locust *(Schistocerca gregaria)* across several East African countries from the end of 2019 to early 2020 (Salih et al., 2020), posed a major threat to food security and livelihoods in addition to the challenge of direct climate change impacts (FAO, 2022). With few livelihood options in rural areas, climate change in combination with related challenges like food insecurity creates another factor that can push rural migrants to urban areas (Henderson et al., 2017).

East Africa is often considered one of the most climate-vulnerable parts of Africa (Gebrechorkos et al., 2019). The IPCC regional climate report for Africa suggests that mean annual temperatures (1995-2014) are on average, 0.6 °C, 1.1 °C and 2.1 °C warmer than the 1994-2005 average, at 1.5 °C, 2 °C and 3 °C of global warming above the 1850-1900 period (IPCC, 2022). The intensity and frequency of unusually hot days are projected to increase from global warming level (GWL) 2 °C (IPCC, 2022). Compared to the period 1985-2005, the possibility of cities in this region being exposed to dangerous heat grows by 2000 times at GWL 4.6 °C (IPCC, 2022). Based on Statistical Global Climate Models (GCMs) and Down-Scaling Models (SDSM), the projected climate in East Africa shows an increase in maximum and minimum temperature throughout the 21st century (Gebrechorkos et al., 2019). Haile et al. (2020) noted that the drought area in East

Africa is projected to increase by the end of the 21st century by 16%, 37%, and 54% under Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5, via an ensemble of five GCMs in the Coupled Model Intercomparison Project (CMIP5). Growing cities will be hotspots of heat-related risks from climate change, as modification and changes in land use and land cover (LULC) during urbanisation processes intensifies the urban heat island (UHI) effect, and subsequently, exacerbates current and projected heat stress (Oke, 1973). This is particularly concerning in newly developing urban areas such as East Africa, which is the least urbanised region but with the strongest growth trend (OECD, 2017). Based on time series observations, a significant rising trend in temperatures has already been recorded in some East African cities. Urbanisation processes, both in terms of urban densification and urban sprawl, will increase the intensity or magnitude of UHIs (Li et al., 2020; Wemegah et al., 2020), which is expected to place additional stress on health and economic systems in the context of climate change (Parkes et al., 2019). Thus, it is crucial to investigate urbanisation and climate change together in rapidly changing regions such as East Africa and West Africa.

1.1.2. Urban thermal environment

Due to the combined effects of climate change and rapid urbanisation, the urban thermal environment in African cities is undergoing dramatic changes. Warmer temperatures and increased frequency of extreme events associated with climate change exacerbate how the urban thermal environment is affected by anthropogenic processes (Sachindra et al., 2016). Increasing impervious surfaces and decreasing blue and green spaces in and around urban areas reduce atmospheric moisture contributed by evaporation and transpiration of latent heat flux of urban areas (Ige et al., 2017; Ramamurthy & Bou-Zeid, 2014; Wang et al., 2014; Yu et al., 2017). Urban thermal environment dynamics and impacts can vary significantly with complex interactions between biophysical variables (e.g., breeze circulation, relative humidity, vapor pressure and soil properties) (El-Kenawy et al., 2020; He, 2018). Furthermore, urban areas change the albedo and nocturnal radiation (Offerle et al., 2005), while urban transportation contributes to greenhouse gas emissions that are likely to increase the local temperature (Grimmond, 2007).

A typical feature associated with urban thermal environmental changes is the formation of the

urban heat island (UHI) (Peng et al., 2016). UHI refers to the phenomenon of higher urban temperatures than the rural surroundings and affects temperatures in the air and at the surface (Oke, 1982). Urban inhabitants can be more susceptible to higher heat-related risk than rural residents due to UHI (Chapman et al., 2017). In 2100, over 300 million African urban residents are projected to be exposed to 15-day heat waves over 42 °C. If we also consider the UHI, this number could potentially be up to 950 million (Marcotullio et al., 2021). Higher temperatures can have direct effects and acutely impact the health of vulnerable populations, such as children, the sick, and the elderly (WHO, 2018); and compound indirect impacts related to productivity loss, disease spread, water shortage, and energy supply disruptions (Sylla et al., 2018). Additionally, high temperatures exacerbated by UHI will accelerate the formation of urban pollution islands with smog and polluted air (Zhong et al., 2019), exacerbating respiratory diseases (D'Amato, 2011). African countries are generally vulnerable to increasing temperatures (Parkes et al., 2019). These climate impacts have an economic cost and cause a reduction in GDP (Burke et al., 2015). Parkes et al. (2019) projected that the extra cost in energy consumption to prevent heat stress will be $51.3 billion in Africa between 2005 and 2035, rising to $487 billion by 2076. If meeting the additional energy demand, the whole energy system will raise its cost by 0.6% from 2005 to 2076, which accounts to 0.06% of the GDP in Africa over the same period (Parkes et al., 2019).

There are various parameters in describing the dynamics of urban thermal environment. Surface temperature is the temperature at a surface, which is often used to examine heat exposure in multi-city studies and for informing urban heat mitigation efforts due to scarcity of urban air temperature measurements (Mushore et al., 2017). LST is the temperature at land surface, due to limitations in observation and modelling, LST is often used as a proxy for urban heat stress (Orimoloye et al., 2018). Air UHI and surface UHI (SUHI) are the UHI intensity observe via different ways, air UHI is based on the air temperature based on site monitoring, and the SUHI is based on the surface temperature data collected by remote sensing imagines (Stewart, 2019).

1.1.3. Data analysis and tools

The urban thermal environment has traditionally been investigated by using meteorological data, as long-term local monitoring records are particularly important to capture temporal climate variability (Brousse et al., 2022). For instance, national weather services operating monitoring networks provide historical and current meteorological data in Europe, including information on air temperature, atmospheric pressure, wind speed, humidity and precipitation (World Bank, 2020). For the investigation of small-scale variations, sensors and observational networks have been established to investigate built environment impacts in the urban canopy layer (Stewart, 2019). However, establishing and operating a high-quality monitoring system is often time consuming and expensive, which has led to data scarcity in some regions, such as Africa (Van de Walle et al., 2021). Stewart (2011) found that less than 5% of the 177 urban climate studies identified focused on African cities.

Temperature maps have nevertheless become more commonly available with advances in thermal infrared and multispectral remote sensing, which provides various-resolution surface temperature distributions to visualize both hot and cold surface spots (Middel et al., 2022). A wide range of remote sensing data can give important insights into the spatial dynamics of thermal environment changes, especially in areas with rapid urban expansion and low-density monitoring networks. Examples include observations with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra and Aqua satellites, which provides land surface temperature (LST) observations with a spatial resolution of 1000m, or Landsat data with more precise 30/60m resolutions (Table 1.1), with increasing datasets becoming available with the launch of new satellites and improved sensors (Figure 1.3). The National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) now provide free access to data archives, which is promoting and inspiring development of new techniques globally (Middel et al., 2022; Stewart, 2019). It is worth noting that satellite-based thermal data surface temperatures are different from air temperatures (World Bank, 2020); and the interpretation and fusion of the different data sources can be markedly different (Almeida et al., 2021; Tomlinson et al., 2011). Beyond meteorological observations, remote sensing provides various data for investigating urban structures, land cover, and biophysical characteristics (Middel et al., 2022). These urban

characteristics are extremely important in understanding the urban thermal environment, especially the relationships between LULC and vegetation indices (Ferreira & Duarte, 2019). Existing remote sensing-based data enable the investigation of temporal and spatial patterns, as well as thermal characteristics, although observations in specific areas can remain challenging. For instance, in the intertropical convergence zone (ITCZ)-dominated regions, cloud contamination may last for several months, resulting in long gaps in useable datasets (Sun et al., 2017). These observation challenges are now partly overcome by advanced algorithms via cloud-based platforms (e.g., Google Earth Engine, Planetary Computer), enabling further research.

Table 1.1 Satellite images for thermal environment studies at urban scale (adapted from (Almeida et al., 2021; Tomlinson et al., 2011)).

Satellite Platform	Sensor	Dataset Availability	Spatial resolution	Orbital Frequency
Aqua	MODIS	2002	1,000 m	Twice daily
CBERS 1	IRMSS	1999-2003	160 m	26 days
CBERS 2	IRMSS	2003-2009	160 m	26 days
CBERS 2B	IRMSS	2007-2010	160 m	26 days
CBERS 4	IRS	2014-present	80 m	26 days
CBERS 4A	IRS	2019-present	80 m	31 days
Envisat	AATSR	2002-2012	1,000 m	35 days
HJ-1B	IRMSS	2008-2018	300 m	31 days
HJ-2A and HJ-2B	IRMSS-2 (HJ)	2020-present	300 m	4 days
Landsat 4	TM	1982-1993	Collected at 100 m and resampled to 30 m	16 days
Landsat 5	TM	1984-2011	Collected at 100 m and resampled to 30 m	16 days
Landsat 7	ETM+	1999-present	Collected at 60 m and resampled to 30 m	16 days
Landsat 8	TIRS	2013-present	Collected at 100 m and resampled to 30 m	16 days
Landsat 9	TIRS	2021-present	Collected at 100 m and resampled to 30 m	16 days
METOP-A, B, C	AVHRR 2	2006-present	1,100 m	29 days
NOAA 6, 8 10, TIROS-N	AVHRR	1978-2001	1,100 m	Twice daily
NOAA 15, 16, 17, 18, 19	AVHRR 2	1981-2007	1,100 m	Twice daily
NOAA 7, 9, 11, 12, 13, 14	AVHRR 3	1998-present	1,100 m	Twice daily
Sentinel3	SLSTR	2016-present	1,000 m	2016-present
Terra	MODIS	1999-present	1,000 m	Twice daily

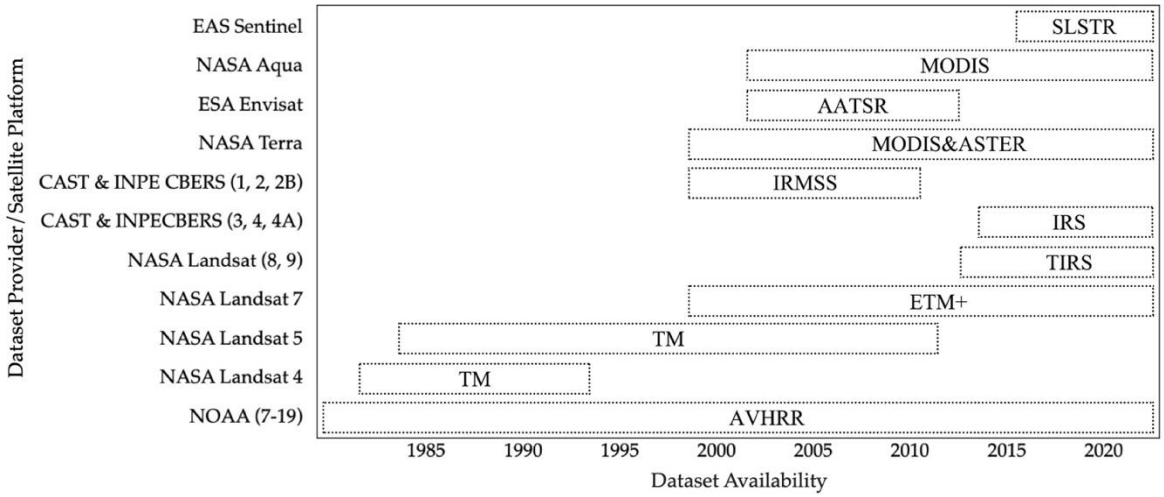

Figure 1.3 Timeline for the major urban thermal environment observation satellites launch and associated sensor data availability (adapted from (Almeida et al., 2021; Tomlinson et al., 2011)).

1.1.4. Urban thermal environment analysis at different scales

Different scale models, based on various data sources, have become fundamental for understanding urban climate processes. Targeting past urban climate dynamics and/or future climate development scenarios, urban climate model simulations can support urban planners to develop optimally cost-effective and science-based solutions for sustainable urban development (Fallmann & Emeis, 2020; He et al., 2019). There is a wide spectrum of models for estimating and describing urban issues on different spatial scales. Regional-scale models have been used to evaluate climate and land use change effects on urban climate across both short-term and long-term temporal scales. These models also enable researchers to understand processes on different spatial scales and interactions with mutually interlinked components (e.g., the atmosphere, land, water bodies, and anthropogenic emissions) (Flato et al., 2014). The major aim of regional scale models is to parameterise urban processes to include the modifications in energy balance, which are often unable to provide sufficient information for certain urban development plans (Früh et al., 2011; Hewitt et al., 2021). City-scale models focus on the area of one or a few cities, which enable the simulation of atmospheric and surface processes to meet specific needs for urban planning and climate adaptation strategies (Masson et al., 2020). City-scale models can help identify and anticipate critical zones of climate risks to improve sustainability and resilience in

urban areas and can serve to support urban-scale UHI mitigation strategies (e.g., improving urban ventilation, blue green infrastructure (BGI) management, air pollution monitoring) (Dai et al., 2021; Li et al., 2018; Masson et al., 2020; Ng et al., 2011).

Furthermore, other crucial parameters related to urban thermal environment and thermal comforts, such as building heights and orientation, surface materials, vegetation and tree planting scenarios, wind speed and direction at street level are often simulated via building-scale models (Van de Walle et al., 2021; Van de Walle et al., 2022). For urban thermal environment studies, building-scale models are commonly used with city-scale models (Ching et al., 2019; Masson et al., 2020).

1.1.5. Current Research Gaps

Currently, there is a strong geographic bias in investigations of the impact of climate change and urban growth on the thermal environment. Europe, North America and China are the main areas of study (Chapman et al., 2017). A limited amount of research has been conducted in regions that are most threatened by and vulnerable to climate change (Chapman et al., 2017), such as Africa. IPCC indicated, "*Africa's rapidly growing cities will be hotspots of risks from climate change and climate-induced immigration, which could amplify pre-existing stresses related to poverty, informality, exclusion and governance (IPCC, 2022)*". Even though work in Africa has begun to consider how to reorient unsustainable urban growth patterns, research efforts still need to focus more strongly on the urban thermal environment for specific regions, particularly because the current pace of urbanisation offers a very time-limited opportunity to move toward sustainable development in the context of global climate change (IPCC, 2022). In this thesis, I focus on the East African urban thermal environment under the combined effect of urbanisation and climate change. To establish specific research questions for East Africa, as described in the following paragraphs, I reviewed available literature between 2000 to 2021 from Web of Science, to identify gaps in current research about the combined effect of urbanisation and climate change on urban thermal environment in Africa.

1.2. Literature review: Impact of urbanisation and climate change on the urban thermal environment in Africa

1.2.1. Aim

The aim of this review is to identify gaps in the literature about the combined effects of urbanisation and climate change on the urban thermal environment in East Africa. Considering the geographic bias and data deficiency in East Africa, related research in the whole Africa region was reviewed. The research questions addressed in this review are:

1. What is the geographic spread and scale of focus in investigations into the combined effects of urbanisation and climate change on the urban thermal environment?
2. Against the background of climate change and rapid urbanisation, what are the specific drivers of changes to the urban thermal environment in Africa?
3. How have urban thermal environment change related risks been studied in Africa?
4. Targeting on urban thermal environment changes, how have the adaptation strategies for different groups been studied in Africa?

1.2.2. Method

Through a literature review of scientific papers between 2000 and 2021, this chapter summarises the results of previous work that studied how the urbanisation process and climate change have reshaped the urban thermal environments in African cities. In order to explore the urban thermal environment from a wider viewpoint and gather various conceptualizations from diverse fields of research, a semi-systematic literature review approach was used (Asif et al., 2020; Bernes et al., 2018; Livoreil et al., 2017). The systematic literature review was not considered, as that only addresses a particular question or looks into a critical factor in the research field and was considered too restrictive (Asif et al., 2020; Bernes et al., 2018; Livoreil et al., 2017). The Collaboration for Environmental Evidence (2018) guidelines are guidance for systematic review

and evidence synthesis in environmental management, which target promoting and offering evidence syntheses for environmental policy and practise as a public service (Pullin et al., 2018; Chapman et al., 2017). Following the guidelines, Web of Science was searched for the period 2000 and 2021. The year 2000 was selected as the earliest point in the literature search given increased international attention on sustainability issues that were associated with the Millennium Development Goals (MDGs) (SDGF, 2022). The MDGs evolved to become the Sustainable Development Goals (SDGs) in 2015 and have a deadline for their achievement of 2030 (SDGF, 2022). Terminology related to urban thermal environments include air urban heat island, urban cool island, temperature. Thus, the search terms “urban heat island” or “UHI” or “urban cooling” or “urban heat” or “urban thermal” or “urban temperature” or “urban climate” or “city temperature” or “city climate”, combined with “urbanisation” or “urbanization” or “land use” or “urban growth” or “urban expansion” or “urban development” or “urban densification” and “Africa” and “climate change” or “global warming” or “changing climate” were used.

There were 631 articles returned from the Web of Science Advanced Search function, which were recorded and stored in the referencing software Endnote. According to the flow chat in Figure 1.4, articles were filtered twice for inclusion and exclusion (Pullin et al., 2018). Firstly, title and abstract screening were conducted to generate a list of potentially eligible articles, then the full texts were acquired and examined. Following this process, 64 articles were selected, and reduced to 38 articles after screening the full article. The reference lists of the retained articles were then checked, from which three articles were found to be eligible for inclusion according to the review criteria, resulting in a final list of 40 relevant articles Figure 1.2.

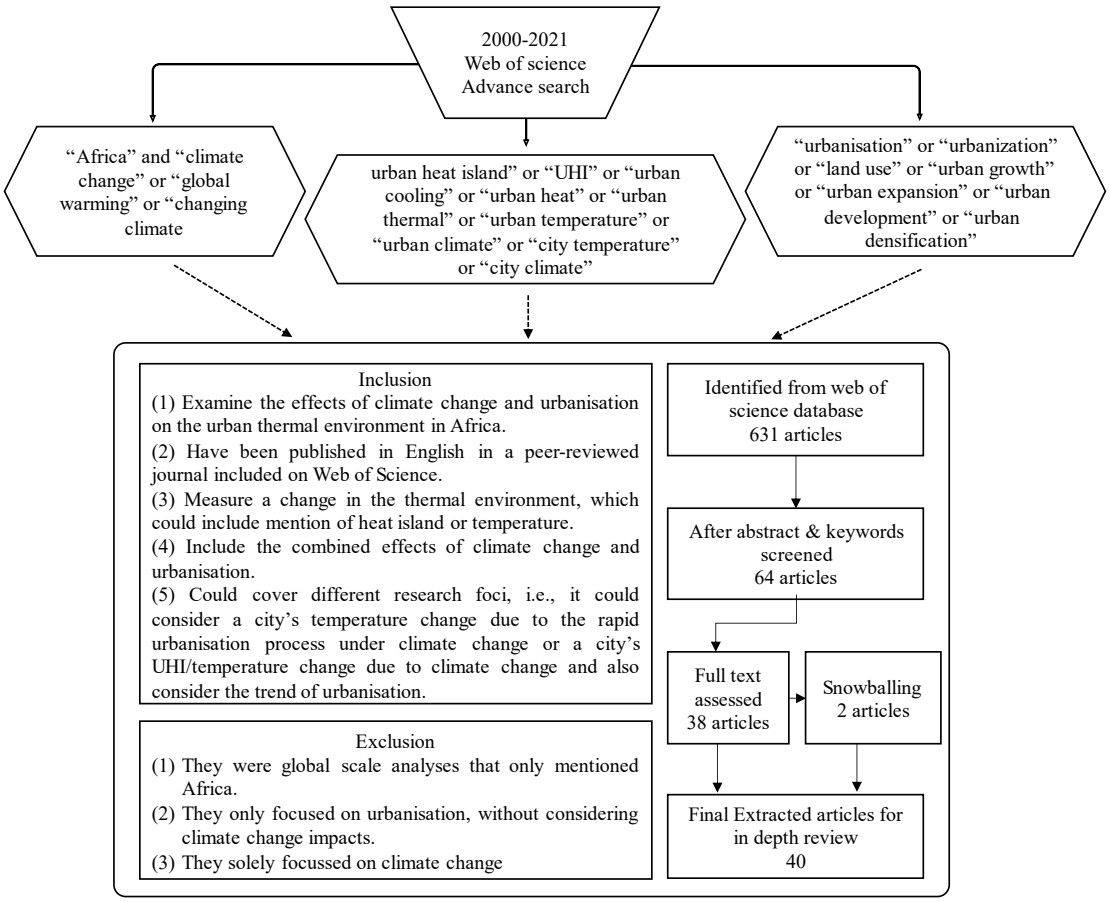

Figure 1.4 Flow chart of article filtering.

Table 1.2 List of semi-systematic review articles.

Impact of urbanization and climate change on the heat island	Authors
The Spatial and Temporal Characteristics of Urban Heat Island Intensity: Implications for East Africa's Urban Development.	(Li et al., 2021)
Influence of urbanization-driven land use/cover change on climate: The case of Addis Ababa, Ethiopia	(Arsiso et al., 2018)
Linking major shifts in land surface temperatures to long term land use and land cover changes: A case of Harare, Zimbabwe	(Mushore et al., 2017)
The influence of seasonal land-use-land-cover transformation on thermal characteristics within the city of Pietermaritzburg	(Odindi et al., 2020)
How urbanisation alters the intensity of the urban heat island in a tropical African city.	(Li et al., 2021)
In search of missing links: urbanisation and climate change in Kano Metropolis, Nigeria	(Mohammed et al., 2019)

Locally optimized separability enhancement indices for urban land cover mapping: Exploring thermal environmental consequences of rapid urbanization in Addis Ababa, Ethiopia	(Feyisa et al., 2016)
The role of urban green infrastructure in mitigating land surface temperature in Bobo-Dioulasso, Burkina Faso	(Di Leo et al., 2016)
Solar Irradiance Reduction Using Optimized Green Infrastructure in Arid Hot Regions: A Case Study in El-Nozha District, Cairo, Egypt	(Elbardisy et al., 2021)
The future urban heat-wave challenge in Africa: Exploratory analysis	(Marcotullio et al., 2021)
Nocturnal Surface Urban Heat Island over Greater Cairo: Spatial Morphology, Temporal Trends and Links to Land-Atmosphere Influences	(El-Kenawy et al., 2020)
Can local fieldwork help to represent intra-urban variability of canopy parameters relevant for tropical African climate studies?	(Van de Walle et al., 2021)
Lack of vegetation exacerbates exposure to dangerous heat in dense settlements in a tropical African city (Snowballing)	(Van de Walle et al., 2022)
Temporal Analysis of Changes in Anthropogenic Emissions and Urban Heat Islands during COVID-19 Restrictions in Gauteng Province, South Africa	(Shikwambana et al., 2021)
Effect of impervious surface area and vegetation changes on mean surface temperature over Tshwane metropolis, Gauteng Province, South Africa.	(Adeyemi et al., 2015)
Urban morphological determinants of temperature regulating ecosystem services in two African cities	(Cavan et al., 2014)
Assessment of urban heat island warming in the greater accra region	(C. S. Wemegah et al., 2020)
Urban modification of the surface energy balance in the West African Sahel: Ouagadougou, Burkina Faso	(Cosmos S. Wemegah et al., 2020),
Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios	(Rohat et al., 2019)
Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa-identifying urban planning priorities for adaptation	(Jagarnath et al., 2020)
Comparative Analysis of Responses of Land Surface Temperature to Long-Term Land Use/Cover Changes between a Coastal and Inland City: A Case of Freetown and Bo Town in Sierra Leone	(Tarawally et al., 2018)
Determination of urban land-cover types and their implication on thermal characteristics in three South African coastal metropolitans using remotely sensed data	(Odindi et al., 2017)
Spatio-temporal variance and urban heat island in Akure, Nigeria: A time-spaced analysis Using GIS Technique	(Popoola et al., 2020)
A quantitative analysis of interstitial spaces to improve climate change resilience in Southern African cities	(Hugo & du Plessis, 2020)
Emerging climate change-related public health challenges in Africa: A case study of the heat-health vulnerability of informal settlement residents in Dar es Salaam, Tanzania	(Pasquini et al., 2020)

Spatiotemporal monitoring of land surface temperature and estimated radiation using remote sensing: human health implications for East London, South Africa	(Orimoloye et al., 2018)
Urban thermal perception and self-reported health effects in Ibadan, south west Nigeria	(Adegebo, 2022)
Scenarios for adaptation and mitigation in urban Africa under 1.5 degrees C global warming	(Lwasa et al., 2018)
Leveraging City-level Climate Change Law and Policy for the Protection of Children	(Fanzbasayi, 2021)
Cities and extreme weather events: impacts of flooding and extreme heat on water and electricity services in Ghana (Snowballing)	(Kayaga et al., 2021)
Urban sustainability and human health: an African perspective	(Smit & Parnell, 2012)
Impact of Landscape Structure on the Variation of Land Surface Temperature in Sub-Saharan Region: A Case Study of Addis Ababa using Landsat Data (1986-2016)	(Dissanayake et al., 2019)
Spatial and temporal monitoring of drought based on land surface temperature	(Mustafa et al., 2021)
Impacts of Climate Change on Outdoor Workers and Their Safety: Some Research Priorities	(Moda et al., 2019)
GIS-based modelling of climate variability impacts on groundwater quality: Cape Flats aquifer, Cape Town, South Africa	(Gintamo et al., 2021)
Climate change, population, and poverty: vulnerability and exposure to heat stress in countries bordering the Great Lakes of Africa	(Asefi-Najafabady et al., 2018)
Indoor Temperatures in Low Cost Housing in Johannesburg, South Africa	(Naicker et al., 2017)
Future changes and uncertainty in decision-relevant measures of East African climate	(Bornemann et al., 2019)
Land cover change effects on land surface temperature trends in an African urbanizing dryland region	(Akinyemi et al., 2019)
Climate Variability and Malaria Incidence: Impact and Adaptation in Owerri Municipal of Imo State Nigeria	(Okorie et al., 2012)

1.3. Results

1.3.1. Study distribution

1.3.1.1. Urban thermal environment studies at regional scales

Urbanisation processes and climate change were associated with the urban thermal environment. Increased temperatures were described in most sampled articles. The focus of most research at a continental level was the combined effect of climate change and urbanisation processes for African cities' thermal environments associated with projections under different shared socio-economic pathways (SSP). Under the "sustainability" pathway (SSP 1) and low relative levels of climate change (RCP 2.6), the potential number of urban dwellers exposed to heat waves by 2100 will be 310 million (ranging from 111 to 608 million) excluding the extra heat from UHI. Under SSP 4 ("inequality") with climate impacts under RCP 4.5, the high-end exposure level will reach 2.0 billion including extra heat from UHI (Marcotullio et al., 2021). For 173 large African cities, and depending on the different SSPs considered, urban dwellers' under the extreme heat across the continent are predicted to increase 20-52 times, reaching between 86 and 217 billion person-days per year by the 2090s (Rohat et al., 2019). The most exposed cities will be located in Western and Central Africa, while exposure in several East African cities will increase over 2,000 times from the current level by the 2090s (Rohat et al., 2019). Other authors suggested that further warming of 1.5°C may double or even triple the climate change impacts that are currently experienced in African cities (Lwasa et al., 2018). Smit and Parnell (Smit & Parnell, 2012) indicated that rapid population growth combined with weak urban management capacity exposed African cities to the threat of ecosystem deterioration and climate change, which might seriously affect health conditions for urban dwellers (Smit & Parnell, 2012). In general, the synergistic interaction between dangerous heat and rapid urban population growth in African cities has rarely been experienced during the historical period but will potentially pose significant impacts on the future urban thermal environment and cause/exacerbate heat stress (Lwasa et al., 2018; Marcotullio et al., 2021; Rohat et al., 2019; Smit & Parnell, 2012).

1.3.1.2. Urban thermal environment studies at city-scales

At the city-scale, most studies on the urban thermal environment focused on LST (n=13), while six of the papers examined surface urban heat islands (SUHI), two studied the surface temperature, and one paper studied the air UHI. Figure 1.5 demonstrate the Distribution of cities identified in the literature review. Table 1.3 illustrated time series studies with corresponding methods, tools, parameters and temporal scales, the difference in their climate zone description, extent of study and temperature-regulating methods make comparisons very challenge, thus bringing attention to the research gaps of comprehensive analysis across various cities.

The SUHI was found to have increased in Accra, Ghana (Wemegah et al., 2020), Addis Ababa, Ethiopia (Arsiso et al., 2018; Li et al., 2021), Akure, Nigeria (Popoola et al., 2020), Dar es Salaam, Tanzania (Li et al., 2021), Kampala, Uganda (Li et al., 2021), Khartoum, Sudan (Li et al., 2021), Nairobi, Kenya (Li et al., 2021), Pietermaritzburg, South Africa (Odindi et al., 2020), and to have decreased in Cairo, Egypt (El-Kenawy et al., 2020). Only one study presented an air UHI study, whereby the air UHI was detected to have increased during the study period in Kano, Nigeria (Mohammed et al., 2019). For LST derived from remote sensing-based analysis, Addis Ababa, Ethiopia (Dissanayake et al., 2019; Feyisa et al., 2016), Bobo-Dioulasso, Burkina Faso (Di Leo et al., 2016), Buffalo, South Africa (Odindi et al., 2017), East London, South Africa (Orimoloye et al., 2018), eThekwini, South Africa (Odindi et al., 2017), Freetown, Sierra Leone (Mustafa et al., 2021; Tarawally et al., 2018), Harare, Zimbabwe (Mushore et al., 2017), Tshwane, South Africa (Adeyemi et al., 2015), Bo Town, Sierra Leone (Tarawally et al., 2018), Gaborone, Botswana (Akinyemi et al., 2019), and Nelson Mandela Bay, South Africa (Odindi et al., 2017) all detected increases during their study periods. For surface temperature based on local meteorological data, Bo Town, Sierra Leone (Tarawally et al., 2018), Cape Town, South Africa (Gintamo et al., 2021) were all found to have increased during their study period.

Studies at regional scales tend to use data from climate models and remote sensing estimation and projection (Lwasa et al., 2018; Marcotullio et al., 2021; Rohat et al., 2019). Research at the city scale generally is based on remote sensing data, especially the Landsat and MODIS products for analysing LST and LULC (Adeyemi et al., 2015; Akinyemi et al., 2019; Dissanayake et al., 2019; El-Kenawy et al., 2020; Mushore et al., 2017; Orimoloye et al., 2018; Wemegah et al., 2020). When considering urbanisation processes and the impacts of climate change on the urban thermal

environment, changes through time were found in most study cities. Such changes commonly included an increase in UHI magnitude and intensity, and absolute changes in temperatures. Unlike air UHI which is more often studied globally (Chapman et al., 2017), SUHI research dominates most studies in Africa. This is partly because of the historical data scarcity that therefore hampers air UHI research. One drawback of this is that the resolution of climate models and remote sensing outputs tends not to be fine enough to identify some of the differences in urban land cover (Marcotullio et al., 2021). Along with low-cost measurement equipment for local data collection (Van de Walle et al., 2021; Venter et al., 2020), it is more achievable to synthesise remote sensing data and fieldwork data to describe the thermal complexity of urban environments. The impacts of climate change and urbanisation processes on the urban thermal environment have been described at the continental scale, and some cities have seen detailed analyses from different aspects. However, there have been few comprehensive analyses across multiple cities with different altitudes, locations and different climate zones.

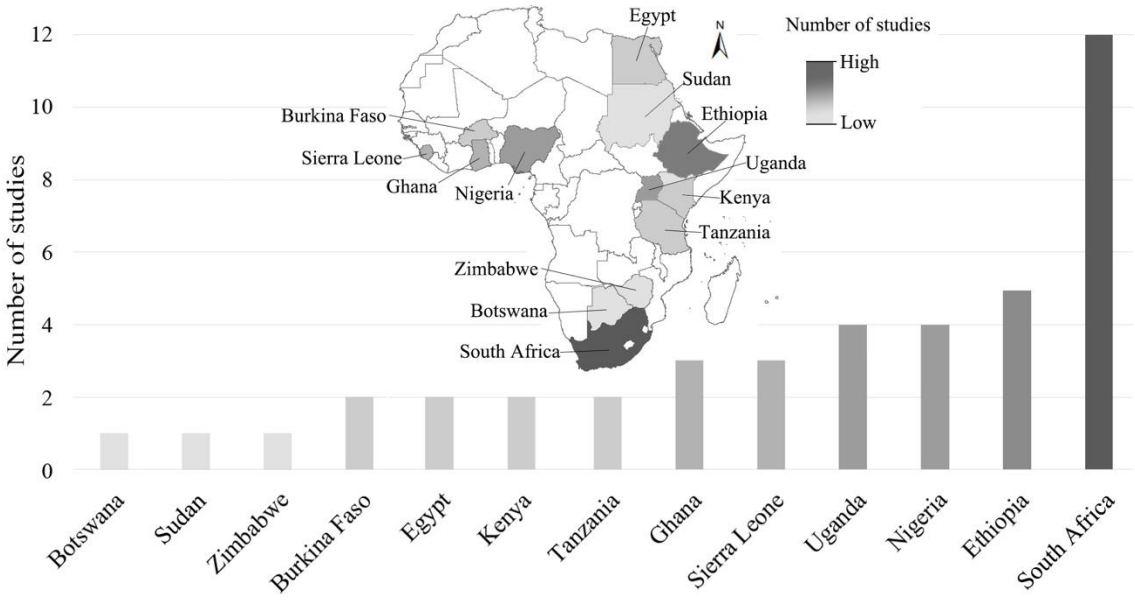

Figure 1.5 Distribution map of selected study cities in literature review.

Table 1.3 City-scale studies about urbanisation and climate change on urban thermal environment change.

City name	Country	Study period	Major data	Major Data processing tools	Study result	Author
Accra	Ghana	1991, 2002,2017(Landsat) 1980-2017(in-situ)	Landsat, In-situ	QGIS	Daytime SUHI increasing, diurnal temperature range decreasing	(Wemegah et al., 2020)
Addis Ababa	Ethiopia	1960-2080	Google Earth, Landsat, HadCM3	ArcMap10.2, ENVI 4.2	Nighttime SUHI increasing	(Arsiso et al., 2018)
Addis Ababa	Ethiopia	1985-2010	Aerial photos, Google Earth, Landsat, Ground survey data	Envi 4.8,	Daytime LST increasing	(Feyisa et al., 2016)
Addis Ababa	Ethiopia	1986-2016	Google Earth, Landsat, spatial population data	GIS (No specified)	Daytime LST increasing	(Dissanayake et al., 2019)
Addis Ababa	Ethiopia	2003-2017	MODIS	Global Surface UHI Explorer, GIS 10.3	Daytime and nighttime SUHI increasing	(Li et al., 2021)
Akure	Nigeria	2000-2018	Google Earth, Landsat	ArcGIS 10.5	Daytime SUHI increasing	(Popoola et al., 2020)
Bobo-Dioulasso	Burkina Faso	1991-2013	Google Earth, Landsat	Ilwis 3.8	Daytime LST increasing	(Leo et al., 2016)
Bo Town	Sierra Leone	1998-2015	Google Earth, Landsat, Meteorological data	GIS (No specified)	Daytime Surface temperature increasing	(Tarawally et al., 2018)
Cairo	Egypt	2003-2019	Google Earth, MODIS, Municipal digital map	GIS (No specified)	Nighttime SUHI decreasing	(El-Kenawy et al., 2020)
Cape Town	South Africa	2041-2060	WorldClim, GCM, Meteorological data	ArcGIS 10.3	Future surface temperature increasing	(Gintamo et al., 2021)
Dar es Salaam	Tanzania	2003-2017	MODIS	Global Surface UHI Explorer, GIS 10.3	Daytime and nighttime SUHI increasing	(Li et al., 2021)
East London	South Africa	1986-2016	Landsat	ArcGIS 10.2	Daytime LST increasing	(Orimoloye et al., 2018)
Freetown	Sierra Leone	1998-2015	Google Earth, Landsat, Meteorological data	Ilwis 3.8	Daytime LST increasing	(Tarawally et al., 2018)
Freetown	Sierra Leone	2000-2030	Landsat, Polynomial model	Envi5.3, GIS (No specified)	Daytime LST increasing	(Mustafa et al., 2021)

Gaborone	Botswana	2000-2018	Google Earth, Landsat, MODIS, Temperature data	GIS (No specified)	Daytime and nighttime LST increasing, built-up core areas were lower in magnitude compared with night-time LST	(Akinyemi et al., 2019)
Harare	Zimbabwe	1984-2016	Landsat	ENVI	Daytime LST increasing	(Mushore et al., 2017)
Kampala	Uganda	2003-2017	MODIS, Landsat	Global Surface UHI Explorer, GIS 10.3	Daytime SUHI increasing	(Li et al., 2021)
Kampala	Uganda	2003-2017	MODIS	Global Surface UHI Explorer, GIS 10.3	Daytime and nighttime SUHI increasing	(Li et al., 2021)
Kano	Nigeria	1980-2018	Landsat, Meteorological data	ArcGIS 10.3	Daytime LST increasing	(Mohammed et al., 2019)
Khartoum	Sudan	2003-2017	MODIS	Global Surface UHI Explorer, GIS 10.3	Daytime and nighttime SUHI increasing	(Li et al., 2021)
Nairobi	Kenya	2003-2017	MODIS	Global Surface UHI Explorer, GIS 10.3	Daytime and nighttime SUHI increasing	(Li et al., 2021)
Tshwane	South Africa	2013-2014	Landsat	ENVI, ArcGIS 10.1	Daytime LST increasing	(Adeyemi et al., 2015)

1.3.2. Drivers of changes to the urban thermal environment

Urban thermal environment dynamics were associated with land use and land cover (LULC) changes as well as seasonal variations. Climate change was noted to play a role in exacerbating or bringing about heat stress and other disasters, particularly increasing disaster vulnerability of low-income urban dwellers.

