



## Master of Urban Climate & Sustainability (MURCS)

---

# Assessment of intra-city urban heat island effect in relation to vulnerable stakeholders in Karachi, Pakistan via LCZ classification, Land Surface Temperature analysis and traverse surveys

**Marina Khan**

**August 2020**



## Master of Urban Climate & Sustainability (MURCS)

---

# Assessment of intra-city urban heat island effect in relation to vulnerable stakeholders in Karachi, Pakistan via LCZ classification, Land Surface Temperature analysis and traverse surveys

Submitted in partial fulfilment of the requirements for the degree of Master's in Urban Climate and  
Sustainability (MURCS)

**Marina Khan**

**August 2020**

Glasgow Caledonian University,  
School of Computing, Engineering and Built Environment, Glasgow Caledonian University,  
Cowcaddens Road, Glasgow, UK

In partnership with  
LAB University of Applied Sciences, Finland &  
University of Huelva, Spain

1<sup>st</sup> Supervisor: Dr Eeva Aarrevaara  
2<sup>nd</sup> Supervisor: Dr Rohinton Emmanuel

## Declaration

*This dissertation is my own original work and has not been submitted elsewhere in fulfilment of the requirements of this or any other award.*

Marina Khan

August 2020

## Abstract

Presently, the urban heat island (UHI) phenomenon and its impacts are gaining momentum as a major research focus in South Asian urban climate literature. However, the case of Karachi, despite recurring heatwaves and increasing temperatures in parallel with sustainability challenges of urbanization, governance, high-density and vulnerable population, lacks in-depth scientific investigations. Hence, this thesis explores the UHI effect in Karachi with respect to the urban morphology and assesses the associated drivers. The methodology employs the LCZ classification, remote sensing data and traverse/stationary devices and establishes the intraurban temperature differences along with temporal UHI intensity, hotspots, and heat sinks. The built form explored via LCZ classification identified a disproportionately heterogenous presence of all 17 LCZ classes with a significant mix of compact built-up classes in the city's urban core along with a terrible lack of blue-green infrastructure. While the summer 2019 Land Surface Temperature along with traverse surveys carried out during the winter 2020 (January-February 2020) established the temperature anomalies among LCZs and the overall UHI magnitude. During the traverses, the nocturnal UHI magnitude was observed to be much higher than that of the day, with the maximum UHI magnitude of 3,0°C during nighttime and 1,5°C during the daytime. Moreover, the high-rise buildings presented with conflicting temperature patterns and served as the heatsinks in the day and the hotspots at night-time. Moreover, in combination with vegetation covers, they enhanced the cooling effects in different LCZ classes during the day. Meanwhile, the UHI effects were consistently found to be prevailing in the compact low-rise (LCZ3) zones.

This study also attempted the extrapolation of future growth/trends and anticipated intense densification in future which may push the UHI effect up, insinuating a likeliness for worse climatic impacts. The critical zones thus identified were simulated for mitigations in ENVI-met and quantified in terms of air temperature and MRT values to determine the degree of efficacy in various mitigation scenarios. Whereby, the midrise densifications seemed like a stable middle ground among density enhancement and climatic repercussions. Along with the midrise density recommendations, the cooling implications of mixed LCZs may also offer opportunities for policies in urban planning in avoiding the exaggerating UHI effects in future and may suit the practical realities of the heterogenous developing cities.

## Dedication

This is for my family, especially my dearest mom, and friends for being my constant supports at every stage of this master's degree and beyond.

This master's degree is very close to my heart and has been an absolute roller coaster ride in terms of learning, transformation, discovering new friends and family, exploring the world and feeling utmost joy! I believe, both my advisors have been a continuous source of guidance, mentorship, and academic advice all through this time, which I genuinely acknowledge and thank them for.

Lastly, to my city and all the people from Karachi, for their perseverance and sisu! You will ever remain my motivation and inspiration!

## Acknowledgements

Specifically, grateful to my MUrCS supervisors and respective organizations for encouragement and support provided during the progress of the work. Also, thankful to Pakistan Meteorological Department for facilitating the weather data free of cost for the purpose of this study.

# Contents

Chapter 1. Introduction .....	1
1.1. Context.....	1
1.2. Rationale/ Problem Statement.....	1
1.3. Aims.....	2
1.3.1. Objectives .....	2
1.4. Methodology .....	3
1.5. Structure.....	3
Chapter 2. Literature Review .....	5
2.1. Background.....	5
2.2. The Big Picture- Climate Change, Urban Form and Its Effects, and Vulnerability.....	5
2.3. Previous Studies- Regional to Local Overview .....	6
2.3.1. Previous Studies in South Asia .....	6
2.3.2. Previous studies in Pakistan and Karachi.....	8
2.4. Urban Climate and its Influences.....	9
2.4.1. Urban Developments and UHI Effect.....	9
2.4.2. Influence of City Design, Street Geometry and Outdoors Spaces .....	11
2.4.3. Land Use Classifications.....	12
2.4.4. Comparison of WUDAPT vs GIS.....	12
2.5. Materials and Methods for Field Measurements.....	13
2.6. Mitigation Pathways .....	14
2.6.1. Outdoor Thermal Comfort .....	15
2.6.2. Simulation Approaches .....	15
2.7. Learnings.....	16
Chapter 3. Methodology .....	17
3.1. Context-.....	18
3.1.1. Climate and Physiography .....	19
3.1.2. Density and Land use/Landcover.....	20
3.1.3. UHI, Heatwaves and Karachi.....	21

3.2. Sources of Data .....	22
3.2.1. LCZ Mapping.....	22
3.2.2. Linking LCZs with LST.....	25
3.2.3. Meteorological Surveys .....	26
3.2.4. Meteorological Data.....	30
3.4. Simulations.....	30
3.4.1. Scenarios for Mitigation.....	31
3.4.2. Site Selection .....	31
3.4.3. Simulation Parameters .....	32
3.5. Analysis Protocol .....	33
Chapter 4. WUDAPT LCZ Mapping, LST and Traverse Survey Results .....	34
4.1. LCZ Mapping Results and Discussion.....	34
4.1.1. Accuracy Assessment .....	37
4.2. LST Results and Discussion .....	37
4.3. Traverse Survey Results .....	40
4.3.1. The IUHI Magnitude.....	40
4.3.2. Relative Differences in Temperature among LCZs .....	41
Chapter 5. Analysis of Current Conditions.....	45
5.1. Trend Identification .....	45
5.1.1. Simulating LCZ Maps for 2009 and 2019 .....	45
5.1.2. LCZ Change Trends and Discussions.....	46
5.1.3 Future LCZ Development and Implications for Urban Planning.....	48
5.2. Collective Results for LCZ map, LST, Traverse Surveys.....	50
5.2.1. Summarized Results.....	50
5.3. Street Canyons and Thermal Comfort .....	51
5.3.1. Scenarios Investigated for Thermal Comfort.....	51
5.3.2. Results.....	54
Chapter 6. Options to Enhance Climate-Sensitivity of Karachi .....	55
6.1. Discussions .....	55



6.1.1. Positive Trends vs Negative Trends.....	55
6.1.2. High-Density/Population Debate .....	56
6.1.3. Disproportionate Vulnerability and Adaptations to UHI Exposure .....	57
6.2. ENVI-met Simulations Results- Comparison of Mitigation Strategies .....	58
Chapter 7. Conclusions and Limitations .....	60
7.1. Results.....	60
7.2. Conclusions.....	61
7.3. Limitations .....	62
Chapter 8. Bibliography.....	63

## Figures

Figure 1. Deaths (white dots) reported during the Karachi heatwave 2015, and the union councils’ vulnerability ratings (1-6 = low vulnerability in yellow to high vulnerability in red). Source: CDKN, (2017) .....	2
Figure 2. Methods and approaches used in UHI research in South Asia. Source: Kotharkar, et al. (2018) .....	9
Figure 3. The research design steps .....	17
Figure 4. Location of Karachi in red (a) in Pakistan and (b) in the southern province of Sindh. ....	18
Figure 5. Karachi Climate Graph. Source: climatemps.com (2020).....	19
Figure 6. High-density urban morphology of Karachi. Source: Compilation of own images and Google Earth open source data. ....	21
Figure 7. LULC map of Karachi, 1998-2018. Source: Raza et. al. 2019.....	21
Figure 8. Calculation of Land Surface Temperature from Landsat8 images .....	26
Figure 9. (a) Device mounted on the fixed location, (b) mobile stations and (c) the insulated and ventilated cardboard box for daytime surveys. ....	28
Figure 10. (a) Karachi on the Google map, (b) Karachi LCZ map and (c) focused route location in the city .....	29
Figure 11. The case study; Moosa colony, Karachi. (a) Building footprint (from Google Earth™), (b) ENVI-met representation. Grid cells in ENVI-met panel are 1 × 1 m; numbers in grid cells: building height (m). Grey/black lines: change in building height (m). Grey/black lines: change in building height between adjacent buildings; SS: Deciduous tree; DS: Palm tree and (c) 3D view of the ENVI-met model. ....	32
Figure 12. WUDAPT LCZ map of Karachi, 2019.....	35
Figure 13. LCZ3 and its different forms. (a) Moosa Colony, low-income informal residential which may have infusion of lightweight materials; (b) F.B. Area, mid-income planned residential; (c) PIB colony, low-income planned residential. Source: Google Earth, pro. 200m.x200m .....	36
Figure 14. Road network vs Built-up LCZ juxtaposition, 2019 .....	36
Figure 15. LST map for Karachi, June 2019.....	39
Figure 16. LCZ 6-Range of spatial arrangements and associated LSTs .....	40
Figure 17. LST juxtaposition with and without the road network, April 2019.....	40
Figure 18. Temperature difference(°C) profiles from fixed station during traverse surveys across the city routes. ....	43
Figure 19. Temperature difference(°C) patterns in LCZs during traverse surveys.....	44
Figure 20. LCZ maps of Peri-urban Karachi, 2009 & 2019 .....	47
Figure 21. (i) Case 1, Central Business District- Commercial Area; (ii) Case 2, Bahadurabad- Residential Area; (iii) Case 3, (a) Moosa Colony and (b) Memon Colony- Residential Area. Source: Google Earth Pro. ....	52
Figure 22. Comparison of (a) Air temperatures and (b) Mean Radiant Temperature for different UHI mitigation scenarios measured at 1.5 m above the street. The x-axis is hrs. of the day, the y-axis is the temperature in °C. ....	59
Figure 23. Air Temperature patterns (1.5 m above street surface) for the site. ....	59

## Tables

Table 1. Description of LCZs as adjusted in Karachi. Source: A. LCZ images from Stewart & Oke (2012) adjusted; B. Google Earth Pro, circle area covering 200 m radius; C. Field survey; D. Own elaboration. ....	25
Table 2. Satellite Images acquired for LST analysis.....	25
Table 3. Summary of measurement equipment installed on both the platforms.....	27
Table 4. Itinerary details .....	29
Table 5. Input details for ENVI-met simulations.....	33
Table 6. LCZ Statistics-2019 .....	36
Table 7. UHI magnitude on various routes (°C) .....	41
Table 8. LULC statistics, 2009 and 2019.....	47
Table 9. LCZ Change statistics, breakdown of built-up 2009 and 2019.....	48
Table 10. Projected daytime temperature differences.....	49
Table 11. Projected night-time temperature differences .....	49
Table 12. Comparative summary of the T <sub>Air</sub> pattern in LCZ 1-6 .....	50
Table 13. Case 1, LCZ1 & 4, Central Business District- Commercial Area .....	52
Table 14 .Case 2, LCZ1-Residential Area .....	53
Table 15. Case 3, LCZ 3 Residential Area .....	53

## Glossary

<i>AR</i>	Aspect Ratio
<i>CLHI</i>	Canopy Layer Heat Island
<i>GI</i>	Green Infrastructure
<i>H/W</i>	Height to width ratio
<i>IUHI</i>	Inter-LCZ UHI
<i>LCZ</i>	Local Climate Zone
<i>LCZC</i>	Local Climate Zone Change
<i>LST</i>	Land Surface Temperature
<i>LULC</i>	Land Use and Land Cover
<i>MRT</i>	Mean Radiant Temperature
<i>NDVI</i>	Normalized difference vegetation
<i>PMD</i>	Pakistan Meteorological Department
<i>RH</i>	Relative Humidity
<i>SUHI</i>	Surface Urban Heat Island
<i>SLHI</i>	Surface Layer Heat Island
<i>T<sub>Air</sub></i>	Air temperatures (°C)
<i>UHI</i>	Urban Heat Island
<i>USGS</i>	US Geological Survey
<i>WUDAPT</i>	World Urban Database and Access Portal Tools

### **1.1. Context**

Despite struggling with sustainability issues for the past two decades, Pakistan continues to face exacerbating climate change challenges and ranks among the top ten most affected countries by the global climate risk index and fatalities (Germanwatch, 2018) bearing setbacks of billions of dollars to its economy (ADB, 2017) and losing millions in human resource (DAWN, 2019; Express Tribune, 2020). Meanwhile, Pakistan's economic capital 'Karachi' is home to 18 million people (CDGK, 2007) and forms 10% of Pakistan's entire population and 22% of its urban population (Hasan, 2016). The city is massively beset by a crisis of governance visible in the destitute state of service delivery (World Bank, 2018), unplanned and unsustainable urbanisation trends and extreme climatic strain on the local population (Hassan, et al., 2015). The current shortcomings and challenges have holistically created multi-scaled vulnerabilities which have intensified climate change impacts (Hasan, et al., 2017) and environmental problems (Qureshi, et al., 2010).

### **1.2. Rationale/ Problem Statement**

In the recent years, Karachi has faced repeated deadly heatwaves characterized by consistently high temperatures that has left little relief to the local people (CDKN, 2017). During such an episode in 2015, more than 1,200 people died while over 50,000 cases of heat illness were recorded (CDKN, 2017; BBC, 2015; CDKN, 2015; Salim, et al., 2015). However, such an event was not a onetime incident and has persisted over the recent years. Moreover, these deaths were observed to be disproportionately distributed in certain towns and areas of Karachi (CDKN, 2017), as shown in figure 1. This variance in susceptibility to climatic effects hints to the inconsistent levels of preparedness and response to climatic extremes and invites attention to the local drivers of such urban climatic conditions. Meanwhile, the IPCC warns that the growing cities, particularly in the low and mid-income countries such as Pakistan, have been escorted by the intense growth of highly vulnerable informal urban communities, where most of them end up living on highly risky lands of extreme weather (Field & Barros, 2014). Unfortunately, the city of Karachi is one such example. It's not surprising that surveys and statistics project a huge population (Bradnock & William, 2002) residing in informal settlements in Karachi including slums and squatter settlements of the inner city along the beds of drainage channels and rivers as well as in the growing urban sprawl (Hasan & Mohib, 2003). Further, the consistent growth of this vulnerable group (The Express Tribune, 2018) is a serious cause of concern as the IPCC suggests that the disadvantaged populations are at disproportionately higher risk of harmful outcomes of global warming (IPCC, 2018). The main trends that collectively add to the vulnerability in Karachi are: unplanned densification, poor governance, and in-migration (Hasan, et al., 2017). And thus, the resulting unregulated land-use trends call for immediate attention at various fronts (IIED, 2015). In this context, the exacerbating climatic challenges are a severely urgent issue, most

importantly for the vulnerable stakeholders living in underserviced poorly constructed informal settlements (Hasan, et al., 2017).

By far, the case of Karachi presents little to no scientific exploration in this crucial issue. Hence, the given situation implores one to investigate the Urban Heat Island (UHI) affect, its hotspots, the planning aspects and the local climatic changes brought about by the urban variables to determine mitigation strategies, plans and approaches for the resiliency of the stakeholders.

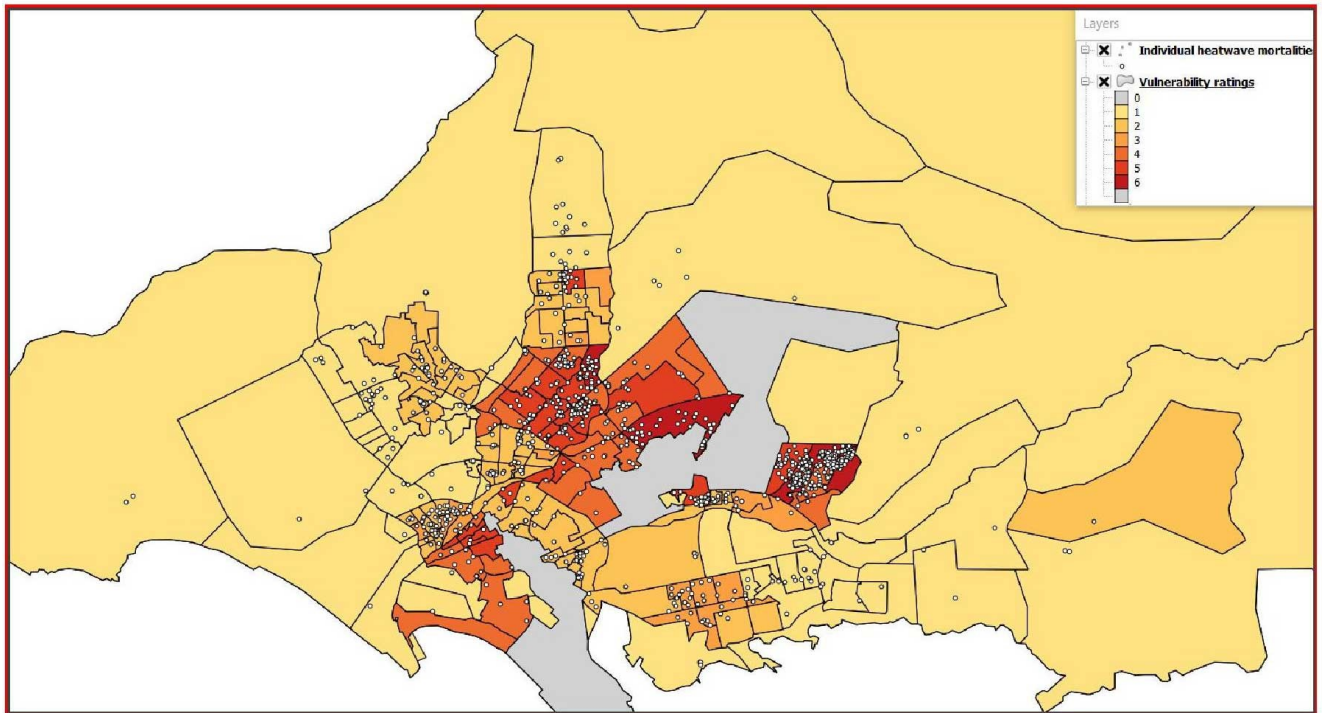


Figure 1. Deaths (white dots) reported during the Karachi heatwave 2015, and the union councils' vulnerability ratings (1-6 = low vulnerability in yellow to high vulnerability in red). Source: CDKN, (2017)

### 1.3. Aims

The aim of this work is to study the impact of urbanization in strengthening the UHI effect in the city of Karachi, and to evaluate the intra-city canopy layer UHI in relation to the prominent determinants such as urban land use/land cover, population, and urban morphology etc. to identify the critical high risk areas.

#### 1.3.1. Objectives

- a) To critically review the literature to identify key urban development/growth factors influencing UHI in South Asia with a specific focus on Karachi and to examine the current data and knowledge gaps to outline methodologies, their relevancy and contextual appropriation for Karachi.

- b) To document the variation of intra-city/ inter-LCZ UHI and assess the thermal anomalies through traverse and fixed survey stations
- c) To locate the microscale hotspots and cold spots present in the heterogeneous urban fabric at various times.
- d) To explore the associated drivers in UHI development such as land use, building density, population density and vegetation etc. for evaluation and repercussion assessment.
- e) To extrapolate how future growth in the city may impact the UHI effect and warming patterns.
- f) To explore mitigation strategies for complex heterogeneous environments for building resilient infrastructure systems to climate-related shocks.

## **1.4. Methodology**

This study employs mixed methods for documentation/mapping, data collection, analysis and mitigations informed by a detailed literature review. Mainly, the Local Climate Zone (LCZ) classification is adopted to analyze the urban morphology and the corresponding UHI effects which is facilitated by the World Urban Database and Access Portal Tools (WUDAPT). While the intracity UHI magnitude and temperature difference assessment is carried through Land Surface Temperature (LST) datasets in GIS substantiated with data collected through field (fixed and traverse) surveys during January and February 2020. This is followed by data analysis using various formats like percentage-based area assessment, interpolation of thermal effects and extrapolation of heating patterns, etc., thereby leading to the identification of critical areas. Eventually, the literature guided mitigations are explored for the critical areas through micro-modelling using ENVI-met to quantify efficacy and thus propose recommendations. The software tools/devices employed for the data collection, segregation and analysis include WUDAPT Saga, Google Earth Pro, ArcGIS, ENVI-met, Leonardo, MS Excel, Tinytag Plus 2 (TGP-4500), Tiny Tag explorer etc. Lastly, the conclusion gathers a holistic picture of the research and identifies the usefulness of the research methodology, followed by recommendations to stakeholders and conclude future research pathways.

## **1.5. Structure**

The chapter 1 establishes the rationale for this research in the context of Karachi and identifies the key aims and objectives. This is followed by a literature review in chapter 2 that serves as the backbone for this thesis. The detailed review informs three main areas i.e., ‘the scope of this research in the local context’, ‘the previously used methodologies’, and ‘urban form and its influence on the climate and its drivers’. This will not only locate the case of Karachi in the south Asian context but will also identify holistic as well as particularly appropriate

strategies from similar settings and highlight the best procedures/software tools for the data collection and analysis.

Chapter 3 then establishes the context of Karachi in terms of land use, climate, density and physiography followed by details of the most applicable methods, as identified by the literature review, used in this study and their intended outcomes such as the LCZ classification mapping to identify the dominant land uses in the city, etc. It also informs analysis protocols at each stage and limitations.

Chapter 4 takes forward the results of these processes after which chapter 5 follows deeper analysis, discussions and relationships to identify the most critical zones on the city such as various urban canyons and building heights being evaluated to understand their relation to population density, temperature, and thermal comfort.

Chapter 6 then explores the positive and negative dynamics of the current scenario to enhance the climate sensitivity of Karachi and evaluates the appropriation of the mitigations in the identified critical zones via ENVI-met modelling. This eventually leads to the successful strategies and possible recommendations for various levels.

Lastly, Chapter 7 is the conclusion which identifies the success of the overall approach opted for along with an introspection into future possibilities for research.



## 2.1. Background

In the urban climate literature, the study of UHI is not a new subject and has been well and widely explored globally (Arnfield, 2003; Gartland, 2008; Cardoso, et al., 2018) across its origin, causes and mitigations via on site investigations, remote sensing applications as well as numerical and physical models (Ramakreshnana, et al., 2019). Consequently, there is a notable collection of observational heat island studies (Stewart, 2011). Although the first of the UHI studies was recognized in London (Howard, 1833; Mills, 2008), due to the heatwaves persistency in the last decades and its potential threats, the study of this phenomenon has expanded to thousands of cities (Zhou, et al., 2017) in Europe, China, America, South Asia, etc, albeit there've been concerns regarding the methodology, reporting and the accuracy associated with them (Stewart, 2011). The scope of such studies is particularly apt for regions with a UHI presence throughout the year (Jonsson, 2004), including several south Asian cities. Moreover, given that the climate change and its unmitigated cum unprecedented combination of severe natural hazards are presenting a serious risk in South Asia (Im, et al., 2017), recently the number of the UHI studies has increased immensely in the region. However, the research scope shows quite a limited capacity i.e., only quantifying the UHI phenomenon and lack of in-depth explorations (Kotharkar, et al., 2018). While, Pakistan despite being home to few of the most populous cities lags far behind in UHI studies (Kotharkar, et al., 2018). It must be noted that globally, there is a substantial development made in surface UHI mapping of cities located in humid and temperate regions, but such studies are still quite limited in arid and semi-arid areas (Rasul, et al., 2017). And even though the south Asian studies seem to be leaning towards tropical-climatic studies, it's substantiated that not only is there a lack of studies on the urban thermal comfort, the existing work is biased and more inclined towards descriptive studies (Perera & Emmanuel, 2016). Therefore, for Karachi as an arid south Asian city, this literature review is informed through a global overview of methodologies, and then particularly locates these practices in the context of South Asia and/or Pakistan. This is to establish a relative as well as general understanding of UHI approaches and to allow comparative references along with finding possibilities for the appropriation.

## 2.2. The Big Picture- Climate Change, Urban Form and Its Effects, and Vulnerability

The global urban population is projected to reach 68% in the next 2 decades (UN, 2018) which will consequently cause an expansion in the urban areas (The World Bank, 2020). It is anticipated that this increase will not only exacerbate issues pertaining to resilience and sustainability for countries with highly concentrated urban populace (Romero-Lankao, et al., 2016) but also poses a responsibility towards implications of this urban expansion (Filho, et al., 2016). Moreover, it may not only give rise the UHI effect but also add to higher urban energy consumption, raising the peak electricity demand and eventually cause lower thermal comfort amplifying risks to human health

(Wang & Akbari, 2016). More recently, the global climate change and its impacts are exaggerating the episodes of extreme heat, their frequency, intensity, and duration (Meehl & Tebaldi, 2004; Alexander & Arblaster, 2009; Collins, et al., 2013), including countries commonly considered cold (Wang, et al., 2015). Such conditions not only further prolong and amplify due to the presence of UHI (Butera, 2010; Leconte, et al., 2015) adding strain on resources (WHO, 2020) but also outline tremendous effect on human health particularly for highly populated urbanized and sprawling cities (Shi, et al., 2018). They may trigger dramatic consequences if proper mitigation measures are not taken (Sherwood & Huber, 2010). It is no surprise that the incidences of heat-related illness and mortality are becoming more common lately (McMichael, 2000; Sailor, et al., 2002; Tomlinson, et al., 2011) and have caused thousands of deaths in various parts of the world (Katsouyanni, et al., 1988; Kosatsky, 2005; Solecki, et al., 2005; Hass, et al., 2016; Taleghani, 2018; Khan, et al., 2019; WHO, 2020). The impacts have been more concentrated in cities where the housing practice has exposed the vulnerables (Demuzere, et al., 2019) with a greater susceptibility for disadvantaged groups towards future morbidity and higher mortality (Nazrul Islam & Winkel, 2017). Although heatwaves are regarded as the first natural cause of mortality (Taleghani, 2018), the studies go on to substantiate the relativity of temperature increase in relations to increased mortality rate such as in Canada and Netherlands (Wang, et al., 2015). With such dangerous repercussions in the developed contexts, it is alarming to even think what impact temperature increases would have in the poverty stricken UHI prevalent developing cities (Ramakreshnana, et al., 2019), especially when the scope of vulnerable population goes much beyond the old and very young, severely bending towards those with low socioeconomic status and health compromised (McMichael, 2000; Solecki, et al., 2005; WHO, 2016). This implores a reconsideration of policies for climate-related threats in the developing cities (McMichael, 2000) and calls for a strategy review to reduce the magnitude of human costs.

## **2.3. Previous Studies- Regional to Local Overview**

### **2.3.1. Previous Studies in South Asia**

The heatwave related incidences have been reported to increase in South Asia more recently (Khan, et al., 2019) effecting the urban areas with impacts such as heat-related deaths, food and water shortages, etc. (IPCC, 2014). And with this claim, South Asian cities being home to approximately 15 % of the total urban population (Kotharkar, et al., 2018), the UHI serves as a severely prominent urban environmental concern (Surawar & Kotharkar, 2017). Although the research publications have greatly increased in the recent years for south Asian cities (Kotharkar, et al., 2018), most of these studies primarily rely on the observations of surface temperature instead of ambient air temperature (Jacobs, et al., 2019). Meanwhile, the investigations on outdoor thermal comfort are still fairly scarce (Kotharkar, et al., 2018) given that this region is deemed to be a climate change hotspot juxtaposed with a massive concentration of vulnerable, poor, or marginalized population (De Souza, et al., 2015). And despite such studies, though few, the results of urban climatology fail to be communicated efficiently or well understood by city planners (Perera & Emmanuel, 2016).

In spite of these faults and failures, detailed examination has allowed introspection into the diversity in range as well as the validity of methodologies for various scales, contexts and foci such as LCZ classification and its heating impacts (Perera & Emmanuel, 2016; Perera, et al., 2012), Land Use and Land Cover (LULC) classification with respect to LST variations (Surawar & Kotharkar, 2017), LCZ and thermal comfort analysis via fixed stations (Kotharkar, et al., 2019) and density/ street canyon-based modelling simulations for thermal comfort analysis along with mitigation options (Emmanuel & Fernando, 2007; Vidanapathirana, et al., 2017; Emmanuel, et al., 2007), etc. However, in terms of field measurement surveys for the assessment of canopy layered UHI, there are a few examples one can find exploring traverse surveys and UHI magnitude assessment (Yadav & Sharma, 2018) juxtaposed with LCZ classification (Kotharkar, et al., 2019; Jacobs, et al., 2019; Kotharkar & Bagade, 2018) and LULC classification (Kotharkar & Surawar, 2016).

Among these studies includes one study from India, Delhi which looks at spatial variations of intra-city UHI via mobile surveys through the kriging interpolation via ArcGIS. The study drew comparisons from different times, seasons and locations to determine the variability of temperatures (Yadav & Sharma, 2018). While another study in Colombo introspects into the influence of high-density developments on the street level utilising the LCZ classification to identify the critical zones (Vidanapathirana, et al., 2017). However, given the complexly built heterogenous form of Karachi, the extensively adopted LCZ classification seems like a viable strategy for land use classification to examine the induced canopy layer temperatures (Kotharkar & Bagade, 2018). The case of Nagpur with similar heterogeneous urban fabric seems useful where the city is studied across various LCZ (Kotharkar & Bagade, 2018) and land use/ cover typologies (Surawar & Kotharkar, 2017) explored via traverse surveys. These studies established the intra-city UHI differences and validated the impact of the population density on the UHI formation with the most prevailing Canopy UHI effects found in high building density with less vegetation and high population density areas (Kotharkar & Surawar, 2016). Contrarily, Emmanuel & Fernando (2007) in their study in Pettah, Sri Lanka found the best thermal comfort in high-density developments and suggested the density enhancement as a practical UHI mitigation choice in warm cities (Emmanuel & Fernando, 2007). They argued that the approaches that lead to better air temperature effects may not certainly create better thermal comfort effects and suggested density manipulations (as a result of shading) highly capable of enhancing the urban thermal comfort (Emmanuel, et al., 2007). Although, these studies acknowledge the role of changes in land cover and the corresponding vegetation cover and population density distribution towards the UHI formation, there are conflicting views in terms of 'high-density' being a positive and/or negative influence for UHI and thermal comfort. Therefore, such views need to be evaluated in case of Karachi to find the validity of these claims in the local context. However, contrary to Karachi, Nagpur is a compact city with a population of approximately 2 million people, meanwhile Pettah/Colombo also significantly differs in the scale as Karachi is huge in size and population. Hence, cases such as Delhi and/or Dhaka appear to be more relevant in scale and density. On the other hand, considering comparative studies in south Asia, assessments have been developed among major cities, particularly in outdoor heat exposure pattern and its effects on the vulnerable populations and informal settlements. One evaluation by Jacobs, et al. investigates intra-urban differences in Faisalabad, Delhi

and Dhaka using observations from mobile and stationary devices while using the same measurement protocol in all cases. The given report examines the LCZ classification to accommodate for the clustering of urban characteristics and their capability to impact the local microclimate. The conclusions affirmed the fact that “the people living in informal neighbourhoods are consistently more exposed to heat than people in richer neighbourhoods” (Jacobs, et al., 2019), as the temperatures are higher in compact and densely built settlements, particularly during the night time. The methodologies opted in this study seem appropriate in terms of scale/size as well as to maintain uniformity with other local analysis methods. Although generally, the UHI study distribution in South Asia are based in India, Sri Lanka and a few in Pakistan, these lack precise references for arid cum coastal cities like Karachi and are more inclined towards tropical studies.

### **2.3.2. Previous studies in Pakistan and Karachi**

Apart from studies based in south Asia, the UHI body of literature in Pakistan is almost non-existent with only a few observational studies across big cities like Karachi, Faisalabad, and Lahore. Sajjad, et al. (2015) analyse the long-term annual and seasonal temperature trends using linear regression over a period of 40 years for Lahore (Sajjad, et al., 2015), while Azeem, et al., 2016 use remote sensing and GIS techniques to compare the LST among the land cover typologies. Such LST based assessment with reference to vegetation density and other urban parameters have affirmed a significant presence of UHI in more developed highly built-up areas as compared to the surrounding areas (Azeem, et al., 2016). Meanwhile, there are studies focused on heatwave prediction models and their accuracy. One such study showed that the wind and relative humidity are the key influencers in defining the heatwaves in Pakistan (Khan, et al., 2019). Such observations are substantiated with studies presenting the humidity increase over the years along with its exaggerated impacts of thermal comfort in case of Karachi (Naveed, 2017).

Specific to Karachi, there have been only few studies in the area on UHI. One of these studies investigates the rising temperature trends analysed via time series data from the years 1947 to 2005 (Sajjad, et al., 2009), while the other signifies UHI presence with 5,6 °C to 13,5 °C higher temperatures in the urban areas than the surrounding non-urban areas by using finite volume mesoscale modelling (Sajjad, et al., 2015). While another study investigated on the empirical microclimate analysis of Karachi to draw comparisons with its urban and rural vicinity based on temperature along various interconnected meteorological parameters like precipitation, rainy days, wind, relative humidity, clouds and solar insolation and focused on the 5 types of physiographic divisions within the city (Sadiq & Ahmad, 2010). The study was built on the idea that the general pattern of weather differs accordingly to the micro-geography along with several other factors, including the population, pollution, and infrastructure. Hence, different parts of the city offering different climatic peculiarities and microclimate zones. The study highlighted that although there is an increase in precipitation in South Asia, Karachi doesn't seem to conform to this notion, while the trend of rising temperatures is expected to persist as the climate change impacts intensify (Sadiq & Ahmad, 2010). These studies although sought to analyse and define the origins and effects of UHI phenomena, none of these identify the drivers of higher UHI in Karachi and /or propose prevention or

mitigation approaches. Neither do the above studies shed light on the contributions of anthropogenic activities to the climatic parameters or meteorological variables. Meanwhile, there have been critiques from the local researchers and scholars who blame the recent trend of high-rise buildings for the worsened heatwave and windless conditions (The Express Tribune, 2018). Global microclimate studies also second such arguments that high-rise buildings adversely contribute to the street-level wind flow (Emmanuel & Fernando, 2007). Given that sea breezes have a cooling effect on UHI (Emmanuel, et al., 2007), they argue that not only these developments block breezes particularly along the coast (The Express Tribune, 2018) and complicate the city's water and electricity shortages (Cheema, 2015).

On a positive note, LST, NDVI and LULC (Yasmeen, et al., 2017) along with UHI formation and its effects on environment and population (Khan & Omar, 2014) have been somewhat explored. These studies validate the drastic effects of urbanization and land cover change over the years through GIS comparisons. And although they attempt to shed light on the urban rural UHI difference, the appropriation of scientific approaches in intra-urban UHI assessment such as one of the most widely used frameworks such as LCZ classification and thermal comfort assessment seem entirely absent. Kotharkar, et al. (2018) in their review of south Asian UHI studies, identify Karachi as one of the least developed cities in terms of explorative methodologies of assessment (Kotharkar, et al., 2018), figure 2. That being said, the UHI research domain in Karachi lacks scientific depth with majority of the studies based on urban-rural differences and vegetation vs built-up density analysis.

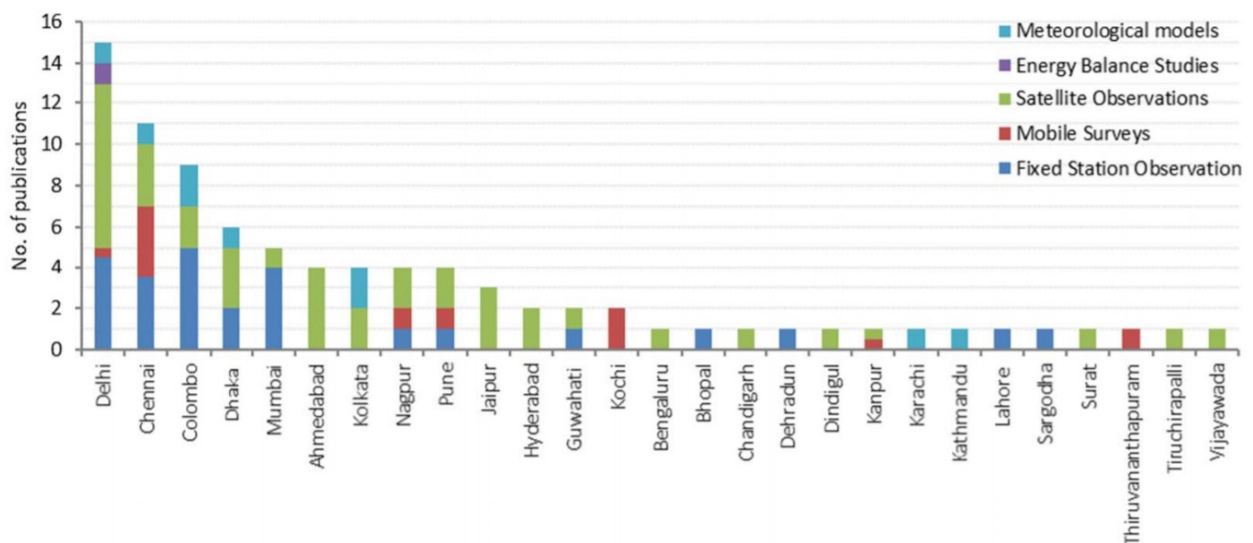


Figure 2. Methods and approaches used in UHI research in South Asia. Source: Kotharkar, et al. (2018)

## 2.4. Urban Climate and its Influences

### 2.4.1. Urban Developments and UHI Effect

The environmental conditions have been incessantly modified in cities to adapt to human interventions (Cardoso, et al., 2018) where these interventions lead to radical land cover changes (Surawar & Kotharkar, 2017). And

consequently, the urban form and structure are closely yet complexly intertwined with the urban climate (Eliasson, 1990) influencing the local climatic conditions (Grimmond, 2007). This effect is called the urban heat island (UHI) effect which is particularly characterized by the increase in the air/surface temperature in urban areas as compared to the surrounding suburban vicinity (Solecki, et al., 2005; Yamamoto, 2006; Synnefa, et al., 2008). While its magnitude is constituted by both, the geographical conditions and meteorological parameters (Yamamoto, 2006) and hence, may be characterized by the uncontrollable and controllable variables (urban morphology and land use, use of material and anthropogenic sources, etc.) (Rizwan, et al., 2008; Leconte, et al., 2020). But, in a heterogeneous urban scenario, the previous UHI description may be insufficient in representing the intra-urban differences between different districts within a big city (Stewart & Oke, 2012; Shi, et al., 2018). And further, the complexity regarding the urban rural dichotomy and selection of an urban area with an external thermal reference in UHI quantification has led to the exclusion of any rural comparison altogether (Martin, et al., 2014). Therefore, UHI effect is also expanded to the variation between the urban temperature thresholds within neighbourhoods in the city's urban limits (Martin, et al., 2014; Hass, et al., 2016). While, the phenomenon is typical to all cities and all climates, regardless of cold or warm (Adinna, et al., 2009), its intensity may vary between and within cities (Hass, et al., 2016) and can construe positive or negative implication depending on the city macroclimate (Stewart & Oke, 2012). However, the city's size, population (Oke, 1973; Taleghani, 2018) and morphology are vital in moderating the UHI magnitude (Roth, 2012) and hence may vary from tropical to temperate climates (Arnfield, 2003) and exhibit higher intensity in case of large-scale cities (Yao, 2013).

Although the UHI may be observed at both, at the surface and in the atmosphere (Erell, et al., 2011), among its 4 sub-classifications (Sun, et al., 2015), the most relevant are the surface layer heat island (SLHI) and the canopy-layer heat island (CLHI), which refer to the relative warmth of the surface and the canopy-layer air temperatures, respectively and may differ in characteristics, intensity, origin, spatial form and temporal behaviour (Erell, et al., 2011). The literature offers a juxtaposed focus on both of these and attributes the relationship between the two as beneficial in understanding the CLHI according to studies of the SLHI (Voogt & Oke, 2003) as the CLHI is more complex due to the direct involvement of various anthropogenic heat/energy flows (Erell, et al., 2011).

It is insinuated that normally the UHI may be 1-3°C warmer, however under proper conditions, it may be as high as 10-15°C (Oke, 1982). However, the heatwave periods further reinforce this effect (Leconte, et al., 2015; Butera, 2010) leading to amplified cost and energy demand (Synnefa, et al., 2008; Stewart & Oke, 2012) to maintain thermal comfort (Adinna, et al., 2009). Due to the wider scope of UHI effects on urban lives and complex generating mechanism with numerous accountable factors (Yamamoto, 2006), increased discomfort and potential threat of heat stress and mortality (Wang & Akbari, 2016) and the likeliness to coincident with the heatwaves in summers (Solecki, et al., 2005), UHI has been the focus of many studies globally (Danylo, et al., 2016; Yadav & Sharma, 2018; Shi, et al., 2018). Though alternatively, the increase in population with inadequate urban planning priorities and a disregard for social and environmental aspects has also caused negative consequences on the urban thermal climate and inhabitant wellbeing (Cardoso, et al., 2018).

#### **2.4.2. Influence of City Design, Street Geometry and Outdoors Spaces**

Cities being the warp and weft of streets, differ in geometry by height/width ratio (H/W), length/width (L/W) and the streets' orientation identified by the long axis (Shishegar, 2013). The impact of street geometry (Eliasson, 1990) and orientation (Al-Sallal & Al-Rais, 2012) contribute immensely to how heat builds up and influences the extent of solar radiation received by the urban surfaces (Arnfield, 2003). While, they also effect the permeability of airflow (Taleghani, 2018; Shishegar, 2013; Al-Sallal & Al-Rais, 2012) along with the cooling potential of the whole urban system (Ali-Toudert & Mayer, 2006). Meanwhile, the outdoor spaces play a vital role to urban liveability as they encourage pedestrian traffic and outdoor activities (Chen & Ng, 2012). However, their usability can be highly impacted due to the deteriorating outdoor thermal environment (Lin, 2009) caused by climate change (Huang, et al., 2018). While alternatively, having a thermally comfortable outdoor design of spaces favours outdoor activities and social vivacity thereby, contributing towards the overall well-being (Fischereit & Schlünzen, 2018). ASHRAE Standard 55 defines thermal comfort as “condition of mind that expresses satisfaction with the thermal environment” (Hensen & Lamberts, 2019), hence identifying the subjectivity in its perception. Meanwhile, literature advocates that the case of thermal comfort is juxtaposed by both, the climatic/environmental and behavioural/personal aspects (Chen & Ng, 2012), and influenced by four ‘environmental’ factors (such as air temperature, relative humidity, wind speed, and radiant temperature) (Ramakreshnana, et al., 2019) as well as solar radiation (Taleghani, et al., 2015; Lin, 2009) and two personal factors (level of clothing insulation and metabolic rate) (Havenith, et al., 2002) to create a subjective, individualized response (IWBI, 2019). Further, it is argued that there are psychological factors involved such as thermal perception, preference and satisfaction (Lin, et al., 2010) and hence may be difficult to measure due to the subjectivity and complexity of the variables involved (Gatto, et al., 2020). In any case, the consideration of thermal comfort is crucial as it impacts the likeliness of people being in the outdoors, particularly in the hot regions (Lin, 2009) and can even potentially expose the people to health risks, stress and vulnerability (Huang, et al., 2018). Alternatively, one of the main rationales for developing a thermally desirable outdoor ambience are the repercussions that go beyond the requisites of urban design and well into the design of buildings (Ahmed, 2003), specifically in the in access to air conditioning systems (Taleghani, 2018). This implies that a thermally comfortable outdoor situation is likely to influence the indoor climate positively which may lead to better/comfortable ambient conditions for free-running buildings (Ahmed, 2003) and lower energy use for mechanically controlled spaces (Emmanuel, 2006), thereby destressing the energy environment relationship (Ahmed, 2003). Such a situation is more so apt as air conditioning is an expensive/inaccessible adaptation for the urban poor (Solecki, et al., 2005) in buildings dependent on passive design with a situation afflicted with power outages like in Karachi. And therefore, necessitates the need for comfortable ambient climate in the outdoors. Thereby, the UHI problem enhances the dual importance of passive cooling as an efficient methodology in saving cooling energy and enhancing thermal comfort for naturally ventilated buildings (Shashua-Bar & Hoffman, 2003).

### **2.4.3. Land Use Classifications**

The literature review provides an introspection into several climate-based land classification schemes to analyze the effects of urbanization and urban form (Auer, 1978; Lotfian, et al., 2019). These classifications are carried out to enhance the spatial awareness related to local climate and assist planners in improving the urban form based on the climatic concerns (Shi, et al., 2018). These land use classifications include, FRAISE scheme (Flux Ratio-Active Index Surface Exchange) (Loridan & Grimmond, 2012), the Urban Zones characterizing Energy partitioning (Loridan, et al., 2013) Urban Climatic Map system built using land use, topographic and climatic data/information (Ren, et al., 2011; Ren, et al., 2019), Urban Climate Zone scheme (Oke, 2004; Oke, 2006) and Local Climate Zone (LCZ) scheme (Stewart & Oke, 2012). All of these are recognised through a variety of urban indicators and via such characterizations, urban form/function classifications are standardized allowing a more precise spatial insight into the inconsistency of intra-urban temperatures (Stewart & Oke, 2012).

However, within these, LCZ classification serves as one of the most widely applicable universal approaches (Ng & Ren, 2015) to study local air/surface temperature features, UHI, outdoor thermal comfort and exposure to air, etc. (Ren, et al., 2019). The scheme was devised to deal with the shortcomings of urban-rural description for UHI researchers (Stewart & Oke, 2012) and comprises of 17 unique zone typologies as a standard framework for reporting and comparing temperature observations across LCZ fields and across-cities (Ng & Ren, 2015). The site classification into typical LCZs needs basic metadata and surface characterization. However, in the South Asian context of high-density urban scenarios, Kotharkar & Bagade (2018) insinuate that LCZ scheme is not always apt due to the exclusively local urban contexts and the combinations/mixed form of land-use and building morphology. And hence, propose a slight modification to the standard classes to fit to the local contextual realities (Kotharkar & Bagade, 2017). Given the problems associated with the system such as in heterogeneous cities where typical zones do not exist as chunks, Stewart and Oke (2012) also provided the provision for creating new subclasses for zones that differ from the standard LCZ classes' description. Such subclasses are resultant of combinations of built types, land covers types and other land cover properties. Thereby, befitting appropriations have been carried out by Kotharkar & Bagade (2018) and Perera & Emmanuel (2018) with additional LCZ subclasses as a result of mixing of two or more classes of built type in case of Nagpur and Colombo, respectively. Such an approach is also proposed for other data-poor developing cities to suit the local realities and enhance applicability (Perera & Emmanuel, 2016).

### **2.4.4. Comparison of WUDAPT vs GIS**

Within the LCZ classification/mapping, there are three approaches i.e., the manual sampling, remote sensing, and GIS (Zheng, et al., 2017), while only the latter two are widely used on a city scale (Kotharkar & Bagade, 2018). The reduction-based GIS approach involves the mapping of LCZ classes using various secondary and primary data sources and necessitates expert knowledge on the landcover, while the remote sensing mainly depends on supervised pixel-based classification techniques to develop the LCZ map from satellite images (Bechtel & Daneke, 2012) and has been adopted into the World Urban Database and Access Portal Tools (WUDAPT) (Mills,



et al., 2015). While it is asserted that the GIS results are more thorough and precise in examining the urban built-up areas (LCZ1 to 6) (Shi, et al., 2018), this approach is quite data-intensive (Zheng, et al., 2017). Alternatively, the WUDAPT philosophy is facilitated by Landsat remote sensing images and follows a simple workflow implemented in SAGA (Danylo, et al., 2016) and can be appropriated for any city in the world. This efficient, low-cost and fast method produces maps of moderate quality and serves a large coverage with an overall accuracy of 50-60% generally (Bechtel, 2019), and 70-90% for high-density urban areas (Ren, et al., 2019). Although all the data required, software and generated maps of WUDAPT are free of charge and publicly accessible, there is a likeliness of errors due to the subjective interpretation of areas and training sites. However, in terms of the applicability on large highly dense heterogeneous cities, Shi, et al., (2018) compares and evaluates two cases of LCZ classification in the city of Hong Kong. One developed an LCZ classification map using GIS-based mapping method (Zheng, et al., 2017), while the other one investigated a set of LCZ maps using the WUDAPT procedure to line up the LCZ map of Hong Kong with worldwide database (Ren et al. 2016). It was observed that although both the resultant LCZ maps showed a high consistency with the other mapping systems, each mapping method holds its own pros and cons. Hence, it is advised that a mixture of both these would offer a more versatile and precise LCZ mapping/classification for other research endeavors (Shi, et al., 2018). Moreover, due to the variation in the urban indicators intra-LCZ, Shi, et al. (2018) suggest that there is still a compulsion of authentication using field measured air temperature data. On the other hand, Wang, et al.(2017) suggest that both GIS-based and WUDAPT methods as suitable methods for detecting different LCZ classes in high-density urban areas and notes that the GIS-based method offers higher accuracy at district level, while the WUDAPT (level 0) method is more appropriate at the city scale (Wang, et al., 2017).

## **2.5. Materials and Methods for Field Measurements**

The field experiments allow recording screen-height air temperature data in numerous streets of the LCZs where there are three types of approaches employed, i.e., fixed station, traverse/mobile surveys, and a combination of both. However, the mobile surveys using moving vehicles have been extensively used (Leconte, et al., 2015) and regarded as a cost-effective, albeit short term, tool to investigate many of the intra-urban environmental variables at street/canopy levels on a predetermined path (Peters, et al., 2012; Yadav & Sharma, 2018). For the measurement, temperature sensors are usually mounted on the roof of the moving vehicle, and the vehicular path allows the potential to fill the monitoring gaps of the sparsely dispersed fixed monitoring sites by offering a larger spatial data coverage (Yadav & Sharma, 2018). Due to the flexibility for varied vehicular options depending on the locations and street widths, the technique has been expediently adopted and enhanced in a variety of studies including the characterization of the urban-rural air temperature difference, correlation of the urban air temperature with remotely sensed LST, relationship between the urban morphology and the microclimate conditions, and the effects of urban greenery (Shi, et al., 2018). Although by far appropriated in many of the major cities of the world (Yadav & Sharma, 2018) including some in south Asia, none of such studies pertaining to UHI have been conducted in Karachi yet.