1.3.2.1. Land use and land cover (LULC) contribute to urban thermal environment changes

In Harare, Zimbabwe, coverage of high-density built-up areas increased by 92%, with 75.5% of green spaces lost between 1984 and 2016 (Mushore et al., 2017). This contributed to a 1.0°C and 2.0°C temperature increase, largely attributed to LULC changes and climate change (Mushore et al., 2017). In Tshwane, South Africa, findings reveal that impervious surfaces and vegetation have experienced changes between 2003 and 2013 (Adeyemi et al., 2015). Although urban expansion is considered as a starting point for growth and prosperity, these changes have caused ecological and hydrological disturbances, further increasing water insecurity in urban areas (Adeyemi et al., 2015). In Akure, Nigeria, the built-up area increased from 4,094 to 12,779 hectares between 2000 and 2018, at the expense of vegetated land. The observed difference in maximum and minimum temperatures between 2000 and 2018 was found to be 27.9°C. The author explained this potential because of the paucity of satellite image samples due to cloud contamination (Popoola et al., 2020). The urban temperature in Kano Metropolis, Nigeria increased from 26.0°C in the 1980s to 27.7°C in 2018. This nearly 2.0°C temperature increase followed the expansion of the city from 39 km^2 in 1986 to 256 km^2 in 2018 (Mohammed et al., 2019).

Findings from Addis Ababa show that the urban area has experienced dramatic LULC structural changes and LST has grown more intense with a substantial loss of the green fraction of the city (Arsiso et al., 2018; Dissanayake et al., 2019). In Addis Ababa, built-up surfaces increased 338%, with growing aggregation of daytime high temperatures from 1985-2010 (Arsiso et al., 2018). The rise in minimum night-time temperature (1.5 °C) in the city centre has also been observed between 1960 and 2001 (Arsiso et al., 2018). Related to urban climate change prediction of UHI formation under A2 (a scenario under increasing global population, accompanied by a disjointed

and slow economic growth) and B2 (a scenario under a continuous basis population growth, accompanied by an intermediate level of economic growth) emission scenarios, the night-time SUHI will be more intense in the winter/dry season period within the city. The highest urban warming is from October to December and is projected to rise 2.5°C-3.2 °C between 2050 and 2080 (Arsiso et al., 2018). The findings for daytime LST did not strongly support thermal differences in the context of urban-rural divides (Feyisa et al., 2016), while night-time SUHI was detected with notable thermal gradient decreases from the centre to suburban areas (Arsiso et al., 2018). This contradiction in the literature can be explained either in relation to the diurnal variation of urban thermal environments, or the different methods used in the two studies.

In Pietermaritzburg, South Africa, SUHI varied in different seasons in response to the differences in LULC changes during the different periods studied. Dense vegetation and low-density buildings had the most thermal influence during summer, while bare surfaces and dense vegetation had the most thermal influence during winter (Odindi et al., 2020). This can be attributed to different surfaces having various albedos, evapotranspiration and vegetation shadows, causing seasonal thermal differences (Odindi et al., 2020). In Bobo-Dioulasso, Burkina Faso, the magnitude and pattern of denser urban land use doubled by almost 7,800 ha from 1991 to 2013, with an average annual growth of 6% in LST differences between urban and peri-urban areas. The urban and peri-urban area LST differences presented seasonal variation over the same period: average LST difference in the “wet and cool” period was 0.8 °C and in the “dry hot” period was 1.4 °C (Di Leo et al., 2016).

In East London, South Africa, Orimoloye et al. (2018) observed that vegetation cover declined by 359 km^2 and built-up area increased by 176 km^2 between 1986 and 2016. This derives from the dramatic change in the urban surface characteristics, including LST and urban surface solar radiation. LST was positively connected with built-up areas and open surfaces, while negatively correlated with the vegetation fraction. In particular, the highest LST was detected around the built-up areas followed by open surfaces across the study period. The findings suggest that vegetation could control or influence LST by correlating with the surface radiative, thermal characteristics, and moisture attributes (Orimoloye et al., 2018). In general, LULC and climate change introduce additional ultraviolet radiation and excessive heat, and result in negative health

impacts for urban dwellers. Actions should be taken to predict and prevent these changes. Remote sensing and GIS provide low cost and efficient change detection opportunities to make this possible, while specific strategies, such as suitable BGI, can be considered.

A comparative study in Bo Town and Freetown, Sierra Leone, showed significant changes in LULC from 1998 to 2015. Bo Town saw a 16 km^2 increase in built-up area and 14 km^2 decrease in dense vegetation, resulting in an increase in average surface temperature from 24.9°C to 28.2°C. During the same period, Freetown's agriculture area decreased by 114 km^2, dense vegetation decreased 23 km^2 and built-up area increased 77 km^2. LST increased from 23.7 to 25.5°C (Tarawally et al., 2018). Another comparative study in eThekwini, Buffalo City and Nelson Mandela Bay, South Africa found the compact built-up and dense vegetation areas had the highest and lowest temperatures. Low vegetation areas like agricultural land and open urban public parks were found to be more efficient in UHI mitigation than moderately built-up areas (with impervious surfaces and scatted grown trees) (Odindi et al., 2017). Furthermore, due to the large proportion of impervious surfaces, eThekwini was more vulnerable to UHI and had higher relative vulnerability to climate change and related impacts than the other two cities (Odindi et al., 2017). In general, while some studies have compared LULC and LST in different cities, usually those cities were relatively near to one another. There is less research that compares cities across different climatic zones.

Built-up areas often increase in parallel with declines in vegetation cover (particularly in forest areas, vegetation cover, and agricultural lands) (Arsiso et al., 2018; Mushore et al., 2017). The important roles of green and blue spaces in regulating the urban thermal environment are described in several studies. Research in Kano, Nigeria suggested that urban green and blue space is under threat due to rapid urban expansion and poor planning (Mohammed et al., 2019). This situation is causing changes in urban form and local climate presents enormous challenges. In Harare, Zimbabwe, greenspaces transformed to low-medium residential areas increased local temperatures by 0.16°C (Mushore et al., 2017). Findings in Bobo-Dioulasso, Burkina Faso, also show that LST in green spaces was detected to be lower than in adjacent impervious, urbanised areas (Di Leo et al., 2016). Research in Cairo, Egypt, examined an area before and after introducing urban trees with changes detected via parametric simulation (air temperature, mean

radiant temperature, relative humidity, and physiological equivalent temperature), proving that the green infrastructure could mitigate climate change and the UHI effect (Elbardisy et al., 2021).

1.3.2.2. Building materials contribute to urban thermal environment changes

Due to the high heat storage capacity of building materials, densely built areas can largely influence local temperatures (Oke 1973), the building materials could affect urban thermal environment due to the variation in evaporating fraction of the materials themselves (Cavan et al., 2014), and alter surface energy balance through affecting net all-wave radiation and heat storage in surface properties (Offerle et al., 2005). A study in Ouagadougou, Burkina Faso et al. (2005) suggested that the use of non-local building materials has increased and that this has affected the local urban thermal environment. Local building materials, such as clay brick and thatch, usually present similar thermal characteristics to the natural surroundings. Rapid urbanisation leads to increased reliance on non-local materials (predominantly concrete, asphalt), together with more paving and increasing building height and density, reducing albedo and increasing heat storage, causing higher night-time temperatures (Offerle et al., 2005). Corrugated metal, a typical roofing material in highly populated areas and informal settlements, was found in the city of Kampala, Uganda, according to field-based investigations (Van de Walle et al., 2021). Corrugated metal improves a building's thermal capacity and conductivity while reducing thermal emissivity (Van de Walle et al., 2021). These studies confirmed the potential of using different building materials to regulate the urban thermal environment and mitigate UHI, especially under climate change futures where heatwaves are expected to become more frequent and intense.

1.3.2.3. Urban morphological characteristics contribute to urban thermal environment changes

Urban morphological characteristics refers to the physical characteristics of urban environments, which have received more attention in recent years (Cavan et al., 2014; Ng et al., 2011; Van de Walle et al., 2021). Urban morphology reflects the historical and contemporary human decisions in how land is used and organisation (Cavan et al., 2014). Urban morphology can have a substantial impact on air movement and can lead to stagnant air in urban areas, aggravating outdoor urban thermal comfort and urban air pollution (Marcotullio et al., 2021). Studies in Addis

Ababa and Dar es Salaam found land surface cover differences associated with surface temperatures up to 25 °C. Compared to climate change projections with changes of less than 1.5 °C, morphological change across cities could affect surface temperatures much more (Cavan et al., 2014). For African cities, Marcotullio et al. (2021) suggested the possibility that more compact urban forms present higher temperatures than sprawled urban forms, but also emphasised that further research is needed to assess the impact of urban morphology on heat exposure. Thus, it is important to conduct research across a wide variety of cities with different levels of compactness/sprawl. Van de Walle et. at. (2021) used local climate zones to investigate morphological and thermal parameters to represent intra-urban variability of canopy parameters (Van de Walle et al., 2021). The potential usage of World Urban Database and Access Protal Tools (WUDAPT, Ching et al. (2018)) framework and LCZ classification in African urban climate studies has been confirmed (Van de Walle et al., 2021), while the data gathering and processing procedures still need further investigation, therefore tropical African cities could potentially benefit from additional measurements of site-specific UCPs (Van de Walle et al., 2021).

1.3.2.4. Other factors contribute to urban thermal environment changes

Several other factors were mentioned in the different studies that were reviewed. The urban cooling effect of vegetation depends on both vegetation density and its altitude. Feyisa et al. (2016) noted the association between vegetation-LST and altitude, and the influence of altitude on surface temperature is relatively higher than the influence of vegetation in Addis Ababa, Ethiopia. There was a tendency that regardless of the vegetation density or cover, higher altitudes typically experience lower temperatures in certain areas (Feyisa et al., 2016). This would suggest that it is important to consider the altitude of different locations when explaining the spatial distribution of UHI.

A comparative analysis conducted in Sierra Leone's Freetown and Bo Town found that Freetown had a larger population size and greater built-up expansion rate than Bo Town but was 2 °C cooler (Tarawally et al., 2018). Such low temperatures are associated with the proximity to the sea and a high proportion of vegetation surrounding the city. Increased surface wetness reduces the temperature via increasing evaporation and latent heat transfer (Tarawally et al., 2018), which

would explain this finding.

Van de Walle et al. (2021) suggested that the measurement methods used also affect the reported changes in the urban thermal environment. Their study recorded the urban canopy parameters during the boreal summer months and generated a local climate zone (LCZ) map for 2018. The derived site-specific data were used as input fields to an urban parametrisation scheme integrated in the regional climate model COSMO-CLM, which reduced the bias, and the surface temperature decreased from 5.3 to 4.0 K (Van de Walle et al., 2021). This is because the description from universal remote sensing-based approaches and site-specific information on typical urban physical characteristics (e.g., building heights and canyon widths, building materials) could be different (Van de Walle et al., 2021).

Seasonal variations can affect the urban thermal environment. For Cairo, Egypt, autumn was the only season that exhibited an increase in the SUHI intensity and magnitude from 2003 to 2019. This may largely be driven by pollution linked to burning of rice straw after harvesting, which is concentrated in agricultural areas (Wang et al., 2014). Another possible reason is the deterioration of air quality as a consequence of severe dust and sandstorms in the Arabian Peninsula (El-Kenawy et al., 2020). Such aerosols and atmospheric pollution combine and contribute to absorbing and re-emitting longwave radiation, hindering the cooling from a radiating surface and increasing air temperature and SUHI intensity (El-Kenawy et al., 2020).

LULC changes are an important driver, associated with climate change-related heat stress and health challenges, accelerating the vulnerability of groups already exposed to other risks. The relationships between built-up area density and the urban thermal environment are not given sufficient attention, which could result in underestimating heat-related risk in the densest, hottest, most vulnerable parts of the city (Chapman et al., 2017). Within the city, urban morphology provides valuable opportunities for researchers to investigate multifaceted urban sustainability, but there has been little research on this in African cities. This scant research attention might be due to local data scarcity. With the development of information technology and a common framework of application, research is needed to understand urban morphology and its connection to urban resilience and sustainability dynamics.

1.3.3. Heat-related risks due to urban thermal environment changes

Climate change and rapid urbanisation trends in relation to the urban thermal environment in African cities are important in terms of temperature increase and heat exposure, but also in terms of their potential indirect and synergetic effects (Marcotullio et al., 2021; Okorie et al., 2012). Moda et al. (2019) focused on the wellbeing of urban outdoor workers and found if outdoor workers are exposed to extreme heat, they will face the direct heat stress, while indirect health hazards include exposure to rising hazardous chemicals and other vector-borne diseases. Research in Durban, South Africa found that due to the combined effect of climate change and urbanisation, heat stress will affect more months in each year and increasingly affect a larger area (Jagarnath et al., 2020). A study in Ibadan, Nigeria, found that human responses to urban thermal environmental changes with increasing temperature involve dehydration, sweating, heat rash, heat exhaustion, headaches and sleep disturbance. Other heat-related effects include fainting, diarrhoea, raised blood pressure, and restlessness (Adegebo, 2022). Radiation in East London, South Africa increased over thirty years (1986-2016) with values reaching above level ten in 2016, which was signified as extreme exposure (possible health effects: skin cancer, cardiovascular disease, heart stroke, and heat stroke) by the WHO and exceeded the same period's global solar radiation index (Orimoloye et al., 2018).

Increasing ultraviolet radiation introduces risks of heat stroke, skin cancer, and heart disease, especially among the elderly, children and individuals with existing diseases (Orimoloye et al., 2018). Van de Walle et al. (2021) highlighted the presence of higher air temperatures in informal settlements among sub-Saharan African cities, indicating the heterogeneous heat-stress vulnerabilities and hazards. Higher heat exposure and vulnerability from 2016 to 2065 have been detected and projected in informal settlements in Durban, South Africa (Jagarnath et al., 2020). Additional heat-related public health risks indicate that high temperatures increase water usage for physical cooling and bathing, and this could result in increased illnesses associated with poor water quality, such as cholera (Pasquini et al., 2020). Insufficient ventilation and warm weather conditions also push people to stay outdoors during the evening, which could expose them to malaria risks, while staying indoors could potentially increase heat exposure and promote people to remove mosquito nets (Pasquini et al., 2020).

Increased temperatures can also increase the possibility of drought. When surface temperatures increase, vegetation stress is higher. This is because there is less water in the soil for plant transpiration. The cooling effect provided by plants will be potentially reduced, leading to further increasing temperatures and extending the drought and further influencing its spatial distribution (Mustafa et al., 2021). A study in Cape Town, South Africa predicted that along with a significant temperature increase of 1.9-2.3 °C in 2060, the water balance is simulated to undergo a decrease of about 8.6% per year. Some city suburbs are more susceptible to groundwater contamination, surface runoff and rising temperatures (Gintamo et al., 2021). The demand for public services such as water and electricity could outstrip the supply and cause severe shortages during episodes of extreme heat (Kayaga et al., 2021). The literature also mentioned similar challenges during flooding, as water is susceptible to contamination, and electricity is often disconnected. An increasing body of work is looking into the nexus between water, energy and food in order to make interconnected systems more resilient (Stringer et al., 2018).

1.3.4. Affected groups and current solutions for urban thermal environment changes

Several studies emphasise the importance of curbing climate change and addressing the socioeconomic influences on Africa's urban heat exposure (Bornemann et al., 2019; Lwasa et al., 2018; Marcotullio et al., 2021; Smit & Parnell, 2012). Borneman et al. (2019) used an interdisciplinary consultation process to define and analyse a set of decision-oriented metrics, involving the critical East African sectors of agriculture, water supply, fisheries, flood management, urban infrastructure and urban health. Based on multi-model climate projections, the approach provides a collection of user-focused information on climate change and its uncertainties (Bornemann et al., 2019). The study in Kano, Nigeria, discusses integrated approaches to address climate change and notes that urban policymakers should increase urban adaptation planning expenditure and strengthen urban planning institutions (Mohammed et al., 2019). It is further necessary to consider risks and vulnerability simultaneously for addressing heat-related hazards in cities. The heat risk framework developed by Jagarnath et al. (2020) helps to target heat risk distribution and provides an early warning from socio-economic, demographic and infrastructure aspects. Many African cities lack early warning systems, however. Local governments could use such a framework to prioritise interventions in social services,

infrastructure delivery and resource planning, and identify hotspots of heat vulnerability. Interventions can include improved planning of BGI. However, further research is needed as to which types of urban BGI are most suitable in different cities across different climate zones.

There is not sufficient literature documenting the ways in which urban thermal environment changes influence different groups. Substantial progress in addressing equity and equality issues towards a number of the MDGs and SDGs was not universal (SDGF, 2022). Low-income groups are underexplored and should be prioritised in coping with heat stress, prioritising thermal comfort and preventing heat-related health effects (Naicker et al., 2017). Pasquini et al. (2020) pointed out that rising temperatures due to climate change will threaten human health in Dar es Salaam as the city is expected to reach extreme temperatures. However, the relationship between heat and health is not sufficiently a priority, even if residents in informal settlements are characterised by high exposure, high sensitivity and low adaptability (Pasquini et al., 2020). A study in Ibadan, Nigeria emphasised that people's heat-health awareness and thermal perception should be promoted when developing thermally comfortable environments (Adegebo, 2022). Popoola et al. (2020) suggested that residents were aware of climate change and UHI, but their understanding was superficial. They do not know about the causes and effects of climate change and UHI, nor do they understand measures that can be taken to ameliorate its impact. Thus, they recommended community awareness programs, as well as integrating climate education into the curriculum of schools and higher learning (Popoola et al., 2020).

Studies that mentioned the impacts of LULC dynamics on the urban thermal environment also proposed LULC solutions. A study in Harare, Zimbabwe suggested that the conversion of bare areas to water bodies could lower 4.5°C surface temperatures (Mushore et al., 2017). Low-medium residential areas converted from green spaces could increase surface temperatures by 0.2°C (Mushore et al., 2017). Hugo and du Plessis (2020) suggested taking advantage of morphological characteristics in interstitial spaces in Hatfield, South Africa. Parking and rooftops were the most prevalent and relatively effortless space types amenable to retrofitting, with significant climate change adaptation and mitigation potential if appropriately retrofitted (Hugo & du Plessis, 2020). Odindi et al. (2020) suggested considering the thermal distribution based on LULC seasonality changes. Leo et al. (2016) highlighted seasonal phenological differences due

to rainfall patterns for maximising temperature regulation benefits.

Research on preserving vegetated areas is often mentioned, as most African cities encourage higher housing densities and infill developments that lead to the loss of green spaces (Di Leo et al., 2016). Dissanayake et al. (2019) suggested that urban development planning should be green-oriented, aligning with SDG 11. Urban trees could regulate the microclimate of urban areas through solar irradiance reduction (Elbardisy et al., 2021). In Cairo, Egypt, a study found that an optimised structure of urban tree canopies could reduce the ground surface irradiance flux, indicating their potential to mitigate the UHI effect (Elbardisy et al., 2021). In Addis Ababa, Ethiopia, a study suggested prioritising green infrastructure in the current urban renewal strategy (Cavan et al., 2014). The conversion of dense informal settlements into formal planned housing should consider the future temperature regulation services (Cavan et al., 2014). For Dar es Salaam, the challenge is to maintain the large proportions of green spaces to provide temperature regulation services into the future (Cavan et al., 2014). In tropical savannah climate cities, such as Bobo-Dioulasso, Burkina Faso, green infrastructure might require additional water for irrigation (Di Leo et al., 2016). Blue infrastructure thus could maximise the cooling effect of green infrastructure by providing an irrigation water supply from stormwater harvesting and recycling greywater (Di Leo et al., 2016).

Human management of the urban environment plays a key role, in particular linking to BGI. Urban expansion should be planned to protect the structure of green and blue spaces, minimize the ecosystem service losses associated with losing green spaces, and increase and attach importance to, planning of green spaces as rapid urban development occurs. Compared with other regions, many cities in Africa are undergoing rapid BGI loss due to their highly dynamic and novel urban forms and this trend needs to be reversed (Mensah, 2014; Titz & Chiotha, 2019). BGI has been identified as an efficient tool for regulating the urban thermal environment. The practice of combining the ecosystem services linked to BGI's function in managing multiple aspects (air pollution, flooding, disease spread) and how to implement BGI to help the most vulnerable groups within cities (informal settlement residence, children, outdoor workers) has been seldom studied, while the challenge remains to incorporate it into policy and decision making. Future research is needed to better understand how to implement the systematic integration of BGI concepts into

urban planning (Titz & Chiotha, 2019).

1.4. Discussion

Climate change is adding more unexpected challenges to urban areas in Africa (Mitchell et al., 2016; Serdeczny et al., 2017), from climate-induced flooding, droughts, heatwaves to sea level rise, coastal erosion and storm surges (Baudoin et al., 2017; Gizaw & Gan, 2017; Mitchell, 2016; Schleussner et al., 2016). Even though previous work in Africa has attempted to reorient unsustainable urbanisation patterns, the findings highlight that research efforts need to focus more strongly on the urban thermal environment, particularly because the current pace of urbanisation offers a very time-limited opportunity if development is to happen sustainably within the context of global climate change (IPCC, 2022). Further improved understanding of the urban thermal environment is urgently needed for urban resilience and sustainability. Here four critical research gaps are highlighted.

1. There is a significant research gap in understanding spatial and temporal variations in SUHI across different climate zones. This requires more in-depth and interdisciplinary studies towards urban thermal environment regulation and land resource utilization in diverse urban settings under different climatic conditions.
2. The review has identified a strong geographic bias, with most studies conducted in South Africa. Due to the emergence of dangerous heat conditions combined with rapid urban population growth, cities in East and West Africa therefore require more attention (Marcotullio et al., 2021). As these regions are also most threatened and vulnerable to climate change, fast urban development can drastically intensify the eventual impacts.
3. Research that quantifies the relationships among built-up area density, configuration, and vegetation on the urban thermal environment in African cities is still limited. This is important because patterns of urban land cover and land use changes are critical factors that influence

mitigation or intensification of the UHI.

4. Although the advantages of BGI include improving urban climate resilience, we found few studies that investigated the practical role of BGI in regulating the urban thermal environment, and mitigating UHI. This means that we still do not know details of the thermal performance of BGI in Africa.

From the gaps identified in this review, the following four research questions emerged and are addressed in this thesis.

Research question 1: What are the spatial and temporal variations of SUHI in different climate zones in East Africa?

When considering the urbanisation processes and the impacts of climate change on the urban thermal environment, changes through time were found in most study cities. Such changes commonly include an increase in UHI magnitude and intensity, and absolute changes in temperature increase. Unlike air UHI which is more often studied globally (Chapman et al. 2017), SUHI research dominates most studies in Africa reviewed in this thesis. This is partly because of the historical data scarcity which hampers air UHI research, while SUHI relies more on satellite imagery and computer-based analysis. Nevertheless, the resolution of climate model outputs is not fine enough to identify the difference in urban land cover (Marcotullio et al., 2021). Along with low-cost measurement equipment for local data collection (Van de Walle et al., 2021; Venter, Brousse, et al., 2020), it is more achievable to synthesise remote sensing data and fieldwork data to describe the thermal complexity of urban environments. The impacts of climate change and urbanisation processes on the urban thermal environment have been described at the continental scale, and some cities have been detailed analysis from different aspects. However, there has been few comprehensive analyses across multiple cities with different altitudes, locations and different climate zones. This gap is addressed in Chapter 2.

Research question 2: What is the influence of urban density on the urban thermal environment?

LULC changes are an important driver, associated with climate change-related heat stress and

health challenges, increasing the vulnerability of groups already exposed to other risks. The relationships between built-up area density and the urban thermal environment (e.g., SUHI) are often ignored, which could result in underestimating temperatures in the densest, hottest, most vulnerable parts of the city. This study addresses this need in Chapter 3 by exploring how urban density results in SUHI intensity change and how the transformation of urban areas influences the SUHI in Kampala, Uganda.

Research question 3: How does urban configuration affect the urban thermal environment and vegetation index?

Within the city, urban morphology provides important new opportunities for researchers to explore complex, multifaceted urban sustainability, but there has been little research on this in African cities. This scant research attention might be due to local data scarcity. With the development of information technology and a common framework of application, research is needed to understand urban morphology and its connection to urban resilience and sustainability dynamics. This is addressed in this thesis in Chapter 4.

Research question 4: What is the practical role of BGI in regulating urban thermal environment and mitigating UHI?

Blue Green Infrastructure (BGI) has been identified as an efficient tool for regulating the urban thermal environment. The practice of combining the ecosystem services linked to BGI's function in managing multiple aspects (air pollution, flooding, disease spread) and how to implement BGI to help the most vulnerable groups within cities (informal settlement residence, children, outdoor workers) has been seldom studied. This thesis advances understanding of the different conditions under which different types of urban BGI can be used. Relationships between BGI and the urban thermal environment are explored in Chapter 4.

1.5. Methodological approach of the thesis

Fig. 1.6 presents the different analysis approaches and tools used in each chapter, and how they

fit together. The detailed methodological approach is described in each chapter. Global climate change and African urbanisation trends have been well mapped by different models, but correlations of these trends with the changing urban thermal environment in Africa have received much less attention. Remote sensing datasets make it possible to evaluate large-scale spatio-temporal change dynamics. However, there is no available information on the spatial distribution of the urban thermal environment in most East African cities. The extent to which the UHI has historically expanded in the region is still unknown. Remote sensing is therefore needed to map the cumulative historical expansion of LULC and UHI changes. Prior approaches for UHI mapping have generally been based on the spectral information extracted from a single date satellite image and have neglected the temporal features of the process. Thus, a time-series based classification algorithm for mapping urban thermal environment changes is used, and the globally consistent methodology Local Climate Zone (LCZ) for publicly accessible urban data been tested.

Remote sensing-based machine learning is used to classify impervious surfaces, but the lack of available ground-truthed data has hampered further improvement of its accuracy. Thus, visual interpretation based on Google Earth has been used as a substitute for ground-truthed data in this thesis. High resolution LST and NDVI in this thesis are based on Landsat imagery and Sentinel imagery. Landsat imagery has become freely accessible since 2008 and considerably improved scientific and operational applications. With the new data becoming freely available from Senntinel-2 (10-60 m resolution), the combination of Landsat-8, Sentinel-2A, and Sentinel-2B provides a global median average revisit interval of 2.9 days. These analyses were conducted in Google Earth Engine (GEE). GEE is a cloud-based geospatial analysis platform, which has made the planetary-scale remote sensing analysis much easier and faster. GEE consists of a multi-petabyte analysis-ready data catalogue housing a large repository of publicly available geospatial datasets which includes observations from a variety of satellites and environmental and climate variables.

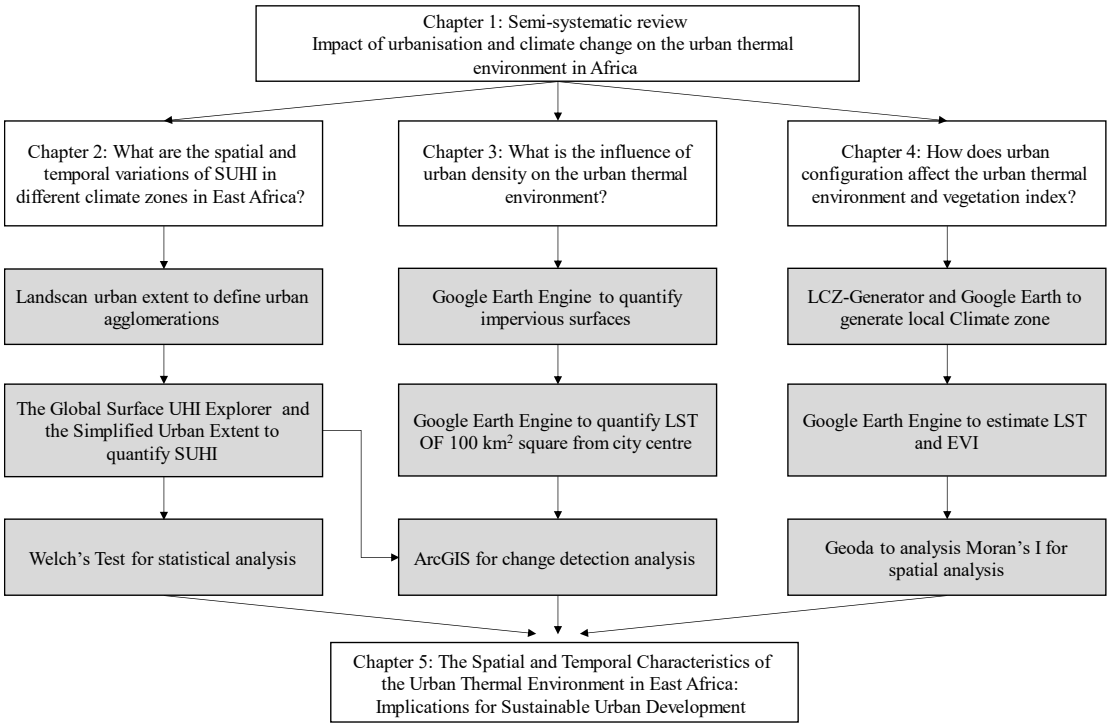

Figure 1.6 Major analysis approaches and tools used in the thesis.

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In Chapter 1, based on an overall introduction of research background and a semi systematic review, three major research questions have been raised. Meanwhile, methodology approaches have been proposed. Seeking to answer research question 1, Chapter 2 will use a remote sensing-based analysis to explore SUHI in five East African cities across different macroclimate zones.

Chapter 2: The spatial and temporal characteristics of urban heat island intensity: implications for East Africa's urban development

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Abstract: Due to the combination of climate change and the rapid growth in urban populations in Africa, many urban areas are encountering exacerbated urban heat island (UHI) effects. It is important to understand UHI effects in order to develop suitable adaptation and mitigation strategies. However, little work has been done in this regard in Africa. In this study, we compared surface UHI (SUHI) effects between cities located in different climate zones in East Africa, investigating how they change, both spatially and temporally. We quantified the annual daytime and night-time SUHI intensities in the five most populated cities in East Africa in 2003 and 2017, and investigated the links to urban area size. We consider the possible drivers of UHI change and consider the implication for future development, highlighting the role of factors such as topography and building/construction materials. The findings suggest that UHI mitigation strategies targeting East African cities may benefit from more comprehensive analyses of blue and green infrastructure as this offers potential opportunities to enhance human comfort in areas where UHI effects are highest. However, this needs careful planning to avoid increasing associated issues such as disease risks linked to a changing climate.

Keywords: Urbanisation; Climate; Cities; Densification; Mitigation; Population; Temperature

2.1. Introduction

More than half of the world's population was residing in urban areas in 2018, with 4.2 billion people living in urban settlements. As the world continues to urbanise, this proportion is expected to increase from 55% to 68% between 2018 and 2050 (DESA, 2019). One major challenge in coping with urbanisation is the urban heat island (UHI) effect: a phenomenon in which urban areas are warmer than their adjacent rural areas (Howard, 1833). Air UHI (AUHI) and surface UHI (SUHI) are two major indicators used in UHI analysis. AUHI is based on air temperature measurements above or below the roof level, whereas SUHI is derived from remotely sensed surface temperatures. Here we focus on the SUHI. The UHI effect is caused by differences in urban and rural energy balance (Oke, 1982). Compared to rural areas, impervious surfaces in urban areas have lower albedo, and higher thermal capacity and thermal conductivity (Li et al., 2020b; Oke, 1973; Zhou et al., 2014). Urban structures and their configurations can also raise the surface roughness, trapping radiation in built-up areas, and changing overall air movement (Li et al., 2020b), with precinct ventilation performance further influencing the UHI and thermal comfort (He et al., 2020).

The UHI effect brings about numerous direct and indirect impacts on urban inhabitants, primarily affecting their health (Grimm et al., 2008a; Holloway et al., 2005; Li et al., 2020b). In particular, the UHI effect exposes urban inhabitants to additional heat stress, generating extra thermal discomfort in many cities under particular urban development patterns and geographic conditions, and increasing heat-related health risks (Bouchama, 2004). Generally, the UHI effect prolongs and intensifies heat waves, which increases morbidity and mortality during the heatwave events (Argüeso et al., 2014; Cai & Kalnay, 2003).

Warming intensified by urban land use and land cover change has been identified in many cities, which implies that heat stresses will be further exacerbated in the future (Georgescu et al., 2013; Li et al., 2020b), as the urbanisation trend continues. For example, the UHI effect became more prominent in areas of rapid urbanisation in the Pearl River Delta of China (Chen et al., 2006); SUHI was found to be influenced by urban land use in Rotterdam in the Netherlands (Heusinkveld et al., 2014); and amplified temperatures detected in Noida, India, were mainly due to an increase

in impervious areas, associated with urbanisation (Kikon et al., 2016). The impacts caused by the UHI effect will be exacerbated when taking climate change into consideration (Dominguez et al., 2009; Grimm et al., 2008a; Li et al., 2020b). The interactions of UHI effect and climate change are non-linear (Li et al., 2020b), and are not simply the sum of the combined contributions (Krayenhoff et al., 2018).

Enhancement of UHI intensity has been detected in various cities around the world. Planners have devised models at different scales for conceptualising UHI effect and urban growth. However, the major focus of these studies is on expansion forms of urban growth, rather than densification (Chapman et al., 2017). In contrast, urban densification targets higher urban density. This approach can lead to economic efficiency and resource conservation as services and infrastructure are more easily integrated into more densely built cities. Urban expansion is usually associated with urban sprawl, which is a kind of rapid urban land expansion with non-contiguous and unplanned development. Urban sprawl is exemplified via unlimited outward expansion, and rapid growth toward suburban areas (Njoh, 2004). Urban sprawl brings numerous challenges for urban development, including unsustainable land use problems, pollution, and environmental degradation (Anas & Rhee, 2006). In developing countries of Africa and Asia, rapid urban expansion has become a critical public policy issue in recent years (Cobbinah & Aboagye, 2017). Urban expansion mainly contributes to the broadening of the area affected by the UHI, while densification is likely to exacerbate the intensity of the UHI effect (Chapman et al., 2018). Although urban expansion has become the most common form of urban development, some African countries have adopted policies that aim to promote urban densification (Fataar, 2012; Seto et al., 2011; Todes et al., 2018).

Many countries with the fastest estimated and projected rates of urbanisation are located in Africa (DESA, 2019), where rapid and often unplanned urbanisation is exacerbating the impacts of a wide range of natural and anthropogenic disasters. The East Africa region is one of Africa's fastest urbanising areas and its growth rate is higher than the average for Africa. Estimates from the United Nations (UN) show that 24% of East Africa's population lives in urban areas in 2018, compared to only 7% in 1960; this represents an increase from 3 million people in 1960 to 65 million urban inhabitants in 2018 (DESA, 2019). As East Africa continues to urbanise, the

proportion of urban populations is expected to increase from 24% to 39% by 2050. The urban poor who live in informal settlements are highly susceptible to heat stress, and are particularly vulnerable to sustained high temperatures due to their location, urban design and poverty levels. As urban area growth and climate change intensify, hundreds of millions of inhabitants will be under heat stress. For example, over 70 million people in Kenya and Uganda experienced 20 to 25 days of extreme heat per year in 2018, yet it could exceed 125 days by 2090, putting far more people at risk (Samarrai, 2018).