In recent times, the traverse measurement method has become more popular in LCZ classification studies (Kotharkar & Bagade, 2018; Shi, et al., 2018; Yadav & Sharma, 2018) given the insufficiency associated with fixed monitoring networks and seems more apt in complex urban contexts of densely populated cities with huge air temperature anomalies across and within different LCZ classes at a somewhat smaller spatial scale (Shi, et al., 2018). The consideration is particularly relevant to street canyons in the high-density areas as the measured data has an improved scope to represent the real situations of heat exposure. Previous studies with mobile measurement in both urban and rural settings have confirmed the viability of monitoring microscale spatial variation of temperatures (Zheng, et al., 2017) and yet acknowledge the potential of validating future researches in utilizing this method (Shi, et al., 2018).

## **2.6. Mitigation Pathways**

UHI is considered too complex a problem and interdisciplinary subject that requires a wide range of mitigation perspectives ranging from geography, meteorology, architecture, and civil engineering, etc. (Yamamoto, 2006). However in the scope of urban planning and buildings, many potential measures have been identified to encounter UHI effect such as using high albedo/cool materials (Synnefa, et al., 2008; Emmanuel & Fernando, 2007), green features (such as vegetation, shade trees and roofs) (Wong, et al., 2007; Ottelé, et al., 2011; Santamouris, 2014), urban planning strategies (such as urban design and density manipulation), shading techniques, pervious pavements, and water bodies/water misting techniques in city areas, etc. (Nuruzzaman, 2015; Nouri, 2015; Emmanuel, 2016; Ramakreshnana, et al., 2019).

However, the scales of application and efficacy at which these mitigations may apply be different, i.e., individual building versus neighbourhood, new development versus redevelopment and retrofitting, etc. and even expand to broader implications such as management of energy resources (Grimmond, 2007). Over the surface, mitigations such as changes in material properties allow modification to the existing buildings without compromising the costs or time for new developments (Grimmond, 2007) as opposed to suggestions of alteration of the spatial arrangement. Meanwhile in case of outdoor comfort, the greatest benefit is attributed to the introduction of green infrastructure (GI) (Shashua-Bar, et al., 2011; Emmanuel & Loconsole, 2015) as a better heat-mitigation strategy in contrast to using high albedo materials for improving thermal comfort (Gatto, et al., 2020). The incessantly proposed green interventions as an effective strategy have been validated in several studies among which are the UHI mitigation by temperature control, the passive cooling of buildings by shading of trees and urban thermal comfort (Coutts, et al., 2007; Nuruzzaman, 2015; Taleghani, 2018; Shinzato, et al., 2019; Gatto, et al., 2020) and even across issues of energy poverty (Tsilini, et al., 2015) as an economically viable way to reduce energy consumption and costs (Solecki, et al., 2005). However, what amount of green and what type of green is a question? It is argued that the intensity of cooling by vegetation is relative to the soil wetness and plants characteristics along with influencing factors such as tree location and typology (Guhathakurta & Gober, 2010), canopy coverage, and leaf density (Coutts, et al., 2007) and shading potential etc. (Middel, et al., 2014; Shinzato,

et al., 2019). While other studies suggest that as low as 20% increase in GI via the German guideline (GAR) can mitigate UHI effects sufficiently (Emmanuel & Loconsole, 2015). However, these interventions are context specific, therefore the validation of the effects is carried out via 3D-micro modelling simulations where the effects are quantified as air temperature ( $T_{Air}$ ) and thermal comfort expressed in terms mean radiant temperature (MRT) and predicted mean vote (PMV) in replicated urban settings.

### 2.6.1. Outdoor Thermal Comfort

As previously discussed, thermal comfort has implications on human health as well as it re-establishes and sustains life outdoors. Studies suggest that the  $T_{Air}$  along with Relative humidity (RH) serve as the most important parameters for thermal comfort especially in hot and humid countries (Lee, et al., 2014). A variety of scales and indices have been proposed for thermal comfort and heat stress (Freitas & Grigorieva, 2016) which provide numerical relations and/or graphical assessments (Abdel-GhanyI, et al., 2014). However, each index offers its own set of strengths in terms of comprehensiveness, usability, validity and completeness, etc. (Freitas & Grigorieva, 2016). Meanwhile, Thom's Discomfort Index (DI) (Thom, 1959) and Heat Index (HI) (Steadman, 1979) have been among the most broadly used indices in urban climate studies (Kotharkar, et al., 2019; Stathopoulou, et al., 2005). Both only employ the  $T_{Air}$  and RH to deduce the thermal comfort, unlike other indices with extensive factor requisites. Thereby, the DI and HI are well suited for limited datasets, cost-effectiveness and ease of data access and have been previously employed in south Asian studies by Kotharkar, et al. (2019), and Jacobs, et al. (2019), respectively. DI is representative of the level of thermal sensation experienced by people because of the modifications in the climatic conditions in the urban areas (Thom, 1959). While the HI (Steadman, 1979) builds an apparent temperature to categorize possible heat disorders (Blazejczyk, et al., 2012). The calculations are carried out as,

$$DI = T - (0.55 - 0.0055 \cdot RH) (T - 14.5)$$

$$HI = -8.784695 + 1.61139411 \cdot T + 2.338549 \cdot RH - 0.14611605 \cdot T \cdot RH - 1.2308094 \cdot 10^{-2} \cdot T^2 - 1.6424828 \cdot 10^{-2} \cdot RH^2 + 2.211732 \cdot 10^{-3} \cdot T^2 \cdot RH + 7.2546 \cdot 10^{-4} \cdot T \cdot RH^2 - 3.582 \cdot 10^{-6} \cdot T^2 \cdot RH^2$$

where  $T$  [ $^{\circ}\text{C}$ ] is the air temperature and  $RH$  [%] is the relative humidity.

### 2.6.2. Simulation Approaches

Currently, there are various computer-based outdoor microclimatic simulation tools being used. Albdour & Baranyai (2019) compare the features of eight primary microclimatic simulation tools (Albdour & Baranyai, 2019) and identify ENVI-met as the most capable of predicting and simulating the thermal comfort indices, meteorological parameters as well as most of the design strategies in outdoor spaces. ENVI-met is a 3d non-hydrostatic model for the simulation of surface-plant-air interactions, particularly but not exclusive to the urban canopy layer, designed with a typical time-space resolution of 10 s/0.5–10 m for the model and a typical time frame of 24 to 48 h (Ng, et al., 2012; Yang, et al., 2012; Emmanuel & Fernando, 2007; ENVI-met®, 2020; Middel, et al., 2014). The software is regarded for its accurate quantification and replication of the physiological and

geometrical properties and effects (Simon, et al., 2018.) in offering different scenarios, seasonal and long-term predictability comparisons (Simon, 2016). Based on this, ENVI-met has been used by several studies where the investigation/ mitigation criteria ranges from thermal properties to albedo enhancement (Emmanuel, et al., 2007), GI (Shinzato, et al., 2019; Gatto, et al., 2020) and urban-area geometry, aspect ratio and building density (Emmanuel & Fernando, 2007), etc.

## **2.7. Learnings**

- The literature review establishes the poorly documented case of Karachi in terms of scientific exploration and methodologies of assessment. Although more focused on tropical UHI studies, the south Asian studies yet offer a relative starting point for Karachi.
- In terms of exploratory methods, the applicability of WUDAPT-LCZ classification in high-density, heterogeneous urban contexts of developing cities is highly substantiated where the intra-LCZ urban drivers can be investigated with cost-effective methods like in-situ surveys and remote sensing data and hence may be explored in Karachi.
- Efficacy of the most common mitigations need to be assessed for practical applicability locally. Moreover, the role of high-density developments/mitigations offer dubious effects such as better thermal comfort and shade enhancement at daytime (Emmanuel & Fernando, 2007) and contrarily beset with increased temperatures in the night-time (Surawar & Kotharkar, 2017). This lack of consensus towards densification's influence on UHI (Lemonsu, et al., 2015) needs to be locally assessed for Karachi.

The literature review has established the scope of this study ranging from mapping approaches, methodologies for analysis, and mitigation strategies in terms of scale, climatic and social scenarios. As the thesis intends to document the intra-city UHI variation and assess the thermal anomalies in the heterogenous city fabric (objective b), given the applicability of LCZ classification across different UHI explorations, this study first employs LCZ classification to study the distribution of LCZs within the city using WUDAPT. This establishes the most common LCZ typologies along with the associated factors like land use, density and vegetation, etc. and will serve as the base map (for objective b and c i.e.,) to assess the presence of UHI at various times by employing two methods. Firstly, deriving the LST through remote sensing and secondly, street level temperature and thermal comfort assessments achieved from the traverse and fixed survey data. The cross-comparison of this data leads to the identification of the microscale hotspots /cold spots present at different times based on the LCZ distribution and the associated drivers (objective c and d). Further, in the next chapter, to analyze how the future growth in the city may impact the UHI effect and the linked warming patterns, a comparison of year 2019 and 2009 LCZ maps is carried out to quantify the change in land use along with extrapolation of extreme temperatures. This identifies the anticipated climatic effects for future (objective e). The critical areas thus recognized are explored with mitigation strategies verified through micro-modelling simulations using ENVI-met (objective f).

The research design workflow is established in fig. 3, while the detail of the sources of data and methods follows.

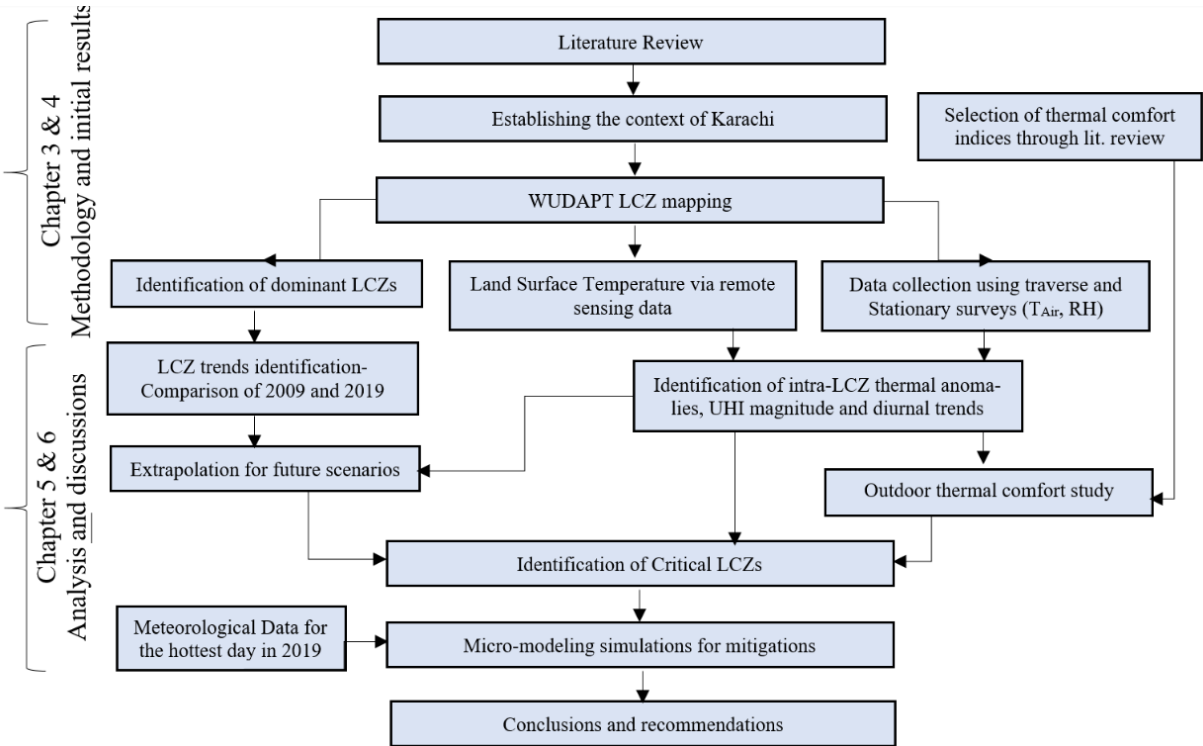


Figure 3. The research design steps

### 3.1. Context-

The city of Karachi as the only meta-city (Hassan, et al., 2015) and the economic hub of Pakistan (DAWN, 2012) is home to the country's major industries and businesses (Hasan & Mohib, 2003). However, the city's nature is characterized with the dichotomy of being a beacon of urbanization's promises and being the epitome multifaceted challenges (World Bank, 2018). Once proudly known as the 'city of lights', the city now holds interpretations like the 'ugly concrete jungle' (The News, 2008) and "Planet of Slums" (Davis, 2006) and has been declared as the sixth least liveable city in the world (Economist Intelligence Unit, 2015). This is mainly because the city has suffered myriad problems in the absence of a proper long-term plan and poses severe sustainability risks dictated by substantial rural-urban migration trends, industrialisation, socio-political conflicts and transportation challenges (Hasan, 2006). Thereby, exaggerating massive environmental (Qureshi, et al., 2010) and socio-economic repercussions (Mangi, et al., 2020). Moreover, the rapid expansion, in terms of population and area, in the last few decades has resulted in over densification and the urban developments' spreading into the city sprawl (Hasan, 2015). Although, the city population is recorded to be slightly over 16 million in 2017 (Pakistan Bureau of Statistics, 2018), many argue these numbers to be politically biased (Samaa.tv, 2017). According to one report, the city is expected to accommodate 27.5 million people in 2020 (Qureshi, 2010). Administratively, the metropolitan area along with its suburban area spreads over 3530 sq. km and consist of six districts (Raza, et al., 2019), further sub-divided into eighteen towns that are administered by the city government, and six military cantonments.

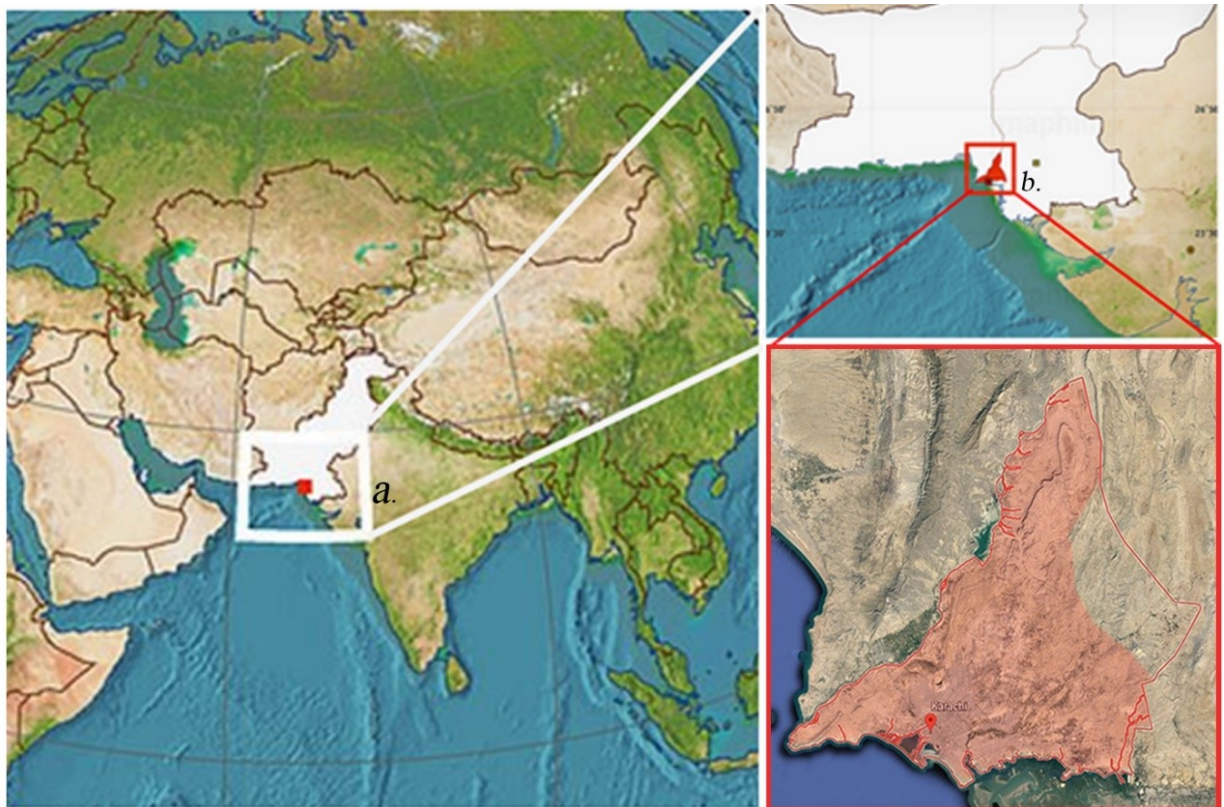


Figure 4. Location of Karachi in red (a) in Pakistan and (b) in the southern province of Sindh.



### 3.1.1. Climate and Physiography

Karachi (Coordinates: 24° 56' 46.3848" N, 67° 0' 20.2140" E) being located in the South of Pakistan can be divided into two distinct categories, the north-western hilly areas of Kirthar range and the undulating plains and coastal area in the south-east along the Arabian sea (Hasan & Mohib, 2003). The city has a long coastline in the south characterized with mudflats, sandbanks, estuaries and mangrove swamps (Kanwal, et al., 2020). Although, there are three major rivers that flow through Karachi and define its physical characteristics, two of them now serve as major drains carrying the city waste and discharging it into the southern sea (Alamgir, et al., 2019).

Climatically, the region is considered to have temperate climatic conditions with the worst summers characterised by very low annual precipitation (Raza, et al., 2019), but according to the Köppen-Geiger system, the climate is classified as BWh, i.e., hot desert climates (Climate-data.org, n.d.). As shown in figure 5, the summer conditions are dominant for most part of the year which intensify due to high humidity conditions adding to the discomfort and leaving little relief for the people (Qureshi, 2010; Naveed, 2017). While in cases of heatwaves, the consistency of high night-time temperatures over a sustained period with no relief in terms of minimum temperatures (The urban Unit, 2017), the coincidence of no wind activity and worsened power outages have caused catastrophic consequences (Salim, et al., 2015).

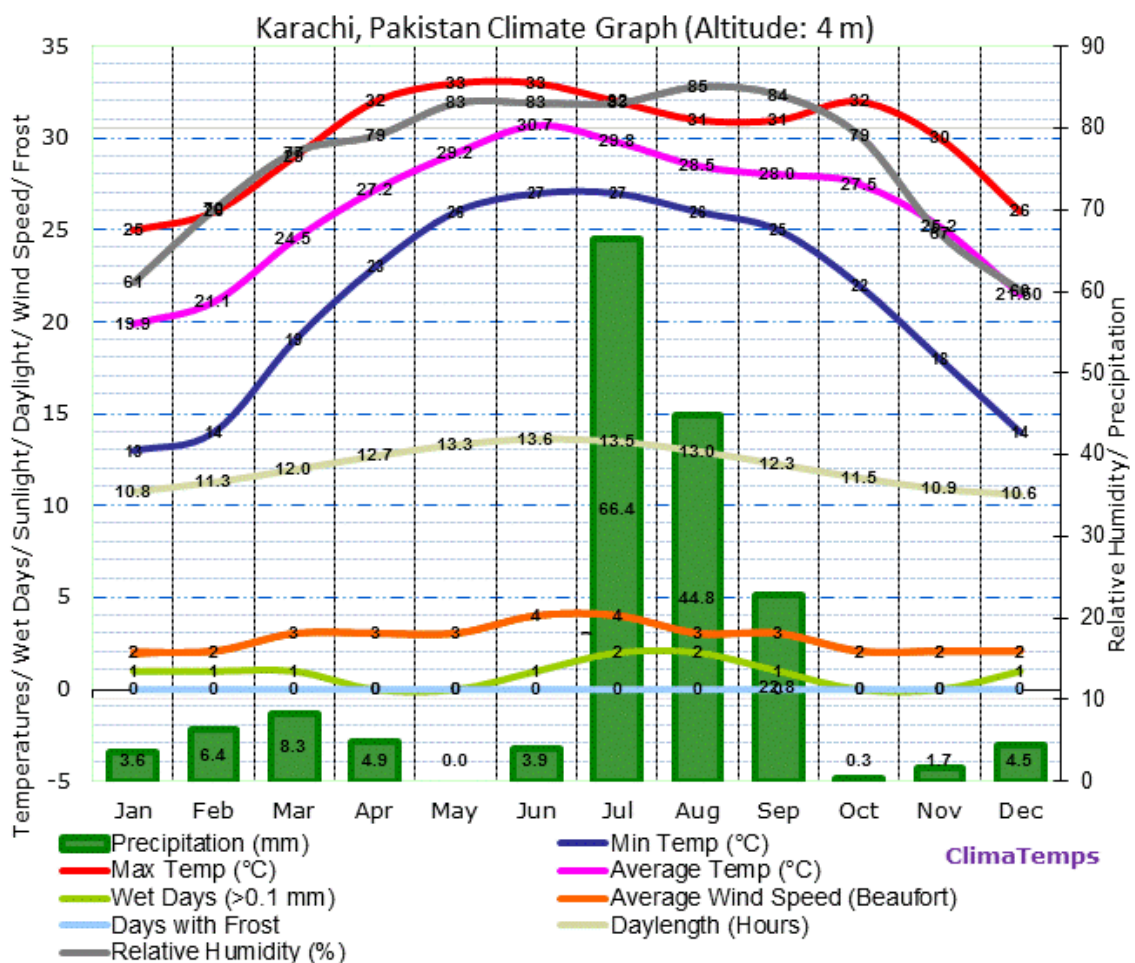


Figure 5. Karachi Climate Graph. Source: climatemps.com (2020)

### 3.1.2. Density and Land use/Landcover

Karachi is characterized with a heterogeneous urban form. With a rich historical background, the city mainly developed around trade/port related activities (Hasan & Mohib, 2003) and has inherited various layers of built elements from different periods during its 250 years' timeline (Hasan, 1996). These include medieval, colonial, Indo-European, post-colonial, modern and post-modern buildings along with the industrial development. Similar may be the case with most south Asian cities having evolved with a colonial legacy (Kotharkar, et al., 2018). Through the years, the inadequate/affordable housing delivery has been a major concern resulting in informal settlements/slums (Soomro & Soomro, 2018; Ellis & Roberts, 2016) and has resulted in a mixed / haphazard spatial growth (Ellis & Roberts, 2016), having older areas in the nucleus with the growing newly planned areas and satellite towns, along with informal settlements and dense slums within inner city and urban sprawl (Hasan & Mohib, 2003). Currently, Karachi is one of the densest cities of south Asia (Kolb, 2019) where the density stats i.e., 2280- 4,000 persons/ha (Hasan & Mohib, 2003), are considered way higher than the allowable density of 1625 persons/ha (Hasan, 2016) and far exceed other densely populated South Asian cities (Yeung, 2011). Experts credit such a situation to land mismanagement and constrained urban land supply (Ellis & Roberts, 2016; Bertaud, 2009), as well as the current land use planning i.e., entirely determined by the land value (Hasan, 2006) as most of the population (62%) in informal settlements lives on 23% of the city's residential land, while in contrast the remaining 34% lives in planned settlements on 77% of the city's lands (Hasan, 2016). This extreme distribution has resulted in densities as high as 1,500 to 4,500 persons/ha in informal areas, and even to as less as 80 persons/ha in formal developments (Hasan, 2016). And even though the sustainability of such megacities, like Karachi, has been questioned incessantly (Annan, 2002; Wu, 2006; Grimm, et al., 2008; Sorensen & Okata, 2010), it is obvious from these disproportionate figures that this development is neither sustainable nor inequitable in terms of socio-economic and environmental development (Mangi, et al., 2020).

Whilst having said that, Qureshi, et al. (2012) note that Karachi's land use is too complex to be identified as per internationally existing classical models due to its complexly developed planned and unplanned areas (Hasan & Mohib, 2003). The fragmented land use along with the incremental city planning phases (Qureshi, et al., 2010) has made the demarcation of specific typologies impossible (Qureshi, et al., 2012). In the two studies employing LULC classification for the city's vegetation, open space, built-up areas and barren land between 1986-2018, it is no surprise that the vegetation covers and open spaces are being taken over hugely by built-up land for residential and commercial purposes (Qureshi, et al., 2012; Raza, et al., 2019), fig 7. Whereas the agricultural areas of Karachi are now almost close to extinction as the barren land in the last decade increases (Raza, et al., 2019). Planners blame the improperly planned development and altered land cover patterns for blocking the flow of natural drains effecting water needs of agriculture (The Express Tribune, 2018) as well as the extreme shortage of blue-green infrastructure for depleting water resources (Veerbeek, 2017). These effects in turn majorly influence the climatic conditions as the increase in vegetation can reduce the surface temperature, while alternatively the increase of urbanization is a symptom of vegetation loss itself (Raza, et al., 2019). Validating



these observations, the LST differences of the congested built up area has also increased alarmingly in the past 20 years (Raza, et al., 2019)

In short, the high population density and the contested land resources have shaped the high-density urban morphology of Karachi associated with compactly packed buildings (formal and informal), reduced open and green space and increased LST.



Figure 6. High-density urban morphology of Karachi. Source: Compilation of own images and Google Earth open source data.

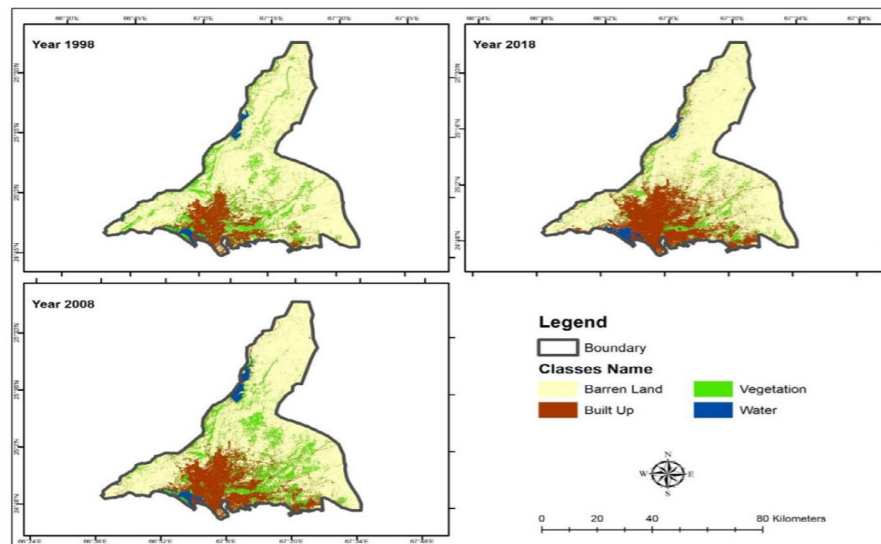


Figure 7. LULC map of Karachi, 1998-2018. Source: Raza et. al. 2019

### 3.1.3. UHI, Heatwaves and Karachi

The recent South Asian heatwaves have caused death of hundreds and thousands of people (Khan, et al., 2019; BBC, 2015), in June 2015 only in Karachi over a thousand people died (Imtiaz & Ur-Rehman, 2015) and thousands suffered from heat related illnesses is an evidence to this claim (CDKN, 2017; BBC, 2015; CDKN, 2015; Salim, et al., 2015). Not only was it identified that most of those who suffered belonged to low-income

neighbourhoods and had no alternative but to be outdoors for daily wages (DAWN, 2015; Hasan, et al., 2017). This demonstrates the influence of UHI intensity on the economic situations (Lee, et al., 2020), particularly the low socio-economic status as a significant factor in enhancing the vulnerability to climate change (Jacobs, et al., 2019). Such a situation is alarming considering that the almost 50% of the vulnerable population living in the city slums and squatter settlements 20 years back (Qureshi, et al., 2012) has now grown to almost a 60% (Bradnock & William, 2002; Hasan, 2016; The Express Tribune, 2018). And though research suggests that the usage levels of urban space are more likely to increase if the outdoor environment is thermally comfortable (Emmanuel, 2006; Emmanuel & Fernando, 2007), but the question remains: how to cope with the usage of urban space in a thermally uncomfortable outdoor environment? Moreover, one must note here that these deaths were more in number in certain towns and areas of Karachi (as observed in fig.1) which suggests different levels of vulnerability in different areas and points to an associated spatial relationship. It is speculated that along with other factors, the UHI intensity is exaggerated due to the air-deprived living circumstances in low-income settlements with extended power outages (Hanif, 2017). The UHI effects hence dictate emergency actions targeted towards the vulnerable populations to deal with the urgency of death threat and the sustenance of life.

### **3.2. Sources of Data**

This chapter details out all the direct and indirect data sources appropriated in this study. The LCZ mapping, LST and the meteorological surveys follow previously identified standard procedures as well as experimental approaches and serve as the central data for this UHI study, while the city meteorological data acquired via PMD will be used post-analysis in the mitigation testing phase.







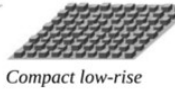


#### **3.2.1. LCZ Mapping**

The LCZ classification was opted to enable an exploratory analysis of the recent urban/ spatial trends on the distribution of UHI phenomenon. It is anticipated that the result of LCZ mapping not only will serve as a base map for thermal analysis in relation to the LST and traverses temperatures and identify the distribution of the land use but will also determine the associated warming/cooling trends based on the abundance of LCZ in the overall cityscape (carried out in the next chapter). Although GIS as a mapping method can usually achieve high accuracies, but not every city's GIS data is complete or accessible to the public especially in developing countries/regions (Wang, et al., 2017). Alternatively, WUDAPT methodology has high accuracy and considerably simple workflow (yet time consuming) for city scale maps (Cai, et al., 2017). Hence, given the scale of the city, it was decided to follow the generalized WUDAPT method. The previous studies identified that the urban form of Karachi shares many similarities with Colombo, Sri Lanka, in terms of low-rise development (Perera & Emmanuel, 2016) along with ad-hoc informal slum developments in Nagpur, India (Kotharkar & Bagade, 2017; Kotharkar & Bagade, 2018), albeit building characterizations do not replicate exactly as the slums and informal low-rise constructions in Karachi are more permanent in comparison (Hasan & Mohib, 2003). However, these

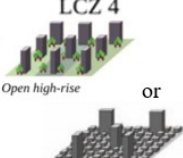


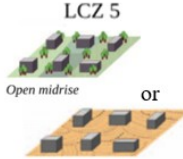


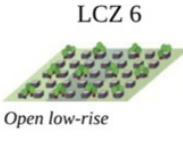


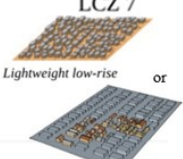


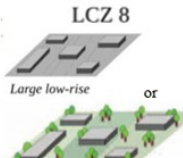


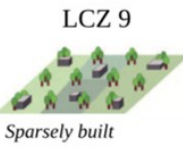





studies provide a locally relatable reference for cities like Karachi with highly dense arrangement of informal classes.

### 3.2.1.1. Towards a Universal LCZ Mapping Scheme - WUDAPT

The WUDAPT (level 0) mapping pursues a standard set of steps for data compilation and processing. Following the method explained by Bechtel, et al. (2015), Landsat 8 imagery (30m) with a cloud cover of less than 10% was downloaded for June 9, 2019 from the US Geological Survey (USGS) Earth Explorer site. The algorithm to create the LCZ classification requires training data using google earth where these samples should cover homogeneous areas that are at least of the minimum size of an LCZ, i.e., approximately 1 km<sup>2</sup> (Danylo, et al., 2016). The classification was carried out based on land cover types identified by Stewart & Oke (2012) while the main source of information for training samples was visual interpretation informed by my own urban and social knowledge of the city substantiated by field campaigns and photos along with secondary data from Karachi Development Authority-KDA and historical/ recent urban maps from the urban planners’ archives of Karachi, etc. Although the LCZ scheme is considered “sufficiently generic” in its design and applicability, there is a huge disparity in how researchers have offered their own context specific interpretation of urban landscapes (Bechtel, et al., 2015). Previous studies establish that developing cities due to their organic/haphazard nature may be hard to be recognized at the standard LCZs as opposed to other well-planned developed cities (Kotharkar & Bagade, 2017). Consequently, for Karachi various LCZ classes required sub-classification/adjustment. And, even though the need for local customisation (Perera & Emmanuel, 2016), and the possibility to define mixed subclasses is recognized (Bechtel, et al., 2015), the WUDAPT method doesn’t provide a detailed description for identifying sub-classes (Kotharkar & Bagade, 2017). Hence, for the purpose of this research, I have stuck to the preestablished LCZ classes only. Subsequently, the WUDAPT level 0 map at a resolution of 100m was generated. Based on a qualitative inspection using Google Earth to identify any poor classification, further training areas were added, and the classification was rerun. The main characteristics and typical features of each LCZ are summarized in table 1.

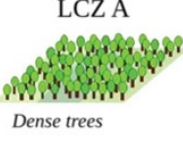


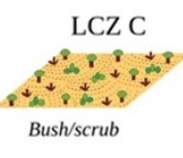
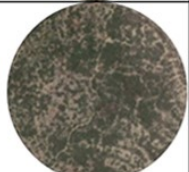
1. Built Types			
A. LCZ	B. Aerial View	C. Eye Level Photos	D. Description
<p>LCZ 1</p>  <p>Compact high-rise</p>			<p>Form: Dense Cluster of highrise buildings with few or no trees. Heavy materials use like concrete, glass, stone and steel.</p> <p>Function: Residential apartments, Commercial (offices, hotels and malls) and mixed use buildings.</p>
<p>LCZ 2</p>  <p>Compact midrise</p>			<p>Form: Closely spaced 4-8 storey buildings along narrow streets with less or no vegetation. Heavy materials like concrete, glass, stone and steel.</p> <p>Function: Residential, Commercial, and mixed use buildings. Even include tightly packed informal settlements.</p>
<p>LCZ 3</p>  <p>Compact low-rise</p>			<p>Form: Closely spaced 1-3 storey blocks along narrow streets with less or no vegetation. Both formal/informally developed areas. Heavy material use like concrete, glass, stone, steel with some light materials like brick, wood, corrugated metal roof etc.</p>



<p><b>LCZ 4</b></p>  <p>Open high-rise or</p>			<p>Form: Open arrangement of highrise buildings mainly along main roads mostly with low plants and scattered trees but sometimes infused with open lowrise. Heavy materials like concrete, glass, stone and steel. Function: Residential apartments, office/commercial buildings including, hotels, malls, etc.</p>
<p><b>LCZ 5</b></p>  <p>Open midrise or</p>			<p>Form: 4-8 storey open arrangement of buildings , built of heavy material but mostly covered with/without pervious features. Heavy materials like concrete, glass, stone and steel. Function: Residential, commercial and mixed use buildings.</p>
<p><b>LCZ 6</b></p>  <p>Open low-rise</p>			<p>Form: Cluster of open lowrise buildings with pervious surfaces and scattered trees. Function: Residential bungalows and apartments. Heavy materials like concrete, glass, stone and steel.</p>
<p><b>LCZ 7</b></p>  <p>Lightweight low-rise or</p>			<p>Form: Densely packed 1 story buildings along narrow streets. Sometimes a mixture of lightweight along with LCZ 3 features. Mostly informal settlement with lightweight materials such as brick, Wood, thatch, corrugated metal sheets/roof and fabric. Function: Informal residential areas or slums and/or commercial.</p>
<p><b>LCZ 8</b></p>  <p>Large low-rise or</p>			<p>Form: Open arrangement of large lowrise buildings. Heavy buiding material such as concrete, glass, stone and steel. Mostly with an abundance of pervious land and trees or paved surfaces. Function: Mostly institutional buildings, ie, schools, colleges and hospitals, along with warehouses, commercial services and storages.</p>
<p><b>LCZ 9</b></p>  <p>Sparsely built</p>			<p>Form: Sparse arrangement of small or midsize buildings, in a variety of natural settings, such as pervious land, scattered trees or dry barren land. Function: Sprawl, informal settlements, newly developing plots. Mixed materials.</p>
<p><b>LCZ 10</b></p>  <p>Heavy industry</p>			<p>Form: Low/midrise industrial structures in a variety of settings, such as pervious land, scattered trees or dry soil along with paved and harpacked surfaces. Function: Industries, refineries, mills, warehouses, etc.</p>

Note: The maps and street views are only meant for visual reference and are unrelated to each other.

## 2. Land Cover Types

1.LCZ	2.Aerial View	3.Description
<p><b>LCZ A</b></p>  <p>Dense trees</p>		<p>Heavily wooded landscape including natural forest, cultivated trees, mangrove forests and urban parks.</p>
<p><b>LCZ B</b></p>  <p>Scattered trees</p>		<p>Lightly wooded landscape with mostly low plants. Includes urban parks, golf clubs, urban forests, cultivated vegetation, natural indeginous tree growth.</p>
<p><b>LCZ C</b></p>  <p>Bush/scrub</p>		<p>Open bushes, short woody trees and shrubs around bare soil mostly growing naturally.</p>




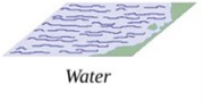
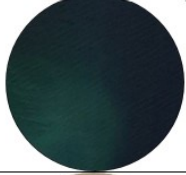

<p><b>LCZ D</b></p>  <p><i>Low plants</i></p>		<p>Landscape with abundant pervious cover such as grass, crops and low plants with no or scattered trees such as grassland, agricultural lands and parks.</p>
<p><b>LCZ E</b></p>  <p><i>Bare rock or paved</i></p>		<p>Hard surface covers such as bituman roads, paved or rock such as airports, terminals, parking lots and other urban transportation.</p>
<p><b>LCZ G</b></p>  <p><i>Water</i></p>		<p>Large, open and small water bodies such as the sea, lakes, rivers and estuaries.</p>
<p><b>LCZ F</b></p>  <p><i>Bare soil or sand</i></p>		<p>Landscape of soil/sand with no or very few scattered trees, mostly natural barren land and the sandy coastline.</p>

Table 1. Description of LCZs as adjusted in Karachi. Source: A. LCZ images from Stewart & Oke (2012) adjusted; B. Google Earth Pro, circle area covering 200 m radius; C. Field survey; D. Own elaboration.

### 3.2.2. Linking LCZs with LST

This part focuses on the LST as UHI is related to the spatial distribution of LST (He, et al., 2007) and hence, allows the surface UHI representation through LST (Cai, et al., 2017). The acquired LST map is overlaid on LCZ map and independent LSTs are calculated for each class. The overall variation of LST is explored within the LCZ classes using mean LST values generated in ArcMap. The analysis herein assumes that certain features typical of a given LCZ regime should demonstrate typical LST ranges. While one must note that given the overall accuracy of these LCZ classification maps may range from 50-90% (Bechtel, 2019; Ren, et al., 2019), a certain level of manual resampling was carried out before the LST analysis. This analysis determines the degree of warmness/coolness associated to each LCZ class and will be cross compared with field data in the next section.

#### 3.2.2.1. LST Retrievals

To determine the mean LST in Karachi, the daytime Landsat 8 datasets (30 m) were downloaded for Karachi from the USGS Landsat Data Access Portal, where only two datasets were selected between April and June 2019 due to the presence of clouds, details mentioned in table 2.

Table 2. Satellite Images acquired for LST analysis.

Satellite Imagery	Entity ID	Acquisition date
Landsat 8	LC08 L1TP 152043 20190609 20190619 01 T1	2019/06/09
Landsat 8	LC08 L1TP 152043 20190422 20190507 01 T1	2019/04/22

The procedure defined by Avdan and Jovanovska (Avdan & Jovanovska, 2016) is used to obtain the LST maps in °C (in fig. 8). These are then overlaid with the LCZs maps and the LST pixels for each LCZ class are extracted. Moreover, a buffer is applied to all the LCZ classes where the smaller areas not equivalent to the minimum LCZ area requirements were disregarded. The mean LSTs thus calculated for each class (averaged over 2 days (i.e., April 22, 2019 and June 09, 2019) identified the overall differences in mean LST and the comparative degree of warmth and coldness among LCZs.

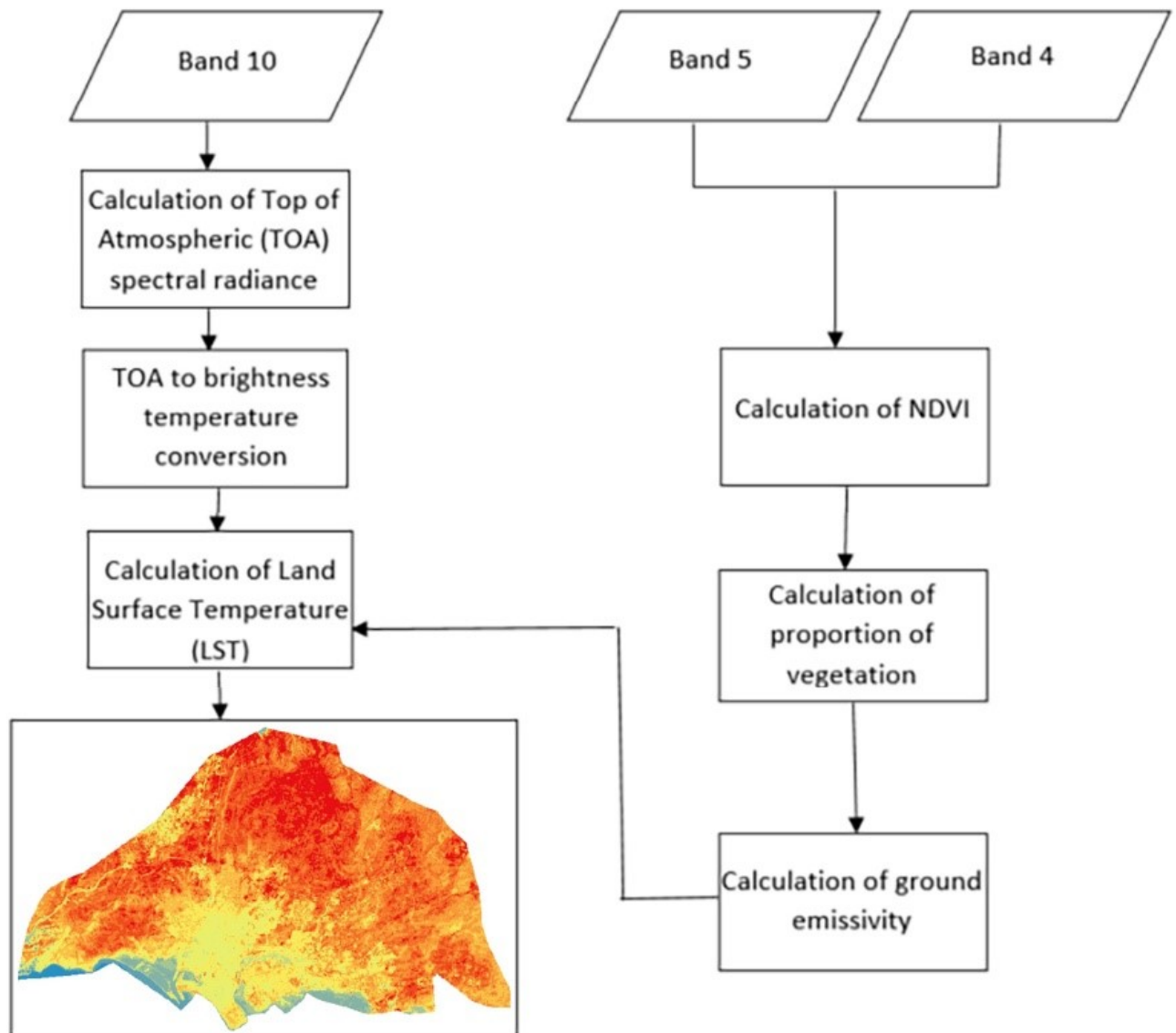


Figure 8. Calculation of Land Surface Temperature from Landsat8 images

### 3.2.3. Meteorological Surveys

In this study, mobile measurement campaigns in parallel with a fixed measurement station were conducted to investigate the intra-urban spatial distribution of UHI across various LCZs at the day and night-time. Seven winter surveys on five routes were carried out between the last week of January and the first week of February 2020 under similar dry condition (clear skies, rain free and less windy days). This mobile measurement method has

been specifically identified since it allows to probe into street level temperature distribution while the routes for the campaigns were planned to accommodate a variety of LCZ combinations spread across the city geography. This assessment is followed by a comparison with LSTs in the next phase to conclude common 'hot spots' and vice versa.

### 3.2.3.1. Measurement Platforms

Mobile survey setups in previous studies were examined for equipment selection, speed of vehicle and accuracy of the sensors. Finally, the device Tinytag Plus 2 (TGP-4500) was selected for collecting the meteorological data due to cost and ease of availability as well as validity in use by previous studies such as (Emmanuel & Kruger, 2011; Krüger & Emmanuel, 2013; Krüger, et al., 2018; Maharoo, et al., 2020). A trial run on selected routes offered examination of the traffic, road conditions and the device response, and thus determined the car/bike itineraries. While two specific times during different stages of a diurnal cycle were selected for the traverses. The first set of measurement campaigns approximately took place between 2:00 to 4:30 p.m. (that is closer to the daily maximum temperature which on average occurred at 3:00 p.m.), and the second were conducted between 7:00 to 10:00 p.m. The day-time was chosen when the air temperatures were most stable, such as in studies by (Jacobs, et al., 2019; Maharoo, et al., 2020), while the 2nd time was chosen to find the extent of the UHI at its max as the greatest temperature difference is observed a few hours post-sunset (Grimmond, 2007).

In total, two cars and one motorcycle served as the mobile platforms for all measurement campaigns where measuring instrument was mounted approx. 2 m high on a PVC pipe over the roof of the car. While the fixed station was similarly setup on the rooftop of an apartment building. This was considered a reasonable compromise overcoming some of the inherent difficulties in positioning instruments on the ground floor such as security from vandalism and anthropogenic influences. During the day, the loggers were placed inside a ventilated and insulated cardboard box to prevent direct sunlight. The detailed equipment description is provided in table 3, while figure 9 shows the device mounting during surveys.

Table 3. Summary of measurement equipment installed on both the platforms

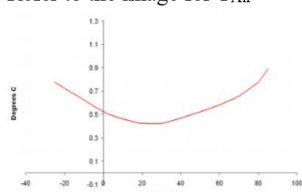
Instrument	Parameter	Accuracy	Resolution	Response time	Logging interval	Reading types
Tinytag Plus 2 Dual Channel Temperature/Relative Humidity TGP-4500 (-25 to +85°C/0 to 100% RH)	T <sub>Air</sub> RH	Accuracy, ±3.0% RH at 25°C / 77°F Refer to the image for T <sub>Air</sub> 	Better than 0.3% RH and 0.01°C or better	T <sub>Air</sub> : 25 mins to 90% FSD in moving air. RH: 40 seconds to 90% FSD (current data loggers, from SN 613165)	1 sec to 10 days	Actual, Min, Max Logging Interval 1 sec to 10 days





Figure 9. (a) Device mounted on the fixed location, (b) mobile stations and (c) the insulated and ventilated cardboard box for daytime surveys.

### 3.2.3.2. Routes

This traverse survey follows an exploratory methodology which is a bit unique and experimental in its own way, as instead of conventional repeated runs on the same routes such as in studies like Kotharkar & Surawar, (2016) and Jacobs, et al. (2019), this study has focused on maximizing the extent of the samples and number of routes to be representative of the larger city area. Moreover, there is an attempt to explore various elements beyond the defined 17 LCZ types such as combinations and edges of various LCZs, i.e., a point, a road, or a junction between two LCZs. This may not be the standard procedure; however, such an approach allows qualitative inspection into the relative temperature patterns in the heterogeneous city as a result of mixing of LCZs.

The literature generally indicates two route approaches for surveys, however, this study has opted for the one-way routes to deal with reasons like covering maximum city areas and varying geographical features, traffic, long distances of pre-decided locations and time for device stability at each pre-decided location. Eventually, five routes with identified stops spread across the city were finalized as shown in figure 10 and table 4. The response time and stability of the device required a stop of 2 minutes 30 sec at each pre-identified spot whereby the GIS location and time were manually collated during the survey. At a measurement interval of 10 seconds, this provided 15 measurements for each point. The first 7 measurements were discarded to allow the logger to stabilize and the last seven were then averaged out.