Climate change leads to higher temperatures and longer, more severe, and more frequent heat waves, causing UHI affected areas to bear the brunt of these harsher heat events. East Africa has been identified as one of the most vulnerable regions in Africa in the face of climate change (Gebrechorkos et al., 2019). Most of the East African region has experienced a significant temperature increase from the beginning of the early 1980s (Anyah & Qiu, 2012). The Famine Early Warning Systems Network (FEWS NET) also reported temperature increases in many areas of Ethiopia, Kenya, South Sudan, and Uganda over the last 50 years (Brown & Brickley, 2012). Temperatures in large parts of East Africa are projected to rise during the current century, and the maximum and minimum temperatures will be higher than the baseline period (1961 to 1990) (Gebrechorkos et al., 2019). Climate model projections under the SRES A2 and B1 scenarios indicate temperature increases in all seasons across the whole of Ethiopia, which may lead to a higher frequency of heat waves as well as higher rates of evaporation and evapotranspiration (Conway & Schipper, 2011).

The UHI effect has become one of the clearest examples of how urbanisation affects the local and regional climate (Chapman et al., 2017). Therefore, essential measures should be taken to reduce the negative effects of UHI, especially in the coming decades, where the frequency and intensity of extreme heat events are anticipated to become more severe due to the interactions between urban climate, heatwaves, global climate change, and anticipated rapid urbanisation (Li et al., 2020b). Globally, the UHI effect has been extensively studied, however most research has been conducted in cities located in Europe, North America and China, while there has been little research in those regions most vulnerable to climate change, such as cities in Africa (Chapman et al., 2017). Most UHI studies also tend to focus on a single city. Variability in methodological

approaches can make direct comparisons across studies (and therefore cities) difficult, making it harder to build a picture of regional changes. This is problematic because climate conditions are important factors, and affect UHI in different ways (Sun et al., 2019). To understand more about the importance of regional climate conditions and patterns of urbanisation in determining the extent and distribution of UHI effects, it is important to undertake analyses across multiple cities simultaneously using a common methodology. Thus far, however, few such studies exist.

Given that the combined impacts of urbanisation and climate change will potentially have large impacts on future urban temperatures (Chapman et al., 2017) and exacerbate existing heat stress in East African cities, understanding the UHI effect in these cities is important if UHI is to be mitigated. In this study, we compare SUHI between East African cities located in different climate zones and assess how it changes spatially and temporally. This allows us to understand the possible driving factors, and consider the implications for future urban development. We address the following questions: (1) How does SUHI vary in different climate zones in East Africa? (2) What are the spatial and temporal variations of SUHI in these cities and what are the possible driving factors? (3) What are the implications for future urban development in the region?

2.2. Materials and Methods

2.2.1 Study area

Five cities spanning the four climate zones in the region were selected as study areas based on the following criteria: (i) being the largest or capital city; (ii) being the main economic and commercial centre of their country; and (iii) experiencing rapid urbanisation with the highest population in their respective countries.

Night-time light and population distribution of East African cities as the representation of representative indicators are obtained by using Google Earth Engine (GEE) (Fig 2.1), and due to reasons of data availability and policy relevance. Climate classification data was taken from 1 km resolution Köppen-Geiger maps. The coarse resolution of Köppen Climate Classification, which is a limitation in study areas selection (e.g. in Köppen Climate Classification Dar es Salaam is tropical savanna or tropical wet/dry climate (Aw), while in traditional climatology, Dar es Salaam is described explicitly as equatorial savannah).

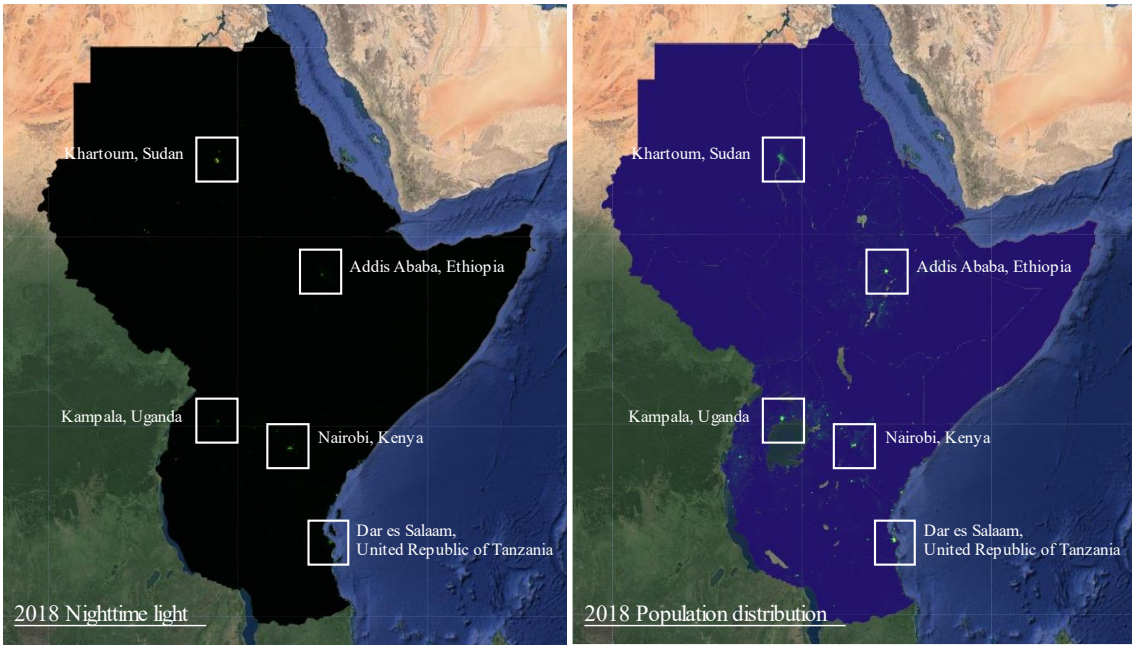

Figure 2.1 2018 nighttime light and population distribution of East African cities.

The location of these cities and the corresponding climatic information (en.climate-data.org) and recorded urban development pattern are provided in Table 2.1, Table 2.2 and Figure 2.2. Climate

classification data was taken from 1-km resolution Köppen-Geiger maps (Beck et al., 2018).

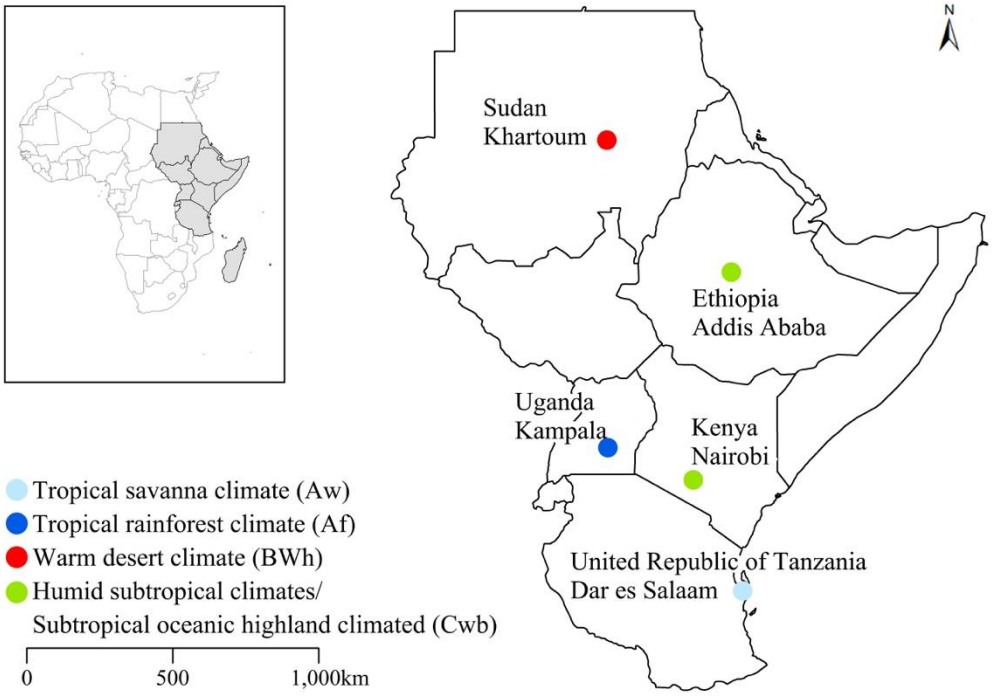

Figure 2.2 The location of study area and Africa.

Table 2.1 Geographic and climatic information of the study cities.

City	Population (2015)	Longitude/ Latitude	Altitude (meters about sea level)	Annual rainfall (mm)	Temperature (°C)		
					Annual	Maximum	Minimum
Khartoum (Sudan)	5,128,000	32.527°E 15.522°N	386	70	29.9	34.3 (May)	22.7 (January)
Dar es Salaam (Tanzania)	5,116,000	39.103°E −6.807°S	16	1114	26.1	27.9 (February)	24.4 (July)
Nairobi (Kenya)	3,914,000	36.858°E −1.181°S	1669	674	18.8	17 (July)	20.5 (February or March)
Addis Ababa (Ethiopia)	3,871,000	38.565°E 8.884°N	2350	1874	15.6	17.2 (April)	14.1 (December)
Kampala (Uganda)	2,577,000	32.596°E 0.291°N	1224	1747	21.4	22.7 (February)	20.7 (July)

Table 2.2 Climate zones and urban development information of the study cities.

City	Climate zone	Climate condition	Urban development pattern
Khartoum (Sudan)	Warm desert climate	There are three seasons in the city, a dry season from November to February, hot season from March to May, and a wet season from June to October (Osman & Sevinc, 2019).	The development of the city is tightly linked to the evolution of the Blue and White Nile Rivers, and is also influenced by increasing land exploitation for intensive and extensive cultivation (Zerboni et al., 2020).
Dar es Salaam (Tanzania)	Tropical savannah climate	The climate of the city is greatly influenced by the northeast monsoon which prevails from March to October. The southeast monsoon dominates between October and March. The climate is also greatly influenced by the sea due to proximity of the city to the Indian Ocean (Ndetto & Matzarakis, 2013).	Due to its location along the coast and the existence of the four main roads entering the city, Dar es Salaam has been observed to expand in a radial structure (Ndetto & Matzarakis, 2013). The city is experiencing multiple development projects involving partnerships between the government and UN HABITAT. These projects aim to reduce the area of unplanned settlements (Ndetto & Matzarakis, 2013).
Nairobi (Kenya)	Subtropical oceanic highland climate	The city experiences a short rainy period in November/December and a heavy rainy season from March till the beginning of June (Egondi et al., 2015).	With functionalism as the main planning principle, the city has grown in concentric zones (Oyugi et al., 2017; Karen C. Seto et al., 2012). More than half the population reside in informal settlements ((KNBS), 2010). The city is served by a highly polluted river (the Nairobi River) and exhibits ahigh proportion of open vegetated spaceswithin the urban area ((KNBS), 2010).
Addis Ababa (Ethiopia)	Humid subtropical climate/	The short rainy season extends from March to May and the main rainy season from June to September, followed by a dry season from October to February (Angassa et al., 2020;	The city is experiencing rapid urbanisation,with increasing built-up area (impervious surfaces), and is characterized by mixed land uses dominated by informal settlements located close to urban growth centers (Karen C.

	Subtropical oceanic highland climate	Feyisa et al., 2014).	Seto et al., 2012).
Kampala (Uganda)	Tropical rainforest climate	There are two wet seasons (March-May and September-November). Torrential rains are often observed from March to May and July is normally the driest month (Kabano, Lindley, et al., 2021).	The city has expanded in all directions with growth primarily concentrated along main roads. Between 1989 and 2010 the total built-up area increased exponentially, a result of both natural increase and migration (Kabano, Lindley, et al., 2021; Richmond et al., 2018).

2.2.2. Data and methodology

The definition of urban and non-urban for SUHI estimation is based on data from Landscan urban extent (Natural Earth; https://www.naturalearthdata.com/). City centres were defined as the centre of the most populated areas in each city. Urban units are closed polygons around contiguous urban agglomerations. An advantage of using this dataset is that it is based on a consistent algorithm implemented on the MODIS land use satellite. It also consistently bounds global hotspots of human habitation. This approach is also more appropriate than using administrative boundaries, as the urban areas of many developing countries have expanded rapidly and do not always map directly onto administrative jurisdictions. Administrative boundaries are also not comparable across East Africa's cities, and often do not include the full extent of the urban areas (Karen C. Seto et al., 2012).

We used the Global Surface UHI Explorer to quantify SUHI. The Global Surface UHI Explorer is based on the Simplified Urban Extent (SUE) algorithm (Chakraborty & Lee, 2019), which defines the SUHI as the average LST difference between the urban and non-urban pixels, as classified from spectral reflectance data, within an urban agglomeration or city (Chakraborty & Lee, 2019).

The SUE uses the MODIS-derived LST data from TERRA (MOD11A2) and AQUA (MYD11A2). After selecting clear-sky pixels with average LST error of less than or equal to 3 K for quality control, data estimated the LST at four local times: 01:30, 10:30, 13:30, and 22:30. Day time and night-time UHI varies according to different climate conditions, so we focus on annual daytime and night-time SUHI here. Based on Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), the SUE eliminated the influence of the elevation differences, by filtering to only include those clusters with a mean elevation difference of less than 50 m (Chakraborty & Lee, 2019).

Data from the TERRA platform is available from February 2000 until the present, and data from AQUA is available from July 2002 to the present. As data in the Global Surface UHI Explorer version 3 was only available from 2003 to 2017, we chose the years 2003 and 2017 for observation (Chakraborty & Lee, 2019).

The Welch's Test (unequal variance) was conducted to see if two years of UHI are significantly different. Welch's Test is a modification of the Student's t-test that performs better than the Student's t-test whenever sample sizes and variances are unequal between groups, and gives the same result when sample sizes and variances are equal (Moser & Stevens, 1992).

$$x = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}}}$$

The degrees of freedom of the Welch t-test is estimated as follows:

$$df = \left(\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}\right)^2 \Bigg/ \left(\frac{S_1^4}{N_1^2(N_1 - 1)} + \frac{S_2^4}{N_2^2(N_2 - 1)}\right)$$

$\overline{X_j} = \text{sample mean},$

$S_{j=} = \text{sample deviation},$

$N_j = \text{sample size, j} \in \{1,2\}$

We set a null hypothesis that 15 years of urban development did not change the UHI intensity. We used Hedges' g (the unbiased version of Cohen's d) to compute the effect size for different years' UHI with different sample sizes (n) (McGraw & Wong, 1992), by adjusting the calculation of the pooled standard deviation with weights for the sample sizes.

$$Hedges'g = \frac{M_1 - M_2}{SD^*_{pooled}}$$

$M_1 - M_2 = \text{difference in means}$

$SD^*_{pooled} = pooled\ and\ weighted\ standard\ deviation$

Overall this approach is identical to Cohen's d with a correction of a positive bias in the pooled

standard deviation (Cohen, 2013; Lenhard & Lenhard, 2017). The result of Hedges' g is represented by gHedge in the subtitle of each plot in Table 4 and 5 (Ellis, 2010). We draw on the suggestions of Cohen (1988) for interpreting the magnitude of effect sizes, whereby intervals for Cohen's d under 0: negative effect; 0 to 0.2: no effect; 0.2 to 0.5: small effect; 0.5 to 0.8: intermediate effect; 0.8 and higher: strong effect (Cohen, 2013). All the statistics analyses were undertaken in RStudio using the function ggbetweenstats from R package ggpubr (Team, 2020).

2.3. Results

2.3.1. Annual SUHI

The results of SUHI intensity in 2003 and 2017 are shown in Table 2.3, Figures 2.3 and 2.4. The highest SUHI intensity in 2003 across the five cites was found in Kampala (tropical rainforest climate zone), followed by Nairobi (subtropical oceanic highland climate), Dar es Salaam (tropical savannah climate) and Addis Ababa (subtropical oceanic highland climate). Notably, Khartoum (warm desert climate) has a daytime SUHI of below zero, indicating that the city was cooler than its surrounds. This SUHI sequence demonstrated a slight change in 2017, when Kampala (tropical rainforest climate) still exhibited the highest annual UHI intensity but Dar es Salaam (tropical savannah climate) rose to second place followed by Nairobi (subtropical oceanic highland climate). The annual SUHI intensity for Addis Ababa (subtropical oceanic highland climate) had become the lowest except for Khartoum which was still showing to be a UCI in 2017, with a below zero daytime SUHI.

For annual night-time SUHI intensity in 2003, Kampala (tropical rainforest climate) still had the highest SUHI intensity. This was followed closely by Khartoum (warm desert climate), Nairobi (subtropical oceanic highland climate), Dar es Salaam (tropical savannah climate) and Addis Ababa (subtropical oceanic highland climate). In 2017, Khartoum (warm desert climate) showed the highest night-time SUHI intensity, followed by Kampala (tropical rainforest climate), Nairobi (subtropical oceanic highland climate), Dar es Salaam (tropical savannah climate) and then Addis Ababa (subtropical oceanic highland climate).

Table 2.3 SUHI intensity during daytime and night-time in the study cities in 2003 and 2017 [a]

City	Annual daytime SUHI (°C)				Annual night-time SUHI (°C)			
	2003		2017		2003		2017	
	n	SUHI intensity	n	SUHI intensity	n	SUHI intensity	n	SUHI intensity
Khartoum	446	−0.44	640	−0.34	446	1.01	640	1.1
Addis Ababa	131	0.17	254	0.42	131	0.25	254	−0.13
Kampala	240	2.21	285	1.93	240	1.02	285	0.82
Nairobi	42	1.73	242	0.57	42	0.93	242	0.43
Dar es Salaam	131	0.89	173	1.85	131	0.26	173	0.3

[a] The n value is the number of UHI pixels.

For all five cities, SUHI intensity and magnitude varied with time. In 2003, annual daytime UHI intensity observations were -0.44 °C in Khartoum, 0.17 °C in Addis Ababa, 2.21 °C in Kampala, 1.73 °C in Nairobi and 0.89 °C in Dar es Salaam. Annual night-time SUHI intensity in 2003 was -1.01 °C in Khartoum, -0.25 °C in Addis Ababa, 1.02 °C in Kampala, 0.93 °C in Nairobi and 0.26 °C in Dar es Salaam. In 2017, annual daytime SUHI intensity observations from GEE were -0.34 °C in Khartoum, 0.42 °C in Addis Ababa, 1.93 °C in Kampala, 0.57 °C in Nairobi and 1.85 °C in Dar es Salaam. Annual night-time SUHI intensity in 2017 was 1.1 °C in Khartoum, -0.13 °C in Addis Ababa, 0.82 °C in Kampala, 0.43 °C in Nairobi and 0.30 °C in Dar es Salaam.

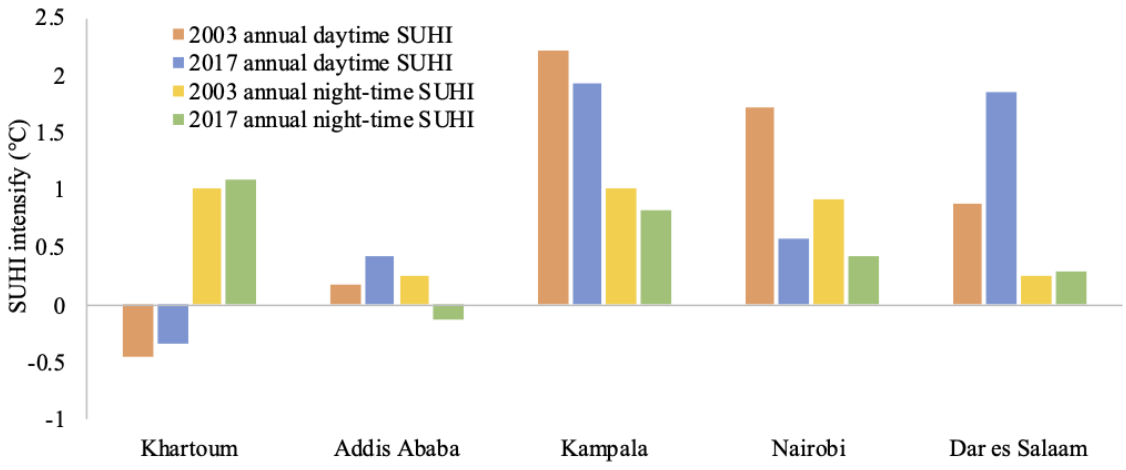

Figure 2.3 Daytime and night-time SUHI spatial distribution of each city in 2003 and 2017.

Addis Ababa, Kampala, Nairobi and Dar es Salaam demonstrate positive daytime SUHI intensity in 2003 while Khartoum, located within the warm desert climate, was found to demonstrate a surface urban cool island (SUCI) effect. In 2017, Kampala, Nairobi and Dar es Salaam still demonstrate a positive daytime SUHI intensity, while Addis Ababa shows a SUCI, as does Khartoum. All cities had positive night-time SUHI in 2003. This was true in 2017, except for Addis Ababa. The urban areas located in the humid subtropical climate changed from displaying a SUHI to SUCI. In 2003 and 2017, Kampala presents the highest daytime SUHI intensity and Khartoum demonstrates the lowest daytime SUCI. In contrast, Khartoum shows the highest SUHI intensity for the night-time while Addis Ababa has the lowest night-time SUHI intensity in 2003 and 2017.

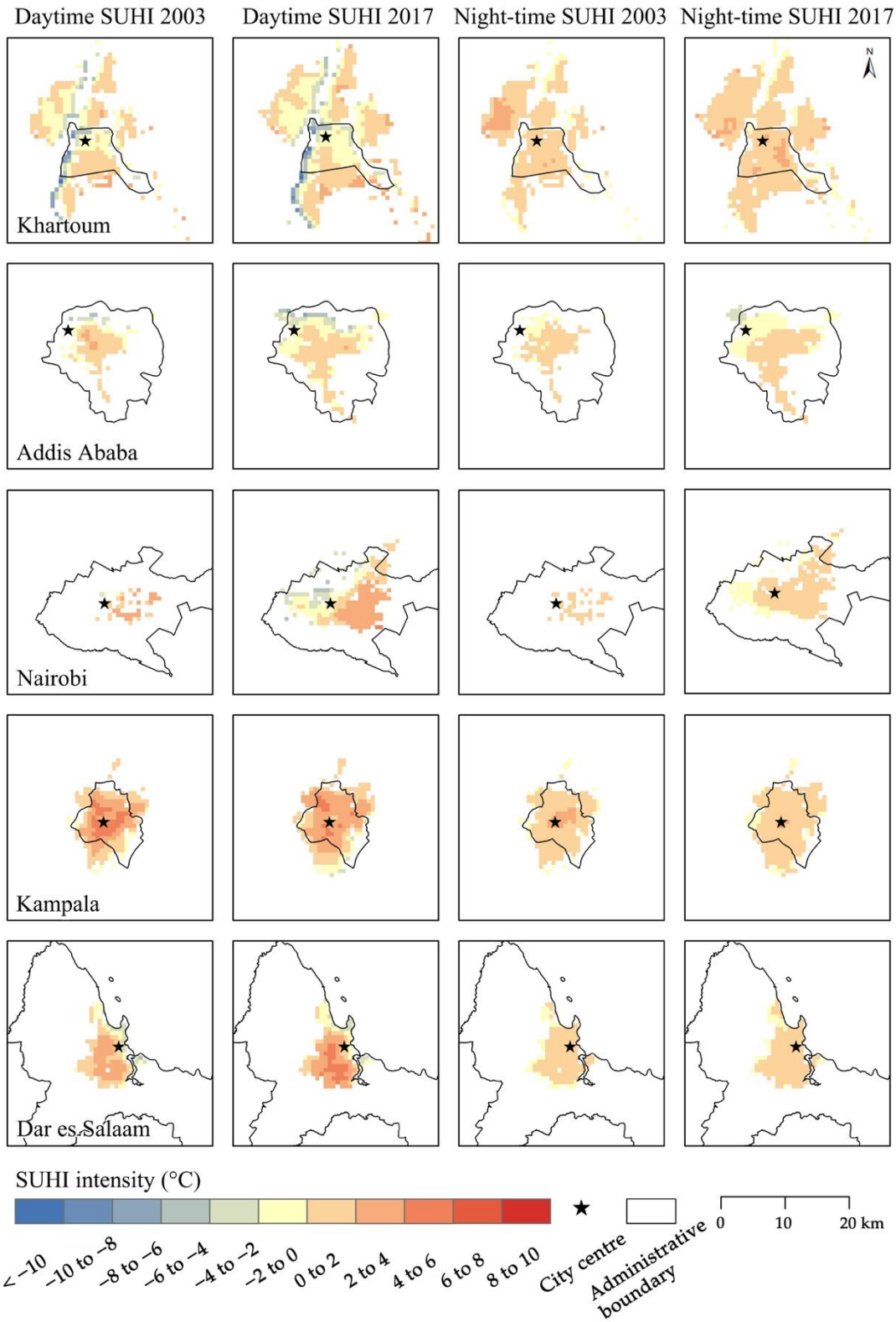

Figure 2.4 Daytime and night-time SUHI spatial distribution in each city in 2003 and 2017.

2003 and 2017 for each of the five study areas. Compared to 2003, the urban area affected by SUHI has increased. For Khartoum, this area increased by 43.5%, from 44,600 ha to 64,000 ha.

In Addis Ababa, the SUHI-affected area rose from 13,100 ha in 2003 to 25,400 ha in 2017, presenting a 93.9% increase. The largest change in the aerial extent of SUHI affected areas was for Nairobi, growing from 4,200 ha to 24,200 ha; an increase of 476.9%. Changes were smallest in Kampala (24,000 ha to 28,500 ha; 18.8%) and Dar es Salaam (6.8% from 16,200 ha to 17,300 ha).

From 2003 to 2017, the strength of SUCI in central areas of Khartoum, Nairobi and Dar es Salaam increased and the SUHI affected areas gradually expanded from the urban centre to the surrounding area. In Addis Ababa and Kampala, the SUHI intensity strength in central urban areas decreased and the affected areas reduced. In particular, in Kampala, the annual daytime SUHI intensity centre fragmented. There were two subsidiary SUHI centres in 2003, which became four separated SUHI centres, surrounding the urban area centre.

Annual night-time SUHI in Khartoum was positive and stronger than in other study cities. In 2003, the SUHI centre was located in the north west, and then moved toward the east, and in 2017 there were two SUHI centres in Khartoum located on the east side and middle west, divided by White Nile river. In 2003, the major SUHI centres in Addis Ababa and Nairobi were located south east of the cities, and their SUHI affected areas expanded and intensified in 2017. Night-time SUCI effect areas also expanded and intensified in 2017. Addis Ababa's SUCI expanded toward the urban north west, the same as the daytime SUHI expansion trajectory. However, Nairobi's night-time SUCI mostly expanded to the west, differing from the SUCI and daytime SUHI which appeared in north west side of the city. Compared to 2003, the area of the central city experiencing an annual night-time SUHI in Kampala shrank in 2017. However, as a whole a larger area of the city was affected by night-time SUHI. Night-time SUHI affected a larger area in Dar es Salaam in 2017, in a similar way to changes in daytime SUHI.

2.3.2. Summary statistics

Figure 2.5 and Figure 2.6 present daytime and night-time SUHI value distributions for each city in 2003 and 2017. A summary of annual mean, Welch's Test, and Hedges' g is provided in Table 4 and Table 5. For Khartoum's urban areas located in a warm desert climate, the annual daytime SUHI was less intense than the night-time SUHI in 2003 and 2017. Daytime SUHI intensity

increased significantly in Khartoum's urban areas over the last decade and a half, even though the expansion of urban areas over time would amplify the SUCI [39]. For Addis Ababa and Nairobi, both located in a humid subtropical climate, the annual daytime SUHI intensity was less than the night-time intensity in 2003, and the annual daytime SUHI intensity was more pronounced than the night-time intensity in 2017. For Nairobi, also located in a humid subtropical climate zone, the annual daytime and night-time SUHI intensities were greater than the night-time intensity both in 2003 and 2017. For Kampala and Dar es Salaam, annual daytime SUHI intensity was greater than the night-time intensity in 2003, and the annual daytime surface UHI intensity is stronger than the night-time intensity in 2017.

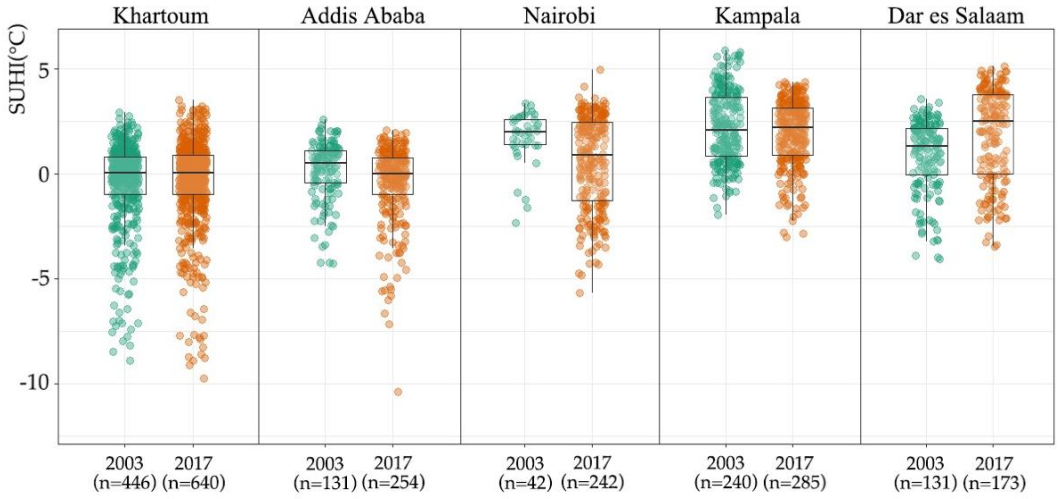

Figure 2.5 Daytime SUHI value distributions for each city in 2003 and 2017.

The boxplots show the distribution of daytime SUHI in 2003 and 2017 in the five cities. The rectangle showing the ends of the first and third quartiles and central line the median. The n value under the x-axis is the number of SUHI pixels.

From Table 2.4, Welch t-tests confirm that there was no statistically significant difference between 2003 and 2017 in terms of annual daytime UHI intensity for Khartoum and Kampala ($p > 0.05$). However, there is highly statistically significant difference between 2003 and 2017 annual daytime SUHI intensity in Addis Ababa ($p = 0.001$), Nairobi ($p =< 0.001$) and Dar es Salaam ($p =< 0.001$). The negative Hedges' g indicates that 15 years of land use change caused a negative effect in SUHI growth in Khartoum (Hedges' g = -0.05) and Dar es Salaam (Hedges' g = -0.48).

Different positive Hedges' g values indicate no size effect in Kampala (Hedges' g = 0.36), a small effect in Addis Ababa (Hedges' g = 0.36) and an intermediate effect size in Nairobi (Hedges' g = 0.65).

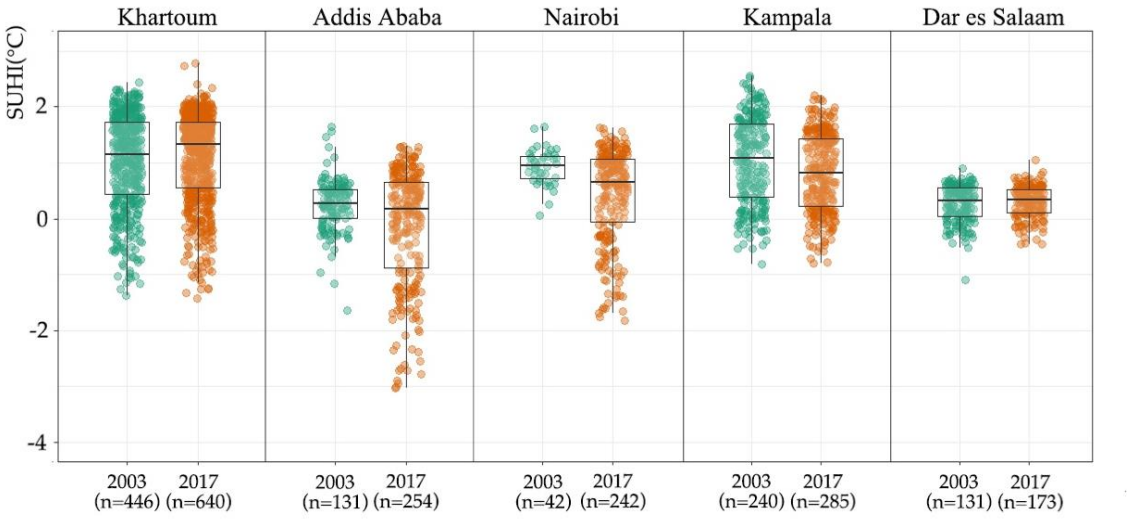

Figure 2.6 Night-time SUHI value distributions for each city in 2003 and 2017.

The boxplots show the distribution of night-time SUHI in 2003 and 2017 in the five cities. The rectangle showing the ends of the first and third quartiles and central line the median. The n value under the x-axis is the number of SUHI pixels.

For night-time SUHI (Table 2.5), Welch t-tests indicate that there is no statistically significant difference between 2003 and 2017 annual night-time SUHI intensity for Khartoum and Dar es Salaam ($p > 0.05$). However, the difference between the 2003 and 2017 annual night-time SUHI intensity is statistically significant ($p < 0.05$) for Kampala. There is a highly statistically significant difference between the 2003 and 2017 annual daytime SUHI intensity in Addis Ababa ($p =< 0.001$) and Nairobi ($p =< 0.001$). The negative Hedges' g indicates that 15 years of land use change posed a negative effect on UHI growth in Khartoum (Hedges' g = -0.1) and Dar es Salaam (Hedges' g = -0.13). Different positive Hedges' g values indicate there is a small effect in Addis Ababa (Hedges' g = 0.47) and Kampala (Hedges' g = 0.27), and an intermediate effect size in Nairobi (Hedges' g = 0.8).

Table 2.4 Summary of annual daytime SUHI intensity statistics.

City	Daytime SUHI intensity (°C)						Welch's Test		Hedges' g
	Maximum		Minimum		Annual mean				
	2003	2017	2003	2017	2003	2017			
Khartoum	2.94	3.51	−8.91	−9.76	−0.44	−0.34	−0.79	p=0.43	−0.05
Addis Ababa	2.6	2.08	−4.28	−10.39	0.17	−0.42	3.45	p=0.001	0.36
Kampala	5.9	4.38	−1.93	−2.99	2.21	1.93	1.93	p=0.054	0.17
Nairobi	3.35	4.96	−2.36	−5.68	1.73	0.57	4.86	p=<0.001	0.65
Dar es Salaam	3.59	5.15	−4.07	−3.49	0.89	1.85	−4.39	p=<0.001	−0.48

Table 2.5 Summary of annual night-time SUHI intensity statistics.

City	Night-time SUHI intensity (°C)						Welch's Test		Hedges' g
	Maximum		Minimum		Annual mean				
	2003	2017	2003	2017	2003	2017			
Khartoum	2.43	2.77	−1.38	−1.42	1.01	1.1	−1.63	p=0.103	−0.1
Addis Ababa	1.64	1.29	−1.64	−3.03	0.25	−0.13	4.92	p=<0.001	0.47
Kampala	2.55	2.21	−0.82	0.79	1.02	0.82	3.12	p=0.002	0.27
Nairobi	1.64	1.63	0.06	−1.82	0.93	0.43	6.91	p<0.001	0.8
Dar es Salaam	0.91	1.05	−1.09	−0.46	0.26	0.30	−1.22	p=0.225	−0.13

2.4. Discussion

2.4.1. Climate zones

The spatial and temporal heterogeneity of the SUHI effect in East Africa is explicitly delineated in this study. Generally, the climate effects on SUHI could be explained by the differences in soil moisture (Oke, 1982; Tran et al., 2006). The hot-wet cities (i.e., Kampala and Dar es Salaam) normally present higher soil moisture contents compared with desert cities (i.e., Khartoum) (Chow & Roth, 2006) and exhibit larger urban–rural differences in soil moisture, resulting in higher daytime and lower night-time LST differences between urban and surrounding rural areas (i.e. UHI), thus amplifying SUHI differences between day and night. In addition, climate

indirectly affects UHI intensities through regulating vegetation conditions, surface albedo, and anthropogenic heat emissions (Santamouris et al., 2001). This partly explains why Khartoum (warm desert climate) presented a SUCI effect during the daytime, but a positive SUHI at night. Vegetation in the Khartoum urban area compared to bare land in the rural buffer is a possible contributor to the negative annual daytime UHI (Ronald R Rindfuss et al., 2016). The reversal of the SUHI diurnality in desert cities has been reported elsewhere e.g. in Las Vegas (Imhoff et al., 2010) and Abu Dhabi (Lazzarini et al., 2013). During 2003 and 2017, almost all the annual mean SUHI intensities of the cities fit the distribution of decreases with latitudinal increases, except Khartoum and Dar es Salaam. Chakraborty similarly notes latitudinal variation in surface UHI for daytime and night-time (Chakraborty & Lee, 2019).

While previous authors (Chakraborty & Lee, 2019) used a global analysis algorithm to analyse multiple cities in East Africa in an attempt to develop a standardized data collection approach our research offers additional insight through our statistical analysis. This allows us to extend existing work. Generally, our results in East Africa show the arid urban areas present the highest UHI intensity for night-time, consistent with (Chakraborty & Lee, 2019) and (Peng et al., 2012). Peng (Peng et al., 2012) identified the range of annual SUHI intensity in Africa as being from -0.2°C to 2.0°C for daytime, and 0.4°C to 1.4°C for night-time. Our results fall outside of this range, spanning -0.44°C to 2.21°C for day-time and -0.13°C to 1.1°C for night-time. These differences in findings may be down to the selection of different study periods and different land cover data, LandScan from Natural Earth was used by Kabano et al. (2021) while MODIS Global Land Cover Map was used by Imhoff et al. (2010).

Similar to findings in previous investigations, mean annual daytime SUHI intensities were higher than mean night-time SUHI intensities in most cities. A study in South America found that the mean daytime SUHI intensities was higher than the mean night-time SUHI intensities in all areas except for the arid climate zone (Wu et al., 2019). The southeast of China also presents stronger SUHI in the daytime than night-time (Yang et al., 2017), but the annual mean SUHI intensity was apparently weaker in arid northwest China's cities (Zhou et al., 2014). The differences between daytime SUHIs and night-time SUHIs are probably because the mechanism of daytime heat island formation is different from that at night. The daytime SUHI was generally explained as the result

of an increase in sensible heat flux and a reduction in latent heat flux due to widespread vegetated and evaporating soil surfaces being encroached by impervious surfaces (Zhou et al., 2014), while the release of more stored energy in the urban areas compared to adjacent areas major contribute to night-time SUHI (Zhou et al., 2014). Compared to 2003, some parts of the cities had a stronger SUHI while some places had a stronger SUCI effect in 2017. This means the temperature differences of all the cities were becoming stronger compared to in the past. Given projected climate changes for East Africa (Gebrechorkos et al., 2019), temperatures in large parts of East Africa will continue to rise during the 21st century. This suggests that these already intensified SUHIs will become more complicated. The important role of climate conditions and their diurnal variations in SUHI intensity should not be ignored (Chieppa et al., 2018; Zhou et al., 2014) but the changes are also inadequately explained by a focus on climate zones alone.

2.4.2. Urbanisation pattern

SUHI intensity and magnitude change is also associated with urban development patterns (Chapman et al., 2017), with built-up areas being one of the most important land-cover types in urban areas, and expected to have a significant effect on SUHI (Yang et al., 2017).

For the case study cities, the pattern of urban expansion and densification explains the change of SUHI intensity to some extent (Chapman et al., 2017). In Dar es Salaam, there is a highly statistically significant difference (Welch's Test, $p=<0.001$) in annual daytime SUHI between 2003 and 2017, with a negative size effect (Hedges' $g = -0.48$). The statistical results could be explained by the densification of Dar es Salaam. Previous research has also pointed out that Tanzania's urban built-up densities and informal settlements have been growing persistently in recent decades (Bhanjee & Zhang, 2018).

The urban growth of Addis Ababa and Nairobi reflect an urban expansion development pattern. From 2003 to 2017, the SUHI influenced areas of Addis Ababa expanded from 13,100 ha to 25,400 ha, with a 93.9% increase. The mean annual daytime and night-time SUHI intensity of Addis Ababa presented a highly statistically significant decrease (Welch's Test, $p=<0.001$) from 2003 to 2017, but the maximum annual SUHI was higher and the minimum SUHI became lower in 2017 compared to 2003. Similarly, Nairobi is experiencing fast urban expansion. The annual

SUHI magnitude of Nairobi saw the greatest changes among the five cities, growing from 4,200 ha to 24,200 ha with an increase of 476.9%. The mean annual daytime and night-time SUHI also presented a highly statistically significant decrease (Welch's Test, p=<0.001) between 2003 and 2017. In particular, the Hedges' g values for Nairobi indicate an intermediate size effect in the daytime (Hedges' g = 0.65) and strong size effect (Hedges' g = 0.8) in the night-time. In other words, these two cities were experiencing rapid expansion with some places getting hotter and some places getting cooler. Researchers have already pointed out that the built-up area of Addis Ababa and its surrounding towns is expanding into the peri-urban region (Kassa, 2013). This development not only influences the SUHI intensity but also leads to high losses of farmland, directly influencing food production for the urban populations (Abo-El-Wafa et al., 2017). The urban growth in Nairobi was at the cost of bare land (land without any cover as well as deserts), showing a star-shaped pattern along the main transport routes from the city centre (Hou et al., 2016).

The statistical analysis could indicate the urban development of Kampala and Khartoum followed a more comprehensive pattern, with urban expansion accompanied with densification. For these two cities, there is no significant difference in annual daytime SUHI between 2003 and 2017, with no effect or negative size effect (both Hedges' g < 0.2). There is no highly significant difference in annual night-time SUHI between 2003 and 2017, with no effect or a small size effect (Hedges' g<0 or 0.2<Hedges' g< 0.5).

Which kind of urban development pattern is best for the development of cities to reduce any increase in SUHI intensity is still unclear. From this study, we suggest that a compact city will face enhanced SUHI, while an overexpanding city will mitigate mean annual SUHI but cause local thermal anomalies. In Africa, urbanisation has not frequently been associated with economic development and improvements in wellbeing (Du Toit et al., 2018), although urbanisation can offer many development opportunities for countries if well managed. Consequently, it is important that further urban development occurs in a way that is beneficial to people, and which does not exacerbate risks associated with climate change, such as increased exposure to temperature extremes.

Policy makers and city planners should pay more attention to one of the main variables influencing rapid urbanisation in Africa: natural rural-urban migration (Hope, 2009). People migrate to urban areas primarily in response to perceived better employment and economic opportunities available there (pull factors); they also migrate to escape unfavourable conditions exacerbated by rural challenges and climate change (push factors) (Yuen & Kumssa, 2010). The IPCC pointed out that climate change could influence the size and characteristics of human settlements in Africa owing to the scale and type of rural-urban migration are partially driven by climate change (Niang et al., 2014).

Fast urbanisation sometimes implies a shift of poverty levels from rural areas to urban areas, which is why we see poverty characteristics often align with settlement patterns in African cities, with informal settlements showing particular growth. In Dar es Salaam, over 70% of the estimated 2.4 million inhabitants lived in informal settlements in 2000 (Kombe & Kreibich, 2000), with this number projected to increase to 80% in the coming decades (Augustijn-Beckers et al., 2011). Such settlements often experience elevated heat exposure (Chakraborty et al., 2019; Chakraborty & Lee, 2019), as well as other environmental risks, such as greater exposure to pollution (Richmond et al., 2018). In informal settlements in Nairobi, temperatures regularly exceed temperatures at the central, non-slum monitoring station by several degrees or more (Scott et al., 2017). The extra heat exposure experienced by residents of informal settlements, is mainly due to their dense population, tin housing and little vegetation, showing the importance of building materials in contributing to UHI effects. In Kampala, millions of urban inhabitants will live in informal areas by 2030 with high potential for them to suffer from epidemiological diseases related to unsanitary conditions (Vermeiren et al., 2012). It is also important to note that urban areas in Africa contain a large proportion of the people who are migrating from rural areas because of climate change impacts, in combination with other factors. Policymakers should consider designing UHI adaptation strategies to minimise its impacts on the most socioeconomically vulnerable populations in informal settlements, who may be less equipped to adapt to environmental stressors. Promoting green space in lower-income neighbourhoods is one appropriate urban strategies that policymakers may adopt to ameliorate some of UHI's inequitable burden on economically disadvantaged inhabitants (Chakraborty et al., 2019), while encouraging

use of building materials with higher heat reflectance offers another strategy (this is explored further below). Improving support for climate change adaptation in the rural source areas of urban immigrants may also be a suitable strategy for policymakers to pursue.

2.4.3. Climate change and urbanisation

Urban areas consume over two-thirds of the world's energy and account for more than 70% of global CO2 emissions (Group, 2020). Moreover, 90% of urban growth will take place in less developed regions in the coming decades (Nations, 2018), where urbanisation is generally unplanned, fuelling the continuous growth of mostly poor informal settlements in areas such as East Asia, South Asia and sub-Saharan Africa (Nations, 2018). One billion urban inhabitants are projected to live in informal settlements, where the impact of climate change is most acute (UN-Habitat, 2018a). The current urban development deficiency in a form of infrastructure shortfalls, brings opportunities to "leapfrog" to low or zero-emission systems and structures (UN-Habitat, 2018a). This implies that a major reconceptualisation of countries' approaches to urban development could still be undertaken. As the World Migration Report (Awumbila, 2014) notes, about two-thirds of the investments in urban infrastructure to 2050 in Africa have yet to be made, offering an opportunity to manage the urbanisation trends in a way that could harness the benefits of rapid urbanisation while reducing the risks. Combining multiple UHI mitigation and adaptation strategies may effectively negate the localised temperature increasing due to both UHI and climate change (Chakraborty et al., 2019; Zhao et al., 2017).

Many researchers have noticed the relationship between urban morphology and the UHI intensity (He et al., 2020; Zhou & Chen, 2018). The morphological characteristics of the city such as building height, building density, road width and orientation may affect the heat balance in urban canyons (Zhou & Chen, 2018). In Dar es Salaam, scattered settlements provided better temperature regulation services than other residential configurations due to their urban morphology characteristics, since former are associated with relatively large proportions of green structures (Cavan et al., 2014). The negative relationship between distance from the city centre and SUHI intensity was detected in Addis Ababa (Feyisa et al., 2016). As noted above, the characteristics of housing materials also influence the SUHI intensity, with different housing types

providing different insulation properties and protecting from heat and cold to different extents, even directly impacting on temperature-related mortality (Scovronick & Armstrong, 2012). Analysis suggests that traditionally constructed housing provides more protection from heat than formal low-cost housing (Scovronick & Armstrong, 2012). This should not be ignored in future African cities development, where the focus is often on upgrading unplanned or informal settlements from traditionally constructed housing (Cavan et al., 2014).

There were various synergies between heat wave and UHI as the varied spatially based on urban development patterns and geographic conditions (He, Wang, et al., 2021). Many countries and region have developed other kinds of UHI mitigation strategies for urban development, and beyond looking at entire cities' development, it is important to take the climate condition and climate projections into account at the local scale. For example, in a predominantly alpine climate country Austria, the ADAPT-UHI project developed tools by mapping the potential UHI risk index, modelling different adaptation scenarios, and evaluating and rating cities' quality of existing green and blue infrastructure (Cavan et al., 2014). Researchers help city planners make decisions on climate change adaptation and minimize the effects of UHI in the future. In the hot desert climate city of Phoenix, Arizona, researchers found that a warming climate was detected to aggravate the interaction between UHI effect and heat waves, while the amplified temperature-exacerbated UHI effect can be almost completely offset by adopting a widespread green roof strategy (Tewari et al., 2019). In Kampala, a project "Promoting Green Urban Development in Africa: Enhancing the Relationship Between Urbanisation, Environmental Assets and Ecosystem Services" conducted under the leadership of the World Bank (White et al., 2017), seeks to conserve the environment as urbanisation proceeds. Addis Ababa is trying to incorporate green infrastructure areas for "multifunctional uses", in order to address stormwater management, UHI mitigation, air filtration, and preservation of urban agriculture (Larsen, 2015). These various approaches offer opportunities for East African cities but require proactive policies and a multi-sector approach to city development (Larsen, 2015; UN-Habitat, 2018b; White et al., 2017). Studies of projects that pursue climate compatible development (CCD) in Malawi, South Africa, Tanzania, India and Kenya have revealed such a framework that advances triple-wins across development, mitigation and adaptation within the developing world is feasible (Colenbrander et

al., 2017; Ficklin et al., 2017; Stringer et al., 2014; Wanjiru & Nunan, 2017).

Anticipated additional climate variability and change could further exacerbate disease incidence and spread in East Africa (Niang et al., 2014). In East Africa's highlands above 2000 m altitude, environmental conditions currently do not support malaria transmission. Due to climate change, these areas will experience increased malaria (Alonso et al., 2011). The changing weather conditions may increase the spread of Rift Valley fever (RVF) virus and could also introduce the RVF virus into domestic animal populations (Baba et al., 2016). When considering the use of blue green infrastructure within city development to mitigate UHI effects, local governments should rationally allocate vegetation and water configurations to avoid creating habitats suitable for viral vectors. In addition, for specific climate zones, such as the desert climate zone, understanding its UCI effect (or oasis effect) in urban areas located is important (Ronald R Rindfuss et al., 2016). More than 90% of the global population residing in deserts and dryland are located in developing countries with high rates of rural to urban migration, indicating that rapid growth in desert cities is likely (UN-EMG, 2011), suggesting further research in this area is urgently needed.

2.4.4. Uncertainty, limitations and further considerations

Our research has focused only on the annual UHI. This decision was made primarily due the different classification of seasons in Africa between study countries. For comparability we therefore chose to present the annual UHI trends in our study cities. We recognise that there may be specific climate features of each selected study year, and our results can only represent the differences between those two selected years. This provides important insights but from the analysis undertaken, we cannot make robust claims about long-term change (Chakraborty & Lee, 2019).

Topography, morphology and biodiversity, are well known to influence UHI effects but were not directly measured in this research (Hamada et al., 2013). We have nevertheless identified their potential contributions when explaining our results. As with all UHI modelling approaches, the reliability of the model output is strongly reliant on the definition and boundary-setting of urban areas. In particular, there remain challenges in integrating data from the Global Surface UHI Explorer with the global-scale Landscan urban extent dataset, as in terms of missing data for

certain months or years, limiting the ability to explore dynamic changes in SUHI associated with urbanisation.

Despite these limitations, this paper has contributed novel empirical information and applied a method that enables comparison across different East African cities, offering an approach that is widely applicable. The method can be used to identify changes in smaller African cities as well as the capital cities considered in this research. Such insights would be particularly valuable in smaller cities where urbanisation is most rapidly accelerating (DESA, 2019).

2.5. Conclusions

The ongoing effects of UHI in rapidly urbanising cities, further exacerbated by global climate change, have intensified heat stress for countless urban inhabitants, especially those who are most vulnerable during heatwave events. We investigated the SUHI in five East African study cities across various climate zones in 2003 and 2017. SUHI intensities differed between day and night, and mean annual daytime SUHI intensities were higher than the mean night-time SUHI intensities in most cities. Results revealed that the differences in climate conditions and urban development patterns had a significant impact on the changes to the SUHI. Policy makers and city planners should consider UHI mitigation strategies, taking into account climate conditions, projected climate changes and urban development patterns, as well as the implications of informal settlement growth. Blue and green infrastructure in general constitutes an essential means for mitigating urban heat and enhancing human comfort, but this needs to be carefully planned to avoid negative impacts linked to human wellbeing and the spread of disease.

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The findings of Chapter 2 contributed to a better understanding of SUHI patterns in five East African cities located in various macroclimate zones. The SUHI intensity increased in the previously identified SUHI hotspot locations, and the SUHI magnitude increased. A thorough assessment of their spatial variations was conducted after the overall temporal pattern had been confirmed. The factors associated with SUHI expansion were further investigated in light of the local climate, urban development trends, and the unplanned proliferation of informal settlements. The findings also suggest the possibility of controlling urban development patterns with specific attention to the size, form, and centrality of built up areas in order to mitigate the growth of the SUHI.

In East Africa, the development of informal settlements is linked to the high rates of urban growth. Potential areas for informal settlements might encroach upon BGI, such as riverfront areas, wetlands, and forests, which could exacerbate social and environmental issues and hinder sustainable development. The social inequalities in environmental resources and exposure to infectious diseases (such as vector-borne and diarrhoeal diseases) introduced by BGI should be taken into consideration and mitigated in order to establish sustainable urban areas that serve all urban inhabitants (both the current residents and those yet to be residents). While Chapter 2 offered a number of valuable insights, it also revealed significant research gaps that demand additional study. Kampala, as one of the cities experiencing the most significant changes in SUHI in Chapter 2, was selected as the case study city for studying built-up density and urban thermal environment relationships in Chapter 3.

Chapter 3: How urbanisation alters the intensity of the Urban heat island in a tropical African city

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Abstract: Due to the combined effects of urban growth and climate change, rapid urbanisation is particularly challenging in African cities. Areas that will house a large proportion of the urban population in the future coincide with where natural hazards are expected to occur, and where hazard risk management institutions, knowledge, and capacity are often lacking. One of the challenges posed by rapid urbanisation is the Urban Heat Island (UHI) effect, whereby urban areas are warmer than the surrounding rural areas. This study investigates urbanisation patterns and alterations in surface UHI (SUHI) intensity for the Kampala urban cluster, Uganda. Analyses show that between 1995 and 2017, Kampala underwent extensive changes to its urban built-up area. From the centre of the city to adjoining non-built up areas in all directions, the urban land cover increased from 12,133 ha in 1995 to 25,389 ha in 2016. The area of SUHI intensity in Kampala expanded significantly over the 15-year period of study, expanding from 22,910 ha in 2003 to 27,900 ha in 2016, while the annual daytime SUHI of 2.2°C in 2003 had decreased to 1.9°C by 2017. Although SUHI intensity decreased in some parts of the city, elsewhere it increased, suggesting that urbanisation does not always lead to a deterioration of environmental conditions. We postulate that urban development may therefore not necessarily create an undesirable impact on local climate if it is properly managed. Rapidly growing cities in Africa and elsewhere should ensure that the dynamics of their development are directed towards mitigating potentially harmful environmental impacts, such as UHI effect through careful planning that considers both bluespaces and greenspaces.

Keywords: Uganda, Africa, Population, Greenspaces, Bluespaces, Climate change, Temperature

3.1 Introduction of Chapter 3

One of the major phenomena associated with the dual challenges of climate change and urbanisation is the urban heat island (UHI) effect, which is when the temperature in urban areas is higher than surrounding suburban and rural areas (Oke, 1973; Oke, 1982). The differences in the urban and rural areas' energy balance results in the UHI effect. Urbanisation processes inevitably increase impervious surfaces, encroache on green and bluespaces, and alter albedo and geometry compared to rural surfaces (Haaland & van den Bosch, 2015; Manoli et al., 2019). The UHI effect not only alters the environment in urban areas including net primary production, biodiversity, water and air quality (Imhoff et al., 2004; Reid, 1998), but also affects human health and well-being, increasing the risk of heat-related morbidity and mortality (Gong et al., 2012; Zhou et al., 2014). Typically, urban heat problems will be exacerbated by the combined impact of heat waves and UHI, when taking future climate projection into consideration (He, Wang, et al., 2021).

According to the methodological approaches to investigate temperature differences between urban and rural areas, UHI can be described as the subsurface heat island, air heat island or surface heat island (Oke, 1995; Oke et al., 2017; Yow, 2007). The subsurface heat island refers to the coupling between surface air temperatures and the ground surface temperature (Ferguson & Woodbury, 2007). The air heat island represents UHI effects in the urban canopy layer or the urban boundary layer (Arnfield, 2003). The canopy UHI measurement is mainly based on situ sensors mounted from ground to roof level (aeronautical meteorological stations or vehicle-mounted sensors) (He et., 2021, Yow, 2007). The boundary layer UHI measurement relies on special platforms above the roof level (tall towers, radiosondes, tethered balloon flights and aircraft) (Oke et., 1995). Developing and installing such measurement stations is expensive and time-consuming. This means that they are only used in a few large cities around the world. Due to this limiting factor, insufficient data on atmospheric UHIs usually fail to provide adequate spatial details for land use strategies and climate change management in urban areas of most developing countries (Anniballe et al., 2014). The surface heat island is also known as surface urban heat island (SUHI), and is measured from land surface temperature (LST), which is primarily observed by satellite thermal remote sensing data (Voogt & Oke, 2003). Advancements

in remote sensing and spatial information sciences provide researchers with consistent and repeatable observation data to analyse the urban thermal environment at various spatial and temporal scales (Deilami et al., 2018; Weng, 2009).

East Africa has witnessed rapid urbanisation over the past few decades, which is likely to continue into the future (DESA, 2018). Cities in this region will undergo enormous change in urban infrastructure and population, leading to increases in UHI intensity, with implications for heat stress, public health, and cooling energy consumption (Kumar et al., 2017), particularly under projected climate changes. Various studies have documented the UHI effect in selected cities in East Africa (e.g. for Dar es Salaam (Gombe et al., 2017a); Nairobi (Ochola et al., 2020) and Addis Ababa (Bisrat Kifle Arsiso et al., 2018; Feyisa et al., 2014)) but knowledge gaps remain. Two crucial environmental challenges rapidly expanding cities are facing relate to the need to prevent flooding after heavy rain, and to reduce excessive heat due to the UHI effect (Koomen & Diogo, 2017; Richards & Edwards, 2018). There is a complex relationship between these two phenomena, as rainfall increases with rising air temperature (Koomen & Diogo, 2017). Indeed, the UHI effect and higher flood risk are different aspects of urban development issues, and need to be addressed together. UHI effects are often associated with, or even drive, more intense rainfall events over cities (Han et al., 2014; Lei et al., 2008; Meng et al., 2007; Rozoff et al., 2003), and could therefore result in the greater likelihood of flooding. While studies in the literature focus on other locations, quantification and analysis of the magnitude and spatial pattern of UHI effects in case study cities in East Africa are less well studied. Such analyses can not only help in further comprehending the characteristics and driving forces of the SUHI effect, which is already reasonably well understood (Zhou et al., 2014), but will also be crucial for seizing opportunities for land-based adaptation and to develop optimal climate mitigation strategies in the region. This paper adds a valuable East African analysis to the growing body of literature, focusing on the Ugandan capital city, Kampala, investigating the relationship between urbanisation and SUHI intensity change. The main objectives of the study are to: a) evaluate the urban growth pattern of Kampala, b) calculate the variations of annual SUHI intensity of Kampala, and c) explore how urban expansion results in SUHI intensity change and how the transformation of urban areas influences the SUHI.

3.2 Method

3.2.1 Study area and data sources

As one of the most densely populated areas in East Africa, the Great Lake Victoria Region (GLR) has over 30 million residents (Smith, 2011; Verschuren et al., 2002). Over the past decade, this region has experienced radical urbanisation, with large influxes of people to urban areas (Linard et al., 2012). All countries in GLR are projected to experience increases in the duration, frequency and intensity of extreme heat events, with parts of Kenya, Uganda, and the Democratic Republic of Congo expected to be the locations with the highest growth (Asefi-Najafabady et al., 2018). Because of the complex and dynamic land-lake-atmosphere interactions, several studies highlight the importance of climate relevant research over the GLR (Camberlin et al., 2018; Souverijns et al., 2016). Since climate change is expected to stimulate change to land and lake breezes and to have significant impacts on local communities (Gasper et al., 2011; Mabasi, 2009; Vermeiren et al., 2012), associated possible extreme weather and climate events (Souverijns et al., 2016; Thiery et al., 2016b) may cause severe socio-economic impacts on vulnerable groups (Hendrix et al., 2011). To support the development of proper mitigation and adaptation strategies, it is imperative to understand the impacts of rapid urbanisation in this part of Africa.

Kampala, the capital and main commercial centre of Uganda, is one of the most populated and fastest growing cities in East Africa (Figure 3.1). The city's population was nearly 1.75 million in 2015 (Amin & Stephen, 2012), and has been estimated to be growing at an average annual rate of 1.97% between 2015 and 2021 (UBOS, 2020). Characterized by the presence of uncontrolled informal settlements (Brousse, Wouters, et al., 2020c), Kampala is located on the northern shore of Lake Victoria at a mean altitude of 1203 m above sea level. The urban topography is characterized by rounded hills and wetlands, while the urban structure is shaped by the socio-economic stratification of wealth: richer neighbourhoods are located typically at the top of the hills, and poorer areas are at lower altitudes, closer to wetlands (Kabumbuli & Kiwazi, 2009; Vermeiren et al., 2012). Residential density has been reported to increasingly be concentrated on the hillslopes, with the wetlands gradually being encroached and filling with informal settlements, in spite of wetland protection laws (Amy Richmond, 2018; Vermeiren et al., 2012). Flooding is

the major climate hazard experienced by Kampala (Kampala Capital City Authority, 2012; Lwasa, 2009). However, Kampala is also defined as one of the region's most vulnerable cities when it comes to heat stress (Parkes et al., 2019b). Urbanisation and climate change could cause heat stress (Asefi-Najafabady et al., 2018; Chapman et al., 2017) and flood risks (Douglas et al., 2008; Pérez-Molina et al., 2017; Richards & Edwards, 2018) to increase. These two challenges could both be magnified by the SUHI effect (Oleson et al., 2015; Richards & Edwards, 2017).

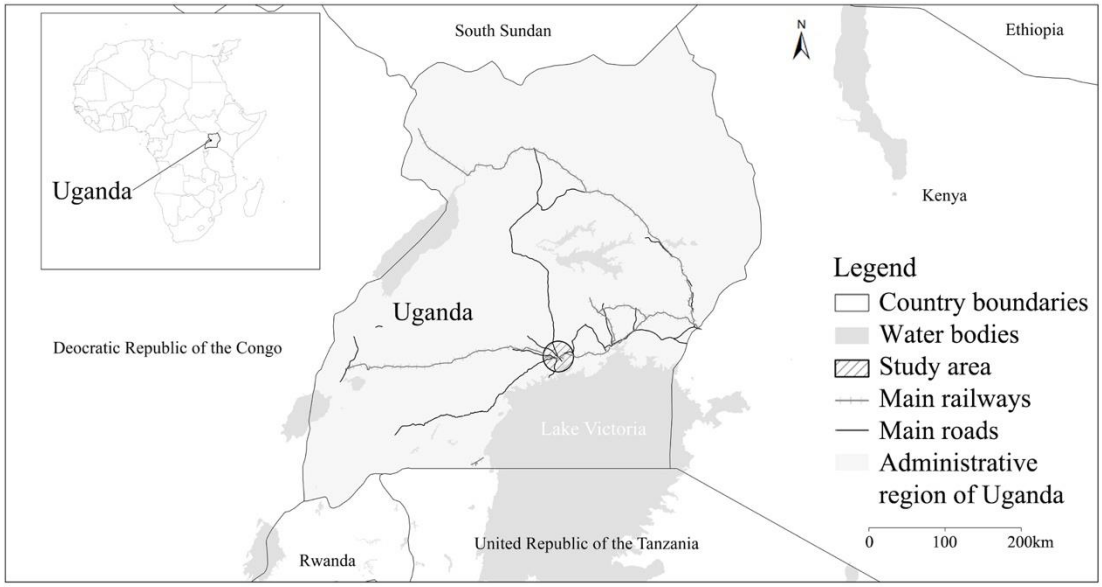

Figure 3.1 The location of Kampala in Uganda and Africa.

In this research, three kinds of data were linked within the analysis. Firstly, we used Landsat imagery through Google Earth Engine (GEE) to quantify the extent of the impervious surfaces associated within the city. The urbanized extent of Kampala is already larger than the administrative boundary of the city (Vermeiren et al., 2012). We therefore based our research on the built-up area within a 20 km-radius from the city centre (Amin & Stephen, 2012; Simwanda et al., 2019). Then, we used MODIS average 8-Day (MOD11A2.006) within a zone 100 km^2 from city centre through GEE to detect the annual daytime LST change in Kampala. Finally, we used the Global Surface UHI Explorer within GEE to retrieve annual daytime SUHI intensity, during this step, the "urban cluster" concept was used to compare the urban-rural LST differences (Chakraborty & Lee, 2019; Semboloni, 2000). Data sources and processing steps, and the overall methodology are summarised in next section and Table 3.1.

Table 3.1 Data sources used to examine historical patterns of urbanisation in Kampala, Uganda.

	Data Layer	Spatial Resolution (m)	Date	Scale
Built-up	Landsat 8 Surface Reflectance (SR)	30	2017	20 km-radius subset from the city centre
	Landsat 5 SR	30	1995, 2010	
	MODIS Land Cover Type	500	2010	
LST	MOD11A2.006	1,000	2003, 2017	100 km^2 square from city centre
SUHI	Global Surface UHI Explorer	1,000	2003, 2017	Kampala urban cluster

3.2.2 Historical patterns of urbanisation

To understand how SUHI intensity and location altered with increased urbanisation, we examined historical patterns of urbanisation in Kampala by quantifying the extent of the impervious surfaces associated with the city. The extent of impervious surfaces can be measured unambiguously by remote sensing data, and therefore can be used in a consistent manner to compare urban areas over time and space (Slonecker et al., 2001). We used Landsat imagery available through Google Earth Engine (GEE) to assess the changes in urbanisation across the Kampala urban cluster. Landsat data were processed using the cloud-computing technology in the GEE platform (https://code.earthengine.google.com/). Kampala's economic zone extends to about 20 km from the city centre and 40 km along the rapidly developing peninsula up to Entebbe Airport (Makita, 2009). We therefore calculated the built-up within a 20 km radius subset from the city centre (Amin & Stephen, 2012; Simwanda et al., 2019). The islands in the Lake that fell with the urban cluster were also included.

Landsat imagery scenes were selected based on availability of high-resolution aerial imagery for Kampala. Many Landsat images inevitably suffer from cloud contamination in the tropics (Asner, 2001), which reduces the accuracy in land cover classification and land cover change (Zhu &

Woodcock, 2012). To select Landsat scenes that are clear from cloud and cloud shadow, the Fmask (Function of mask) algorithm was applied by selecting the best cloud-free pixel. Due to cloud contamination, no images could be found that were suitable for extracting urban land cover in the years 2003 and 2017. Landsat imagery scenes were used from 1995, 2010 and 2016. To enhance the classification of results and ensure an objective identification of the Landsat imagery data, we used MODIS Land Cover Type 2010 in this study. Since the reference dataset is an important consideration in terms of the accuracy of remotely sensed data. When analysing the imagery, the random forest classifier with 10 trees was used to downscale MODIS data to Landsat resolution and generating two random samples (training and validation) from the MODIS data. The training sample is used to train the classifier (Waske & Braun, 2009). From the validation sample, we assessed the classifier performance by Confusion Matrix (Stehman, 1997), and set the limits of the training overall accuracy as 90% and the validation overall accuracy as 80%. Training overall accuracy ranged from 0.906 in 1995 to 0.967 in 2016; validation overall accuracy ranged from 0.814 in 2016 to 0.906 in 1995, indicating that overall accuracy is good.

After obtaining the urban built-up classification result, we estimated the intensity of urban built-up area coverage across the Kampala urban cluster using the kernel density (KD) function of ArcGIS Spatial Analyst. Generally, the KD tool estimates the density of point features around each output raster cell (ESRI, 2020) This measures Euclidean distances by calculating a smoothly continuous curved surface to fit the frequency distribution (Bailey & Gatrell, 1995; Davis et al., 2011; Parzen, 1962). In the visualisations provided by KD estimation, the peak of the surface value is the location of the point representing the presence of clusters or ‘hot spots’ in the distribution of events (Cai et al., 2013; ESRI, 2020). The surface values diminishing with increasing distance from the point represent events that occur much less frequently in the area (Cai et al., 2013; ESRI, 2020). KD has often been used for the purpose of point-pattern analyses, such as population analysis (Jenkins, 1995), crime hotspots analysis (Bailey & Gatrell, 1995; Yutaka & Shimada, 2000) and wildlife management (Amstrup et al., 2004). It is consequently becoming more common to use a KD approach to study ecological networks and landscape changes (Adeel, 2010; Cai et al., 2013; Leslie, 2009; Jing Yang et al., 2019). The results of KD estimation directly reflect the spatial patterns of the mutation in the built-up area (Peng, Zhao, et

al., 2016). ArcGIS uses the KD function calculation (Eq.(1)), originally developed by Silverman in 1986 (ESRI, 2020; Silverman, 1986):

$$f_n(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - xi}{h}\right)$$

Where $f_n(x)$ is the estimated value of probability density of point x, $k()$ is the KD function, h ($h > 0$) is the bandwidth of the estimation model, which is the radius of the analysis neighborhood; and $(x - xi)$ is the distance from the estimation point to the sample xi (Peng, Zhao, et al., 2016). In KD estimation, the bandwidth h plays an important role on the computed outcome. The dot density in the space becomes smoother accompany with the h, which may reduce the density structure. Conversely, the estimation point distributes uneven when h decreases (Cai et al., 2013). In this study, we used the 30m bandwidth.

3.2.3 Estimation of land surface temperatures and the SUHI effect

We used MODIS Collection-6 MODIS /Terra Land Surface Temperature/Emissivity products here, as Kampala is located in a very cloudy region due to the bi-annual overpassing of the intertropical convergence zone and lake-induced convection (Brousse, Wouters, et al., 2020a; Nicholson, 2019; Thiery et al., 2016a). The accuracy of the MODIS Collection 6 (C6) Land Surface Temperature product (MOD11) has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts (*Status for: Land Surface Temperature and Emissivity (MOD11)*, 2018). MODIS Collection based approach has been found to be acceptable even in locations with frequent cloud cover within global SUHI studies (Chakraborty & Lee, 2019; Peng et al., 2012). Generally, the MODIS LST accuracy is better than 1°C in the range from −10 to 50°C (Wan et al., 2004). The fine space-based climatic information provided by MODIS LST has been validated for detailed spatial assessment of climate variability in Africa, such as in Egypt (El-Kenawy et al., 2019) and other locations in north Africa (*Status for: Land Surface Temperature and Emissivity (MOD11)*, 2018).

To detect the annual daytime LST change in the Kampala urban cluster, we used GEE to generate

LST from the MODIS average 8-Day (MOD11A2.006) within 100 km^2 from city centre in 2003 and 2017.

To quantify SUHI effects in Kampala over time in relation to urbanisation, we used the Global Surface UHI Explorer within GEE to retrieve annual daytime SUHI intensity. The SUHI dataset was created based on the simplified urban-extent (SUE) algorithm (Stehman, 1997), by using the concept of an urban cluster and rural areas as the basis for the calculation of SUHI intensity. An urban cluster is more appropriate than using administrative boundaries, as the latter can frequently change over time. Equally, administrative boundaries are sometimes not comparable across cities and often do not include the full extent of a city (Chakraborty & Lee, 2019; Semboloni, 2000). Our chosen approach allows us to focus on the locations where the expansion and SUHI is occurring. In the SUE algorithm, SUHI is calculated from the difference between the mean of the land surface temperature (LST) over the urban land use pixels, or the non-urban, non-water land use pixels. These two subsets of pixels are based on the urban extent dataset MODIS land cover classification (MCD12Q1.051) and the European Space Agency Climate Change Initiative (ESA CCI) land cover data.

To detect the variability of SUHI and extent of impervious surfaces within the Kampala urban cluster, change detection analysis was used to designate differences between images of the same area at different times. The change detection approach was applied intervals 2003 and 2017, which provides “from-to” change information and the type of change that has occurred can be easily calculated and mapped (Yuan et al., 2005). The change areas are illustrated using mosaic plot methods to provide a visual representation of SUHI intensity losses and gains and urban built-up expansion.

There are some limitations in our research that need to be acknowledged. First, we only discuss changes in SUHI, whether positive or negative. However, what might bring about the changes cannot be discerned in detail from our approach. Second, our results illustrate what might be expected from the expansion of urban areas, while there is relatively little detail on the actual urban surface cover or its characteristics through the methods used. Further considerations would include topography, morphology and biodiversity of the study cities (Guo et al., 2020; Yang, Wang,

et al., 2020). These features could be explained more by using alternative approaches, such as a local climate zone maps (Bechtel et al., 2019; Ng & Ren, 2015; Yang, Zhan, et al., 2020), which is our next step in this research.