Table 4. Itinerary details

Route	Trip	Dis. Km	Date	Time	Device Used	Time Interval	Mode
Route 01	01	18	31/01/2020	14:10-16:50	Tinytag Plus 2 (TGP-4500)	1 sec. (averaged over 10 sec interval)	Car
Route 02	02	12	01/02/2020	13:50-15:20	Tinytag Plus 2 (TGP-4500)	1 sec.	Car
Route 03	03	12	02/02/2020	15:20-16:50	Tinytag Plus 2 (TGP-4500)	1 sec.	Car
Route 04	04	25	02/02/2020	14.35-16.35	Tinytag Plus 2 (TGP-4500)	1 sec.	Car
Route 05	05	36	03/02/2020	20:05-21:55	Tinytag Plus 2 (TGP-4500)	10 sec average	Car
Route 04	06*	36	04/02/2020	14.35-16.35	Tinytag Plus 2 (TGP-4500)	10 sec average	Car
Route 02	07	12	04/02/2020	19:00-21:10	Tinytag Plus 2 (TGP-4500)	10 sec average	Bike

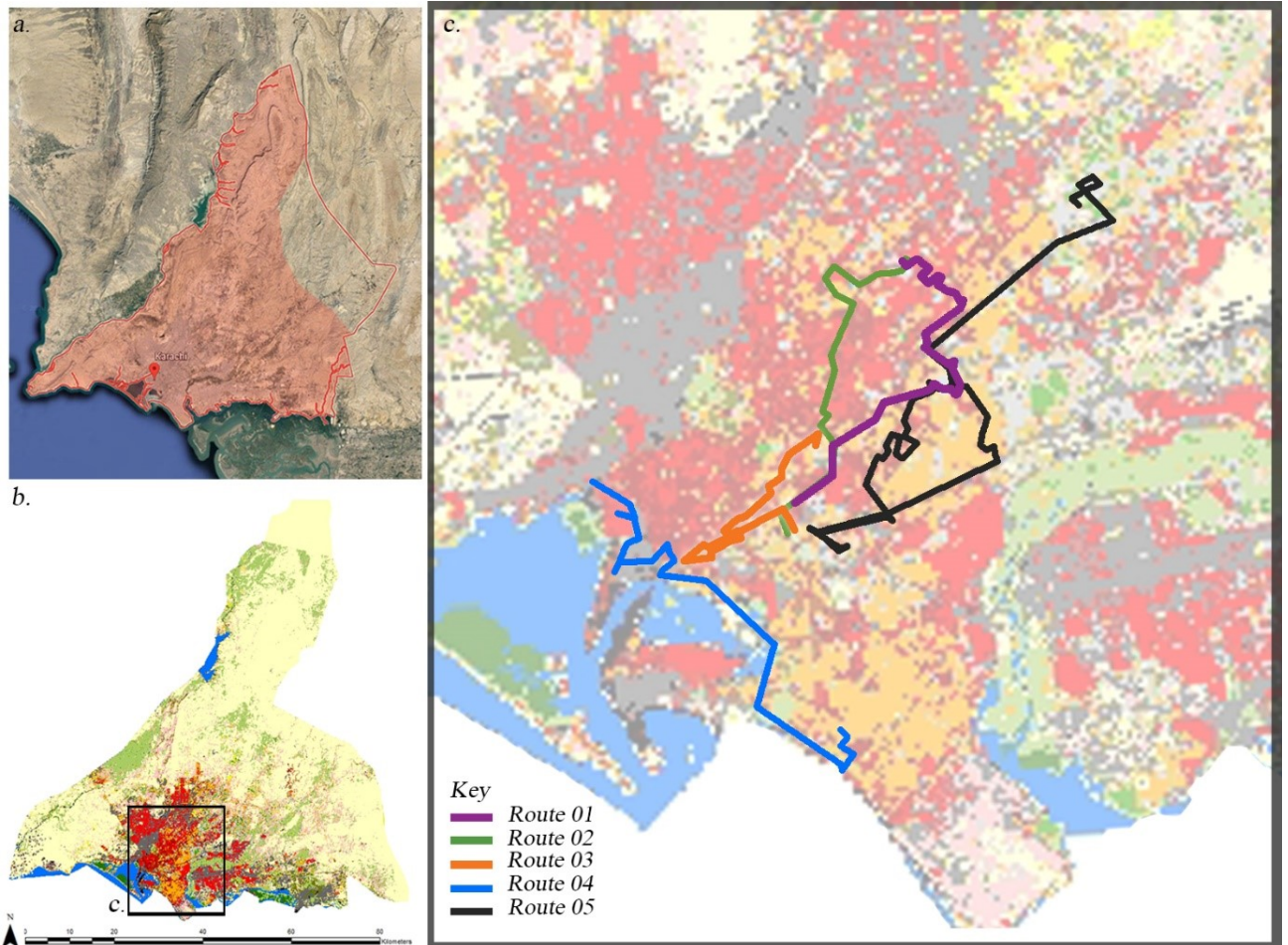


Figure 10. (a) Karachi on the Google map, (b) Karachi LCZ map and (c) focused route location in the city

### 3.2.3.3. IUHI Magnitude and Temperature Difference ( $\Delta T$ ) Calculations

The data obtained by the traverse surveys were overlaid on the LCZ map and the corresponding  $T_{Air}$  readings and time stamps were coordinated. Moreover,  $T_{Air}$  difference and the inter-LCZ UHI (IUHI) magnitude is measured using the formula,

$$T_{Air} \text{ difference } (\Delta T) = T_{Fixed \text{ station}} - T_{LCZ}$$

Where the  $T_{Fixed \text{ station}}$  is the  $T_{Air}$  at the fixed station and  $T_{LCZ}$  is the  $T_{Air}$  at the LCZ in the mobile route. Note that negative  $\Delta T$  values indicate fixed station noted higher  $T_{Air}$  during the traverse than the observed  $T_{Air}$  at the mobile route.

$$I\text{UHI magnitude} = \Delta T_{LCZ_{max}} - \Delta T_{LCZ_{min}}$$

Where,  $\Delta T_{LCZ_{max}}$  is the  $T_{Air}$  of LCZ having the highest  $\Delta T$  value &  $\Delta T_{LCZ_{min}}$  is the  $T_{Air}$  of LCZ having the lowest  $\Delta T$  value compared to the fixed station. This value may be in + or -, however, the magnitude is irrespective of the + or - value.

The filtered datasets of the traverses were tabulated and the UHI magnitude was calculated.

#### **3.2.3.4. Preconditions, Observations and Anomalies**

- The canopy layer covers a combination of urban (built and green) elements and anthropogenic heat sources such as vehicles, air conditioning outlets etc. Therefore, the data reporting was filtered and the potential influences and errors such as high traffic and congestion etc. were scrutinized by identifying outliers.
- For the calculation of  $T_{Air}$  difference, the  $T_{Air}$  data from fixed station and the mobile station have been measured in parallel. Hence, the  $T_{Air}$  differences are assumed to be stable and independent of time considering that the temporal air temperature changes occur simultaneously at all locations.
- The measurements on certain points despite 2.5 mins of stopover continued to change. This suggested that the device takes more time to stabilize than expected. Hence, the temperature noted may not have been the final temperatures, however, in cases of no alternate temperature data these values have been used for this research
- Trip no. 6 was discarded from comparative measurements since there was an instrumental issue encountered in the afternoon run on Feb 4, 2020, however, the data was used to derive other analysis.

#### **3.2.4. Meteorological Data**

To evaluate mitigation potential for real settings, the study required meteorological data for input parameters to run the ENVI-met simulations. This weather data was facilitated by the Pakistan Meteorological Department (PMD) - Airport station readings for 12<sup>th</sup> June 2019 and 13<sup>th</sup> June 2019 i.e., the hottest day of the year 2019.

### **3.4. Simulations**

One of the objectives of this study is to explore mitigation strategies for complex heterogeneous environments. Although there is a variety of urban climatic models (Albdour & Baranyai, 2019) widely varying with regards to their physical basis and spatial/temporal resolution (Emmanuel & Fernando, 2007), however, the most suitable for complex micro scales seems to be Envi-met as perhaps the only one capable of examining the thermal comfort regime within the street canyon at fine resolutions (Ali-Toudert & Mayer, 2006). Moreover, its completeness in terms of human comfort calculations (Taleghani, et al., 2015) and reliable performance for fine analysis of the microclimate at street level has been validated by many previous studies (Taleghani, et al., 2015; Ali-Toudert &

Mayer, 2006; Emmanuel & Fernando, 2007; Shinzato, et al., 2019; Gatto, et al., 2020). Therefore, due to the compact nature of LCZ3 as the critical zone (as identified in chapter 5 and 6), ENVI-met Version 4.4.5 was selected to simulate the environmental conditions and analyze the effect of UHI mitigation options.

### **3.4.1. Scenarios for Mitigation**

The literature offers abundant research evidences for the use of green roofs, adequate amount and/or location of vegetation, albedo enhancement, modification of urban designs and pavement materials. However, mitigations are advised to take into account the contextual issues that impact the design choices (Emmanuel, 2006) and hence, dictate low-cost and independent solutions in the given context (Hasan, 2006). The two strategies that stand out in term of cost efficacy and efficiency are albedo/reflective surfaces and vegetation (Solecki, et al., 2005). Both have different impacts not only related to the mitigation potential but also in terms of the economic tradeoff value (Sproul, et al., 2014), however, the form and spatial arrangement are considered to pose more influence on cooling than only being a function of the two (Middel, et al., 2014). Therefore, this study explored all three of these options to test their efficacy and hence simulated the following cases for the site:

- ‘Base Case’-existing
- ‘High albedo case’-all building surfaces painted white, pavements to be light colored
- ‘Green Case’- with green roof
- ‘Medium Density (Height enhancement) case’-all buildings in the model area to be taller (mid-rise) than the existing ones bearing in mind the anticipated future expansion.

### **3.4.2. Site Selection**

The selected area, Moosa colony, is a highly dense low-rise informal residential neighborhood in Karachi. The built fabric is mostly characterized by wall-to-wall low-rise buildings (1 to 3 stories) and a few mid-rises with extremely narrow streets and scarce trees. The surface cover is dominated by concrete-laid streets. Most of the buildings show poor architectural quality made of concrete blocks and at times feature metal roofing on higher floors. The selected area is intended to be representative of ‘typical’ informal LCZ3 found in Karachi. Since ENVI-met requires an area input file which defines the 3d geometry of the target area including the physical urban factors like buildings, vegetation, soils and the receptors, the model is created by tracing building outlines from the Google maps directly into ENVI-met. The screen shot of the model is shown in figure 11, where the north is at an angle of 34° and the exact parameters of longitude and latitude are (24.96, 67.07).

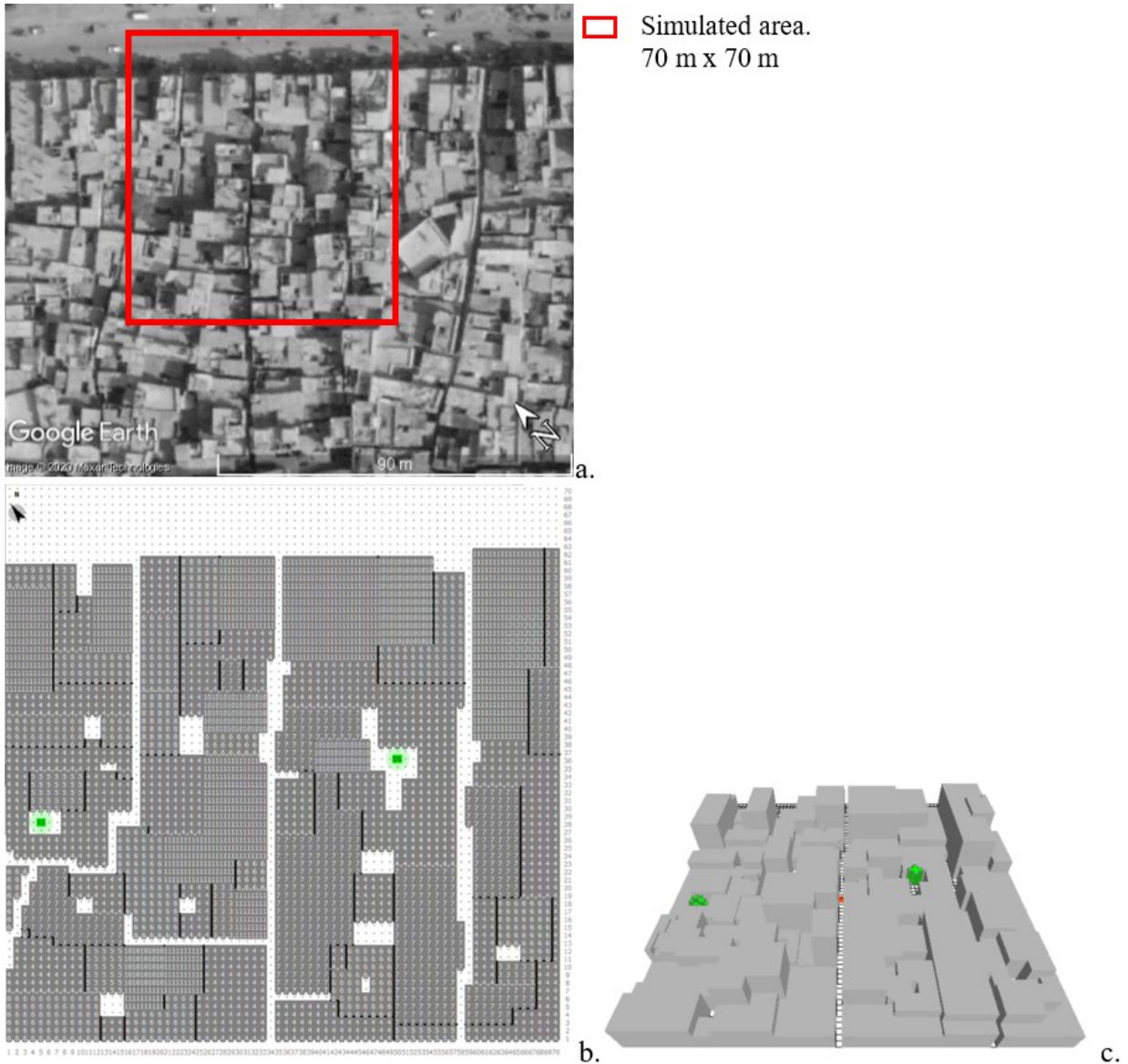


Figure 11. The case study; Moosa colony, Karachi. (a) Building footprint (from Google Earth™), (b) ENVI-met representation. Grid cells in ENVI-met panel are  $1 \times 1$  m; numbers in grid cells: building height (m). Grey/black lines: change in building height (m). Grey/black lines: change in building height between adjacent buildings; SS: Deciduous tree; DS: Palm tree and (c) 3D view of the ENVI-met model.

### 3.4.3. Simulation Parameters

Since the objective is to compare the effects of mitigations on human thermal comfort, simulations are carried out to derive MRT along with  $T_{Air}$  instead of exclusively attempting to enhance  $T_{Air}$ . MRT is defined as “the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings” (ASHRAE, 2016) and has been investigated in various studies such as Emmanuel & Fernando (2007), Jacobs, et al. (2019), Taleghani, et al. (2015), Gatto, et al. (2020), etc. as a thermal comfort parameter. The hottest summer day of the year-2019 is selected to perform the simulation, such as in other studies by Taleghani, et al (2015), and has been assumed as representative of a heatwave state (intense solar radiation and absence of cloudiness) considering that the study aims to scrutinize the potential scenarios of mitigation for reducing UHI in the most extreme situation. The 30 hr. hourly data was acquired from the Pakistan meteorological



department (PMD) since 18:00 pm 12<sup>th</sup> June 2019 to begin the simulations for 13<sup>th</sup> June 2019. The detailed initial input parameters are shown in table below. All parameters not mentioned were kept at the default values for ENVI-met.

Table 5. Input details for ENVI-met simulations

<b>Model Parameters</b>			
<b>Parameter</b>	<b>Definition</b>		<b>Value</b>
Main Data	Domain Size		70m x 70m x 35m
	Cell Size		1m x 1m x 1m
Simulation Time	Start Date		12 June 2019
	Start Time		18:00
	Simulation Time		30 hrs
Meteorological Conditions	Wind Speed		2.05 m/s
	Wind Direction		180.00
	Min and max. T <sub>Air</sub> (°C)		Min= 30.50, Max= 41.00
	Min and max. RH		Min= 39.00, Max=82.00
<b>Case Parameters</b>			
<b>Scenarios</b>	Urban Geometry	Green cover	Surface properties
Base Case	3- 11m	None/sparse	4" Concrete block walls, 6" Cast concrete roof
High Albedo	Same as Base	Same as Base	All walls and roofs to be painted white, Street to be light concrete.
Green roofs	Same as Base	Green roofs for buildings	Same as Base
Medium Density	24m	Same as Base	Same as Base

### 3.5. Analysis Protocol

This study follows a combination of methods, which are often juxtaposed and interrelated with each other to form multidimensional collective assessments. Firstly, the LCZ map is analysed via a comparative percentage and area distribution calculation, thereby identifying the spread of the dominant land uses in the city's overall geographical vicinity. This map then serves as the base to facilitate mean LST extrusion from remote sensing data as well as area profile identification for traverse surveys. The mean LST for all LCZs are numerically/ graphically compared to find the highest and lowest temperature impacts while the temperature data obtained in traverse surveys is translated into route-wise area patterns and temperature profiles. This leads to the identification of relative thermal anomalies among LCZs, the diurnal behaviours and the minimum and maximum temperature thresholds, thereby, identifying the UHI magnitude. The similar heating and cooling behaviours with respect to the associated drivers are also established in this process. This data is then collectively processed to identify qualitative relative temperature patterns among standard built-up classes LCZ 1-6. Further assessments include the study of future trends and their climate impact via comparative percentage and area distribution between 2009 to 2019 and extrapolation of temperatures in the tentative LCZ change. The critical zones thus identified were simulated for mitigation in ENVI-met and quantified in T<sub>Air</sub> and MRT values to determine the efficacy in the reduction of degree of warmth.

This chapter articulates the initial findings of the WUDAPT LCZ mapping, LST and the traverse surveys. Since chronologically, the simulations served as the last step of this thesis study, the results will be discussed later in chapter 6.2.

### 4.1. LCZ Mapping Results and Discussion

The WUDAPT level 0 map, figure 12, highlights the LCZ layout for Karachi identifying the dominant land characters. The built-up area (LCZ 1-10) is mostly found near the city core constituting almost one third (33.8%) of the total peri-urban area of Karachi and is predominantly surrounded by barren land-LCZF (48%). Generally, the built-up areas show extreme scarcity of green/blue LCZ classes where the green covers (LCZ A, B, C and D) collectively and the water resources-LCZG only formed 14% and 2.7% of the total peri urban area, respectively. The built-up cover identified that although Karachi is majorly dominated by industrial areas i.e., LCZ10 (24%) and the abundance of low-rise zones i.e., LCZ3(15%) and LCZ6 (15%), the compact low rise often intersects with compact midrise (3.5%), followed by the LCZ7-lightweight low rise (4%). Although the significant chunk of LCZ10 is no surprise given the industrial relevance of Karachi, the dominant LCZ3 and LCZ6 may correspond to the extensive residential land use in the city and insinuate a dichotomy of extremes, in terms of density as well as social classes in the low-rise built form. Interestingly, it has been observed that LCZ3 covered a wide range of aspect ratios in different regions of the city and included both, the unplanned informal and formally planned areas. It also displayed an association with the lightweight low-rise (LCZ7) building elements in cases of low-income social status and/or informal development nature. Similarly, the LCZ7 also indicated likeliness towards sub-classes in combination with LCZ3. However, since the mix is very organic, the boundaries are hard to distinguish. This may be like other developing south Asian cities with mixed urban fabric and a high dominance of LCZ3 such as Nagpur (Kotharkar & Bagade, 2018) and Colombo (Perera, et al., 2012). Fig. 13 shows LCZ3 and its types across different areas in the city.

Meanwhile, the low-rise blocks, mostly LCZ6, are infused with loosely distributed high-rise buildings i.e., LCZ1 and LCZ4. These LCZs associated with high-rises form a very small portion of Karachi's built fabric and especially LCZ1 is insignificant in size comparatively. Moreover, the built-up areas also seems to be spreading outwards as the sparsely built areas-LCZ9, which comprise of almost 1/3 of the total built area (36%), are most prominently found towards its boundaries often extending into the surrounding barren/ agricultural land. This truly reflects the exponential expansions of the city in terms of urban sprawl (Anwar, 2012). Further, land parcels in urban planning are generally divided by the road network (He, et al., 2018). The role of the road network in the LCZ formation may be an important consideration for the professional planners and hence, as an alternate insight, such a juxtaposition was attempted in Fig 14. and feels true to a degree. In case of Karachi, it not only

shows new developments along the main highways but also identifies the infusion of high and midrise developments along the main roads on closer inspection.

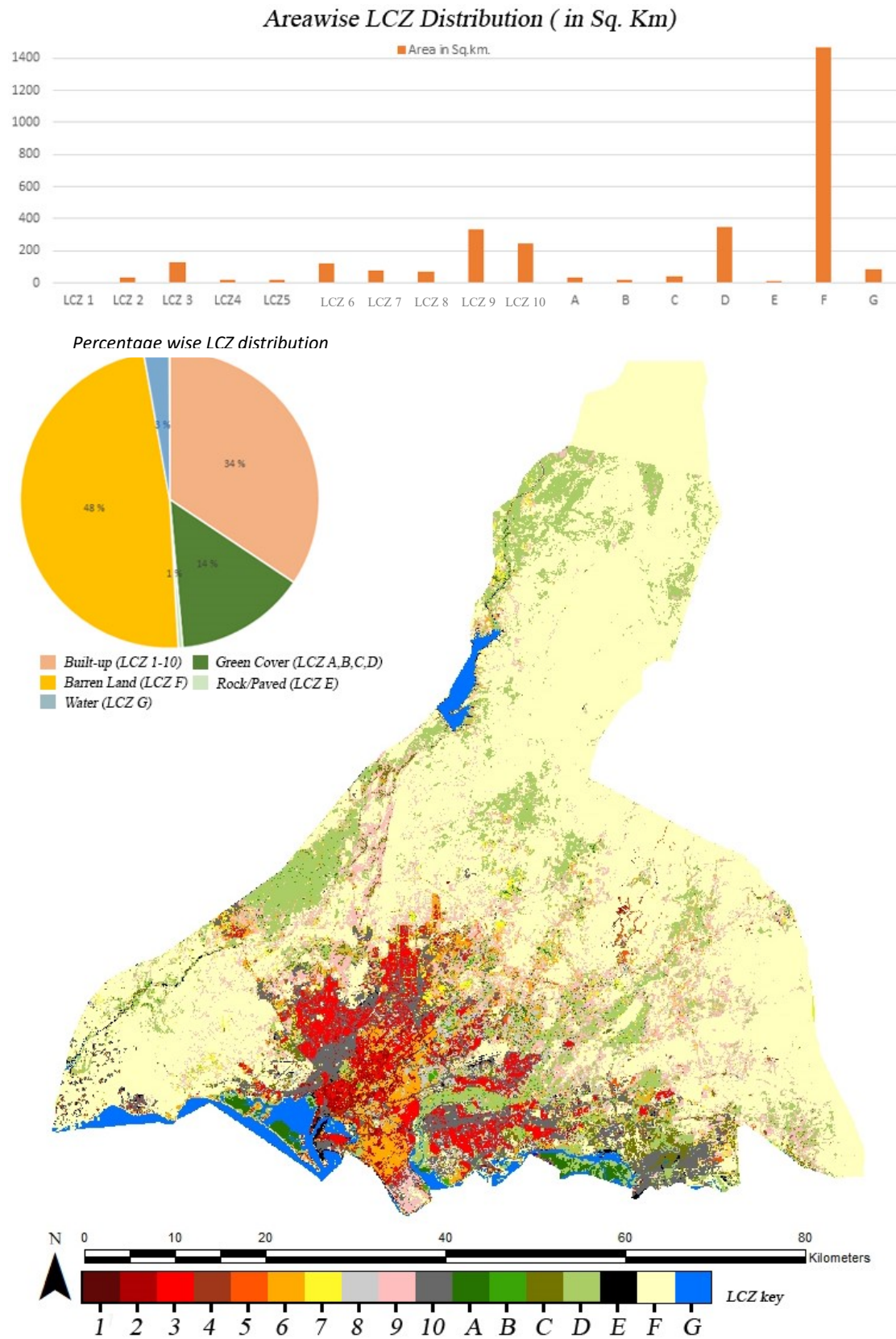


Figure 12. WUDAPT LCZ map of Karachi, 2019

Table 6. LCZ Statistics-2019

LCZ	Description	Area in Sq.km.	% of Built-up Area	Total Built-up Area	% of Total Area	Total Area
1.	Compact High-rise	2,83	0,003	1022,822	33,83	3022,97
2.	Compact Mid-rise	30,87	3,34			
3.	Compact Low-rise	145,09	15,72			
4.	Open High-rise	13,60	1,47			
5.	Open Mid-rise	17,73	1,92			
6.	Open Low-rise	138,32	14,98			
7.	Light Weight Low-rise	40,23	4,359			
8.	Large Low-rise	75,26	8,15			
9.	Sparsely built	331,19	35,88			
10.	Heavy Industrial	227,64	24,66			
101.	Dense Trees	30,33			0,99	
102.	Scattered trees	12,90			0,42	
103.	Bush /Shrub	51,17			1,67	
104.	Low plants	324,81			10,63	
105.	Bare rock or Paved	10,85			0,35	
106.	Bare soil/sand	1485,35			48,64	
107.	Water	84,82			2,77	



Figure 13. LCZ3 and its different forms. (a) Moosa Colony, low-income informal residential which may have infusion of lightweight materials; (b) F.B. Area, mid-income planned residential; (c) PIB colony, low-income planned residential. Source: Google Earth, pro. 200m.x200m

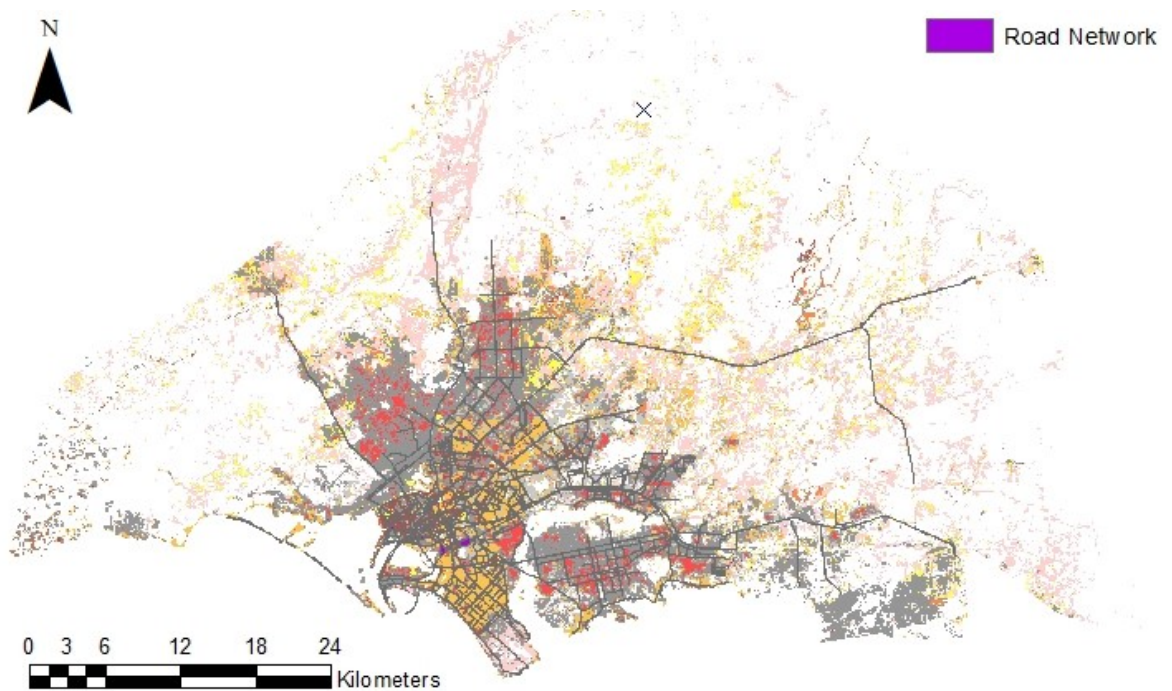


Figure 14. Road network vs Built-up LCZ juxtaposition, 2019



### 4.1.1. Accuracy Assessment

It can be observed that a portion of LCZ classes, built areas and land surfaces, notably have misclassification errors. Therefore, an accuracy assessment via a confusion matrix was carried out to assess the performance of the LCZ map to quantify the inaccuracies. The classification is validated using a new set of randomly selected ground truth samples different from training areas and digitized from Google Earth. The overall accuracy was found to be 68.3 %, and Kappa coefficient was 0.53 respectively, which indicated the classified map may need more scrutiny to satisfy the requirements for further analysis.