3.3 Results

3.3.1 Historical patterns of urbanisation

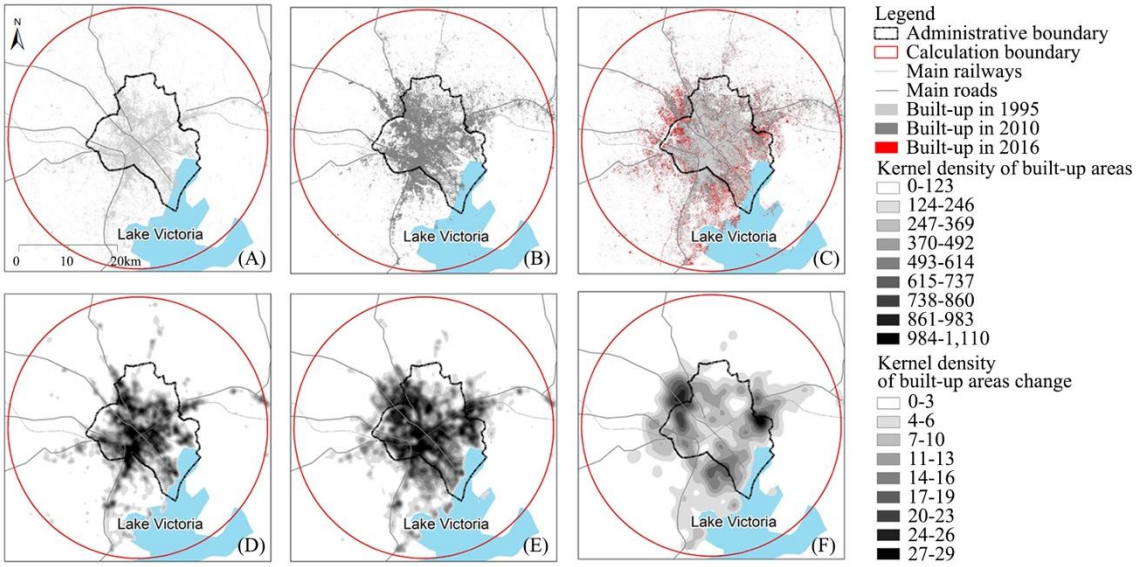

Figure 3.2 The built-up distribution of Kampala.

Built-up distribution in 1995 (a), 2010 (b) and 2016 (c); the built-up kernel density of Kampala in 1995 (d), 2016 (e) and the new built-up area in 2016 compared to 1995 (f) significantly or show strong evidence of infilling urbanisation developments. The classification method is natural breaks (Jenks), with nine classes and a white to black color scheme to point towards high (black) and low (white) point pattern densities. The highest point pattern densities represent the hotspots of city growth from 1995 to 2016, defined as compact growth within the city.

Between 1995 and 2016, Kampala underwent extensive changes to its urban built-up area (Figure 3.2). Urban land cover extended from the centre of the city to adjoining non-built-up areas in all directions, but in particular to the southwest, east, northwest and north along major transport corridors. The urban built-up area of Kampala was 25,389 ha in 2016, representing an average annual rate of increase of 6.9% since 2010. The urban built-up area in 2010 was 15,952 ha, increasing at an average annual rate of 1.8% since 1995, when its urban built-up area was 12,133 ha. In total, 13,256 ha of non-built-up land has been converted to urban land use. Different parts of the city experienced different patterns of development. Figure 3.2 (d, e, f) shows KD outputs for built-up areas in 1995, 2016 and the new built-up areas in 2016 compared to 1995, and their

default value, respectively. The central region consolidated over time and the eastern regions underwent relatively compact growth, while the southwest and western regions showed fragmentation followed by infill and expansion at the edge of the city. The northern and the peri-urban regions were the most fragmented, with scattered areas of urban land cover, indicative of leapfrog development.

3.3.2 Changes in land surface temperatures and SUHI effect

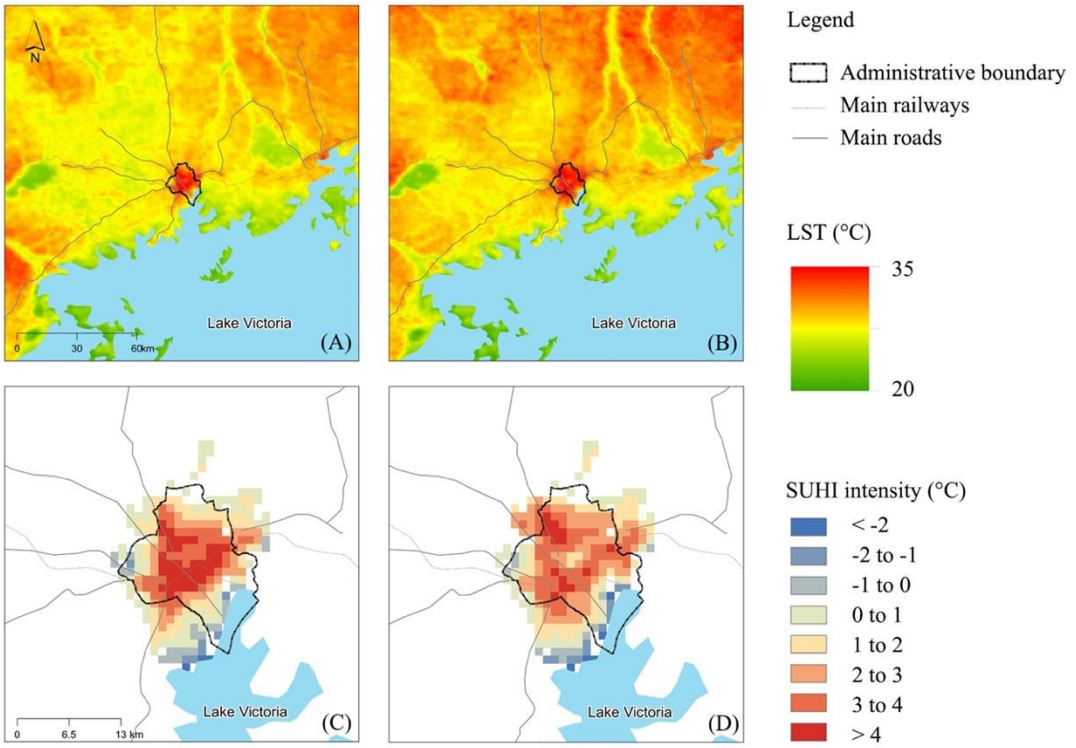

Figure 3.3 Average annual daytime temperature and SUHI intensity in Kampala.

Average annual daytime temperature in 2003 (a) and 2017 (b) for Kampala and the surrounding region. Annual daytime SUHI intensity of Kampala in 2003 (c) and 2017 (d).

In 2003, the annual LST within the Kampala urban cluster was 26.5 °C. This increased to 26.8 °C in 2017 (Figure 3.3). In both years, the built-up areas of Kampala were hotter than the surroundings, indicating a SUHI effect (Figure 3.3 c, d). In 2003, the annual daytime SUHI was 2.2 °C, and 1.9 °C in 2017. The SUHI intensity area expanded from 22,910 ha in 2003 to 27,900 ha in 2017.

The areas affected by SUHI expanded in two different ways that directly linked to patterns of urbanisation, namely (i) infilling areas that were already experiencing a SUHI, and (ii) extending SUHI into areas of the region that were previously unaffected. By 2017, SUHI intensification was spreading from the centre of the Kampala urban cluster towards the north, northwest and east. These areas were relatively unaffected by SUHI effects in 2003. At the same time, the intensity of the SUHI effect in the centre of the urban cluster dropped.

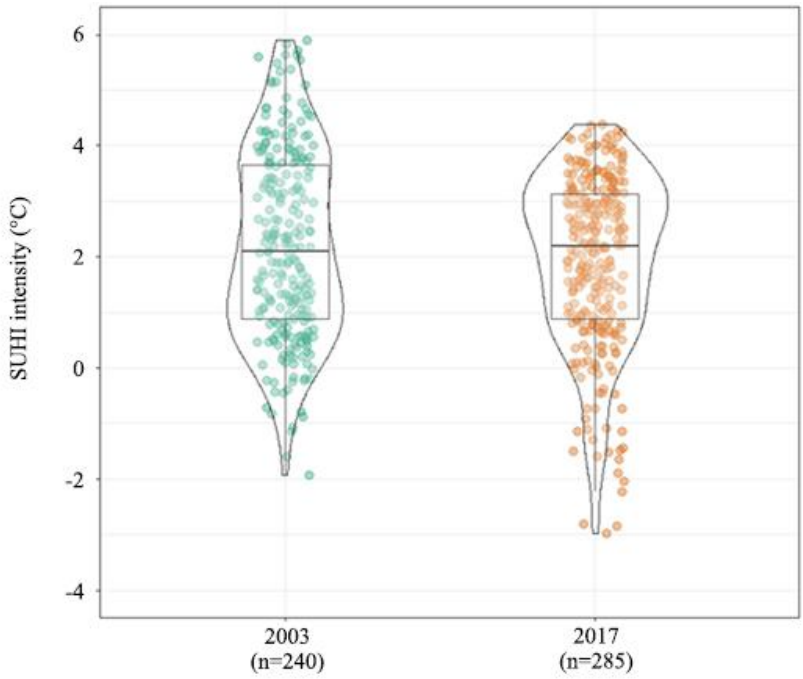

Figure 3.4 The distribution of built-up land cover within the Kampala urban cluster.

The violin plots (Figure 3.4) show the different distribution of daytime SUHI in 2003 and 2017 in the Kampala urban cluster (Patil, 2021). The widest width of the curve which indicated the peak frequency distribution located in the third quartile in 2003 moved to the first quartile with a longer tail in 2017. The changes in the violin plots could be explained by the difference spatial distribution of the SUHI between the two years. The frequency of SUHI value presents an overall rise (the peak of violin plot width), with more below negative SUHI outliers present (longer tail of the violin plot in 2017).

In 2003, the highest intensity of SUHI effect (5.9 °C) was in the centre of the urban cluster, this dropped to 3.9 °C in 2017. The mean annual LST also drop from 34.7 °C to 34.0 °C. The highest

intensity of SUHI effect in 2017 was 4.3 °C, and this was located in northwest of the urban cluster where in 2003 the SUHI was 4.4 °C. And the mean annual LST increased from 32.9 °C to 34.7 °C. In other words, the intensity of SUHI experienced in areas that were already affected in 2003 became less intense, but new areas, subject to even more intense SUHI effects emerged. Further, the southeast and east of the urban centre became cooler relative to the surrounding rural areas – and urban cooling effect. The largest cooling effect also shifted from the very south of the urban cluster (-2.0 °C in 2003, -2.8 °C in 2017) in 2003 to the south and south east (non-urban areas in 2003, -3.0 °C in 2017) by 2017. Annual mean LST of these two locations both increased in 2017, the former increased from 26.5 °C to 27.7 °C and the latter rose from 27.4 °C to 28.2 °C. The reduced SUH I and the cooling effect is likely due to the proximity of Lake Victoria.

Changes in SUHI intensity were spatially coincident with alterations in the distribution of built-up land cover within the Kampala urban cluster (Fig 3.5). Although patterns of change were similar, they were not totally synchronized. The areas exhibiting the greatest SUHI intensity change were towards the north and northeast of the urban cluster, but these parts of the city did not expand.

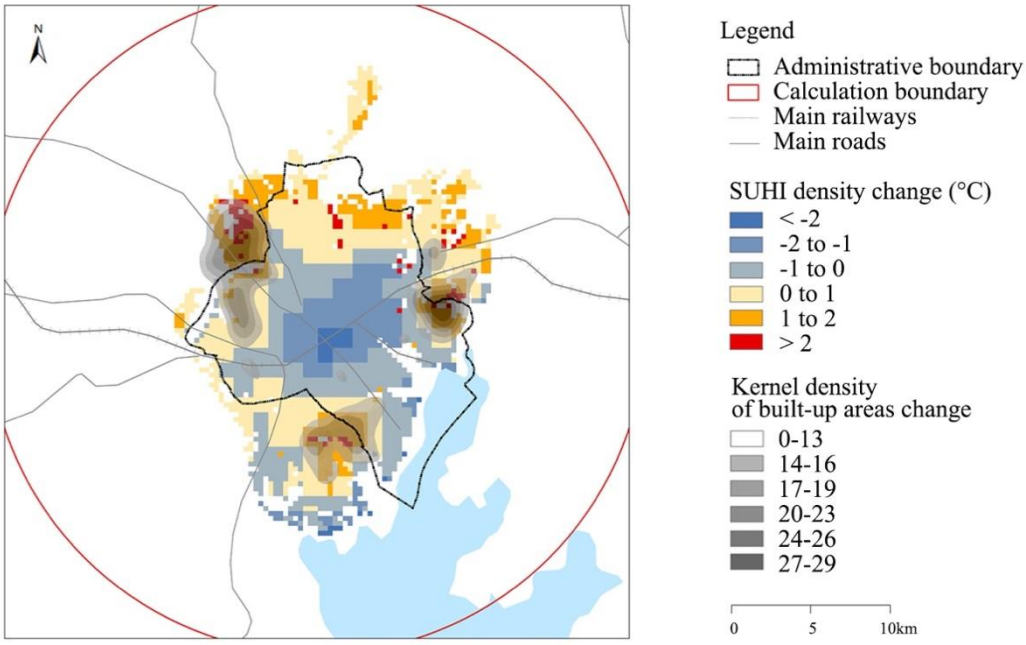

Figure 3.5 Daytime SUHI value distributions for Kampala urban cluster in 2003 and 2017.

The width of each curve corresponds with the approximate frequency of data points. There is a small box plot in the middle of each density curve, with the rectangle showing the ends of the first and the third quartiles and central line the median. The n value under the x-axis is the number of SUHI pixels.

3.4 Discussion

Kampala is situated on the northern shores of Lake Victoria, and has experienced exponential urban population growth since 1970 (Gasper et al., 2011; Mabasi, 2009; Vermeiren et al., 2012), largely influenced by rural-urban migration (Nyakaana et al., 2007). Fast urban population growth requires the construction of more infrastructure and the conversion of greater areas of land to coverage by built structures, such as buildings and sealed surfaces. We found that the spatial patterns of urbanisation in Kampala showed urban sprawl along radial corridors, such as major traffic lines from the city centre, as well as a more general spread around the edges of the existing urban areas (Amin & Stephen, 2012; Vermeiren et al., 2012). This is a very common phenomenon, both historically in high-income countries in the past (Hamidi & Ewing, 2014) and across many cities in Africa at present (Azócar et al., 2007; Douglas, 2018; Xu et al., 2019). The SUHI affected areas of the Kampala urban cluster also expanded concomitant with the urbanisation process. In particular, the relentless urban built-up land expansion at the expense of bluespace or green space (such as wetland, cropland and forest) has caused the SUHI effect to increase in certain areas of the city and its fringe (Douglas, 2018; Lin et al., 2018).

Such rapid urbanisation could increase the vulnerability of informal communities to natural hazards as green and blue spaces are converted to build uses. Over 60% of the population live in informal settlements in Kampala (Lwasa, 2009), and many of these unplanned developments occur in low-lying areas which are vulnerable to natural hazards (Amy Richmond, 2018). Green and blue spaces can provide important climate change mitigation services, such as carbon sequestration and shade through presence of trees in greenspaces, so their loss has important implications.

As in many other cities, rapid urbanisation in Kampala is characterised by poor and vulnerable groups moving into large informal settlements (Amy Richmond, 2018; Kahangirwe, 2012). In these parts of the city, SUHI was exacerbated, perhaps caused by the presence of informal settlements in peri-urban areas that create densely built-up sites. Houses in informal settlements are often poorly constructed, which means that many are unlikely to withstand climate impacts and lack adequate air circulation or insulation, which is particularly threatening for vulnerable

groups during heat waves (He, Wang, et al., 2021; Mark et al., 2013). Even these SUHI intensity changes do not provide direct evidence of the unprecedented challenge of human health, wellbeing and economic development (Martilli et al., 2020). Such transformations could enhance the vulnerabilities of informal communities in this climate and environmentally sensitive area. Indeed, the 50-year flood zone map developed by World Bank Group (Rentschler et al., 2019), suggests the high risk flooding areas in Kampala are largely located in middle and low employment density areas, which overlap with emerging SUHI intensity and urban built-up sprawl areas identified in the present study.

In contrast, in the south east of the city, near Lake Victoria, SUHI is negative, and the intensity of SUHI has decreased over time. This is likely to be due to the urban breeze effect, which will have been strengthened as the urban area changed. Former studies have highlighted the importance of lake breezes resulting from the thermal contrast between land and water surfaces (Brousse, Wouters, et al., 2020a). Urbanisation can impact the intensity of the main wind flows, either increasing or decreasing its intensity (Brousse, Wouters, et al., 2020a; Roth, 2000). Also, changes in city roughness could impact lake breezes, and modulate wind velocities (Roth, 2000).

The interaction between the global phenomenon of climate change and the local phenomenon of the SUHI effect (Santamouris et al., 2019), driven by an accelerating urbanisation path is creating a potentially dangerous heat stress risk that is expected to increase. However, in most East African cities, the problem of SUHI has received less attention, as planners instead put emphasis on water management and flood control in city development plans (Bakibinga-Ibembe et al., 2011; He et al., 2019; Li et al., 2016). Since there is a close connection between these two phenomena of flooding and SUHI (Richards & Edwards, 2018), extra warming caused by SUHI may lead to greater upward motion and turbulence of the air, which in turn induces precipitation (Han et al., 2014; Richards & Edwards, 2018). Urban surface roughness, and the presence of aerosols from air pollution can also induce precipitation (Han et al., 2014; Richards & Edwards, 2018). There has therefore been a growing recognition that both flooding and SUHI need to be tackled together (Richards & Edwards, 2017), and efforts to mitigate the SUHI effect are gradually becoming an increasing priority in city planning (Brousse, Wouters, et al., 2020c).

For the Kampala urban cluster, one study has suggested that sustainable urban development should use restrictive urban planning measures to stop wetland encroachment, developing satellite towns to secondary urban hubs, and building a more structured metropolitan area (Vermeiren et al., 2012). In the meantime, contributions of greenspace and bluespace to urban cooling should be considered in Kampala's urban future development. Greenspace and bluespace (e.g., green roofs, green alleys and streets, urban forests, parks, gardens, wetlands) are often highlighted as providing significant ecosystem services: improving residents' health and wellbeing, providing food, lowering wind speeds, reducing storm-water run-off, modulating ambient temperatures, reducing energy use and sequestering carbon (Hathway & Sharples, 2012; Völker et al., 2013a). Bluespace and green space can mitigate the SUHI effect, providing cooling benefits, important for reducing energy consumption and improving human health and well-being (Gunawardena et al., 2017; Thomas & Elavinamannil, 2011). Research has suggested that tree dominated greenspace offers greater heat stress relief while improperly designed bluespace may exacerbate heat stress (Gunawardena et al., 2017). To address the SUHI effect in Kampala, a collaborative effort between scientists and urban planners to devise contextually relevant strategies is needed (Corburn, 2009).

Related impacts can be anticipated from urban development combined with potentially more frequent occurrences of extreme climatic events such as heat stress and flooding (Richards & Edwards, 2018). Kampala is located in a tropical rainforest climate zone (Köppen climate classification) with two dry seasons per year (December to February and June to July). SUHI exacerbation in this area during the dry season has been detected by previous research (Kabano, Harris, et al., 2021). Urban residents in the most built-up parts of the urban areas are the most vulnerable to heat stress, as well as heat-related health complications (Chapman et al., 2017). Accompanied with rising poverty, and vulnerability of the urban poor to these impacts, these combined issues are bringing about greater awareness for the need to sustainably mitigate and adapt to climate change risks (Corburn, 2009; Mark et al., 2013). Increased temperature combined with flooding has introduced health challenge and caused a surge in disease outbreaks of malaria, dysentery and cholera since 1997's El Nino oscillations (Lwasa, 2010; Twinomugisha et al., 2008). To cope with these, basic urban infrastructure such as drainage, supply of sanitation and water are

required and need to adequately maintained (Lwasa, 2010). To enhance adaptive capacity, more equitable and adequate access to basic urban infrastructure should be a priority for poorer communities (Van Aalst et al., 2008). In addition innovative community-based adaptations coupling climate change impacts and poverty reduction have proved effective (Moser & Satterthwaite, 2010), including domestic energy briquettes from waste, productive greening and urban agriculture, as well as household-level rainwater harvesting and nutrient recycling from waste (Jerneck & Olsson, 2008; Lwasa, 2010).

The growth of cities will inevitably continue and successfully managing city growth will be critical to economic development and social stability (He et al., 2019). Climate change and its impacts cannot be tackled by a single solution that is universally applicable. Since 2015, Uganda government has been adopting explicit National Urban Policies (NUPs) for coordinated policy responses to enhance sustainable urban growth in line with Sustainable Development Goal (SDG) 11 and the New Urban Agenda (NUA). For instance, Uganda's NUP highlights that: "*The SDGs provide an opportunity for Uganda to bring all stakeholders together to decide and embark on new paths to improve the lives of people in urban areas, and to make cities and human settlements inclusive, safe, resilient and sustainable by creating mechanisms to ensure good urban governance*" (Uganda, 2017). Even though governments are becoming more sensitive to the threats and opportunities posed by the process of rapid urbanisation (Bandauko et al., 2021), identifying appropriate implementation pathways to achieve the policy aspirations is still a challenge, as NUPs remains high-level policy expressions, with little impact in practice (Turok, 2015). NUPs are conducive to but not sufficient to achieve sustainable cities (Hohmann, 2017), and require concrete action plans and tools to enforce practical actions on the ground (Bandauko et al., 2021).

The urban design approach will need to vary according to the humidity and the amount of ventilation needed (He, 2018; Ng & Ren, 2015), as climate change and urbanisation not only affect the land and lake breezes over the Lake Victoria region but also alter the urban humidity (Brousse, Wouters, et al., 2020a). In particular, the enhanced surface temperatures associated with UHI can actually result in shorter vegetation growing seasons; a contrast with results reported for temperate cities (Kabano, Lindley, et al., 2021). SUHI mitigation strategies using bluespace and

green space could potentially realise synergies for SUHI mitigation and urban flooding (He et al., 2019), as well as support adaptation to climate change (Matthews et al., 2015). The possibility of harnessing both mitigation and adaptation benefits from bluespace and greenspace opens up a 'window of opportunity' to achieve climate compatible development, by simultaneously realising double- or triple-wins (Broto et al., 2015; Ryan-Collins et al., 2011).

3.5 Conclusions

This study tracked the dynamics of annual SUHI intensity in the Kampala urban cluster, Uganda, and their response to urban built-up area changes over the period 2003–2017. We extracted the urban built-up area using GEE for the study area between 1995 and 2017, then explored the SUHI growth patterns and their responses to the urbanisation processes. We used Global Surface SUHI Explorer for retrieval of annual daytime SUHI intensity to reduce uncertainties in SUHI estimation and to investigate the long-term variability of the SUHI (Chakraborty & Lee, 2019). Our analysis allowed us to reach the following conclusions:

The expansion of SUHI effect areas and urban built-up areas in Kampala urban cluster is substantial in the study period. The main increment of SUHI effect areas in 2017 appeared in the peri-urban parts of the study area, accompanied with SUHI effect mitigation in the urban cluster centre. In particular, SUHI in Kampala occurred as a spatial process of diffusion and coalescence, originally being located around the urban cluster centre, and subsequently stretching across previously unaffected areas, and detracting from the centre.

The SUHI effect areas of Kampala urban cluster show expansion concomitant with the urbanisation process. Relentless expansion of urban built-up land at the erosion of bluespace or greenspace (e.g., wetland, cropland and forest) has caused the SUHI effect impacted areas to be dramatically expended. The fast urbanisation could enhance the vulnerabilities of informal communities with the loss of bluespace and greenspace in rural and peri-urban areas, particularly where strong institutions for risk management are lacking.

Kampala is one of the most populated cities in GLR region, and is growing in a fragmented-complex way (Lemoine-Rodríguez et al., 2020), with urban expansion partly accompanied with

densification (X. Li et al., 2021). Fast urbanisation and climate change accompany complex and changing land-lake-atmosphere interactions, requiring city planners and policy makers to carefully determine the direction of their urban growth strategies and consider the cooling effect provided by greenspace and bluespace. Efforts should be more targeted to ensure that they optimise the health and wellbeing of vulnerable inhabitants by maximising ecosystem services, as well as utilising collaborative approaches involving different groups of stakeholders (Guenat et al., 2021).

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Chapter 3 provided insights into the urban thermal environment and SUHI change related to the development of built-up urban regions, urbanisation patterns, and changes in gains and losses of BGI. The findings showed that the SUHI reduced in the city centre in Kampala, probably as a result of the increase of green space there. The temperature differences decreased as a consequence of rising temperatures outside the city centre. Geographical variables, in particular the southern region of Kampala near Lake Victoria and interactions with its lake breeze, helped to explain the findings. The reduced SUHI intensity in locations close to Lake Victoria is due to the thermal differential between the hotter, built-up land in cities and the cooler, lake surface. These places of convergence increase the lake breeze. The significance of geographic features and whether additional water bodies of various sizes and locations can provide a similar cooling effect deserve further study. With regard to other important factors, the relationships between urban configuration, urban thermal environment and vegetation indices, are discussed in Chapter 4.

Chapter 4: The role of blue green infrastructure in the urban thermal environment across seasons and local climate zones in East Africa

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Abstract: Rapid urbanisation and climate change are two major trends in Africa in need of further investigation. In this paper, the urban thermal environment and vegetation abundance in four East African cities (Khartoum, Addis Ababa, Kampala and Dar es Salaam) were characterised, providing new insights into the role and potentials of blue green infrastructure in differing climate regions. The Local Climate Zone (LCZ) framework was employed to detect the seasonal Land Surface Temperature (LST) and Enhanced Vegetation Index (EVI) derived from Landsat-8 data. Significant LST differences between LCZs in dry and rainy seasons were confirmed using a Welch's T test. The LCZs were found to offer potentially new approaches to investigating issues pertaining to urban heating in data-scarce regions. Higher LST during the dry season was detected in all study cities via paired sample tests. Greater surface urban heat island (SUHI) intensity during the rainy season was apparent in Khartoum and Addis Ababa, emphasising the importance of seasonality in urban thermal studies. Spatial correlations between EVI and LST within each LCZ were analysed through Moran's I and further illustrated the complex relationships of vegetation and thermal behaviour in urban areas. Despite these complexities, urban blue green infrastructure was found to moderate the SUHI, with different types of intervention required across different LCZs.

Keywords: Surface urban heat island; Enhanced vegetation index; Blue green infrastructure; Green infrastructure; Climate change; urbanisation; Thermal environment

4.1. Introduction

Urbanisation and climate change are two of the most important trends influencing global development (Rogers, 2012). The global population living in urban areas is expected to increase from today's 55% to 68% by 2050 (United Nations, 2019). The fastest rates of urbanisation will occur in the least developed regions of Asia and Africa (United Nations, 2019). Cities serve as engines of change, dominating economic progress, and offering the potential to pull more people out of poverty (Demuzere et al., 2021; Rogers, 2012). Meanwhile, challenges in natural resource management exacerbated by climate change in rural areas can act as a push factor, causing people to move into cities. Despite potential economic advantages of urban living, many who move to urban areas are at risk from various environmental and social challenges, particularly as the climate changes and more of the urban population is exposed to heat stress (He, Zhao, et al., 2021; Van de Walle et al., 2022a).

Burgeoning urban populations require more land for housing and infrastructure (Boke-Olén et al., 2017; Omumbo et al., 2005), driving land use/ land cover transformation. Large amounts of natural surface are replaced by impervious surfaces, changing the patterns of biodiversity and ecosystem services in different ways across different climate zones and contexts. One of the most significant challenges is transformation-induced climate alteration; in particular, the urban heat island (UHI) effect. UHI refers to the temperature difference between an urban area and its surrounding rural area (Oke, 1982). UHI is caused by development and modification in urban infrastructure (He, 2019), in areas where higher proportions of impervious surface store more heat and restrict natural radiative cooling potentials (Gunawardena et al., 2017; Kabano et al., 2021). UHI intensities are influenced by the local micro-climate, with important factors including urban morphology, biome, meteorological conditions, presence or absence of water bodies and vegetation cover (He, et al., 2021; Imhoff et al., 2010; Li et al., 2021). As the climate changes and urbanisation proceeds at pace, it is important to understand differences in these relationships across different cities and climate zones.

A lack of climatological observations and urban cover/use information has previously restricted the number and quality of systematic studies for African cities (Brousse et al., 2019; Brousse et

al., 2020b). This impediment has been gradually overcome by improved high-resolution remote-sensing data and enhanced modelling capacities (Brousse et al., 2019). Furthermore, observational approaches to investigating temperature heterogeneity between urban surfaces have improved through development of the concept of local climatic zones (LCZ). The LCZ framework provides a uniform and generally recognized classification of urban cover/use that allows the comparison of cities in terms of urban form and urban function (Geletič et al., 2019; Stewart & Oke, 2012). The LCZ framework classifies urban areas into 10 “built” and 7 “land cover” types, with a LCZ type defined as a region that is uniform in properties of surface cover, structure, material, and human activity. Each LCZ type characterises a particular surface thermal climate (Stewart and Oke, 2012). LCZs have now been generated for cities globally (Bechtel et al., 2015; Ching et al., 2018), becoming a new standard for characterizing urban landscapes (Zhao et al., 2021), particularly following further simplification of the process of LCZ classification with the LCZ Generator (Demuzere et al., 2021). LCZs may offer the potential to better understand the role of blue and green areas within the landscape and their moderation of SUHI effects. Nevertheless, this has not yet been fully explored. This paper takes up this challenge and provides novel empirical insights that can guide planners on the use of blue green infrastructure (BGI) in different LCZs.

Although LCZ classification has been used in some African cities to study UHI (Ochola et al., 2020), vegetation growing season length (Kabano et al., 2021) and urban health issues (Brousse et al., 2020b), existing studies tend not to focus on the urban thermal environment in Africa there. Nor do studies consider the role of blue green infrastructure (BGI) in shaping thermal outcomes in different LCZ, while few take a comparative approach encompassing multiple cities in different climate zones within Africa. Indeed, land surface temperature (LST) variations among LCZ types are less studied under different microclimatological conditions in Africa, compared to land cover types within a single city, which have gained a lot of attention in the UHI literature (Geletič et al., 2019).

The main aim of this study is to examine the suitability of the LCZ classification for urban thermal studies under varying microclimatological conditions in different climate zones in Africa and to assess the role of BGI in explaining any thermal differences with a view to informing planning.

By doing so, we advance knowledge into the role of BGI in the urban thermal environment within different LCZ. We address the following questions: (i) Does using LCZ classifications bring new understanding to quantifying UHI effects in African cities? (ii) How do LST and SUHI within LCZs change seasonally, and are seasonal variations similar between cities with different climates? (iii) What is the relationship between LST and EVI within LCZs in different seasons? (iv) What is the potential for the retention, restoration or construction of BGI to mitigate SUHI, and how does this potential vary in different cities and LCZ?

4.2 Method

4.2.1 Study areas

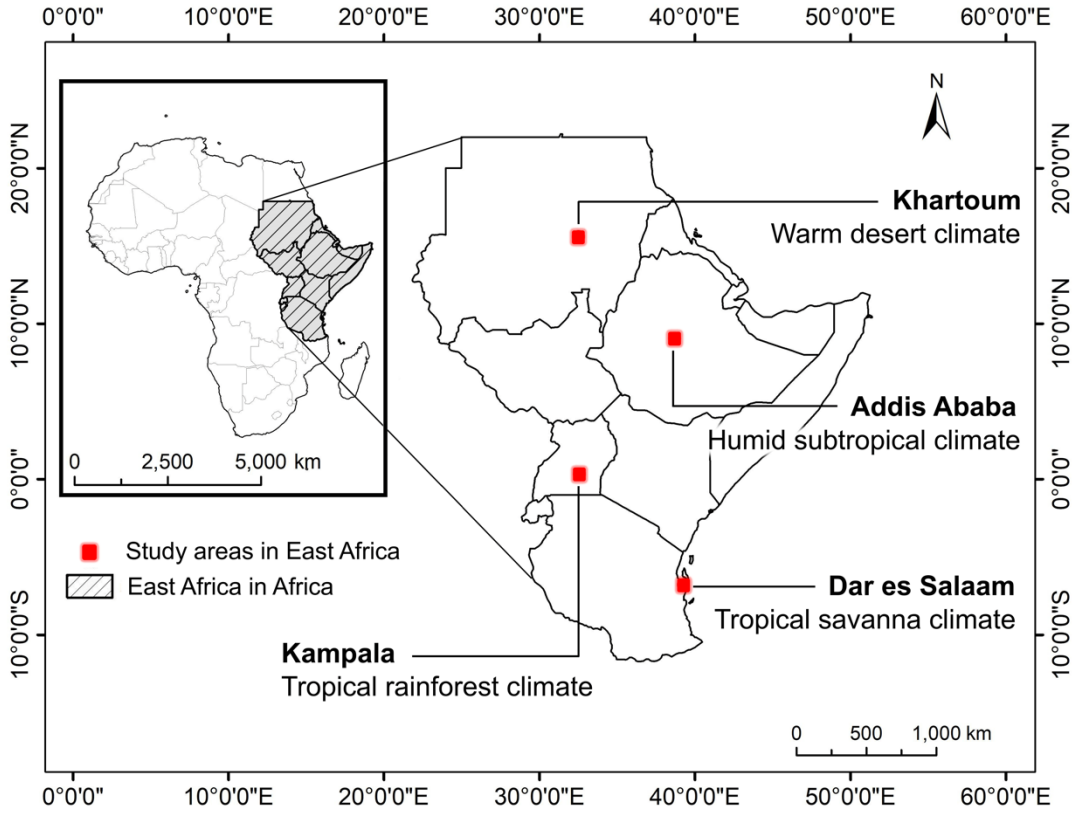

Figure 4.1 Location of study cities in East Africa, with their climate zones.

Four cities in East Africa across different climate zones (Köppen classification): Khartoum, Addis Ababa, Kampala, and Dar es Salaam, were selected in this study (Figure 4.1). In general, these cities could be considered as the engines of their respective country's economy and social

development, and thus their rapid urbanisation could be expected to result in increased UHI intensity. The largest city in 2021 in terms of permanent residents among the study cities is Dar es Salaam (6.21 million), followed by Khartoum (5.99 million), Addis Ababa (5.01 million), and Kampala (3.47 million). These cities are characterised by highly fragmented vegetation surrounded by dense residential, commercial, and industrial areas. Further, the cities vary in the type and length of seasonal variations in temperature and rainfall that they experience, allowing us to explore seasonality in more depth (Borhara et al., 2020; USAID, 2020).

4.2.2 Data sources and analysis

4.2.2.1 LCZ classification

To reflect the spatial continuity of the urban built-up area outside the administrative boundaries (Lemoine-Rodríguez et al., 2020), we mapped the urban area boundary from Copernicus Global Land Cover Layers: CGLS-LC100 Collection 3 (Copernicus, 2021), downloaded via Google Earth Engine and processed in ARCGIS. Informal settlements, river channels and wetlands etc. were retained within the urban area boundary.

Following the “Guidelines for Digitizing Training Areas” and the WUDAPT LCZ classification method (Bechtel et al., 2015; World Urban Database and Access Portal Tools, 2021), we digitised the training areas and mapped the LCZ for the study cities. Due to the cloud contamination across different times in different cities, the comparatively clear and distinct year of 2018 was selected as a representative year. Based on previous LCZ research in Africa (Bechtel et al., 2016; Brousse, Georganos, et al., 2020; Kabano, Lindley, et al., 2021; Ndetto & Matzarakis, 2015), the most common LCZ classes were selected in each city. Depending on the area covered by each LCZ class and the feasibility of digitisation, the number of training samples per LCZ class ranged between 20 and 100. The overall process involved: (i) selecting and creating the training areas in Google Earth, (ii) submitting the training areas into the LCZ generator and getting results, (iii) using the results to revise the training areas, resubmitting and improving the accuracy to 70% or above in the final output. Representative aerial image in each LCZ class across different cities are presented in Figure 4.2 and Figure 4.3.

Figure 4.2 Representative aerial image in each LCZ class (built-up LCZ) across different cities.

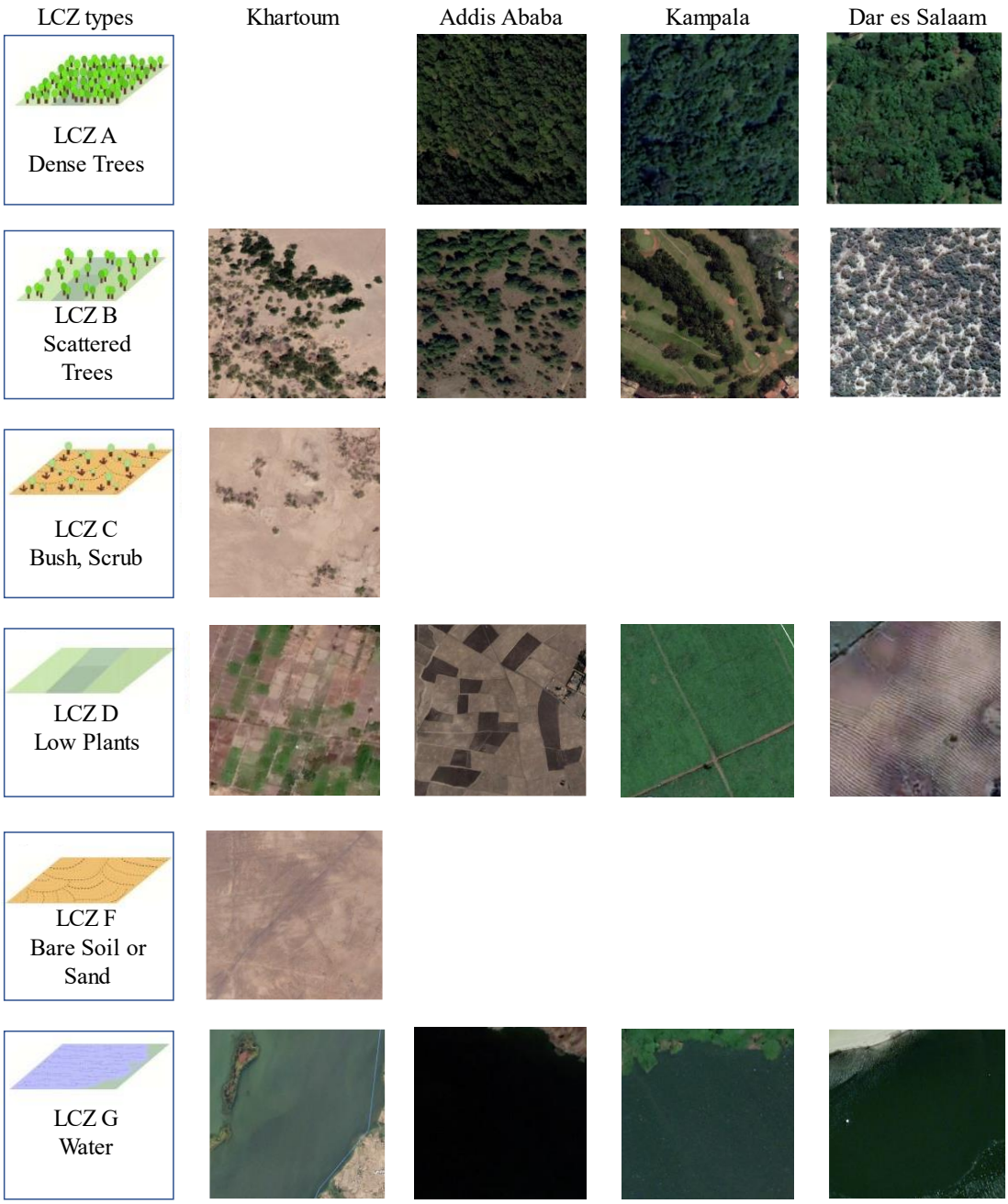

Figure 4.3 Representative aerial image in each LCZ class (natural LCZ) across different cities.

4.2.2.2 LST/SUHI processing and relationship within LCZs

Rainy and dry seasons were defined based on previous research in East Africa (see supplementary document 2). When mapping LST across different regions, finding clear images especially for the rainy season can be challenging. Cloud cover can mean that many Landsat tiles are required. To select the optimal images, we masked out cloud and shadows from the images using pixel_qa band to get the 3-year periods' seasonal image collection for each city considering the years 2017, 2018 and 2019. We used the ee.Reducer and ee.ImageCollection.median of Google Earth Engine (GEE) to produce a cloud-free composite image from image collection (Google Earth Engine, 2022), for each season for each study city. Temporal aggregation and time series composition are two composition methods that have been widely used in multi-temporal Landsat images to reduce contamination by cloud and other problems (Phan et al., 2020). Time series composition involved a composition of cloud free images in a time series, while the temporal aggregation method used the metrics (e.g., median, mean and min/max) derived from time series images. Pre-processing in traditional time series composition methods requires significant storage capacity and access to high power computing (Phan et al., 2020). Recent advances in the temporal aggregation method significantly reduces data volume and generates data of equally high accuracy (Flood, 2013; Frantz et al., 2017; Phan et al., 2020). Nevertheless, despite being widely used in recent research (Chen et al., 2021; Richards & Belcher, 2020), one major disadvantage of this method is that composite images from multi-year data produce land cover maps with lower accuracy than those from a single year, due to land cover change and loss of phenological consistency (Frantz et al., 2017). While a common strategy for generating an annual cloud free composite is to use images acquired over three years (Hu & Hu, 2019; Nyland et al., 2018; Xie et al., 2019), this research tried to capture the temporal variability on a seasonal time scale, so this challenge was avoided but phenological consistency was retained. Three years (2017, 2018, 2019) of satellite imagery over the dry and rainy seasons were composited to produce composite images representing the desired period (Flood, 2013).

Based on the USGS formulas (USGS, 2021b), the LST for the study areas was derived using the Mono-Window Algorithm (MWA) from Landsat data following five steps (Qin et al., 2001): (i) using the TIR band 10 to estimate brightness temperature; (ii) calculation of the Normalized

Difference Vegetation Index (NDVI); (iii) obtaining proportional vegetation from NDVI values; (iv) calculation of land surface emissivity; and (v) calculation of the LST.

With the hypothesis that each LCZ class represents a distinct thermal characteristic (Stewart & Oke, 2012), we compared LCZ and LST. Firstly, the LSTs obtained from GEE and LCZ classes retrieved from the LCZ-generator were analysed in ArcGIS. As our data did/did not conform to the assumptions of ANOVA (Levene's test, p-value < 0.05) we ran Welch's t tests to detect the significance of the difference between LST and LCZ groups and then a post hoc Games-Howell test to determine which group caused the difference when the variances were not equal. The spatial distribution and variability of LSTs within LCZ classes were demonstrated in boxplots (See section 4.3.2, Figure 4.4.).

To investigate the seasonal variation of the SUHI in different LCZ classes, the SUHI intensity is defined as the difference between the LST value of a LCZ type when compared with LCZ D (low plants) (Bechtel et al., 2019; Stewart & Oke, 2012). The formula for calculating SUHI intensity is as follows (Stewart & Oke, 2012):

$$SUHI_{LCZ_x} = LST_{LCZ_x} - LST_{LCZ_D}$$

Where LCZ_x represents a LCZ in study city, $SUHI_{LCZ_x}$ is SUHI intensity in LCZ_x, LST_{LCZ_x} is LST value in LCZ_x, and LST_{LCZ_D} is LST value in LCZ D.

4.2.2.3 EVI processing and correlation with LST within LCZs

We chose the Enhanced Vegetation Index (EVI) for characterising vegetation abundance as it retains sensitivity to the density of urban vegetation and also minimises canopy background variations (Kabano, Lindley, et al., 2021). EVI was calculated following USGS approaches (USGS, 2021a). The spatial variability influence of EVI on the performance of LST was analysed through spatial correlations between different study cities in the rainy and dry seasons. Through

Geoda 1.20, the bivariate Moran's I function was used to represent the overall spatial correlation between seasonal LST and EVI within each LCZ class for the study cities (Anselin, 1996, 2020).

4.3. Results

4.3.1 LCZ classification

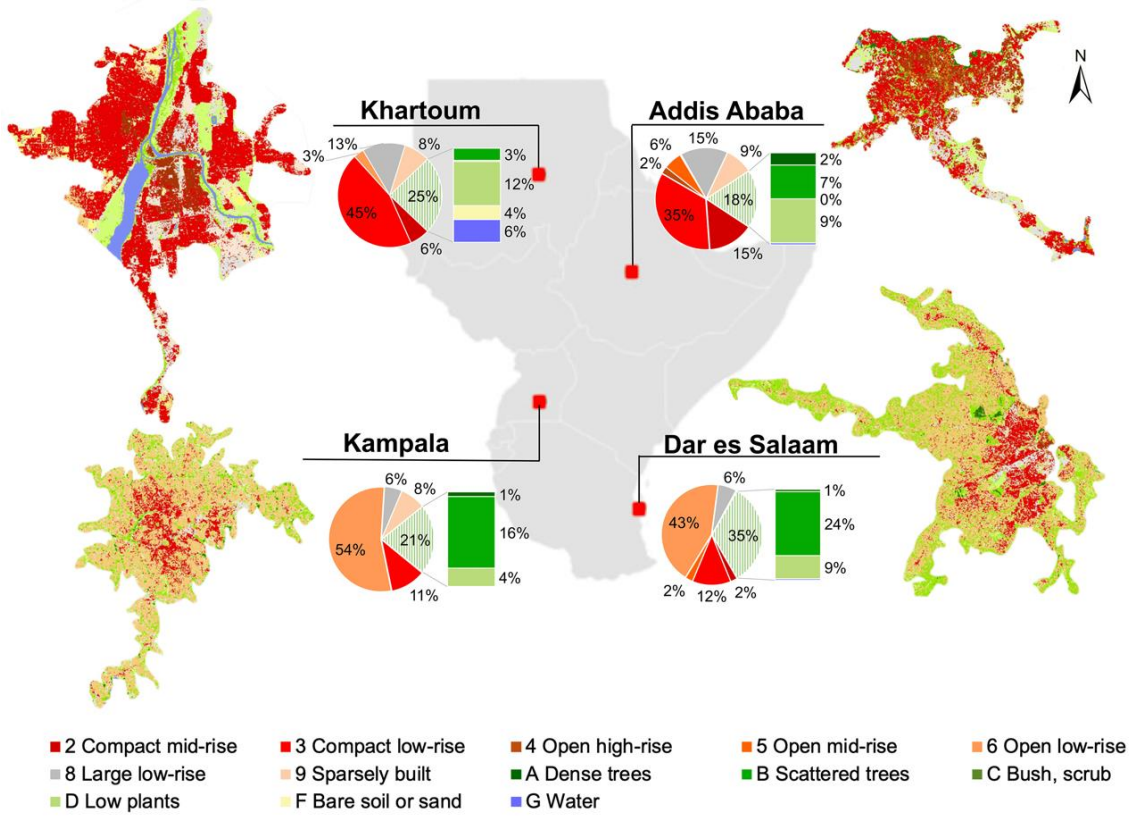

Figure 4.4 LCZ maps for four study cities.

The original LCZ documents (training area information and accuracy) are provided in supplementary document 2.

LCZ maps (Figure 4.4) capture the morphological characteristics and the percentage of different LCZs across the four cities. Across all cities, the total areas of the built-up LCZs (LCZ 1-10) accounted for more than 50% of their area. Khartoum has the largest urban area among all the study cities. The urban area is dominated by compact commercial areas (LCZ 2) while residential areas (LCZ 3) have connected with adjacent cities, namely Khartoum North and Omdurman.

These three cities have been integrated into a large urban cluster with no obvious boundary. The vegetation in southern Khartoum is dominated by low plants (LCZ D) while the northern and north-western Khartoum megaregion are mainly bush and scrub (LCZ C).

The city centre and central business district in Addis Ababa are highly dense and compact so they are mainly classified as LCZ 2–4. There are also many isolated built-up areas in the southwestern part of Addis Ababa, which are mainly compact residential areas (LCZ 2) and factories (LCZ 8). This explains why the large low-rise LCZ account for 15.11% in Addis Ababa.

The LCZ map of Kampala indicates that residential areas with green infrastructure (LCZ 6) occupy most urban areas. A compact commercial centre (LCZ 2) and compact residential area (LCZ 3) are concentrated in the central downtown area. The rest of the areas are mostly classified as factories and sparsely built-up areas (LCZ 8 and LCZ 9). Scattered trees and farmland are interspersed in the urban areas. The total area of compact mid-rise and compact low-rise in Kampala accounted for only 0.13% and 10.90%. However, the open low-rise (LCZ 6) accounted for 54.18%.

A commercial centre (LCZ 2) and compact residential areas (LCZ3) are also found in Dar es Salaam. In addition, continuously connected factories are located in central and south-eastern areas. Scattered trees (LCZ B) accounted for 23.5% of the land area, an amount substantially greater than in Khartoum (3.05%), Addis Ababa (6.77%), and Kampala (16.23%).

4.3.2 LST and SUHI analysis

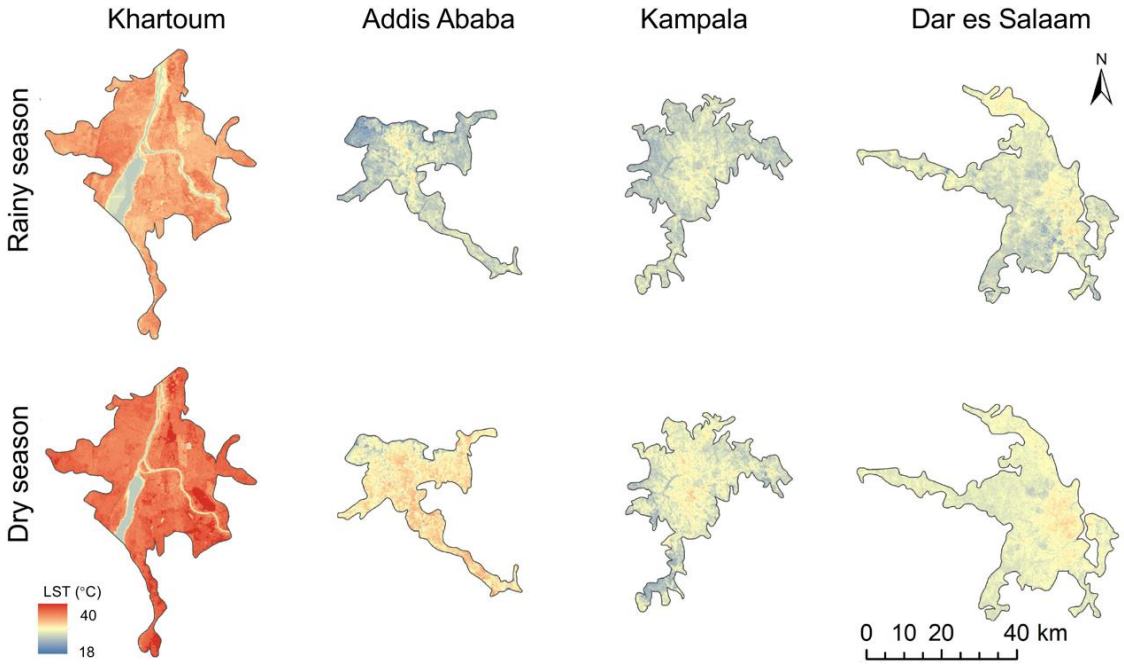

Figure 4.5 The spatial distribution of LST in the rainy (top row) and dry (bottom row) seasons.

As shown in Figure 4.5, Khartoum's LST varied between 23.9 °C and 40.3 °C in the rainy season, while in the dry season, LST varied between 26.5 °C and 38.6 °C. LST in Addis Ababa ranged from 13.1 °C to 33.0 °C in the rainy season, and from 17.4 °C to 35.5 °C in the dry season. For Kampala, LST varied from 19.4 °C to 30.9 °C in the rainy season, with this range expanding to 17.8 °C and 33.0 °C in the dry season. LST in Dar es Salaam was from 13.4 °C to 32.4 °C in the rainy season, and from 21.5 °C to 32.4 °C in the dry season.

For crosswise comparison among the LCZs, LST for all LCZ types in different season was evaluated with the Welch's one-way ANOVA test (Figure 4.6). In addition, each LCZ type in different seasons was compared by a paired sample test (Figure 4.6). The Welch's test results confirm the statistical significance of variances ($p < 0.00$) for all study cities in different seasons. The Games–Howell post hoc test was used for pairwise comparisons of mean LST value to identify their significant differences between LCZs (Figure 4.7). Games-Howell test results indicate significant LST differences were observed in most LCZs during rainy and dry seasons.

For the four cities considered in the research, the LSTs in the dry season are higher than in the rainy season, except for LCZ G (water) in Addis Ababa and Kampala. The LST of urban built-up

LCZ classes (LCZ 2-9) was generally above that of the land cover classes (LCZ B-G) (Figure 4.6). The differences in mean LST value across LCZ types varied greatly with the seasons. Even though there were relatively large variations in LST across different LCZ types, the general LST pattern was found to be similar during rainy and dry seasons. In particular, dense trees and water showed the coolest mean LST, and compact mid-rise buildings and large low-rise building presented more significant deviations from the mean LST for both seasons.

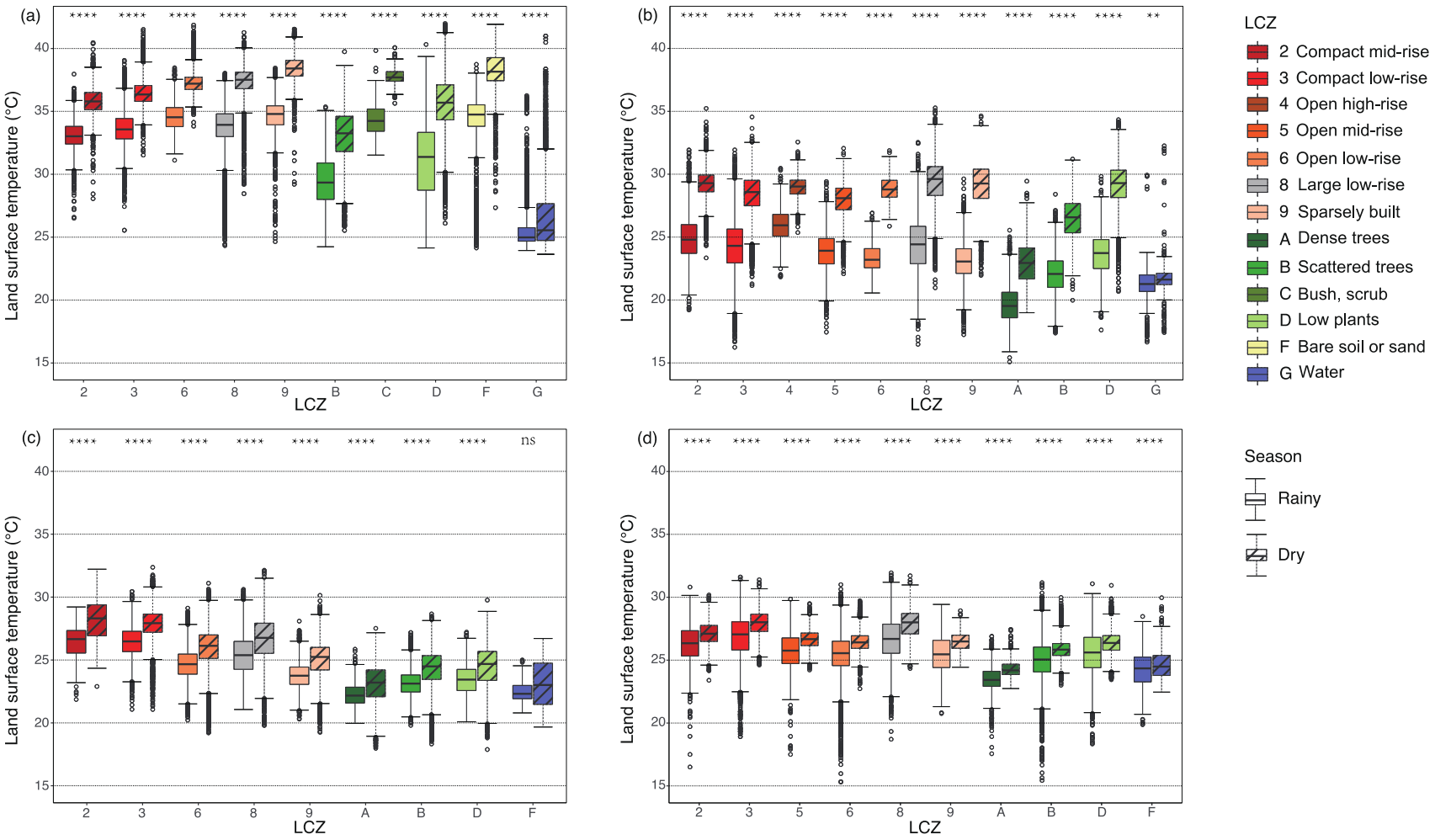

Figure 4.6 Boxplots of the LST distribution in different LCZ in different cities.

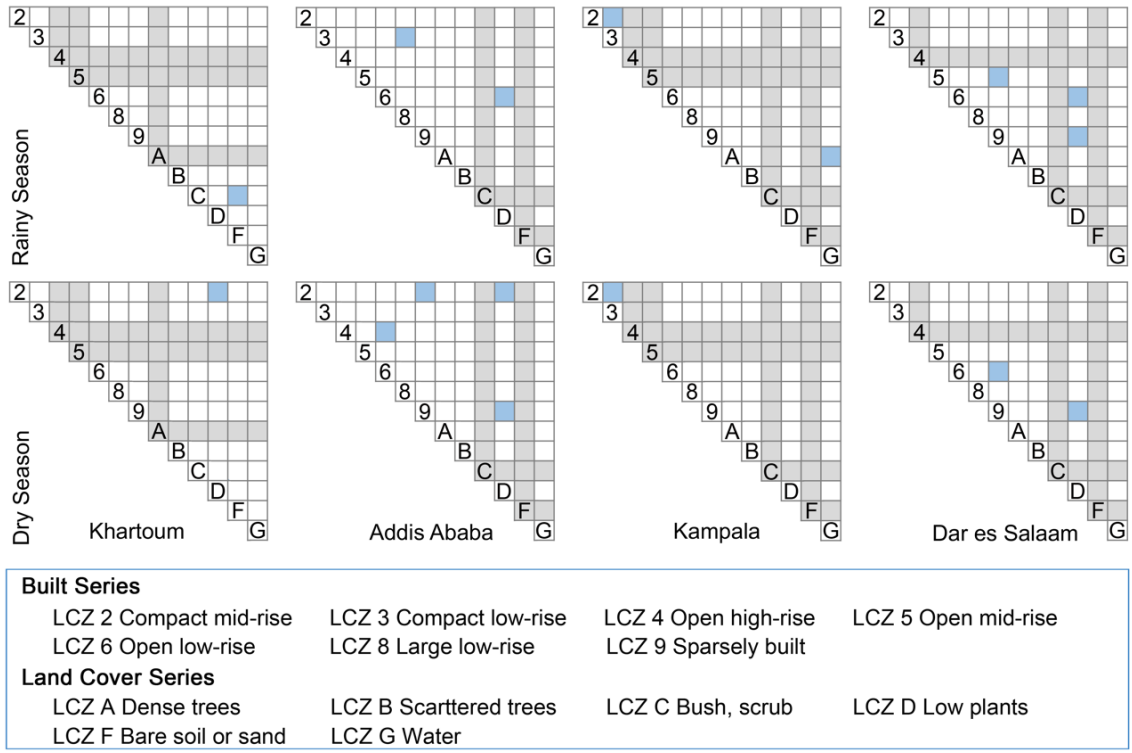

Figure 4.7 The Games-Howell test results of differences in the LSTs between LCZ types.

Grey squares represent non-representative LCZ classes, white squares stand for significantly different classes ($p < 0.05$), and blue squares represent LCZ pairs whose are not significantly different ($p > 0.05$).

In Khartoum, there are large variations in SUHI across LCZ classes, and greater differences can be observed in the two seasons. In Khartoum, sparsely built areas (LCZ 9) during the rainy season have the highest SUHI (3.7 °C) among the built-up LCZ classes, followed by open low-rise built-up areas (LCZ 6) and large low-rise built areas (LCZ 8), with mean SUHI of 3.6 °C and 2.8 °C respectively. Scattered trees (LCZ B) and water (LCZ G) show the opposite trend in the two seasons with -1.6 °C and -5.6 °C mean SUHI. The pattern of SUHI in the dry season in Khartoum is similar to that of the rainy season: the highest SUHI was observed in LCZ 9 with 2.7 °C, with areas of scattered trees (LCZ B) and water (LCZ G) presenting stronger cooling by -2.7 °C and -9.2 °C.

Addis Ababa also has a higher SUHI intensity in the rainy season. During this season, compact mid-rise areas have the highest SUHI (2.3 °C), and second is the open high-rise areas, LCZ 2

(1.3 °C). SUHI in the dense tree zone (LCZ A) was -3.9 °C SUHI and in water areas (LCZ G) was -2.5 °C. While positive SUHI intensity was only detected in large low-rise (LCZ 8) 0.1 °C and compact mid-rise areas 0.02 °C in the dry season, water (LCZ G) presented -7.5 °C while areas with dense trees showed (LCZ A) -6.2 °C.

In Kampala, SUHI in all built type LCZs in both seasons are positive. Dry season SUHI is higher than in the rainy season, typically with 3.8 °C in LCZ 2 and 3.5 °C in LCZ 3 but the SUHI in the rainy season is still strong, at 3.0 °C in LCZ 3 and 2.8 °C in LCZ 2. Dense trees play the most important role in urban cooling, supported by -1.4 °C SUHI in the dry season and -1.2 °C SUHI in the rainy season. Water also plays a critical cooling role with -1.4 °C in dry season and -0.9 °C in rainy season.

For Dar es Salaam, the LST in LCZs were statistically different between the two seasons, and SUHI was higher in the dry season. The city presented similar SUHI distribution patterns across different LCZs. The highest SUHI intensity was located in compact low rise (LCZ 3) areas with 1.6 °C in the dry season and 1.3 °C in the rainy season. Dense trees had a SUHI of -2.0 °C SUHI in the dry season and -2.1 °C in the rainy season. For water, SUHI was -1.7 °C in the dry season and -1.3 °C in the rainy season.

4.3.3 The relationship between LST and EVI

Figure 4.8 shows the spatial distribution of EVI in the study cities. Differentiation of the vegetation cover across different macroclimate regions can be observed. The mean EVI value in Dar es Salaam (Tropical savanna climate) was similar to that of Kampala (Tropical rainforest climate), followed by Addis Ababa (Humid subtropical climate), and Khartoum (Warm desert climate). The mean EVI value is generally higher in the rainy season (1.04 in Kampala, 1.02 in Dar es Salaam, 0.81 in Addis Ababa, 0.21 in Khartoum), and decreases in the dry season (1.01 in Kampala, 0.57 in Addis Ababa, and 0.19 in Khartoum), except for an increase in Dar es Salaam which had a mean value of 1.13.

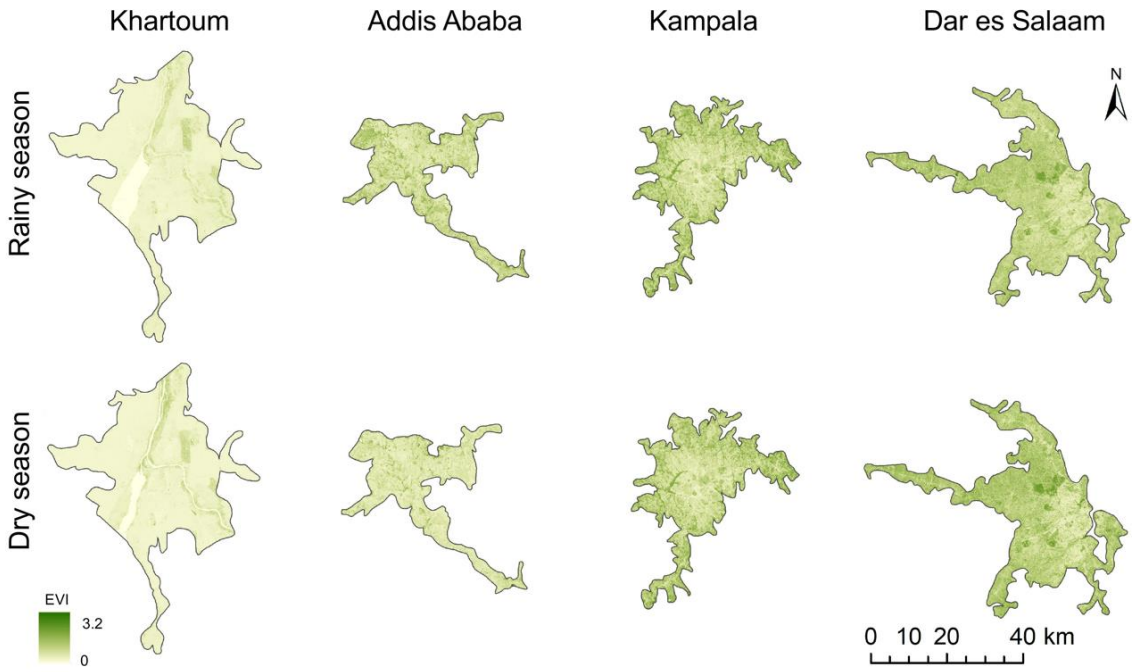

Figure 4.8 The spatial distribution of EVI in the rainy (top row) and dry (bottom row) seasons of 2018.

The bivariate Moran's I between LST and EVI was measured for the study cities. In Khartoum, Moran's I was 0.357 in the rainy season and 0.439 in the dry season, denoting a positive spatial relationship among the values of the adjacent variables. On the contrary, a relatively high negative spatial correlation was found in Kampala (−0. 54 in the rainy season and -0.43 in the dry season). Addis Ababa (−0. 18 in the rainy season and -0.06 in the dry season) and Dar es Salaam (−0.02 in the rainy season and -0.07 in the dry season) presented a weaker correlation.

To observe the internal relationship between the LST and EVI, we calculated the bivariate Moran's I between EVI and LST for each LCZ (Figure 4.9). In general, LST in dense trees (LCZ A) presents a negative correlation with EVI for all cities, while LST in scatted trees (LCZ B) and low plants (LCZ D) shows a variable correlation with EVI in the different cities and the different seasons. There were negative correlations between LST and EVI located in most LCZ types in Addis Ababa, Kampala and Dar es Salaam. In the dry season, highly negative correlations are found in Khartoum's LCZ 2; Addis Ababa's LCZ 3, LCZ D; Kampala's LCZ 2, LCZ 3 and LCZ 6. Highly positive correlations are found in Khartoum's LCZ B, LCZ D, LCZ F, LCZ G. As for the rainy season, highly negative correlations are found in Khartoum's LCZ 2 and LCZ D; Addis Ababa's LCZ 4; Kampala's LCZ 2, LCZ 3, LCZ 4 and LCZ A; Dar es Salaam's LCZ A. Highly

positive correlations are found in Khartoum's LCZ 6, LCZ 9, LCZ F, LCZ G. The weakest correlation was observed in Dar es Salaam's LCZ 2 in the dry season with a value of -0.00. In Dar es Salaam, the bivariate Moran's I values fluctuate over a relatively small range: the magnitude of correlation is between -0.26 and 0.01, which shows less correlation compared to the other study cities.

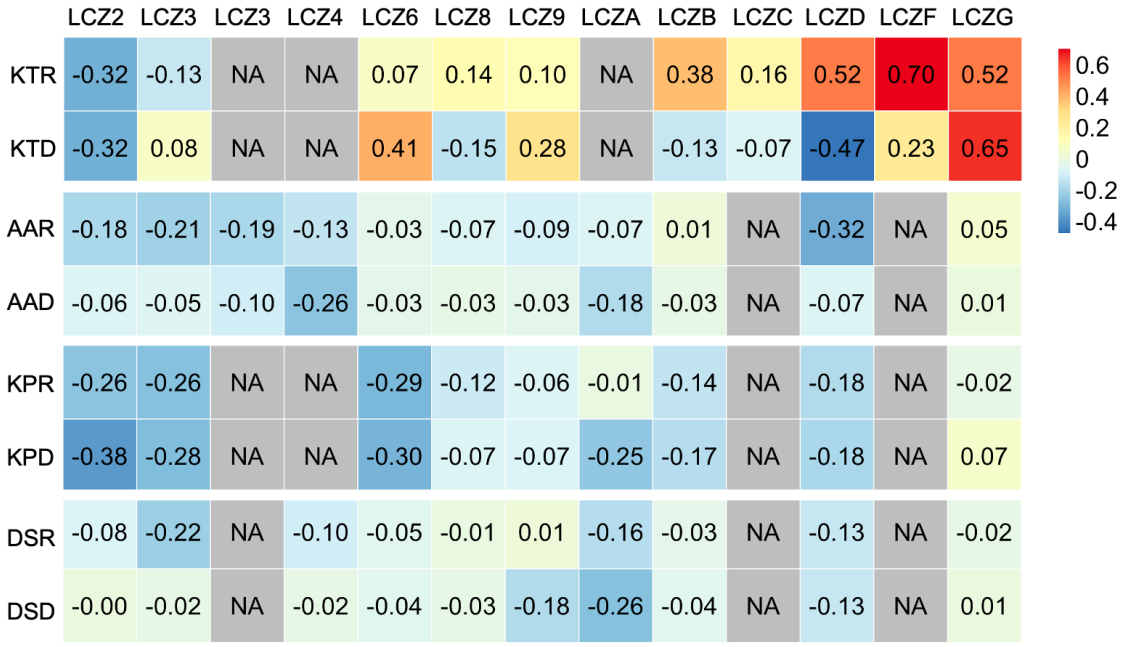

Figure 4.9 Heatmap of global bivariate Moran's I between EVI and LST for each LCZ in different seasons.

NA indicates there is no specific LCZ class in corresponding city. The detailed Moran scatter plots are provided in supplementary document 2.

4.4 Discussion

4.4.1 LCZ classification for African urban issues

Local Climate Zones (LCZs) have been adopted as a standard way of analysing a wide variety of urban issues. While initial LCZ mapping procedures relied only on satellite data and software, which required time-consuming downloading and pre-processing, the cloud-based tool LCZ generator (Demuzere et al., 2021) addresses this shortcoming. The results of our analysis indicate that LCZ classification can be efficiently used across the different macroclimate regions and

seasons in East Africa. Significant LST differences between built and natural LCZs and within built types further support the suitability of LCZ for urban thermal environment analysis.

The LCZ maps illustrate clear variation in urban form across the study cities. Khartoum and Addis Ababa had a spatial structure that lies somewhere between fragmented and compact patterns, which is characteristic of cities undergoing rapid transformation (Lemoine-Rodríguez et al., 2020), dominated by diverse initial patterns and differential development trajectories (Lemoine-Rodríguez et al., 2020). Kampala and Dar es Salaam were characterized by a low-density and dispersed spatial pattern, which is closer to a fragmented urban form. This can be a consequence of sprawled urban development. Moderately fragmented urban forms can be beneficial in terms of a less intense UHI and higher accessibility to BGI (Schwarz & Manceur, 2015). In contrast high urban fragmentation exacerbates impacts on the wider landscape and can increase urban pollution and exacerbate ecosystem services degeneration (Degefu et al., 2021; Huang et al., 2018; Tratalos et al., 2007). Africa is projected to experience rapid urban transformation in the coming decades (OECD et al., 2020). Comparisons via spatiotemporal analysis of urban land densities have pointed out that urban forms in African cities are less compact than in China, Europe, and India (Xu et al., 2019). LCZ classification incorporates urban morphology into a mapping protocol, generating sufficient heterogeneity and design flexibility in the urban fabric (Perera & Emmanuel, 2018; Stewart & Oke, 2012). Climate sensitive and data-scarce urban areas could harness such advantages, supporting the development of dynamic strategies for urban development design and monitoring.