The main observations suggest that the heavy industry (LCZ10) seemed to be mistakenly recognized as large low-rise (LCZ8) as well as compact low-rise (LCZ 3) and may possibly contain large paved surfaces (LCZE). Similar mixing is the case of compact low-rise (LCZ 3) and compact mid-rise (LCZ 2). Moreover, the findings suggest that the sparsely built (LCZ9) in open settings is difficult to distinguish such as from bare soil (LCZF) and even misinterpreted when found in large agricultural fields. The green surfaces (LCZA-D) also seemed to overlap among each other.

Furthermore, since the high rises were observed to be scattered in very small chunks across the city during the sampling, it was hard to find training samples with size larger than 100m<sup>2</sup> which may have likely caused misclassification (Cai, et al., 2017), or under-classification. These considerations were kept in mind before the LST retrieval.

## 4.2. LST Results and Discussion

In general, there are no large variations in the mean LST across built-up LCZ classes. However, contrary to the common observations where the densely built-up area exhibits highest temperatures and the temperature reduces with decrease in built-up density, in case of Karachi, during the day the densely built-up areas exhibit lesser temperatures as compared to the barren surrounding areas as observed in Figure 15. The highest LST values were observed in the non-urban barren land (LCZG) followed by the sparsely built-up areas with less/no vegetation (LCZ9). While the coolest LST was correspondent with the water body coverage (LCZG) followed by dense trees (LCZA). The highest (barren land-LCZG) and the coolest (Water-LCZF) mean LST values insinuate an SUHI magnitude of almost 15°C. In addition, the results of the LST analysis of the built classes LCZ 1-6 show that the compact low-rise buildings (LCZ3) and open mid-rise buildings (LCZ 5) were the warmest. Contrarily, the LCZs that are higher vertically (both, open and compact) except for LCZ5, exhibit lower LST than others. Meaning that during the day, LCZ1, LCZ4 and LCZ2 are almost 1°C cooler in comparison with LCZ3. One must note here that despite open arrangement, most of the LCZ5 in Karachi exhibits minimal vegetation. Overall, the warmest built classes are LCZ7, LCZ9 and LCZ10. Given that the adaptation to climate change holds better scope at the city-scale (Mills, 2007; Perera & Emmanuel, 2016), the proportion of spatial distributions of LCZs with respect to LST can identify the overall city impact to identify the collective SUHI effect and will be explored in the next

chapter. However, further investigations of the SUHI phenomenon at night-time are still needed to understand the diurnal cooling behavior of these LCZs.

Moreover, there are unlikely (extreme) LST patterns observed within the same LCZs, for instance in LCZ6 in fig. 15. The visual inspection points towards the different amounts of vegetation, spatial arrangement, and aspect ratios in different geographical vicinity of the city. Further, it was also observed that generally, many of the LCZs exhibited higher temperatures as they moved away from the coast and hence, the areas closer to the southern side of the city were cooler in comparison. These findings seem to relate well with previous studies as the literature identifies the different thermal temperatures within the same LCZs attributing to the impact of street orientation, street aspect ratio, surface properties (Maharroof, et al., 2020), asymmetric urbanization patterns and even to the vicinity to the coast (Campbell-Lendrum & Corvala'n, 2007; Chakraborty, et al., 2019) with the sea breeze and its effects on adding to the moisture and blowing heat away (Li, et al., 2016). Additionally, on closer examination, the LST maps highlight higher temperature patterns associated with the road/street network as shown in the LST vs road network juxtaposition in fig. 17. Several other studies have validated these observations concerning the temperatures of the major roads due to the impervious nature of roads and the reduced likelihood for cooling (Ibrahim, et al., 2016). However, such observations seem unaligned with shading effects of building on streets during the day substantiated during the traverse surveys (discussed in 4.3.2). These broad observations implore deeper analysis of LCZs in the context of Karachi.

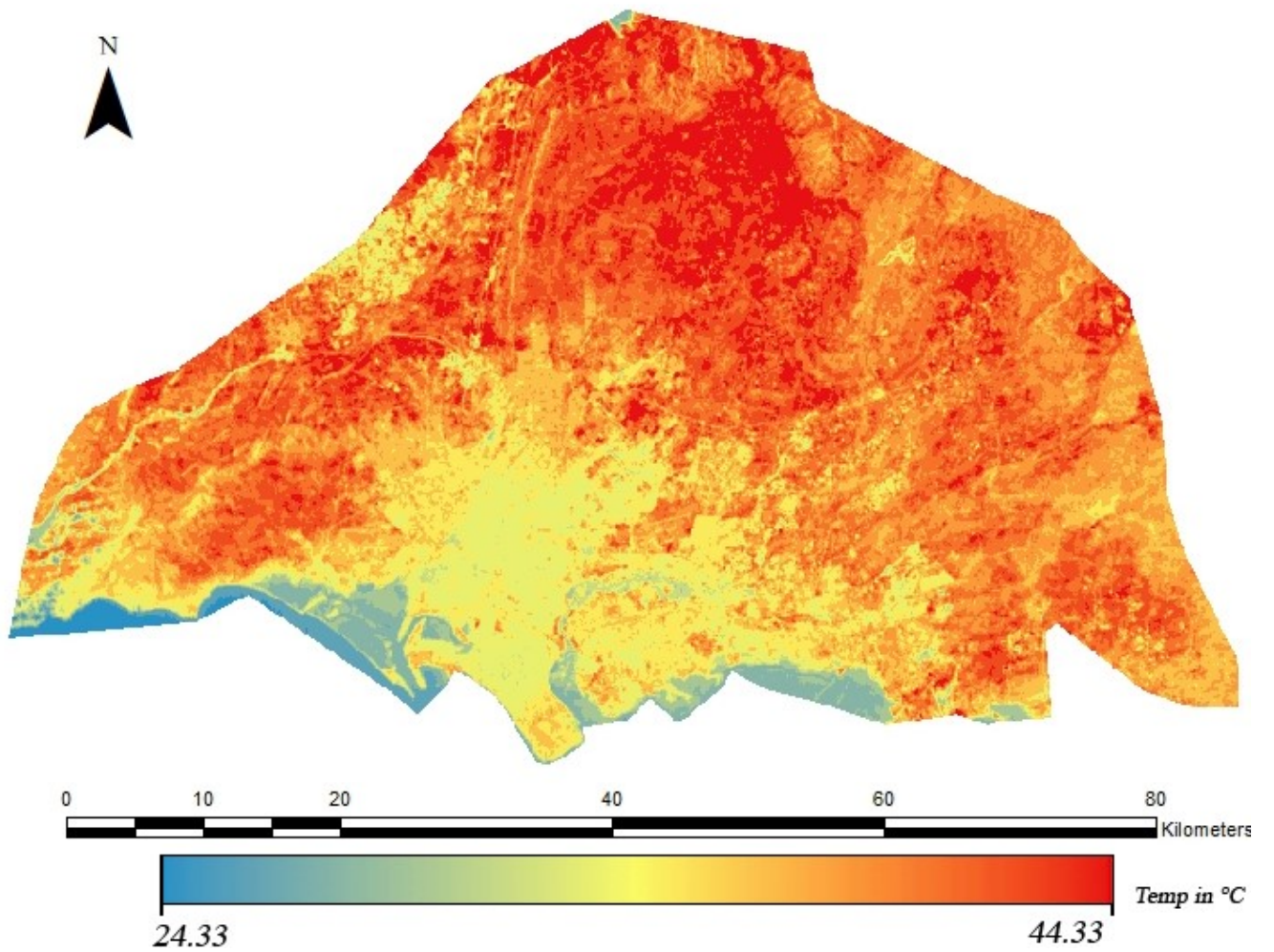
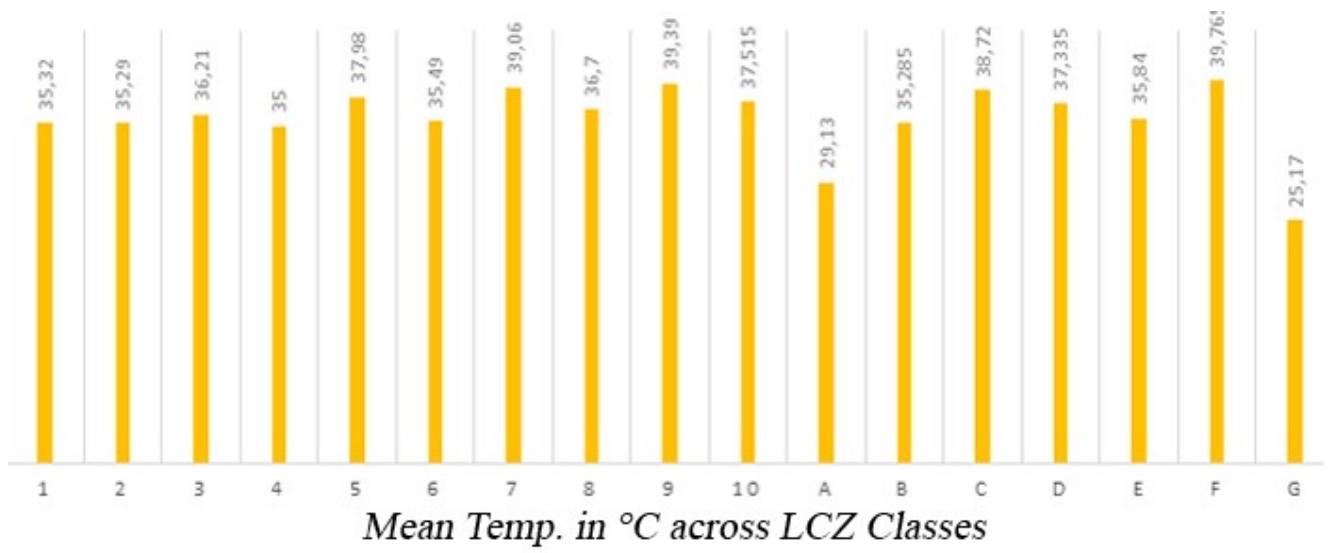


Figure 15. LST map for Karachi, June 2019

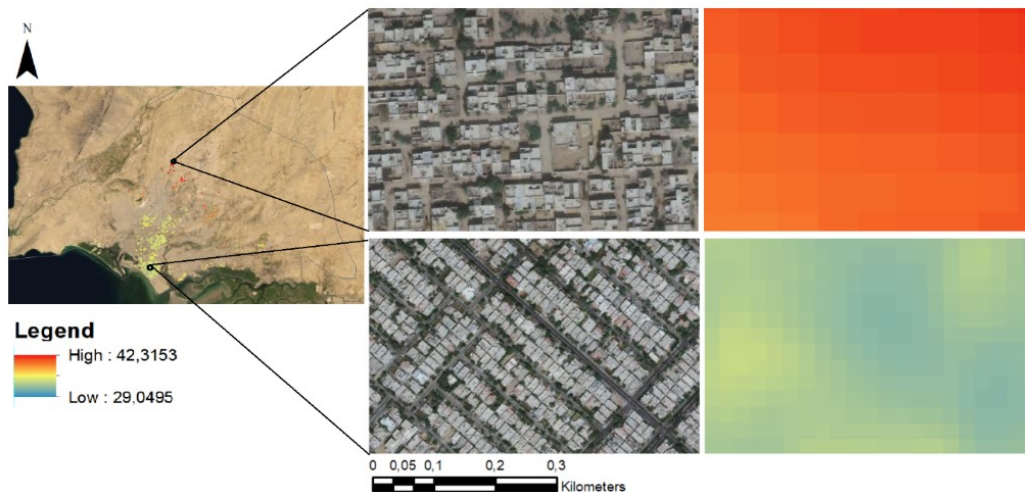


Figure 16. LCZ 6-Range of spatial arrangements and associated LSTs

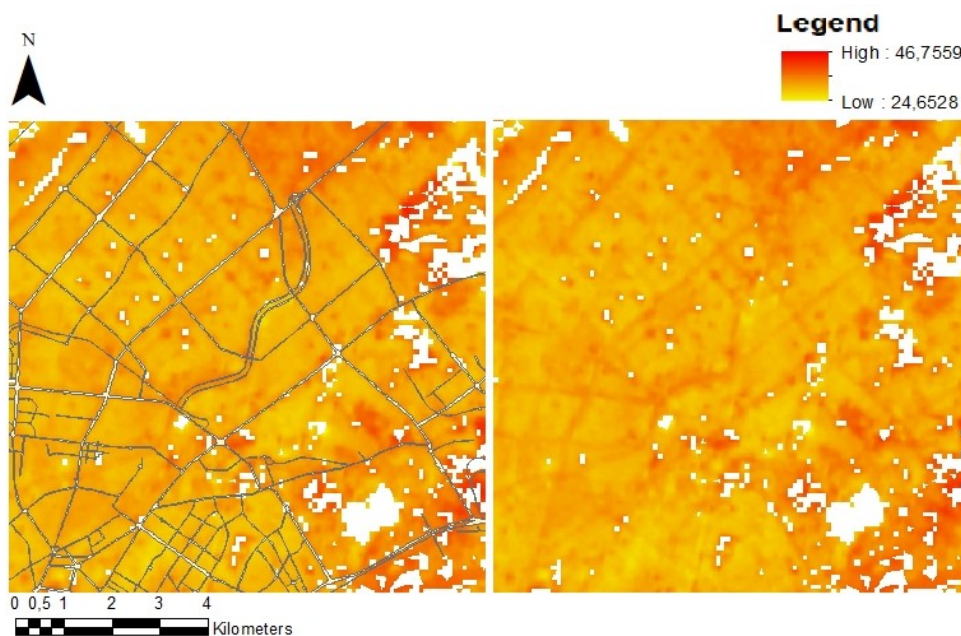


Figure 17. LST juxtaposition with and without the road network, April 2019

### 4.3. Traverse Survey Results

#### 4.3.1. The IUHI Magnitude

This methodology not only establishes the UHI magnitude and typical thermal characters associated to the standard LCZs defined by Stewart and Oke (2012), but also provides an introspection into unique combinations and subclasses of these LCZs in Karachi. This is a relevant consideration bearing in mind the formal/informal nature as well as mixed built typologies of Karachi's development. Table 7. identifies the UHI magnitude observed on each route during the winter 2020 traverse surveys. Through these, the overall UHI magnitude observed is between 0.99-3.00°C where the results show that the daytime UHI intensity observed is weaker than

that of night-time, as expected from Oke (1982). However, the night-time traverses identify the highest UHI magnitude observed on 3rd Feb 2020 i.e., 3°C. The highest UHI magnitude during the day was only half as much observed on 2nd Feb 2020 i.e., 1.5°C. In general, the results show a lesser temperature variation within LCZs. However, inter-zone temperature differences tend to be underestimated as temperatures are taken over paved roads and across areas accessible to cars (Stewart, et al., 2014). Similar observations are the case of many other cities showing a lesser temperature variation (Eliasson, 1990), while in terms of night-time UHI (Yadav & Sharma, 2018; Lemonsu, et al., 2015) had similar observations.

Table 7. UHI magnitude on various routes (°C)

Route	Dis. Km	Date	Time	Lowest ΔT	Lowest ΔT LCZ	Highest ΔT	Highest ΔT LCZ	UHI Mag.
Route 01	18	31/01/2020	14:10-16:50	-0,115	LCZ6/B	0,88	LCZ5	0,995
Route 02	12	01/02/2020	13:50-15:20	-0,978	LCZ2	0,276	LCZ5	1,254
Route 02 (Night)	12	04/02/2020	19:00-21:10	0,449	LCZ6	1,674	LCZ5	1,225
Route 03	12	02/02/2020	15.20-16.50	-1,484	LCZ1	-0,222	LCZ2	1,262
Route 04	25	02/02/2020	14.35-16.35	-0,531	LCZ4	0,937	LCZ3 <sub>7</sub>	1,468
Route 05 (Night)	36	03/02/2020	20:05-21:55	-1,448	LCZ8	1,55	LCZ1	3,000

### 4.3.2. Relative Differences in Temperature among LCZs

Figure. 18 and 19 establish the detailed temperature difference profiles on each route and the relative temperature patterns. The overall pattern identifies the temperature variation among various LCZ classes as well as deflections across the same LCZs, reflecting the inconsistencies within the same built typologies as observed in LST. During the day, the coolest LCZs were found to be LCZ 1 and LCZ4 (commercial areas) with the maximum difference of 1,3 and 1,5 °C respectively from the fixed station, followed by LCZ2. Alternatively, at night, the LCZ8 and LCZ6 were found to be the coolest with the maximum temperature difference of 1,5 °C from the fixed station. While the warmest LCZs were noted to be LCZ5 and LCZ 3<sub>7</sub>-compact low rise nested in lightweight low-rise with the temperature difference of 0,93°C and 0,88°C during the daytimes, respectively. While at night the LCZ4 (commercial) showed significantly high temperatures followed by LCZ1 (Residential- Bahadurabad). Comparing the temperatures difference associated with each LCZ, the maximum ΔT was found to be 3 °C between LCZ 1 and LCZ 8 at night-time while the maximum difference in day time featured between LCZ 3<sub>7</sub> and LCZ4 where the ΔT was found to be 1.5°C.

Also, LCZ3 and LCZ5 (without vegetation) were consistently warm during the day as well as night. Contrarily despite the absence of greens, the high-rise buildings still showed steadily lesser temperatures during the day. The extreme temperature pattern associated with high-rises (LCZ1 and LCZ4) at day and night may be explained by the street level shading effects (Emmanuel, 2006; Jacobs, et al., 2019) as ample shading can lead to stronger cooling at daytimes and vice versa (Giridharan & Emmanuel, 2018). Similar holds true for compact midrise (LCZ2) buildings as it was roughly noted that the higher the building height, the lesser the temperature during the day, especially on route 3. It could be due to the same reason or perhaps the variation in building heights being beneficial likely for stimulating air movement (Emmanuel, 2006) that the high-rises even in combination with other LCZs, such as LCZ3/1 on route 1 and LCZ6/1 on route 4 exhibited lesser temperatures as compared to

standard LCZ classes on the same routes during the day. Such observations also extended towards combinations of other open LCZs and green covers often serving as relative cold spot among the dense and compact LCZs. Such as LCZ 6/B on route 1 and LCZ 6/B route 2, along with LCZ 2/D and 2/8 on route 3 exhibited lesser temperatures as compared to standard LCZ 6 and 2 respectively on the same routes (refer to figure 18 for clarity). Thereby, identifying correlation between the juxtaposition of LCZs with high rise buildings, open forms, and green covers in subduing the heat intensity in comparison to standard LCZ zones.

Moreover, it is also observed that despite being characterized as a certain LCZ, there is an effect of the surrounding LCZs and geographical context on the temperature pattern. For instance, large or open low-rise classes (LCZ8 and 6) adjacent with abundance of soft land covers (LCZ A through D) were observed to greatly modulate the local warming intensity. As in the Karachi University (KU) vicinity on route 4- 03 February, both the large or open low-rise classes (LCZ8 and 6) in combination with green land covers(LCZA, B, D) served as the cold spots during the nighttime. All these observations, although limited, attest that diverse types of adjacent zones influence the UHI intensity of standard zones (Thomas, et al., 2014 ), and may contribute as cold spots such as in combination with LCZ1 and 4 and green surfaces in the day and open forms and green surfaces/elements at nighttime. And for heterogenous cities which are unlikely to have standard zones, such variation may be explored to find the best possible situations.

It is acknowledged that this procedure may not be reflective of traditional ways, however it does shed light on the relative temperature patterns of the LCZs and may be useful to assess limited datasets. However, more data in different times and seasons is needed to establish better understanding and precision. While, it must be noted that this approach although acknowledges the role of building density, it doesn't necessarily identify the dynamics of population density in the temperature patterns due to the density dynamics as discussed in 3.1.2.



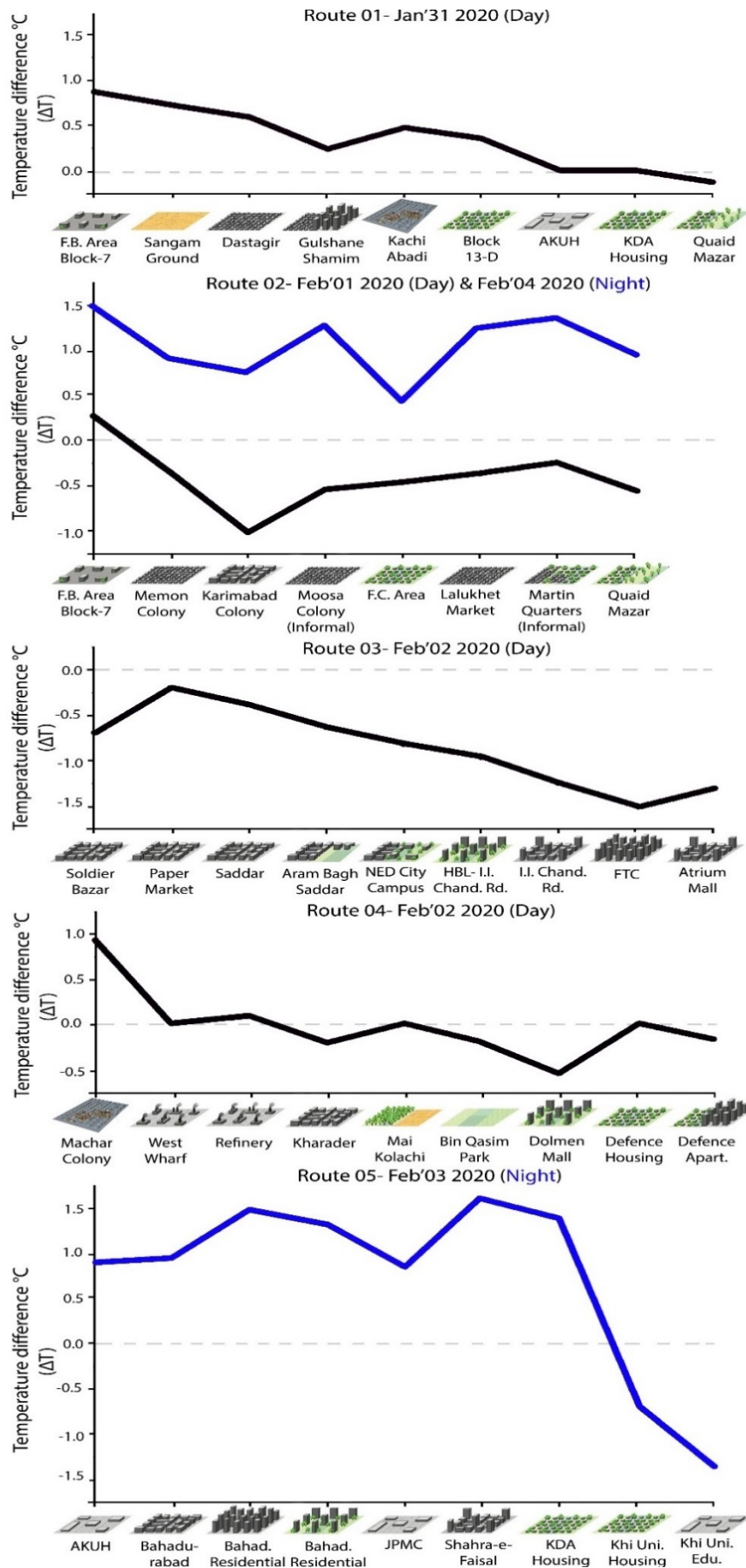


Figure 18. Temperature difference(°C) profiles from fixed station during traverse surveys across the city routes.