4.4.2 LST and SUHI differences in LCZ

Statistically significant LST differences in the study cities during different seasons further support the hypothesis that LCZs represent distinct surface temperatures (Stewart & Oke, 2012). The highest LST/SUHI intensities were generally located in LCZ 2, LCZ 3, LCZ 8, major commercial and industrial areas. The lowest LST/SUHI intensities were found in LCZ A and LCZ G, represented by dense trees and water. This corresponds with previous research findings in African cities (Brousse et al., 2019; Brousse et al., 2020b; Kabano et al., 2021; Ochola et al., 2020). Generally, the temperature differences between cities can be expected to be related to the macro-

climate, geographic region and urban area (Bechtel et al., 2019; Geletič et al., 2019; Potgieter et al., 2021). Even in different climate zones, there were statistically significant differences in mean LSTs between most LCZ. In this study, large low-rise (LCZ 8) LST in most cities was considerably higher than the other LCZ types. This may correspond to the large roof surfaces that frequently occur in LCZ 8. Surprisingly, LCZ 2 and LCZ 5 in Addis Ababa and Dar es Salaam, characterised by high-rise buildings, were the coolest built types, perhaps due to the shading effects of buildings. Similar distributions at certain time scales have also been observed in Toulouse, France (Kwok et al., 2019), Beijing, China (Zheng et al., 2019). The possible reasons for this can be summarised as follows: (i) The number of training areas for LCZ 2 and LCZ 5 affected the classification accuracy; (ii) Vegetation in LCZ 5 and shading effects from the high-rise/mid-rise buildings provided cooler thermal environments (Kwok et al., 2019); (iii) The high proportion of vertical surfaces may affect the LST by preventing solar and surface interactions (Cilek et al., 2021; Zheng et al., 2019). This should nevertheless be further tested with more observations for high-rise buildings. Dense trees (LCZ A) and water (LCZ G) were identified as a lower LST zone, and the high LST variability of water would be expected, since temperature variation reflect the characteristics (depth, rate of flow, etc.) of individual water bodies (Geletič et al., 2019). Considerable temperature differences between agriculture (LCZ D) and other zones were apparent. These might be due to the lower proportions of vegetation and the more robust radiation response of bare soil in different seasons (Geletič et al., 2019).

4.4.3 LST/EVI correlation in different cities

Previous research has demonstrated that differences in LST depend on: i) variation in radiation intensity; ii) influences of evapotranspiration processes; iii) higher albedo of tree crowns during the vegetation period (Geletič et al., 2019; Gombe et al., 2017b; Gunawardena et al., 2017; Stewart & Oke, 2012; Sun et al., 2019; Zhao et al., 2014). The present study demonstrated that LST/SUHI dynamics in different LCZs also vary between seasons. For example, both rainy and dry seasons EVI were negatively correlated with LST in LCZ 2, and LCZ 3 for Khartoum, Addis Ababa and Kampala, indicating a cooling potential of increasing green space cover percentage in these LCZ types. Positive correlations were found in LCZ 6, LCZ 8, LCZ 9 during Khartoum's rainy season, also a higher SUHI was detected in this period. For Dar es Salaam, the most negative

correlation between LST and EVI was observed in the rainy season in compact low-rise areas (LCZ 3), but in the dry season it was located in areas with dense trees areas (LCZ A) and low plants (LCZ D). The interactions between seasonal UHI and urban vegetation phenology could limit the provision of beneficial ecosystem services, such as urban agricultural productivity and the regulation of human thermal comfort (Kabano, Lindley, et al., 2021). For year-long effectiveness, greening strategies should account for seasonal effects (Chun & Guldmann, 2018). Such variability provides theoretical and practical information for urban planners on maximising the BGI efficiency in mitigating the UHI (Guo et al., 2019), as an integral part of sustainable urban planning and as an adaptation to higher temperatures under climate change.

4.4.4 Implications for urban development

African cities have been shown to be the most dynamic in terms of expansion and change in urban form (Lemoine-Rodríguez et al., 2020), offering many potential opportunities to ensure these cities develop more sustainably (Lemoine-Rodríguez et al., 2020; Xu et al., 2019). Climate change has been recognised as one of the most pervasive and challenging issues to the sustainable development of this region (Du Toit et al., 2018). To ameliorate the expected overheating problem under a changing climate in the East African cities, cooling strategies could take advantage of urban morphological information through LCZ classification. The effects of solar radiation shading in mid- and high-rise buildings may lower LST (Yang, Ren, et al., 2021); controlling the wind movements through the streetscape, as wind breezes are affected by buildings (Jun Yang et al., 2019); enhancing ventilation through linear parks and wind corridors (Ochola et al., 2020; Yang, Wang, et al., 2021). Meanwhile, greater attention could be paid to the potential applications of BGI to microclimate regulation. LCZs have been used to classify the urban areas and help to select target locations to develop BGI (Emmanuel & Loconsole, 2015; Wang et al., 2021). Findings from the present research indicate which types of BGI could maximise cooling effects across seasons.

The cooling island effect of water (LCZ G) was confirmed by our results and ranges from -9.2 °C to -0.9 °C. The precise magnitude of the cooling effect depends on surrounding environmental conditions such as microclimate, urban development, wind conditions, temperature and humidity.

Water is a core feature of urban blue spaces. Hence, to enhance cooling performance of LCZ G, city planners and policy makers should take advantage of seasonal variations in blue space (Völker et al., 2013b); the quantity and spatial distribution of water bodies (Yang et al., 2015); and how cooling effects are distributed with distance from, and flow rates within, rivers (Geletič et al., 2019; Wood et al., 2013). Considering increasing flood-drought risks in East African cities (Kalantari et al., 2018), urban water retention and flood regulation functions need to cope with the seasonal variation and climate changes. These factors should be accounted for in blue infrastructure design (Douglas, 2018; Kalantari et al., 2018).

The cooling effect of dense trees (LCZ A) has also been demonstrated in the results, ranging from -6.2 °C to -1.4 °C, indicating the necessity to retain and add areas of dense tree cover in urban areas. However, when planning such programmes, prioritising indigenous species can help avoid the detrimental effects of homogenisation of urban biodiversity (Lemoine-Rodríguez et al., 2020; McKinney, 2006). In general, indigenous trees also consume less water and can enhance groundwater recharge relative to faster-growing exotic species (Kagawa et al., 2009; Singh et al., 2022). The greater water use of exotic species is enhanced in hotter, wetter climates (Cavaleri & Sack, 2010). In South Africa, Australian Acacia invasions have significantly reduced surface water runoff, impacting ecosystem services and water security (de Lange & van Wilgen, 2010; Morris et al., 2020). Conserving dense tree cover for their cooling effects should therefore focus on promoting preservation and restoration of local indigenous species (McKinney, 2006), while future research should aim to understand differences in cooling effects between exotic and indigenous trees.

Compact built-up areas (LCZ 2, LCZ 3) were characterised by densely built environments with little or no vegetation (Van de Walle et al., 2022a), and comparatively high temperatures. To mitigate SUHI by planting more vegetated areas, urban planners could take advantage of improving the evapotranspiration-based cooling influence of green space through urban canopy-layer conditions (Emmanuel & Loconsole, 2015; Gunawardena et al., 2017). Street trees, green roofs and green walls could improve evapotranspiration and the shadowing effect of vegetation for compact LCZ types in Khartoum, Addis Ababa and Kampala. Cool roofs with lower albedo material to prevent sunlight radiation caused by reflection could be considered in Dar es Salaam

(Cilek & Cilek, 2021), as slight correlations between LST and EVI were observed in most built-up LCZs. Sparsely built areas (LCZ 9) with high SUHI and a low vegetation index were observed in all our study cities. Such underdeveloped lands within urban areas could be considered a valuable commodity for dynamic urban development.

The temperature-regulation capacity of BGI can potentially reduce heat stress in urban areas, but the choice and design of BGI type and distribution should be coordinated across different LCZs. The effects of BGI on temperature regulation have not however been quantified sufficiently, and so remain underrepresented in research and in recommendations for action and planning. For example, strategic planning for UHI mitigation and energy savings has faced the practical concern of the trade-off between energy and water use, as the cooling effect of some vegetation types, such as grassland in an arid city, is highly dependent on the water supply (bencheikh & Rchid, 2012; Wang et al., 2016). Moreover, inappropriately designed bluespaces come with the risk of exacerbating heat stress during oppressive conditions (Gunawardena et al., 2017) and present other potential risks under climate change linked to flooding and vector-borne diseases. Incorporating public health awareness and interventions into urban planning at the earliest stages could help ensure that BGI achieves its full potential for public health (Lõhmus & Balbus, 2015).

Rapid urbanisation inevitably results in a loss of natural land covers, an increase in the amount of vertical surfaces that are present associated with a densification of existing built infrastructure; something that is apparent across many LCZ classes. If urban populations continue to grow as projected (United Nations, 2019), current scattered trees (LCZ B), low plants (LCZ D) and water (LCZ G) in urban areas will be gradually replaced by compact mid-rise (LCZ 2), compact low-rise (LCZ 3), open low-rise (LCZ 6), and dense trees (LCZ A) will be in danger of disappearing. It is notable that LCZ 2, 3 and 6 have higher temperatures than LCZ A (dense tree). Therefore, urban planners and policymakers should optimise both the spatial configuration and the cooling effects of BGI when working with limited land resources, taking into account seasonal differences.

4.5 Conclusion

Under the LCZ framework, this study conducted several statistical analyses for comparative study

in four East African cities. It revealed the LST/SUHI dynamics and the complex relationship between LST and EVI in different LCZ across seasons. The results supported the assertion that the LCZ classification and LCZ-generator can be efficiently used in future urban thermal studies in a more spatially explicit way. Suggestions were also given as to how BGI could potentially facilitate the implementation of UHI mitigating strategies to support sustainable urban development, as urbanisation and climate change continue at pace within Africa's cities.

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Chapters 2, 3 and 4 examined the urban thermal environment and its related aspects. Key findings from each chapter are linked and addressed based on the general purpose and goals of the thesis, and corresponding policy implications and solutions are highlighted. The concept of urban BGI for urban resilient development is introduced and examined using an example from Kampala, drawing on the knowledge presented in these findings. The implications of the study techniques, data sources, potential analytical tools, and collaboration with online communities are then compiled in Chapter 5.

Chapter 5: Discussion

Unprecedented rates of rural-urban migration and natural population increases, in a context of climate change, places urban challenges at the centre of sustainable development. As warming associated with urban development and climate change intensifies, city dwellers will be at greater risk of heat-related morbidity and mortality. This chapter provides a more comprehensive understanding of the urban thermal environment and its related factors drawing from findings presented in Chapters 2, 3 and 4 and placing this in the context of the broader literature. Based on the overall aim and objectives of the thesis, key findings of each chapter are linked and discussed, and corresponding policy implications and solutions are highlighted. Then, building on the information across the previous three sections, an example from Kampala is introduced that examines the concept of urban BGI for urban resilient development and how this can be applied in practice. Lastly, the implications of the research methods, data sources, possible analysis tools and online community cooperation are summarised.

5.1. Introduction

The combination of global warming and population growth has become the major driver of increased heat exposure in Africa (IPCC, 2022). Rapid urbanisation accompanied with infill development and urban sprawl are leading to the loss of BGI and ecosystem services in many African cities, making it harder for urban areas to adapt to climate change. Such reduced adaptive capacity and exacerbated UHI effects are projected to add 2°C to local warming in mid-21st century under the RCP 8.5 scenario (unchanged current GHG emission trends) (IPCC, 2022).

Even though previous work in Africa has attempted to reorient unsustainable urbanisation patterns, research efforts need to focus more strongly on the urban thermal environment particularly because the current pace of urbanisation offers a very time-limited opportunity if development is to happen sustainably within the context of global climate change (IPCC, 2022). This thesis has sought to explore the urban thermal environment in the context of fast urbanisation and climate change considering LST, SUHI and vegetation dynamics. In Chapter 1, I formulated three research objectives that involved:

• Exploring the spatial and temporal variations of SUHI in different climate zones in East Africa: from the possible driving factors to the implications for sustainable urban development. To explore these aspects, I quantified the annual daytime and night-time SUHI intensities in Chapter 2 in the five most populated cities in East Africa in 2003 and 2017 across different climate zones, and discussed the links to urban area size.

• Investigating the influence of urban density for urban thermal environment: I contributed to this challenge by exploring how urban density results in SUHI intensity change and how the transformation of urban areas influences the SUHI, focusing on the Ugandan capital city, Kampala. The complexity of urban development patterns was described through the consideration of kernel density in Chapter 3.

• Exploring the urban configuration: Through this question I tried to understand how urban configuration affects the urban thermal environment and vegetation index. This question was addressed in Chapter 4 using the LCZ classification for four cities in East Africa. In particular, seasonal variation was analysed, which addressed an important gap in the literature as a seasonal perspective is rarely taken. LST, SUHI and EVI in different seasons were discussed in the study areas, and their spatial autocorrelation was modelled through Moran's I to consider possible BGI benefits.

By addressing these questions, this thesis has advanced understanding of the urban thermal environment and the role of factors such as climate, vegetation and urbanisation patterns that add to its complexity. In doing so the work has contributed to knowledge in various ways. The research has: (i) demonstrated the utility of methods to analyse SUHI in data deficient areas; (ii)

examined and extended the framework of LCZ classification in different climate zones, analysing the influence of urbanisation on both the urban thermal environment and vegetation indices; (iii) improved understanding of the issues in the urban thermal environment in the context of fast urbanisation and climate change; and (iv) elaborated the benefits of BGI and enhanced understanding of the potential of nature based solutions in sustainable urban transformation.

5.2. Presentation of the Published Papers

5.2.1. SUHI in different climate zones in East Africa

In Chapter 2, the research results advanced understanding of SUHI trends in five East African cities across different macroclimate zones. The magnitude of the SUHI expanded, and SUHI intensity in the previous SUHI hotspot areas intensified. Findings were consistent with previous descriptions across the five cities that were studied (Khartoum (Elagib, 2011), Addis Ababa (Gombe et al., 2017; Terfa et al., 2020), Nairobi (Gombe et al., 2017; Ochola et al., 2020), Kampala (Kabano et al., 2021), Dar es Salaam (Brousse et al., 2020; Gombe et al., 2017)). This chapter is the first to provide insights by using a comparative approach for these cities. After confirming the overall temporal trend, a comprehensive comparison of their spatial differences was conducted. The underlying drivers of SUHI growth were further explored according to the climate conditions, specific urban development patterns, and unplanned informal settlement growth.

The SUHI dynamics in different macroclimate regions implies the importance of adapting differential SUHI mitigation strategies according to the background urban climate. Given that world macroclimate regions are shifting, and some regions are changing more than others toward a dynamic climate (IPCC, 2022), cities located in these regions should be investigated in more depth in further studies (Eldesoky et al., 2021). The results here imply the potential of mitigating SUHI growth by regulating urban development patterns, with explicit consideration of the size, shape, and centrality of land developments. Massive urbanisation expected in the near future also provides opportunities to address the challenges from climate change (IPCC, 2022).

The high rates of urban growth are associated with the expansion of informal settlements in East

Africa. If continued, unabated expansion may exaggerate social and environmental problems and impede sustainable development as the disordered growth of informal settlement could also encroach upon BGI, such as riverside areas, wetlands and forests. In order to establish sustainable urban areas that serve all urban inhabitants (both the current residents and those still to come) the social inequalities in environmental resources and exposure to infectious diseases (such as vector-borne and diarrhoeal diseases) introduced by BGI should be considered and mitigated.

This thesis used UHI explorer to undertake the analysis in Chapter 2. It offered various advantages. As a result of its application here, the UHI explorer is recommended as an efficient tool for detecting SUHI. The shortcomings associated with the tool are that a comparatively coarse resolution and incomplete urban built-up data reduce its utility. A large number of secondary cities are experiencing rapid urban growth in Africa and these areas have received less attention and often have inadequate local data. UHI explorer could carry out an overall assessment with efficiency through a consistent analytic environment using massive remote sensing data. This offers lots of untapped potential and opportunities to better understand the urban thermal environment under changing conditions. While Chapter 2 provided several new insights, new research gaps were also revealed and need further attention. In particular, urban built-up change and urban morphology were not described. This opens up specific challenges in urban thermal studies that were addressed in Chapters 3 and 4.

5.2.2. Urban density and urban thermal environment relationships - empirical evidence on urbanisation patterns in Kampala

Kampala, as one of the cities experiencing the most significant changes in SUHI in Chapter 2, was selected as the case study city for studying built-up density and urban thermal environment relationships in Chapter 3. Kampala is one of the fastest growing African cities (Vermeiren et al., 2012), while the SUHI effect, thermal comfort and heat stress also have been detected before (Brousse et al., 2020; Kabano et al., 2021; Nsaire, 2021). This chapter provided further understanding of the urban thermal environment and SUHI change associated with the growth of built-up urban areas, urbanisation patterns and changes in gains and losses of BGI between 2003 and 2017. The results indicated the SUHI decreased in the city centre in 2017, which was possibly

due to the increased green areas in city centre. Temperatures surrounding the city centre increased causing a decrease in the temperature differences. Geographical factors helped to explain the findings, in particular, the southern part of Kampala close to Lake Victoria and interactions with its lake breeze. The thermal contrast between hotter urban built-up land and cooler water surface leads to areas of convergence that amplify the lake breeze (Brousse et al., 2020), thus the reduced SUHI intensity in areas close to Lake Victoria. More research is required to examine the important role of geographical factors, and if a similar cooling effect can be achieved by other water bodies of different sizes and geographical intervals.

The relationship and associated analyses between built-up land uses and SUHI in Kampala further provided some implications for urban development. Results indicated that: (i) the development of satellite towns surrounding the administrative city could slow down the growth of SUHI; (ii) land rehabilitation, such as rearrangement of informal settlements with increased green areas in the city centre could deliver cooling effects and relieve heat stress; and (iii) wetlands could deliver urban thermal regulating services via functioning as "urban cooling islands", while also delivering various ecosystem services such as flood prevention and water quality improvements. The encroachment of wetlands in urbanisation processes could compromise the cooling effect more than in other land types, indicating expanding built-up areas onto wetlands should be avoided.

5.2.3. Urban configuration relationships with urban thermal environment and vegetation indexes

Chapter 4 advanced understanding of the relationships between urban configuration, urban thermal environment and vegetation indices. 70% or above accuracy levels confirm that LCZ classification is suitable for East African urban areas considered within this study. Statistically different LST in each LCZ provided further evidence that LCZ could describe the local climate features for urban areas well. Seasonal variations in the thermal environment were also found to be important for these cities, as stronger SUHI were observed in Khartoum and Addis Ababa during the rainy season, while Kampala and Dar es Salaam were the opposite. The correlation between LST and EVI seasonally underlines the complexity of BGI as an approach to managing SUHI.

The results have important implications for the use of LCZ for urban thermal environment research. LCZ maps identify heat-stressed areas and critical hotspots relate to temperatures or UHI magnitudes with quantifiable metadata (e.g., surface cover, thermal, radiative, metabolic properties), which can be incorporated into local building regulations and design (Eldesoky et al., 2021). The results have implications for urban development and future studies: (i) development strategies targeting the regulation of the urban thermal environment should simultaneously take urban macroclimate and microclimate into account; (ii) traditional SUHI mitigation strategies are heavily focused on what happens in the dry season, while SUHI is higher in the rainy season in Khartoum and Addis Ababa, indicating the seasonal variation of SUHI needs consideration in some cities; (iii) conservation of current BGI, especially water and dense trees, could bring substantial urban cooling; (iv) currently available resources and infrastructure (such as unused land, roofs) that are converted to BGI could take advantage of correlations between vegetation and LST enabling existing green areas to be used more efficiently (with reduced land resource consumption and lower economic cost) to mitigate SUHI.

This chapter used the new version of the LCZ classification tool, LCZ generator, offering convenience in data verification and revision. It was this efficiency that enabled the quick classification of LCZ for different cities. In Chapter 4, LST and EVI calculations required a large amount of data, not only in terms of seasonal variation, but also cloud contamination in the equatorial regions presented the need to composite all the available images in the collection to generate a clearer one. GEE was employed and proved its suitability and productivity again. Welch's T test was used for comparing LST differences between different LCZ types using R studio and Moran's I was employed for analysing spatial correlation via Geoda. These tools are freely accessible for every researcher, which can be useful when research resources are limited. It is worth mentioning that LCZ belongs to the community-based project WUDAPT, and different LCZ maps following standard classification steps are shared online within the community but accessible to all. Just like code sharing and discussion communities StackExchange and Github, these online knowledge exchange communities offer important tools that can be applied to target sustainable development in new ways.

5.3. Limitations of the thesis

Although satellite and remote sensing data have been employed to study urban climate in this thesis, there are still limitations in its application. One major limitation is the results of this thesis are only from a remote sensing-based approach, and different and/or more nuanced results could emerge if site-specific field-derived information was used instead. However, in East Africa, data scarcity and lack of historical research mean that there is insufficient field-based information for reference or comparison to be explored in this thesis. In particular, most satellite sensors do not fully view the urban surface, where usually vertical surfaces and other shadowed areas are missing. Furthermore, there is a trade-off between spatial resolutions and temporal coverage of the open-source satellite imagery (Eldesoky et al., 2021). For instance, MODIS imagery provides global day and night land surface temperature and emissivity with a coarse spatial resolution (1000 m above). Landsat satellites can be used to derive LST data at a moderate spatial resolution (30/60 m) with low revisit times (every 8/16 days). For regions that witness strong seasonal cloud cover, the data samples are particularly susceptible to cloud contamination.

In this thesis, this limitation has been partly overcome via cloud-based computing GEE, while the missing data in some months is still inevitably an issue. This resulted in an inconsistent study period in Chapter 3. Furthermore, even though the LCZ generator simplified the classification process, three primary steps (sampling, input, and resampling to improve accuracy) required a heavy workload. Thus, I only selected four cities as study areas in Chapter 4, while still ensuring coverage of a range of different climate zones. Several limitations and challenges in the urban thermal environment remain unsolved and require further study. GEE has successfully used existing satellite images to analyse past trends, like in this thesis. To simulate a variety of urban dynamics, future research can target developing land-use prediction models in GEE, such as using Markov chain coupled with Cellular Automata. In addition, the suitability of LCZ classification for African cities in other different climate zones needs further investigation. To detect the complexity and heterogeneity of BGI, such as the tree species for UHI mitigation, the current 100-meter resolution of the LCZ generator is not sufficient. Higher-resolution satellites and LiDAR data in object-oriented classification methods (e.g., eCognition Developer) can be considered.

5.4. Further work and research development

This thesis presents an important step toward exploring the urban thermal environment in African cities but in the process of writing it, new research opportunities emerged. According to the findings, the sections below set out some additional directions for sustainable urban development that require further investigation.

- LULC changes and projection

This thesis investigated how urban built-up areas are affected by urban expansion in different East African cities, and how the past urban growth process of these cities can be characterised. Given the current high dynamic growth, policy makers in rapidly expanding urban areas confront unprecedented challenges in relation to governance, urban planning, and land use management. Hence, information about past, present, and future growth is crucial for decision-making processes. Current research has examined the mechanisms of urban expansion but these investigations have been limited to retrospective analysis (Reba & Seto, 2020; Zhang et al., 2022). Predictive models, however, are also empirically significant since they evaluate the effects of spatial change in addition to mapping the status quo. Accordingly, a number of established statistical and geographic models, including logistic regression models, Markov chains and cellular automata models (Bindajam et al., 2021; Shafizadeh Moghadam & Helbich, 2013), have been established but not yet thoroughly investigated in African cities. Thus, further research is needed for optimising available resources and decision making. Key outstanding questions include:

a) Which simulation models are most suitable for to investigating spatiotemporal urban growth dynamics in African cities?

b) What growth patterns in African cities can be expected from now to 2030 and 2030 to 2050? How will land use will be affected by future changes in the climate, but also the feedbacks from land use change to the global climate system?

The LCZ maps utilized in this thesis are referred to as the ‘level 0’ product, as they depict the

basic level of information regarding urban areas. More detailed and higher resolution information is available at levels 1 and 2, as described by Bechtel et al. (2019). The procedure for generating the LCZ level 0 product involves creating training areas (TA) using Google Earth and freely available Landsat imagery, and then processing the data with the open-source SAGA software and the online cloud computing platform LCZ-Generator. This workflow is designed to be easy to follow, allowing researchers around the world to produce and compare LCZ maps. In parallel, in most African cities, the data to derive urban boundary layers (UCPs), known as level 1 or 2 WUDAPT products, are either not available/incomplete and/or available at poor spatial/temporal resolutions (Ching et al., 2018). Thus, additional efforts are needed to generate spatially precise UCPs for improved urban applications at the city level:

a) Incorporating various types of data sources like crowdsourced data, SAR images, and ground level images like Google Street View.

b) Exploring alternative classification algorithms and deep learning techniques, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), can enhance the efficiency and accuracy of the UCP generation process.

- UHI and vulnerabilities

The vulnerability of urban areas to heat-related disasters has been exacerbated by the rapid pace of urbanisation. There is an urgent need to identify the factors that contribute to the impact of heatwaves on human health and the areas that are most at risk. Vulnerability is defined as a function of exposure, sensitivity, and adaptive capacity (IPCC, 2007). Exposure is the nature and degree to which a system is exposed to significant climatic variations, while sensitivity is the degree to which a system is affected by a climatic event, positively or negatively. Human vulnerability will continue to concentrate in areas where infrastructure and basic services is inadequate, and vulnerability hotspots are likely to be concentrated in informal settlements and rapidly growing smaller settlement (IPCC, 2022). Future research is needed to analysis the heat vulnerability in these locations, using images collected by satellite-based remote sensing , in conjunction with meteorological observation data and census data. Key questions need answering, including those considering:

a) The influence of urbanisation and climate change on heat wave exposure, sensitivity, and adaptability and how they differ.

b) The spatial heterogeneity of vulnerability to the effects of heat waves in city centres and suburban areas, and the spatial distribution of risk for disaster-associated mortality.

c) Providing direct scientific guidance to public health officers, emergency preparedness personnel, the National Weather Service, and urban residents to assist in preparation and mitigation of potential heat-related illnesses

In addition, the heat stress on humans and its associated health impacts are not only determined by the air (dry bulb) temperature but also by humidity, wind, and incident radiation, especially the solar radiation if one is exposed to it outdoors. To accurately predict heat stress, both ambient temperature and humidity must be considered. The wet-bulb temperature is a commonly used indicator of heat stress that takes into account both temperature and humidity, by measuring the temperature of a wet and well-ventilated object in equilibrium with the surrounding air (Monteiro & Caballero, 2019). Thus, surface temperature alone sometimes is not a reliable proxy for the intra-urban distribution of the heat index (Chakraborty et al., 2022), and there are variable differences between surface temperature from satellites and the air temperature. When investigating the geographical distribution of the most vulnerable populations to heat in urban areas, research should consider not only the temperature and humidity but also the differences between surface temperature from satellites and the air temperature. Important questions include:

a) Which weather patterns lead to dangerous levels of heat stress and how climate change may affect these patterns?

b) Considering the humidity aspect, what are the functions of and impacts of shortages of green landscapes and water bodies in mitigating extreme heat in urban areas?

c) Without urban-scale observations and a lack of better alternatives for surface temperature in most Africa cities, how can we accurately obtain wet-bulb temperature and inform heat mitigation strategies within and across cities?

- Comprehensive urban planning

Cities are undergoing significant growth and transformation due to increasing population,

changing social dynamics, geographical factors, and increased complexity, climate change further exacerbates these challenges. In particular, urban heat islands and floods will pose severe impacts for human life and the environment, so future study needs to identify those zones that are vulnerable to urban flooding and extreme heat together. Thus, there is a demand for a multi-disciplinary approach to develop a thorough understanding of the social-economic and environmental vulnerability in cities. Given this gap, there is a need for:

a) Development of vulnerability indexes to identify current and future hotspots of the city that are most at risk from the heat and flooding impacts of climate change, based on a combination of environmental data (e.g. stormwater runoff, surface temperature data) and social data (e.g. on poverty, elderly people, and population density).

b) Analysis of hotspots combining social-economic and environmental vulnerability data to identify areas of the city that would benefit most from a focus on the implementation of BGI. To create priority attention, mapping should be used as a planning tool for implementing new BGI.

c) Considering downscaled climate models, LULC, and population projections under different scenarios.

5.5. Conclusion

Under rapid urbanisation and against a background of the changing climate, cities need a better understanding of what drives changes in the urban thermal environment. From a literature review, Chapter 1 identified research gaps in Africa and set up four research questions for this thesis:

• What are the spatial and temporal variations of SUHI in different climate zones in East Africa?

• What is the influence of urban density on the urban thermal environment?

• How does urban configuration affect the urban thermal environment and vegetation index?

• What is the practical role of BGI in regulating urban thermal environment and mitigating UHI?

Chapters 2, 3 and 4 answered the research questions through spatial and statistical analyses, and Chapter 5 provided an improved understanding of the complexities of the urban thermal environment and the role of different factors that contribute to this complexity across East African cities. Specifically, this thesis highlights the combined effects of rapid urbanisation and climate change on LST, SUHI effects and the role of BGI and vegetation dynamics. In parallel to improve preparedness and responses to heatwave and UHI effects, cities need to consider multiple hazards that may be prevalent, such as floods, drought and storms. Thus, in the context of the broader literature, wider implications in terms of urban BGI are considered in relation to minimize the influence from climate change and rapid urbanisation. Furthermore, this thesis used various tools and modelling at different scales that enabled identification of critical zones in cities with increased heat risks and in this way shows how such analyses can support the prioritisation of adaptation plans so that they target the most vulnerable groups and geographies. GEE features a multi-petabyte catalogue of satellite imagery and geospatial datasets with planetary-scale analysis capabilities, which provided added value with high consistency, efficiency and repeatability in the analyses presented here. Welch's T test is suitable for detecting the SUHI affected areas between years, under a difference in sample size or spatial data differences. Kernel density analysis for the spatial distribution to represent urban built-up density was confirmed to be useful in visualising the shape of built-up and SUHI change data. Such straightforward mapping expression can enable planners to identify hotspots more efficiently, helping to demonstrate the

complex spatial variation. While this thesis has focused on Africa, the research methods offer potential to be applied to other locations facing dual urbanisation and climate change challenges.

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Supplementary Document 1 for Chapter 1

```
# The data were found in the file 'WorldPopulationData.csv'
# Data source: https://population.un.org/wpp/

# Load program package
library(ggplot2)

# Load population data
# set the folder including the data
setwd("E:/R_Files")
# load data
Data <- read.csv('data.csv',header=TRUE)

# Remove spaces
for(j in 6:26){
    Data[,j] <- as.numeric(gsub(" ","",as.character(Data[,j])))
}

Zero <- which(Data$X1990 == 0)
Data <- Data[-Zero,]

#Calculate the population growth rate
Data$Group_1 <- (Data$X2005-Data$X1990)/Data$X1990 # log( (Data$X2005-
Data$X1990)/Data$X1990 )
#2005-2020
Data$Group_2 <- (Data$X2020-Data$X2005)/Data$X2005
#2020-2035
Data$Group_3 <- (Data$X2035-Data$X2020)/Data$X2020
#2035-2050
Data$Group_4 <- (Data$X2050-Data$X2035)/Data$X2035

#Filter data
Data_Used <- subset(Data, num %in% c(1,2,3,4))
Plot_Data <- data.frame(num=rep(Data_Used$num,times=4),

percent_increase_in_population=c(Data_Used$Group_1,Data_Used$Group_2,Data_Us
ed$Group_3,Data_Used$Group_4),
                        group_year=rep(c("1990-2005","2005-2020","2020-
2035","2035-2050"),each=nrow(Data_Used)))
Plot_Data$region <- factor(Plot_Data$num, labels = c("North America + Europe +
Australia + Japan","Africa","Asia","Latin America"))
```

```
##########################World map
#Load program package
library(rworldmap)

#Load world map
Wmap <- map_data(map="world")
Plot_Data2 <- merge(x=Wmap, y=Data_Used, by.x="region", by.y="Region..subregion..country.or.area", all.x=TRUE)
classN <- function(a){return(ifelse(a<0.2,"<20%",ifelse(a<0.4,"20-40%",ifelse(a<0.6,"40-60%",ifelse(a<0.8,"60-80%",ifelse(a<1,"80-100%",">100%")))))}
Plot_Data2$Group_1 <- sapply(X=Plot_Data2$Group_1, FUN=classN)
Plot_Data2$Group_2 <- sapply(X=Plot_Data2$Group_2, FUN=classN)
Plot_Data2$Group_3 <- sapply(X=Plot_Data2$Group_3, FUN=classN)
Plot_Data2$Group_4 <- sapply(X=Plot_Data2$Group_4, FUN=classN)
Plot_Data2 <- Plot_Data2[order(Plot_Data2$order),]

#Plot the world map
gg1 <- ggplot()
gg1 <- gg1+theme(legend.position = c(0.1,0.4))
#gg1 <- gg1 + theme(legend.position="none")
gg1 <- gg1 + geom_map(data=Plot_Data2, map=Plot_Data2, aes(map_id=region, x=long, y=lat, fill=Group_1))
gg1 <- gg1 + coord_equal()
gg1 <- gg1 + labs(x=NULL, y=NULL, title="1990-2005")
gg1 <- gg1 + scale_fill_discrete(breaks=c("<20%","20-40%","40-60%","60-80%","80-100%",">100%"))
gg1 <- gg1 + theme(legend.title=element_blank())

gg2 <- ggplot()
#gg2 <- gg2+theme(legend.position = c(0.1,0.4))
gg2 <- gg2 + theme(legend.position="none")
gg2 <- gg2 + geom_map(data=Plot_Data2, map=Plot_Data2, aes(map_id=region, x=long, y=lat, fill=Group_2))
gg2 <- gg2 + coord_equal()
gg2 <- gg2 + labs(x=NULL, y=NULL, title="2005-2020")
#gg2 <- gg2 + scale_fill_discrete(breaks=c("<20%","20-40%","40-60%","60-80%","80-100%",">100%"))
gg2 <- gg2 + theme(legend.title=element_blank())

gg3 <- ggplot()
#gg3 <- gg3+theme(legend.position = c(0.1,0.4))
gg3 <- gg3 + theme(legend.position="none")
gg3 <- gg3 + geom_map(data=Plot_Data2, map=Plot_Data2, aes(map_id=region, x=long,
```

```
y=lat, fill=Group_3))
gg3 <- gg3 + coord_equal()
gg3 <- gg3 + labs(x=NULL, y=NULL, title="2020-2035")
#gg3 <- gg3 + scale_fill_discrete(breaks=c("<20%","20-40%","40-60%","60-80%","80-
100%",">100%"))
gg3 <- gg3 + theme(legend.title=element_blank())

gg4 <- ggplot()
#gg4 <- gg4+theme(legend.position = c(0.1,0.4))
gg4 <- gg4 + theme(legend.position="none")
gg4 <- gg4 + geom_map(data=Plot_Data2, map=Plot_Data2, aes(map_id=region, x=long,
y=lat, fill=Group_4))
gg4 <- gg4 + coord_equal()
gg4 <- gg4 + labs(x=NULL, y=NULL, title="2035-2050")
#gg4 <- gg4 + scale_fill_discrete(breaks=c("<20%","20-40%","40-60%","60-80%","80-
100%",">100%"))
gg4 <- gg4 + theme(legend.title=element_blank())

#Combine four maps
require(gridExtra)
grid.arrange(gg1, gg2, gg3, gg4, ncol=2)

####################################Box plots
ggplot(Plot_Data, aes(x=region,y=percent_increase_in_population)) +
  facet_grid(.~group_year) +
  geom_boxplot(aes(fill=region)) +
  labs(x="Region category", y="Percent increase in population") +
  guides(fill=F) +
  scale_x_discrete(breaks=c("North America + Europe + Australia +
Japan","Africa","Asia","Latin America"),
                   label=c("North\nAmerica +\nEurope +\nAustralia
+\nJapan","Africa","Asia","Latin\nAmerica"))
```

Supplementary Document 2 for Chapter 4

LCZ maps can be found in following links

Khartoum:

Li, X. (2021). WUDAPT Level 0 training data for Khartoum (Sudan, Republic of), submitted to the LCZ Generator. This dataset is licensed under CC BY-SA, and more information is available at https://lcz-generator.rub.de/factsheets/762cfe184a69418ce6da5d55035eba3de4a369f7/762cfe184a69418ce6da5d55035eba3de4a369f7_factsheet.html

Addis Ababa:

Li, X. (2021). WUDAPT Level 0 training data for Addis Ababa (Ethiopia, Federal Democratic Republic of), submitted to the LCZ Generator. This dataset is licensed under CC BY-SA, and more information is available at https://lcz-generator.rub.de/factsheets/4fef5c45c686584937882b6ca03c5d6092614d70/4fef5c45c686584937882b6ca03c5d6092614d70_factsheet.html