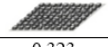

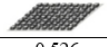

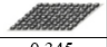
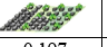




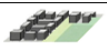

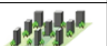
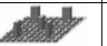

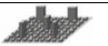
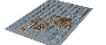



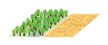











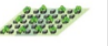

Route 1, 31 January 2020										
Time	LCZ 5 FBA 	LCZ F SG 	LCZ 3- For DG 	LCZ 3/1 GS 	LCZ 3 <sub>7</sub> KAL 	LCZ 6 13D 	LCZ 8 AKUH 	LCZ 6 KDA 	LCZ 6/B QM 	IUHI Mag.
Day	0,88	0,75	0,573	0,239	0,45	0,353	0,066	0,052	-0,115	0,995
<b>Temperature pattern- Day: LCZ5 &gt; LCZF &gt; LCZ3-Formal &gt; LCZ3<sub>7</sub> &gt; LCZ6 &gt; LCZ3/1 &gt; LCZ8 &gt; LCZ6 &gt; LCZ6/B</b>										
Route 2, 01-Feb & 04-Feb 2020										
Time	LCZ 5 FBA 	LCZ 3-For MC 	LCZ 2 KC 	LCZ 3-Inf MC 	LCZ 6 FCA 	LCZ 3-For LK 	LCZ 3/6 MQ 	LCZ 6/B QM 	-	IUHI Mag.
Day	0,276	-0,323	-0,978	-0,526	-0,393*	-0,345	-0,197	-0,58	-	1,254
Night	1,674	0,986	0,779	1,302	0,449*	1,285	1,383	1,03	-	1,225
<b>Temperature pattern- Day: LCZ5 &gt; LCZ3/6 &gt; LCZ3 Formal &gt; LCZ3 Formal &gt; LCZ6 &gt; LCZ3-Infomal &gt; LCZ6/B &gt; LCZ2</b>										
<b>Temperature pattern- Night: LCZ5 &gt; LCZ3/6 &gt; LCZ3-Infomal &gt; LCZ 3-Formal &gt; LCZ6/B &gt; LCZ3- Formal &gt; LCZ2 &gt; LCZ6</b>										
Route 3, 02-Feb 2020										
Time	LCZ 2 SB 	LCZ 2 PM 	LCZ 2 SD 	LCZ 2/D AB 	LCZ 2/8 NED 	LCZ 4 HBL II. 	LCZ 4 II. CR 	LCZ 1 FTC 	LCZ4 AM 	IUHI Mag.
Day	-0,698	-0,222	-0,372	-0,631	-0,8	-0,938	-1,246	-1,484	-1,296	1,262
<b>Temperature patter - Night: LCZ2 &gt; LCZ2 &gt; LCZ2/D &gt; LCZ2 &gt; LCZ 2/8 &gt; LCZ4 &gt; LCZ4 &gt; LCZ4 &gt; LCZ1</b>										
Route 4, 02-Feb 2020										
Time	LCZ 37 MC 	LCZ 10 WW 	LCZ 10 WWR 	LCZ 2 KH 	LCZ A/F MF 	LCZ D BQP 	LCZ 4 DM 	LCZ 6 DH 	LCZ 1/6 DA 	IUHI Mag.
Day	0,937	0,06	0,115	-0,244	-0,005	-0,244	-0,531	-0,005	-0,161	1,468
<b>Temperature pattern- Day: LCZ37 &gt; LCZ10 &gt; LCZ1/6 &gt; LCZ A/F ≈ LCZ6 &gt; LCZ2 ≈ LCZD &gt; LCZ4</b>										
Route 5, 03-Feb 2020										
Time	LCZ 8 AKUH 	LCZ 2 BB 	LCZ 1 BB 	LCZ 4 BB 	LCZ 8 JPMC 	LCZ 4 SHF 	LCZ 6 KDA 	LCZ 6 KUR 	LCZ 8 KU1 	IUHI Mag.
Night	0,781	0,826	1,374	1,239	0,744*	1,552	1,139*	-0,805	-1,448	3,00
<b>Temperature pattern- Night: LCZ4 &gt; LCZ1 &gt; LCZ4 &gt; LCZ8 &gt; LCZ6* &gt; LCZ2 &gt; LCZ8</b>										

Figure 19. Temperature difference(°C) patterns in LCZs during traverse surveys.

Note 1: Image source: Stewart and Oke (2012) and self-elaboration. References: 'For' refers to the formally planned ; 'Inf' refers to informally planned; the '/' between LCZs refers to the edge between two LCZs, this may be a road dividing two LCZs or a junction '\*' on the temperature values shows the unstable( decreasing or increasing) temperature trend while the temperature is noted.



The previous section has identified the dominant LCZs in the city along with the respective temperature trends substantiated with LST maps and traverse surveys. This also tracked the unique behavioral identification of patterns relating to spatial arrangement, greens, vicinity to coast, effect of adjacent LCZs and other urban elements. This section extends this analysis and collectively looks at the results of all three of the previous methods to identify the most critical zones. The points of discussion are the future LCZ trends and associated heating, role of density and effects of street canyons on thermal comfort and usage typology of LCZs, among others.

### **5.1. Trend Identification**

The LCZ map of the Karachi shows an irregular pattern which conforms to its heterogeneity. Further, within the built forms (1-6), open and compact low-rise (LCZ3 and 6) are the majorly dominant LCZs and present us with the possible juxtaposition of both, the formal and informally planned areas. Given the current information of LCZs and their impact on the temperature trends, it is possible to estimate the likely UHI in the rapidly evolving areas of the city. This is studied via two methods. Firstly, a comparative cross analysis of overall LCZ change is explored for year 2009-2019 to shed light on the anticipated/potential increase in the LCZs in the future. And secondly, by extrapolating the expected effect on the temperature and local warming in the 'built up' LCZ classes (LCZ 1-8) when these are subjected to more intense developments. Both exercises will not only inform future directions but will also allow preparedness in extreme cases.

#### **5.1.1. Simulating LCZ Maps for 2009 and 2019**

Researchers have widely employed LULC studies to quantify urban change detection (Aguirre-Gutiérrez, et al., 2012; Zhan, et al., 2002), urban climatic effects (Auer, 1978; Kotharkar & Surawar, 2016; Mustafa, et al., 2019), and environmental variables on urban-rural land dynamics. However, it is argued that such traditional approaches are based on inconsistent scopes and functions (Stewart & Oke, 2012) due to a lack of a standardized classification system (Verma & Jana, 2019). The absence of strict class boundaries and a well-documented approach to generate these maps has resulted in opting for subjective requirement-based classes to distinguish intra-urban features (Verma & Jana, 2019) and are even often incapable of quantifying factors of change and multilevel relationships (Millington, et al., 2018). Since, the LULC's purpose or intent of design hasn't been to classify heat island field anyway, the LCZ as a standard well-classified research framework may be construed as an equivalent to LULC for UHI studies (Stewart & Oke, 2012). The previously LULC studies in Karachi (Yasmeen, et al., 2017; Zaidi & Zafar, 2018; Raza, et al., 2019; Mangi, et al., 2020) fail to detail out the climate-based classifications and change. Therefore, a percentage-based assessment with respect to LCZs is attempted in this study. In this case, another LCZ map was generated for 2009 along with the already developed 2019 LCZ map where the same

WUDAPT sampling procedure as mentioned in 3.2.1 was carried out. However, Landsat 5 dataset was used instead of Landsat 8 for 2009 (as recommended by [http://www.wudapt.org/prepfeat\\_overview/path2step3a/](http://www.wudapt.org/prepfeat_overview/path2step3a/)) as Landsat 8 data is available only after 2013. The new developed map is manually compared to determine accuracy from Google Earth. Both maps are further analysed to establish the specific change in the land use.

### **5.1.2. LCZ Change Trends and Discussions**

From an LULC perspective, previous studies substantiate that the built-up areas of Karachi have been expanding intensively overtime (Mangi, et al., 2020). This multiyear analysis of LCZ change verifies this claim as the built cover increases from 690,10 km<sup>2</sup> to 1022,82 km<sup>2</sup> from 2009 to 2019 along with the identification of specific classes. Various accounts have attested to the expedient change of land use in Karachi where both the formal and informal settlements have noted the low-rise residences and other such buildings being expanded vertically and/or being consumed into high-rise developments (Hasan & Mohib, 2003; Khan, 2010; Hasan, 2016; The News, 2019) along with subdivisions of larger plots (Anwar, 2012). The resultant substandard narrow building blocks (Hasan, et al., 2017) not only impact the over densification across all classes, including the illegal (UN-Habitat, 2017) and the informal (Hasan, 2016), but also pose major risks of system collapse in the absence of any civic infrastructure, service provisions and environmental reporting to support such changes (Anwar, 2012; DAWN, 2016). These discussions insinuate a probable change of low-rise classes (LCZ6 and LCZ8, and LCZ3) to further compaction or conversion into high and mid-rises (i.e., LCZ1, LCZ4 and LCZ3, and LCZ2 and LCZ1, respectively).

This study validates this assertion as the comparison of both the maps identify that generally significant areas of the built-up area in Karachi remain low-rise (LCZ3 and LCZ6) in both the years, however, LCZ6 is the only as well as massively decreasing LCZ class observed in terms of area, while LCZ3 and LCZ2 are hugely increasing. This implies the identification of vertical and/or horizontal expansion among the low-rise and/or less dense LCZ types. Meanwhile, several areas along major roads are witnessing an infusion of mid-rise and high-rise blocks (a change from LCZ6 to LCZ1, 4 and 2). However, the change observed in LCZ1 and LCZ4 is quite insignificant to other LCZs, albeit, it shows strong inclination towards this trend in future. Moreover, the huge increase in sparsely built class (LCZ9) affirms the growing sprawl development as observed by Raza, et al. (2019). Both these trends authenticate the vertical as well as horizontal densification of the city. This also establishes the claim of heavy strain on the resources of the city, and questions whether such densification is supported by infrastructural layout and amenities of the city. Meanwhile, the hugely diminishing green areas which pretty much illustrates in the significant reduction in LCZA-D(14%) and water resources(1%) along with the substantial increase in barren land (3,8%) not only justify the previous claims of the urban development costing the cut down of trees and vegetation, diminishing greenbelts (Qureshi, et al., 2010; Raza, et al., 2019) and the surrounding agricultural land, and the reclaimed land from the sea (Mangi, et al., 2020) but also identify the current city's GI to be in a disproportionate state (Qureshi, et al., 2010). These results recognize the previously identified challenges to UHI, i.e., the increase in density, urban sprawl, unplanned growth and the shrinking green areas (Anwar, 2012).

Table 8. clearly identifies the LULC statistical change from 2009 to 2019, table 9 depicts the rate of change in built-up areas between the time frame of 2009 to 2019, while the fig. 20 shows visual evaluation of both the maps.

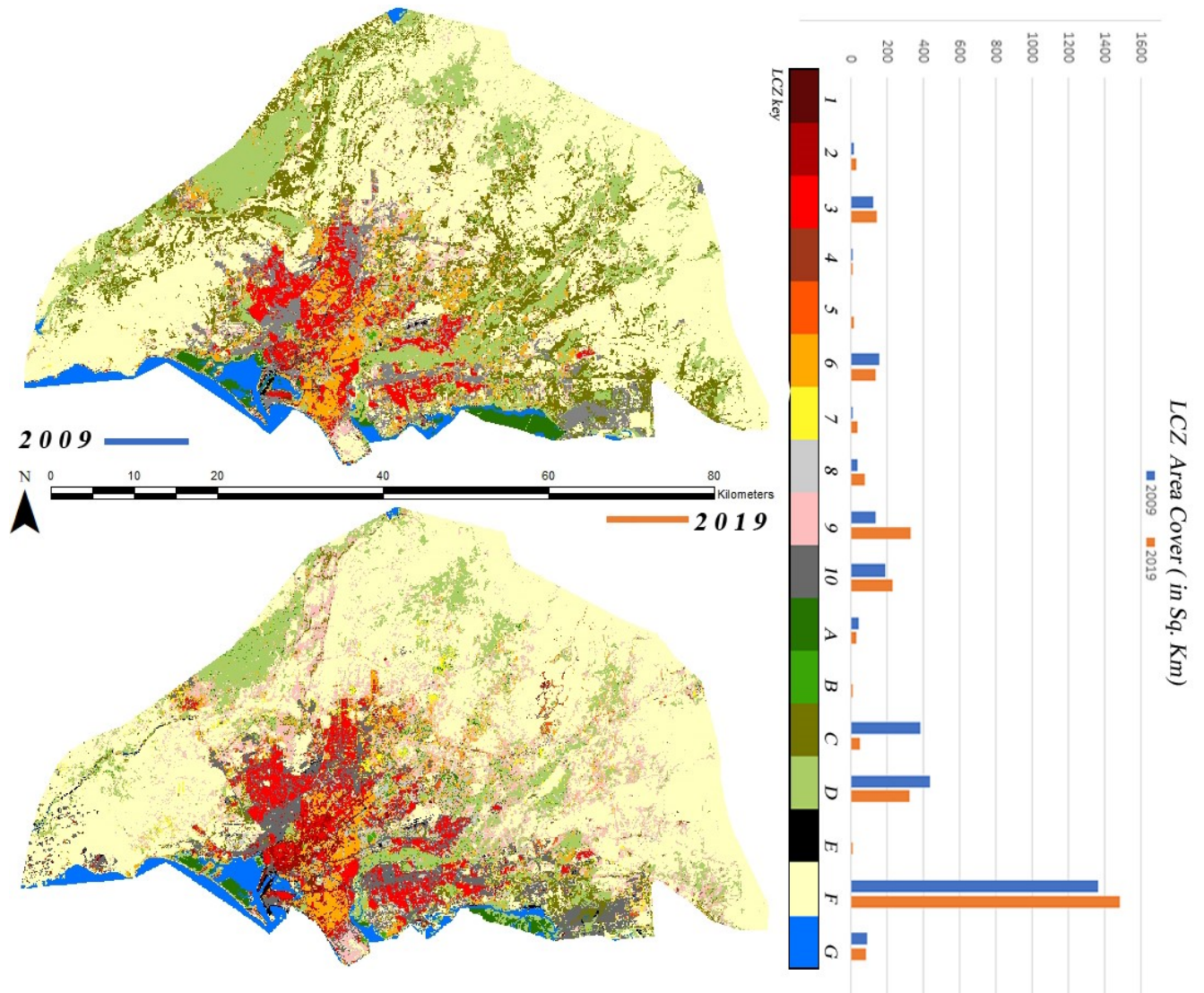


Figure 20. LCZ maps of Peri-urban Karachi, 2009 & 2019

Table 8. LULC statistics, 2009 and 2019

LCZ Distribution	2009		2019		Change Detection	
	Km <sup>2</sup>	%	Km <sup>2</sup>	%	Km <sup>2</sup>	%
<b>Built-up</b>	690,10	22,82	1022,82	33,83	332,71	11,00
<b>Agriculture</b>	871,44	28,82	419,22	13,86	-452,21	-14,95
<b>Hard Surface</b>	5,18	0,16	10,85	0,35	5,67	0,185
<b>Barren</b>	87,34	2,86	1485,35	48,64	116,45	3,8138
<b>Water</b>	87,34	2,86	84,82	2,77	-2,52	-0,082

Table 9. LCZ Change statistics, breakdown of built-up 2009 and 2019

Type LCZ	2009			2019			Change Detection			
	Km <sup>2</sup>	% of Built-up Area	Total Built-up Area	Km <sup>2</sup>	% of Built-up Area	Total Built-up Area	Km <sup>2</sup>	% of Built-up Area		
Compact High-rise	1,30	0,0013	690,10	2,83	0,003	690,10	1,53	0,0016		
Compact Mid-rise	18,56	2,70		30,87	3,34		12,30	0,64		
Compact Low-rise	124,91	18,19		145,09	15,72		20,17	-2,47		
Open High-rise	9,56	1,39		13,60	1,47		4,03	0,08		
Open Mid-rise	1,48	0,21		17,73	1,92		16,24	1,70		
Open Low-rise	157,48	22,93		138,32	14,98		-19,16	-7,94		
Light Weight Low-rise	13,36	1,946		40,23	4,359		26,87	2,413		
Large Low-rise	37,98	5,53		75,26	8,15		37,27	2,622		
Sparsely built	136,04	19,81		331,19	35,88		195,15	16,071		
Heavy Industrial	189,37	27,57		227,64	24,66		38,27	-2,914		
LCZ A Dense tree	42,47	1,39		3022,97	30,33		0,99	3022,97	-12,14	-0,39
LCZ B Scattered trees	3,47	0,11			12,90		0,42		9,43	0,308
LCZ C Bush/ shrubs	386,26	12,65		51,17	1,67		-335,09	-10,97		
LCZ D Low plants	439,22	14,38		324,81	10,63		-114,40	-3,74		
LCZ E Bare rock or paved.	5,18	0,16		10,85	0,35		5,67	0,185		
LCZ F Bare soil or sand	1368,90	44,83		1485,35	48,64		116,45	3,8138		
LCZ G Water	87,34	2,86		84,82	2,77		-2,52	-0,082		

### 5.1.3 Future LCZ Development and Implications for Urban Planning

To identify which modifications hold the most harmful heating implications, a scenario of land use and planning proposition is studied. By appropriating Perera & Emmanuel's strategy to predict the likeliness of local warming in the 'built-up' LCZ classes (LCZ 1-8) when these are subjected to more intense development, an attempt is made to possibly guide future developments with the issues of land use and associated thermal effects (Perera & Emmanuel, 2016) to incorporate climate-sensitive planning.

The satellite imagery data has limited capacity in terms of spatial and temporal resolution (Voelkel & Shandas, 2017), and thus considered too broad to take preventative actions (Sobrino, et al., 2011) as the temporal insufficiency deprives the understanding of how fast specific areas heat up or vice versa (Voelkel & Shandas, 2017). Alternatively, ground-based measurements serve as a balanced approach in potentially providing accurate readings throughout the day (Yokobori & Ohta, 2009; Kotharkar & Surawar, 2016). Therefore, to analyze future LCZs and their associated thermal behavior, the maximum temperature differences acquired via traverse surveys are extrapolated for the day and night times.

#### 5.1.3.1. Transformation- Extrapolation of temperatures

The results of Table 10 and 11 allow identification of the possible extent of temperature changes in future scenarios. At daytime, all LCZ intensifications lead to cooling effects except for open mid-rise (LCZ5), and mostly increase as the LCZs go higher in terms of height. However, the same association to building heights at night-time leads to extreme heating. This night-time UHI is pertinent given that people spend a significant amount of time indoors (Giuli, et al., 2012; IWBI, 2019), particularly during night-time and the high susceptibility of outdoor temperature impacting indoor is high for naturally ventilated buildings (Jacobs, et al., 2019). Further, under the pretext that LCZ 6(open low-rise) and LCZ8(open low-rise) (as discussed 5.1.2) are drastically being transformed in to LCZ4, LCZ1, LCZ5 and LCZ2, it is evident that all the tentative intensifications cause extreme

local warming at nighttime except for LCZ 2, with the greatest nighttime heating observed in LCZ1, LCZ4 and LCZ5, i.e., 2,81 °C, 2,99°C and 3,11°C respectively. Given the above repercussions of high-rises, the previous legislations in Karachi in favor of high-density zones not just merely exploit enhanced constructions (with increased building sizes and elimination of setbacks) along with a disregard for corresponding infrastructure and utility networks (DAWN, 2016), but their growing numbers now may also insinuate extreme climatic consequences at the city scale if unregulated.

Meanwhile, horizontal densification of low-rise towards a more compact form i.e., LCZ6 to LCZ3 also induces 1,78 °C at nighttime. Since LCZ3 is already dominant in the city, more additions may have a disproportionate temperature impact on the overall city heating. While interestingly the vertical transition of LCZ3 (formal and informal towards LCZ2) seems to be most stable, balanced and least harmful change from a diurnal perspective. Lastly, the most beneficial transformation is LCZ8 changing into LCZ6 with a reduction of 0,33 °C, at daytime, and the least temperature increase at night i.e., of 0,64 °C.

Note: It is recommended to carry out this study with values verified with a bigger data set across different season. However, this exercise has merely utilised the limited dataset for this thesis purpose only due to covid-19 limitations and may not be reflective of summer extremes as the dataset was gathered in the winter season.

Table 10. Projected daytime temperature differences

Existing LCZ		Projected LCZ								
LCZ	Title	1	2	3-For	3-Inf	4	5	6	7	8
1	Compact High-rise	-1.48								
2	Compact Mid-rise	-1.48	-0,97							
3	Compact Low-rise	-1.48	-0,97	-0,33	-0,52					
4	Open High-rise	-1.48	-0,97	-0,33	-0,52	-1.12				
5	Open Mid-rise	-1.48	-0,97	-0,33	-0,52	-1.12	0,88			
6	Open Low-rise	-1.48	-0,97	-0,33	-0,52	-1.12	0,88	-0,393		
7	Light weight low-rise	-1.48	-0,97	-0,33	-0,52	-1.12	0,88	-0,393	x	
8	Large Low-rise	-1.48	-0,97	-0,33	-0,52	-1.12	0,88	-0,393	x	0,06

Table 11. Projected night-time temperature differences

Existing LCZ		Projected LCZ								
LCZ	Title	1	2	3-For	3-Inf	4	5	6	7	8
1	Compact High-rise	1,37								
2	Compact Mid-rise	1,37	0,82							
3	Compact Low-rise	1,37	0,82	0,98	1,30					
4	Open High-rise	1,37	0,82	0,98	1,30	1,55				
5	Open Mid-rise	1,37	0,82	0,98	1,30	1,55	1,67			
6	Open Low-rise	1,37	0,82	0,98	1,30	1,55	1,67	-0,80		
7	Light weight low-rise	1,37	0,82	0,98	1,30	1,55	1,67	-0,80	x	
8	Large Low-rise	1,37	0,82	0,98	1,30	1,55	1,67	-0,80	x	-1,44

## 5.2. Collective Results for LCZ map, LST, Traverse Surveys

This section collectively explores the comparative relationships between temperature patterns obtained from LST maps and traverse surveys (day and night) in the standard LCZ 1-6 to identify the most sustainable LCZs with the least harmful warming effect and vice versa. The hypothesis is that each LCZ demonstrates unique and typical character due to the different building density, surface features (Ansar, 2012) and exposed surface area (Emmanuel & Steemers, 2018) and hence, may offer inter-comparisons for identifying the most critical zones. For comparative purposes within typical LCZs, all transitional LCZs are disregarded for the summary.

### 5.2.1. Summarized Results

Table 12. identifies that all three patterns show mostly coherent results. During the day, both the LST and the traverse surveys identified LCZ3 and LCZ5 as the warmest built-up LCZs. Meanwhile, although LCZ1 and LCZ4 are the coolest at daytime in both the methods, their nighttime temperatures are the warmest in comparison. This suggests an association of building height contributing to the comparative coolness in the day and vice versa. Moreover, even though LCZ3 may not be the warmest at nighttime, it consistently remains a high temperature zone, however, LCZ2 despite being denser than LCZ3, seems to perform better i.e., less warmer in comparison with LCZ3 for both the day and nighttime. Also, it is important to simultaneously analyse the spatial coverage associated with these LCZs since LCZs with major heat impact covering a huge chunk of the built area may have a city level implication in contributing to UHI development. The spatial coverage (as observed in 5.1.2.) suggests that LCZ3 is the most dominant (15%) among the built-up classes 1-6 at this point of time and may likely continue to do so. And therefore, the current thermals pattern may lead to consistently high day and nighttime temperature for a huge area of the city. Meanwhile, LCZ 1 and 4 although currently insignificant in size, are likely to increase in future, thereby causing extreme temperature repercussion for the nighttime. While the increasing LCZ2 trends may play a cathartic role to balance the repercussions of other LCZs. Generally, the nocturnal temperatures observed in compact built zones tend to be highest, followed by open built zones with the exception of LCZ5 which has been observed to be consistently one of the warmest. Such observations are also seen in other comparative studies (Stewart, et al., 2014; Middel, et al., 2014). Also, given that densification is a widely supported strategy in urban planning (Lemonsu, et al., 2015) where high-building with open spaces are advised in order to meet the density needs and yet leave room for open space, this exceptional role of LCZ5 suggests that it may exacerbate thermal effects and hence, not recommended at this point for future developments.

Given this exercise, the next chapter explores LCZ3 along with LCZ 1 and 4 to derive a better understanding with reference to the thermal comfort and functional roles and follows mitigation for the critical areas.