Kampala:

Li, X. (2021). WUDAPT Level 0 training data for Kampala (Uganda, Republic of), submitted to the LCZ Generator. This dataset is licensed under CC BY-SA, and more information is available at https://lcz-generator.rub.de/factsheets/0ccdffa6ec0f1fcd50ffd4bf8f7ec322c5f6d1c2/0ccdffa6ec0f1fcd50ffd4bf8f7ec322c5f6d1c2_factsheet.html

Dar es Salaam:

Li, X. (2021). WUDAPT Level 0 training data for Dar es Salaam (Tanzania, United Republic of), submitted to the LCZ Generator. This dataset is licensed under CC BY-SA, and more information is available at https://lcz-generator.rub.de/factsheets/

80f553f2d0b63dc878517119ab40387a44372eaa/80f553f2d0b63dc878517119ab40387a44372ea

a_factsheet.html

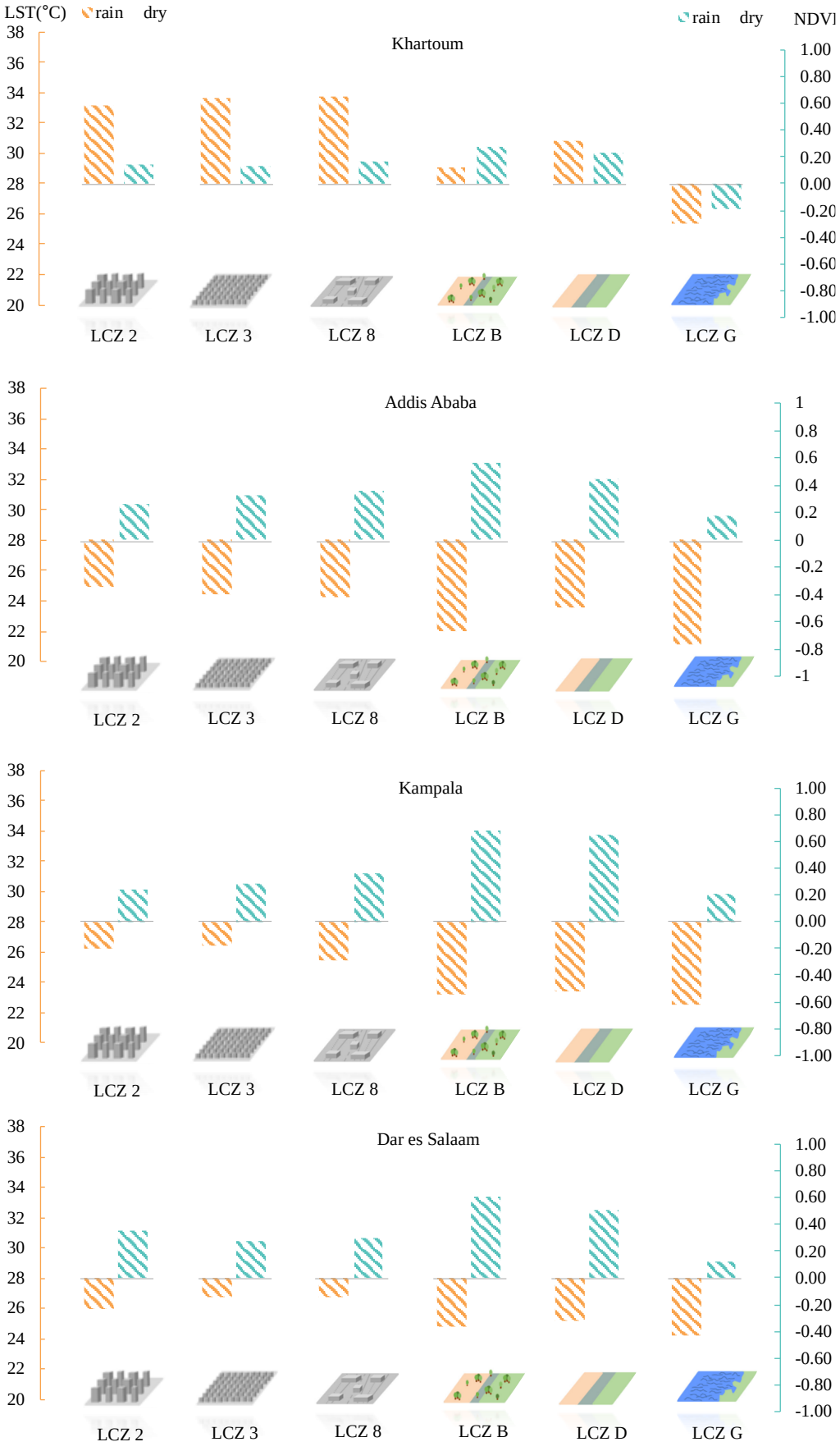


Figure S2.1 Seasonal SUHI distribution in different LCZ

Khartoum Rainy Season

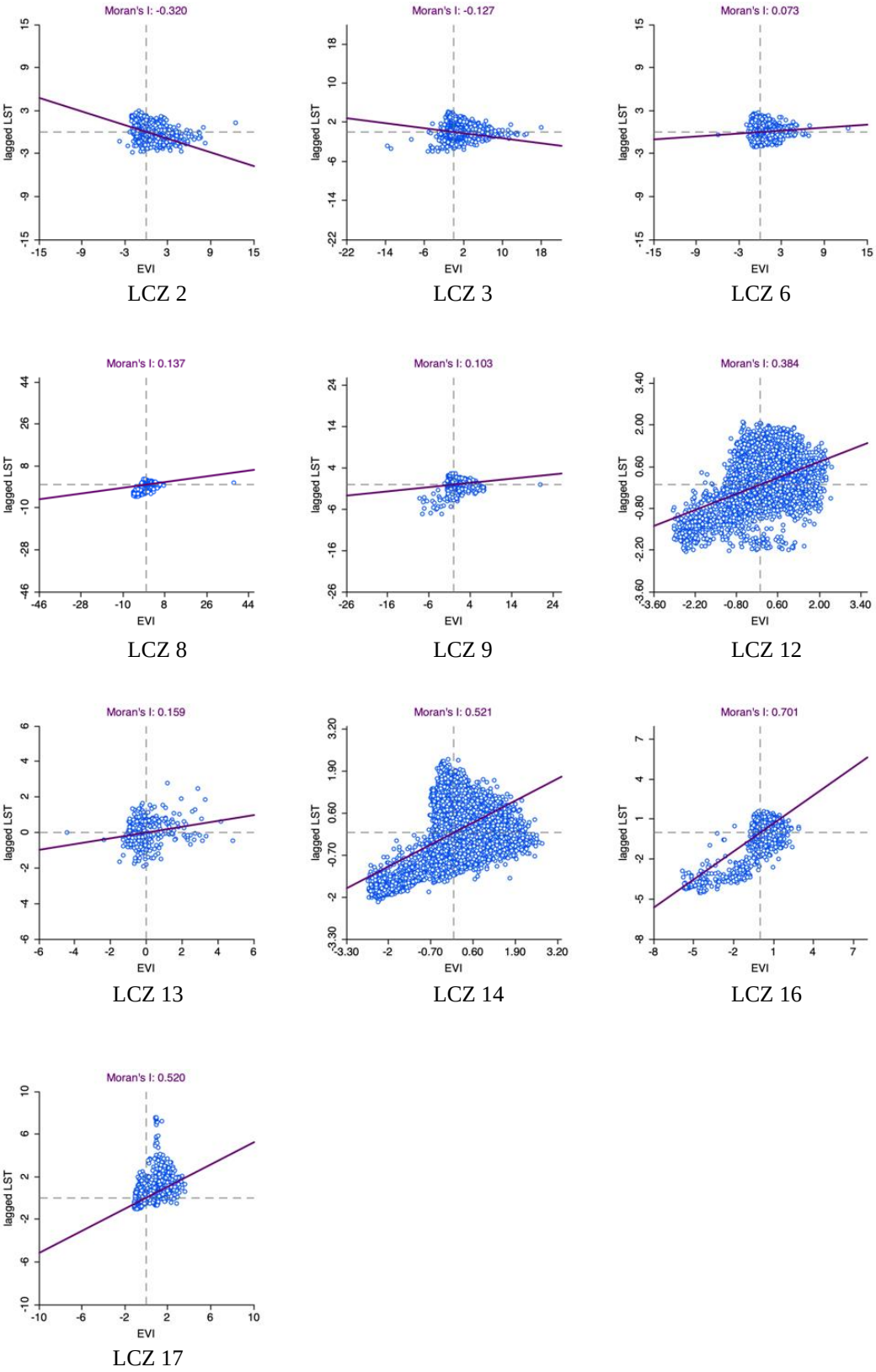
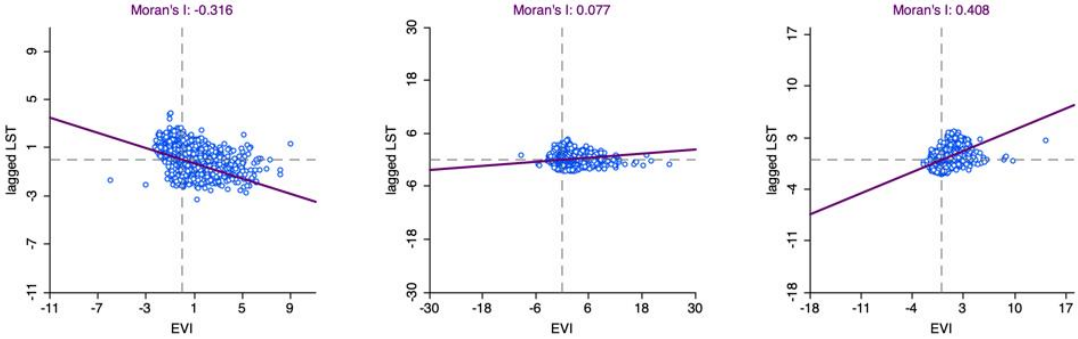


Figure S2.2 The correlation of Khartoum's LST and EVI in different LCZ during rainy season

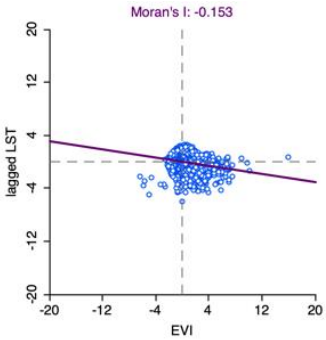
Khartoum Dry Season



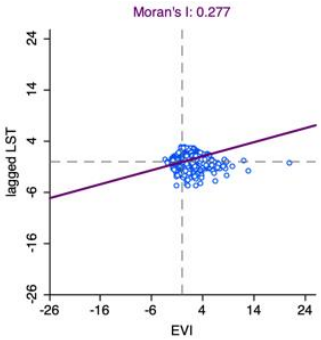
LCZ 2

LCZ 3

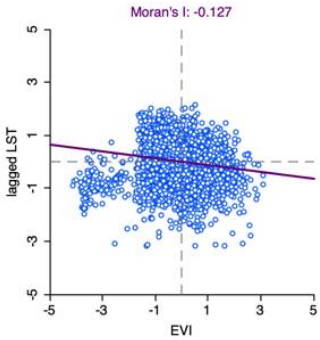
LCZ 6



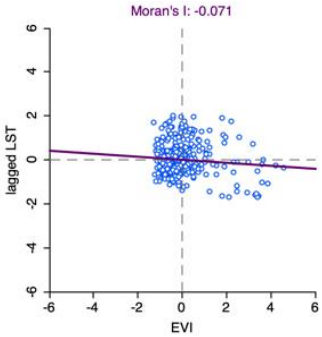
LCZ 8



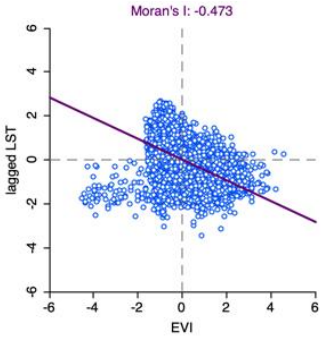
LCZ 9



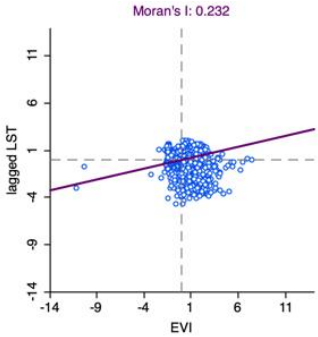
LCZ 12



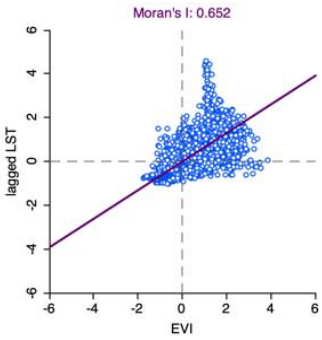
LCZ 13



LCZ 14



LCZ 16



LCZ 17

Figure S2.3 The correlation of Khartoum's LST and EVI in different LCZ during dry season

Addis Ababa Rainy Season

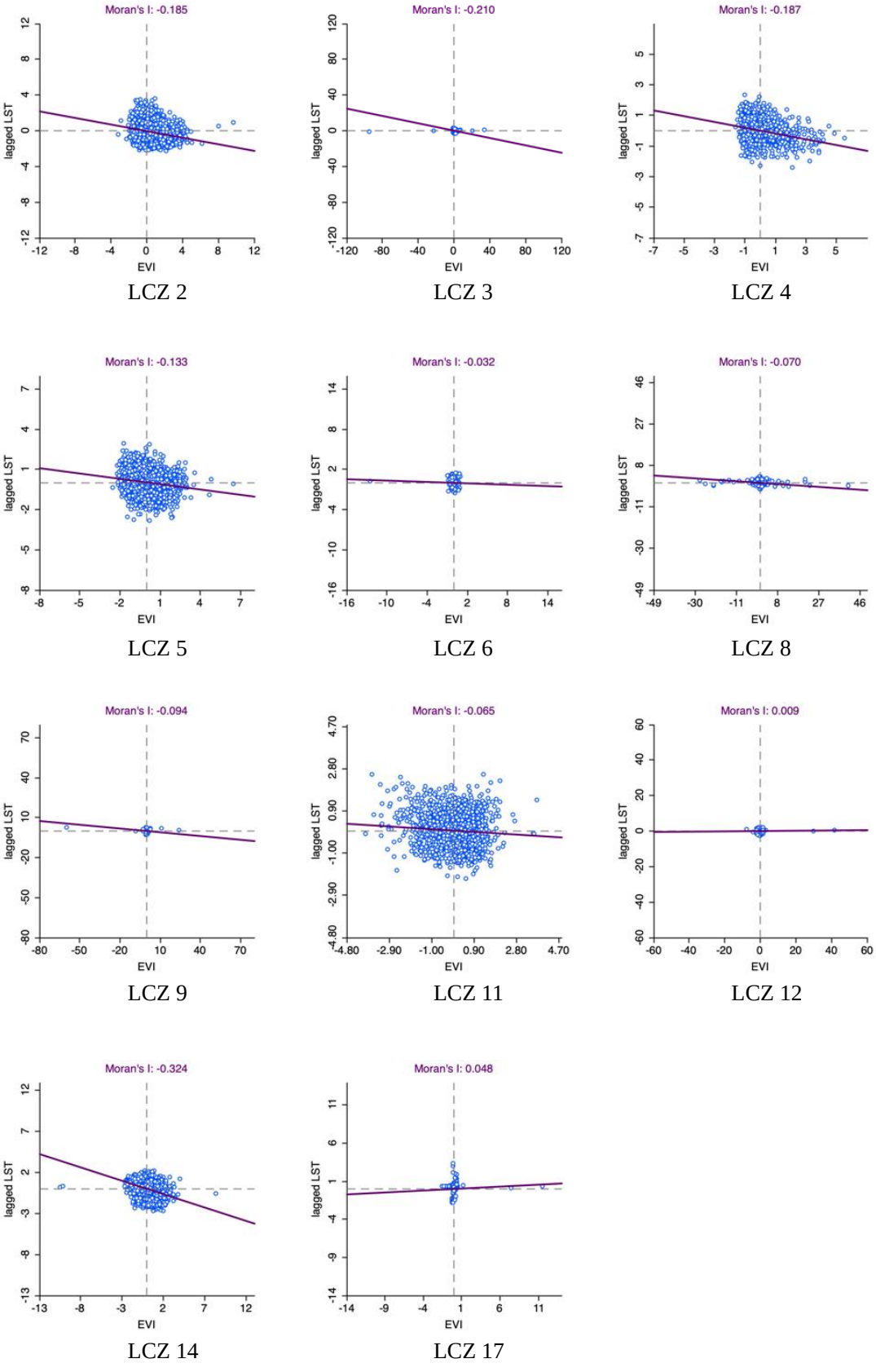


Figure S2.4 The correlation of Addis Ababa's LST and EVI in different LCZ during rainy season

Addis Ababa Dry Season

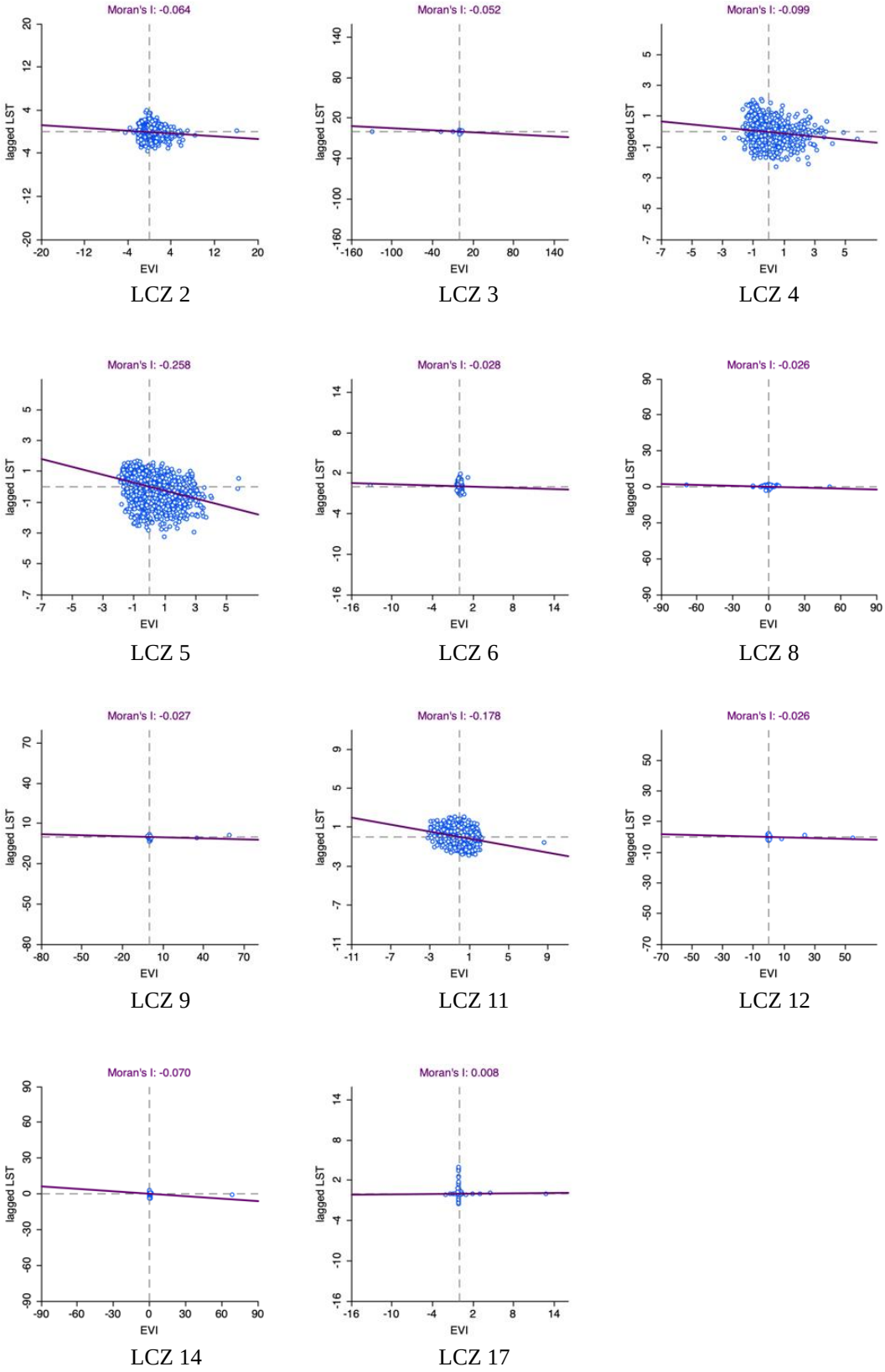


Figure S2.5 The correlation of Addis Ababa's LST and EVI in different LCZ during dry season

Kampala Rainy Season

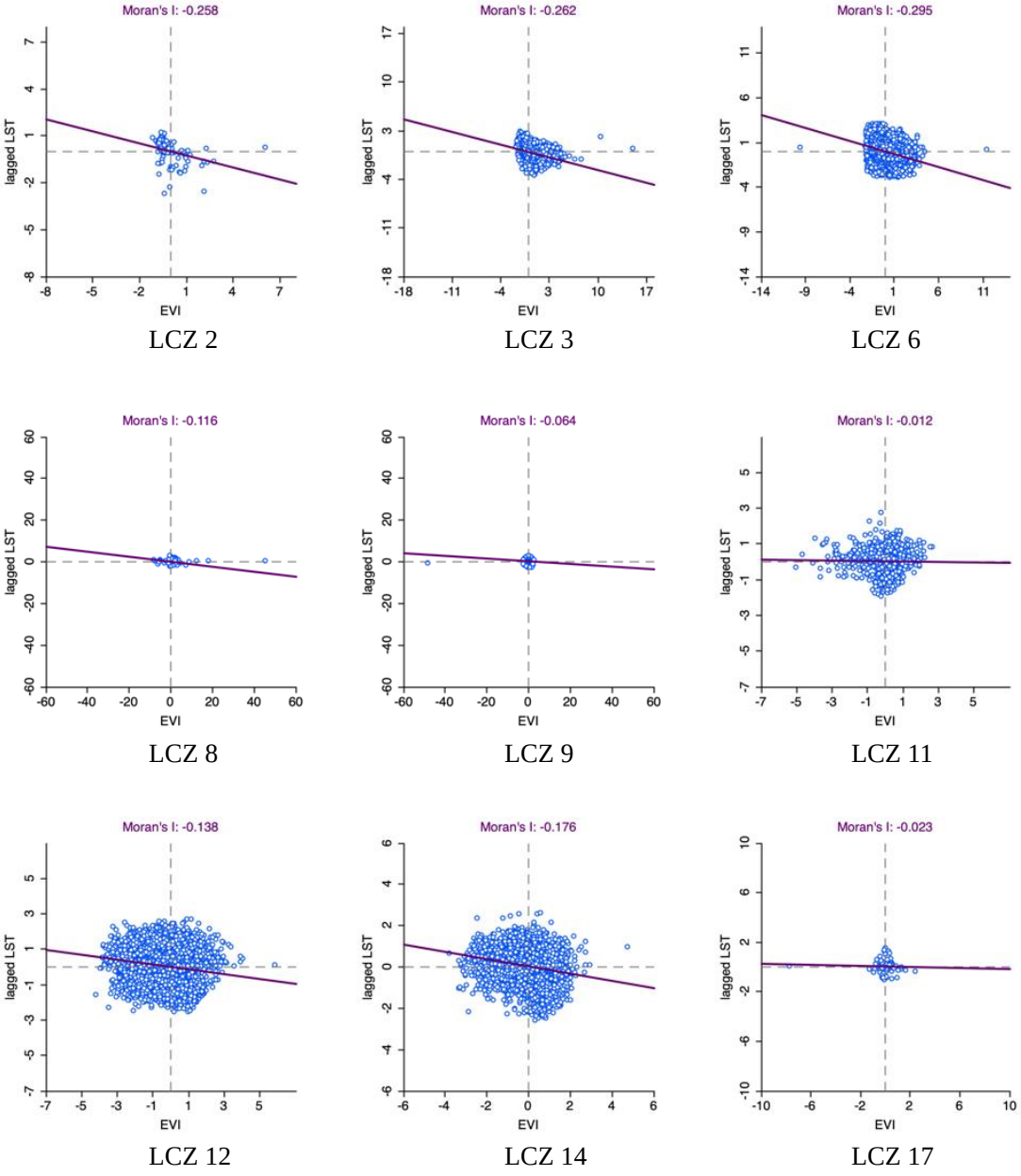


Figure S2.6 The correlation of Kampala's LST and EVI in different LCZ during rainy season

Kampala Dry Season

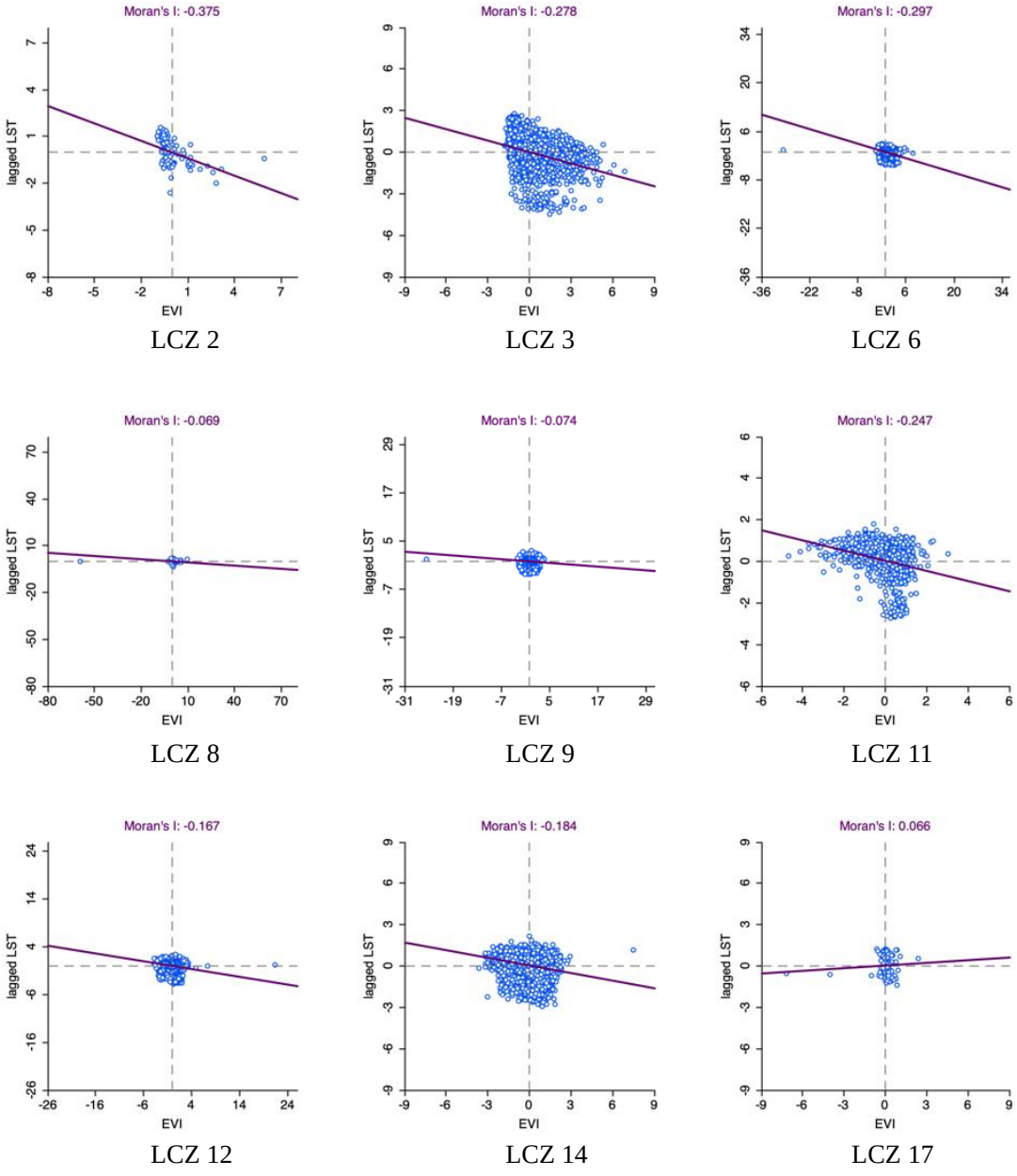


Figure S2.7 The correlation of Kampala's LST and EVI in different LCZ during dry season

Dar es Salaam Rainy Season

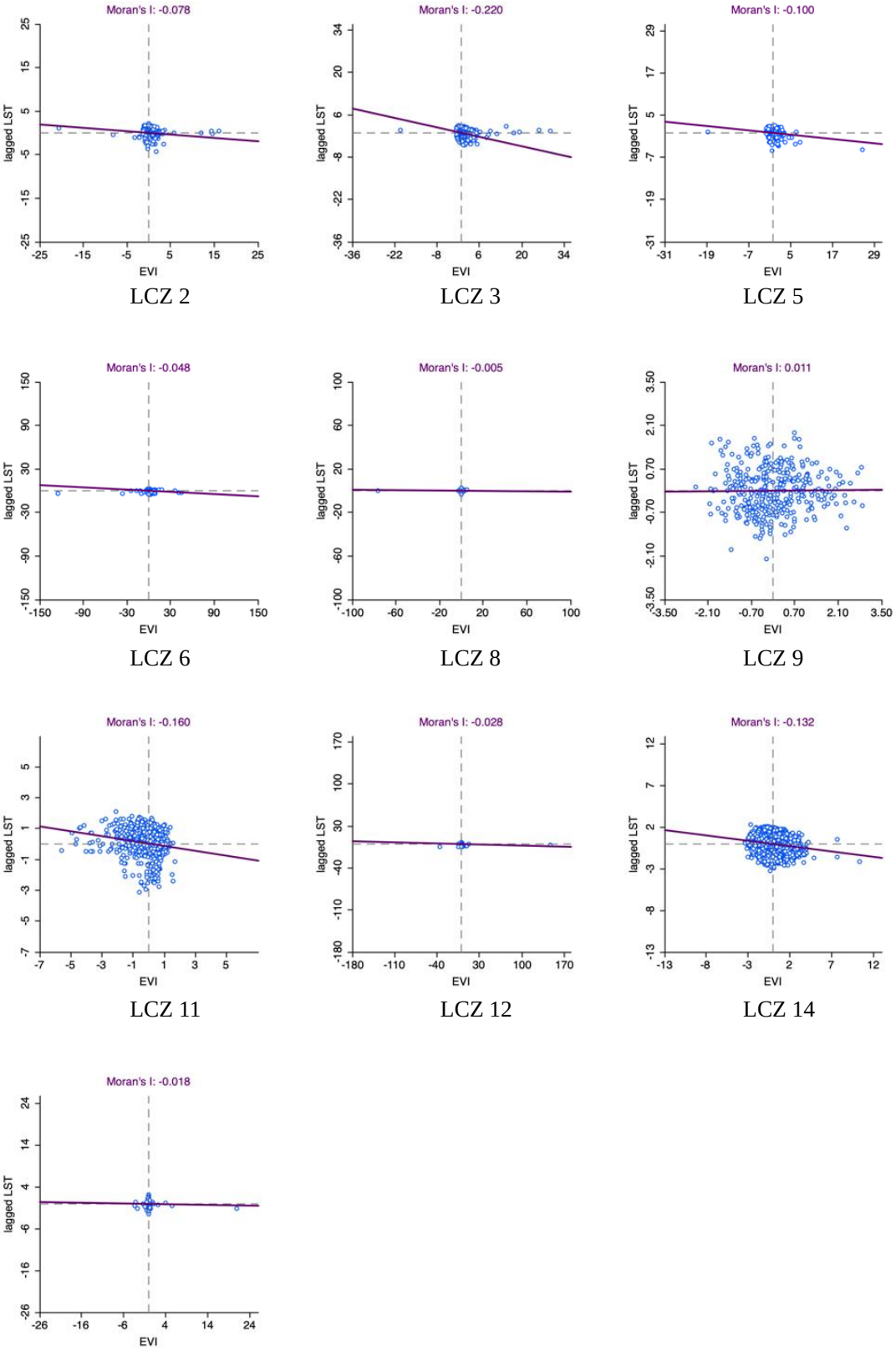


Figure S2.8 The correlation of Dar es Salaam's LST and EVI in different LCZ during rainy season

Dar es Salaam Rainy Season

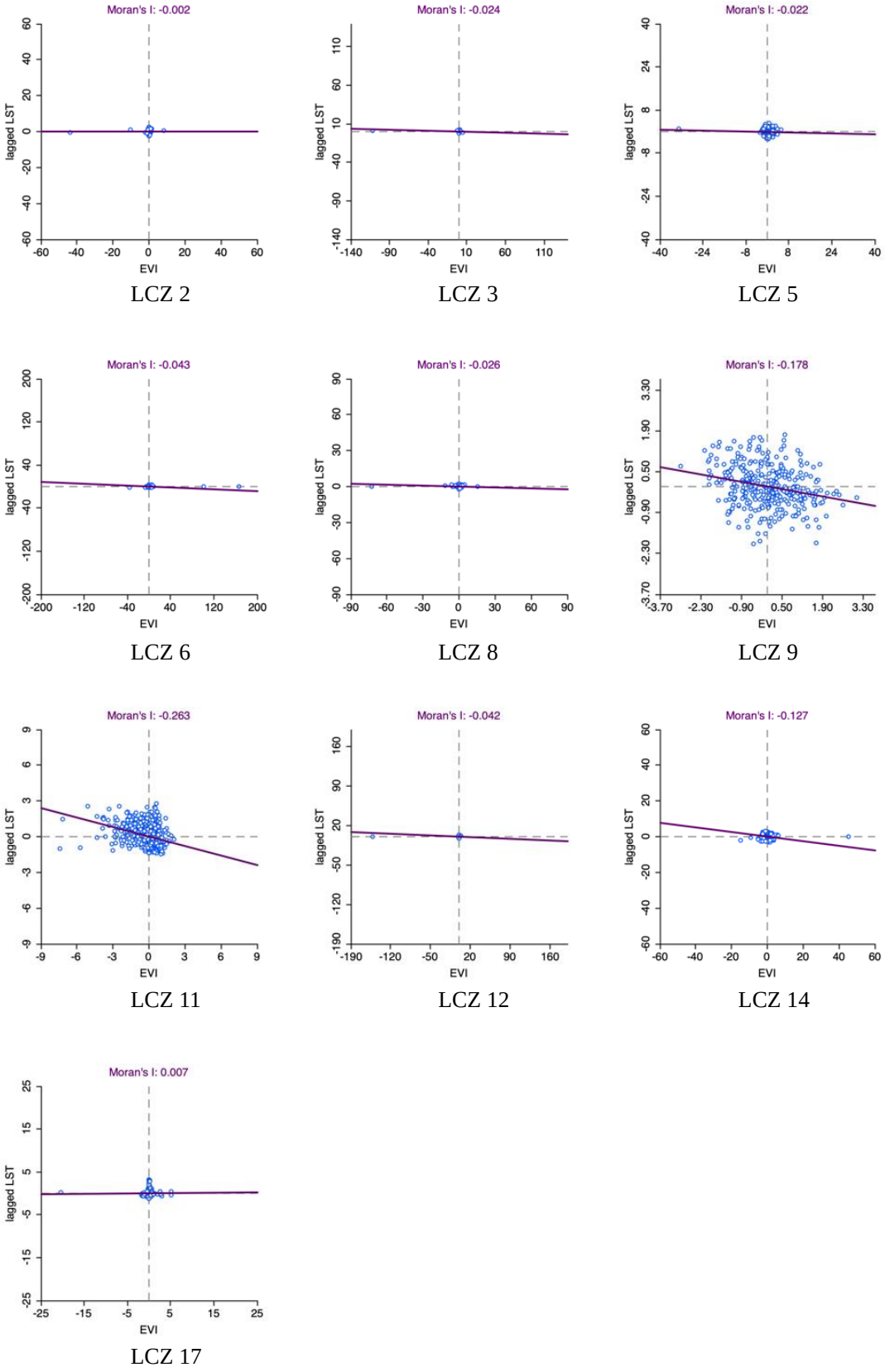


Figure S2.9 The correlation of Dar es Salaam's LST and EVI in different LCZ during dry season