Table 12. Comparative summary of the  $T_{Air}$  pattern in LCZ 1-6

Method	Time	Indicator °C	Summary of the temperature difference ( $\Delta T$ )
LST	Day	$T_{Air}$	<b>LCZ5 &gt; LCZ3 &gt; LCZ6 &gt; LCZ2 &gt; LCZ1 &gt; LCZ4</b>
Traverse Surveys	Day	$T_{Air}$	<b>LCZ5 &gt; LCZ3-Formal &gt; LCZ3-Infomal &gt; LCZ6 &gt; LCZ2 &gt; LCZ4 &gt; LCZ1</b>
Traverse Surveys	Night	$T_{Air}$	<b>LCZ4 &gt; LCZ1 &gt; LCZ5 &gt; LCZ3-Infomal &gt; LCZ 3-Formal &gt; LCZ2 &gt; LCZ6</b>



### 5.3. Street Canyons and Thermal Comfort

‘Streets’ are identified as the most fundamental and stable element in the physical urban form due to their greater resistance to the process of urban transformation as well as their capacity of serving as the only open public space in most urban areas (Maharroof, et al., 2018). Although, in Karachi, streets are starting to identify as the opposite in terms of resistance to the vertical street character due to their susceptibility to new commercial developments and vertical expansions (Anwar, 2012), however, the latter identification of streets as the only open public space couldn’t be truer with the intensely rising compact built character, the diminishing green and open areas of Karachi (DAWN, 2019). Moreover, along with the streets/urban canyons being a dominant element in traditional place/zone-based approaches to urban planning with their value associated with placemaking, a similar association is carried forward in urban climatology in enhancing thermal comfort (Maharroof, et al., 2020) and building energy (Strømman-Andersena & Sattrup, 2011). In this process, acknowledging the influences of the street on the typology/functional role is an important consideration despite the applicability of LCZ classification (Maharroof, et al., 2018). Moreover, as discussed in 4.2. and 4.3.1, roads and street network exhibit higher temperatures during the day in LST analysis, while patterns in the traverse surveys identified the opposite that the building heights around streets exhibit lower temperatures due to shading effects, even substantiated by other studies (Emmanuel, et al., 2007; Emmanuel & Fernando, 2007). Thereby, the dubious role of streets and roads in Karachi implores a deeper investigation in different contexts and functional scenarios and may be well-related to the street aspect ratios. The present study explores the association between  $T_{Air}$  along with DI and TI (detail of indices in 2.6.1) and the street aspect ratios (AR) to find correlations for the outdoor thermal comfort.

Note: HI is valid for air temperatures above 20°C (Blazejczyk, et al., 2012) and since this dataset is conducted in winter, some measurements may not satisfy the criteria. And hence, DI also assessed simultaneously as an alternate.

#### 5.3.1. Scenarios Investigated for Thermal Comfort

The section assesses the role of street canyons based on time of occupancy and thermal comfort. The three street typologies explored are, Case1- the central business district dominated by high-rise building (LCZ1&4) in several variations of street canyons; Case2- the residential area of “Bahadurabad”, a mid-high-income neighborhood mostly dominated by high-rises (LCZ1&4) on the main street and LCZ6 otherwise; and Case3- two high-density low-rise (LCZ3 formal and informal) residential neighbourhoods in F.B. Area, i.e., (a) Moosa colony- a residential informal settlement and (b) Memon colony, residential planned settlement, as shown in fig 21.

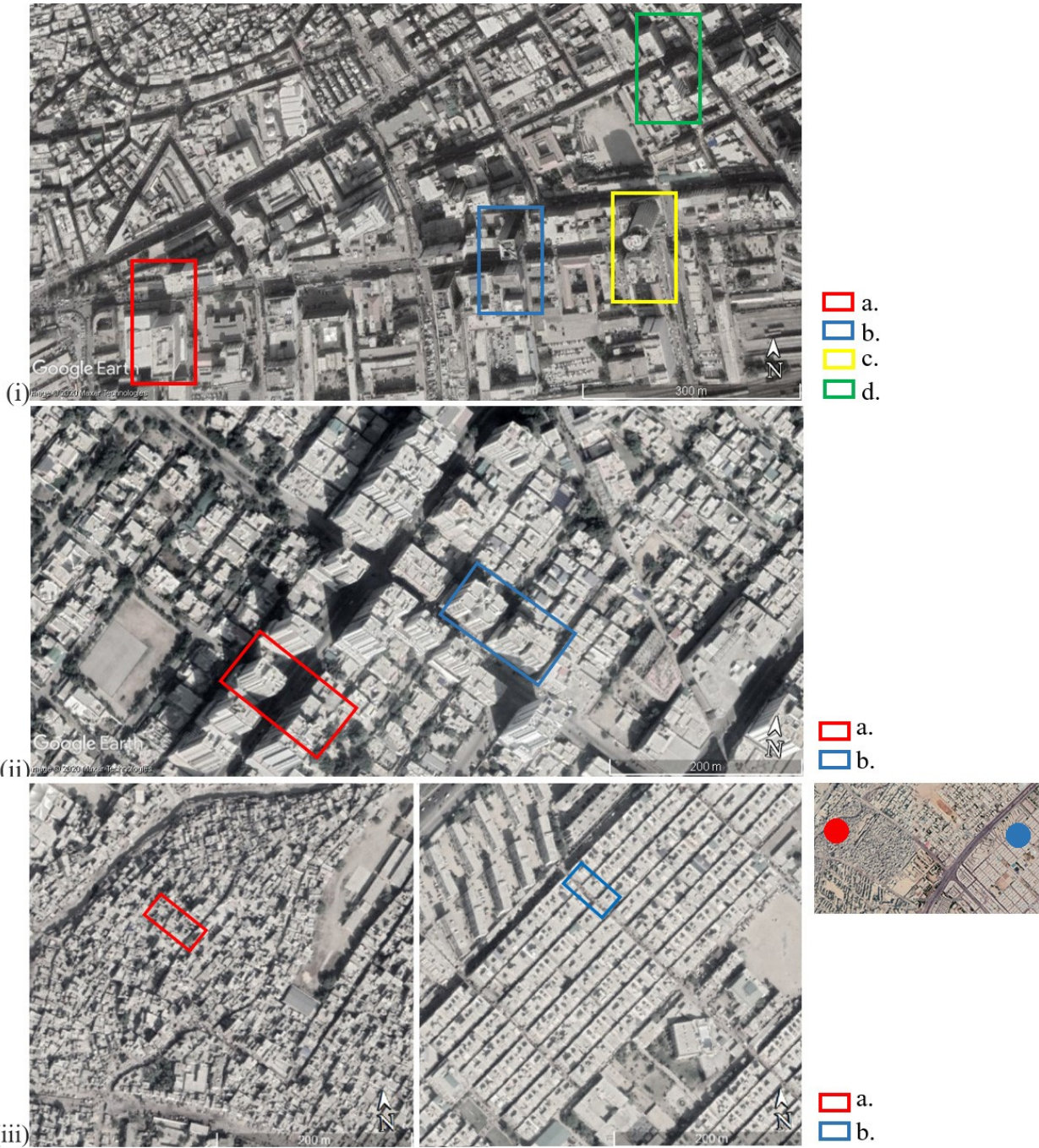


Figure 21. (i) Case 1, Central Business District- Commercial Area; (ii) Case 2, Bahadurabad- Residential Area; (iii) Case 3, (a) Moosa Colony and (b) Memon Colony- Residential Area. Source: Google Earth Pro.

Table 13. Case 1, LCZ1 & 4, Central Business District- Commercial Area

Type	LCZ	Street orient.	Street prof.	H/W=AR	T <sub>Air</sub> °C	TI °C	DI °C	Dif. from Fixed °C	T <sub>Air</sub> at Fixed °C
I.I. Chand. Rd	LCZ4	E-W	A	0.93	26,44	26,01	21,71	-1,24	27,23
			B	1.44	26,16	25,88	21,59	-1,13	27,29
			C	1.5	25,98	25,8	21,57	-0,93	27,38
Sh.-Liaquat Rd	LCZ1	NE-SW	D	2.08	25,75	25,60	21,22	-1,48	27,23



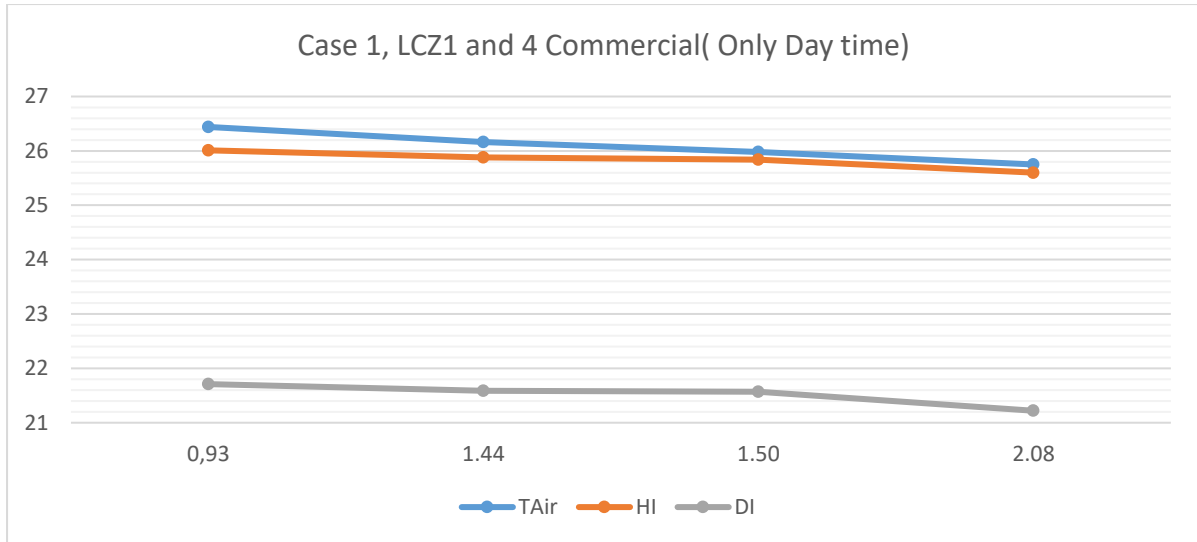


Table 14. Case 2, LCZ1-Residential Area

Type	LCZ	Street orient.	Street prof.	H/W=AR	T <sub>Air</sub> °C	TI °C	DI °C	Dif. from Fixed °C	T <sub>Air</sub> at Fixed °C
Bahadurabad	LCZ1	NE-SW	A-Day	3.6	25,78	26,16	22,21	-	-
			A-Night		20,03	24,34	18,87	1,374	18,65
	LCZ4	NE-SW	B-Day	1.78	25,70	26,10	22,14	-	-
			B-Night		19,98	24,36	18,83	1,2393	18,74

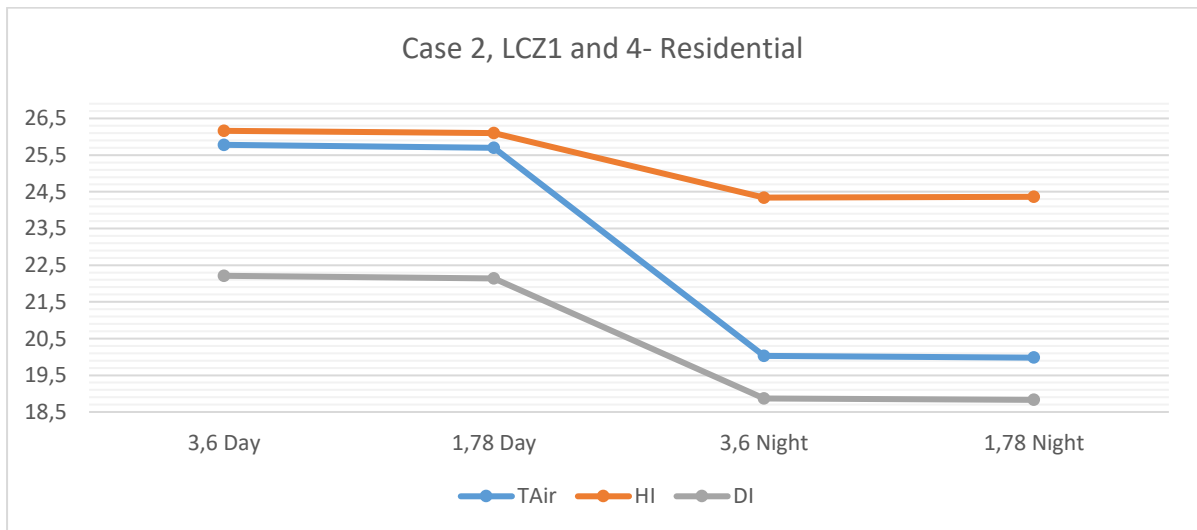
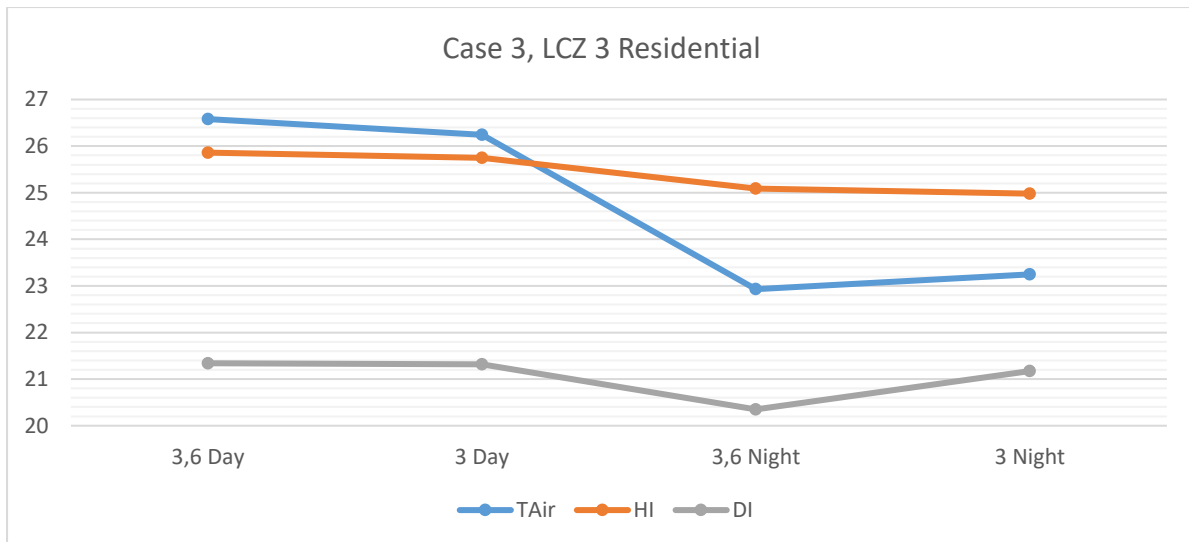


Table 15. Case 3, LCZ 3 Residential Area

Type	LCZ	Street orient.	Street prof.	H/W=AR	T <sub>Air</sub> °C	TI °C	DI °C	Dif. from Fixed °C	T <sub>Air</sub> at Fixed °C
Moosa Colony	LCZ3- Inforal	NE-SW	A-Day	3.6	26,58	25,86	21,34	-0,534	27,11
			A-Night		22,93	25,09	20,35	1,302	21,63
Memon Colony	LCZ- Formal	NE-SW	B-Day	3	26,24	25,75	21,32	-0,328	26,55
			B-Night		23,25	24,98	21,17	0,986	22,26



### 5.3.2. Results

In case 1, it was previously established that LCZ4 and LCZ1 are cooler in  $T_{Air}$  as compared to other LCZs during the day. The detailed introspection, table 13, shows that for commercial developments, there is generally a synonymous behavior of different street widths and aspect ratios in LCZ4, however increasing the aspect ratio resulted in slightly lesser effects consistently. Moreover, LCZ1 seems to be more efficient in term of TI,  $T_{Air}$ , DI in all three as compared to LCZ4, albeit the differences are minute. Although, this area is characterized as LCZ4 due to the building aspect ratios and built form, the vegetation or trees are sparse in the immediate vicinity. Based on this limited dataset, LCZ1 seems like least harmful in the daytime, and may suit well for the areas with daytime uses.

While in case 2, despite a huge variation of aspect ratios, on street level both residential scenarios present similar observations. There is no insightful difference in terms of  $T_{Air}$ , HI or DI observed apart from the fact that in both cases night-time temperatures are much higher than that on fixed station and the HI values remain high even at nighttime despite a significant drop in  $T_{Air}$ , as shown in table 14. Similar extends to case 3 as well as although the low-rise informal developments have higher aspect ratios in LCZ3, their thermal effects do not display much of an exaggerated difference in  $T_{Air}$ , HI or DI as compared to the formal settlements but both scenarios are consistently high in HI values for nighttime despite lower temperatures, as shown in table 15.

This small data set acknowledges the shading effect of deeper street canyons in creating lesser impacts on  $T_{Air}$ , HI or DI in the daytimes, however, it doesn't identify a significant impact of the variation of aspect ratios within the same LCZ apart from case 1. However, it is evident that mitigations need to be evolved for night-time thermal comfort along with  $T_{Air}$  in LCZ1 and LCZ4 residential and LCZ3 residential.

### 6.1. Discussions

This section follows the previous analysis and builds on other studies pertaining to UHI to find niches of opportunity within the current climate situation of Karachi and ways to ameliorate the negative areas.

#### 6.1.1. Positive Trends vs Negative Trends

The high-rise LCZs in Karachi offer contrasting temperature observations for day and night. However, the link between urban canyons and building energy use offers a complex juxtaposition and opportunity with the climatic factors and usage patterns of urban spaces and buildings. Such as in hot regions, the alignment of timing of use and shading provided by deeper forms is reciprocally beneficial for both, the outdoor as a ‘solar umbrella’ (Emmanuel, 1993) and indoors via decreasing the energy demand, such as for areas with dominated commercial buildings with peak daytime functions (Futcher, et al., 2013). Hence, the so appearing dichotomy may suit the commercial high-rises (LCZ1 and 4) in Karachi. However, the implication of the urban canyon geometry has varying effects on residential and office building types (Strømman-Andersena & Sattrup, 2011) as this limited daytime phenomena (Brazel, et al., 2000; Georgescu, et al., 2011) of ‘cool island’ effect (Pearlmutter & Berliner, 1999) may contrarily lead to greater UHI intensity at night (Emmanuel, 2006) and hence, dis-serve other building typologies whose occupancy is independent of peak insolation hours (Emmanuel & Steemers, 2018). This trend under deeper consideration of disadvantages like the potential decrease in ventilation and night-time cooling of buildings (Emmanuel, 2006) may even be disastrous for Karachi. This study has validated the extremity of these assertions via traverse surveys (4.3.2) as well as thermal comfort analysis (5.3.1) for both, residential and commercial buildings. And it has been established that along with air temperature, the thermal comfort also needs attention at nighttime as despite the reduction in air temperatures, the thermal comfort values yet remain high. And although, this LCZ in question only features an insignificant chunk of built-up area at this point, the strong likeliness towards future developments under these heating implications further jeopardizes the climatic situation for Karachi besetting the city with extreme dangers of local warming.

Meanwhile, Karachi is facing a considerable increase in compact midrise(LCZ2) buildings which may continue to grow, however this LCZ offers a more stable transformation in comparison to high-rises by offering sufficiently low daytime temperatures as well as moderate warming intensity at night. Alternatively, the regularised midrise buildings are also suggested as a viable density tool in converting the informal settlements to serve the dire housing needs of the Karachi (Hasan, 2020). Thereby, this balance between accommodation needs, climatic effects and their confluence with the ongoing urban development trends may be a blessing in disguise for Karachiites.

Moreover, generally the dynamics of ventilation are crucial in buildings with the consideration of energy efficiency and reducing environmental load (Hyde, 2000), albeit this consideration is more pertinent for Karachi's disadvantaged settlements with poorly constructed free running buildings with issues of affordability of heat alleviating amenities (Nazrul Islam & Winkel, 2017) as well as frequent protracted spans of power outages (Samaa News, April 2018). These may likely be the informal settlements in LCZ3 which Karachi is in abundance of, that remain consistently warm at all times. In these compact communities with extremely narrow streets, the outdoor temperatures are bound to impact the indoor temperatures due to impeded airflow between the built spaces and adjacent environments (Nicol, et al., 1999). Hence, these settlements are at the losing end with the implications of reasonably expected strong relationship between indoor and outdoor temperature (Jacobs, et al., 2019) as well as the vulnerability dimensions.

### **6.1.2. High-Density/Population Debate**

The UHI literature recognizes the role of population, urban density and street canyons in urban thermal environments (Toy & Yilmaz, 2010) and advises high-density developments as a viable strategy for UHI mitigation (Emmanuel & Fernando, 2007). And with this statement, it is contradictory that Karachi, despite being considered high-density is majorly dominated by low-rise zones (LCZ3 and LCZ6), and yet exhibits a considerable UHI magnitude. Hence, it is imperative to establish that the typical reference to the high-density developments in literature recommendations is the idea of urban-area geometry enhancement/manipulation via taller buildings/high-rises (Rescha, et al., 2016), and not necessarily high population density. whilst, it must be understood that the dynamics between outdoor climate, population density and urban form are context oriented (Chatzipoulka & Nikolopoulou, 2018) and relative to the community of the development (Urban Land Institute, 2005). Subsequently, the recent literature evidences that density and height of the built form may not be synonymous, unlike the popular opinion that high densities can only be achieved via high buildings (Steadman, 2017). Chatzipoulka and Nikolopoulou (2018) offer insights to define 'urban form' in relation to 'density' and differentiate between 'horizontal' and 'vertical' densities. They assert that to achieve a certain level of density, the horizontal surface coverage or the vertical building height may be altered (Chatzipoulka & Nikolopoulou, 2018). While, in case of Karachi, the characterization of high density, more obviously seen in the growing compact informal settlements with excessively overcrowded living conditions (Hasan, 2016), may be an intense combination of both the vertical as well as horizontal densities characterized with intensely high population density, and hence may require targeted interventions. Additionally, this also establishes that the LCZ studies do not necessarily identify the population dynamics as the population density is a relative concept in Karachi based on the socioeconomic situations, not merely the built form. In this context, the density analysis and its effect on temperature need to be understood as;

- The connotation of high-density does not translate into high-rise buildings in Karachi as LCZ classes vertically high featuring higher aspect ratio may not be equivalent to high population density given the

disparity in formal / informal growth and dominance of highly dense compact low/mid-rise informal developments.

- The high-rise buildings have contradictory roles for day and nighttime heating patterns and may instigate positive or negative implications based on usage.
- Karachi is anticipated to have increasing number of high-rise buildings and the intensification of the already high population density (Mangi, et al., 2020), both critical for UHI formation (Coutts, et al., 2007; Kotharkar & Surawar, 2016) and causing/increasing vulnerability towards heat health risks (Harlan, et al., 2006; Dolney & Sheridan, 2006; Tomlinson, et al., 2011; Hass, et al., 2016).

### **6.1.3. Disproportionate Vulnerability and Adaptations to UHI Exposure**

The consideration for vulnerability is essential in developing cities given the massive volume of vulnerable populations forming a majorly ignored stakeholder. It is asserted that vulnerability is not just a condition, but a consequent process of the physical, social and environmental factors that enhances the susceptibility to the impact of hazard (Westlund, et al., 2007). It also entails the response and coping mechanism to withstand or react to a disaster (Rafiq & Blaschke, 2012). In case of UHI, although atmospheric conditions form its basis, the features of the human systems such as the intra-city socio-economic disparity, characteristics of individuals/community, building structure and density and the resultant inaccess to resources (Wilhelmi & Hayden, 2010) not only cause the disadvantaged groups to suffer disproportionately from the adverse effects of climate change (Nazrul Islam & Winkel, 2017), elevated heat exposures (Solecki, et al., 2005; Chakraborty, et al., 2019; Jenerette, et al., 2007), socio-economic vulnerabilities (Uejio, et al., 2010; Nayak, et al., 2018) and susceptibility towards associated health hazards but also determine the response mechanism/adaptive ability to cope with these exposures (Wilhelmi & Hayden, 2010; Nazrul Islam & Winkel, 2017). These effects also stretch towards mitigative capacities to UHI, for instance GI and green features. Despite the incessant recognition as a UHI mitigation strategy, three factors impede the practical utility of these vulnerable neighborhoods to adopt it. These include, less available open space for tree planting in compact areas (Solecki, et al., 2005), weak structural integrity of built forms to support roof/wall greens (Naveed, 2017), and the need for water (Lemonsu, et al., 2015) and its varying economic and social equity implications associated across neighbourhoods (Jenerette, et al., 2011), especially, in the dry and arid cities like Karachi with dire shortage of water in the informal settlements (Anwar, et al., 2019). Hence, despite appearing the most sustainable option, it may not be ideal from a human vulnerability viewpoint (Jenerette, et al., 2011; Middel, et al., 2012) and of least potential benefit (Solecki, et al., 2005) for the less affluent neighbourhoods in dry-arid regions facing the greatest hazard potential. Hence, these observations not only entail a comprehensive understanding of the complex interplay between the temporal and spatial phenomena but also implore a recognition of the qualitative and quantitative attentions (Strømman-Andersena & Sattrup, 2011) for bespoke identification of drivers to UHI and mitigation capacities.

Bearing in mind all these discussions, the informal developments which may potentially be a major part of LCZ3 thus, not only identify as highly dense in terms of population but may also be contrasted with social and environmental vulnerability dimensions which highlight its potential to risks and preparedness concerns for UHI. Hence, the LCZ3 with the current dominance in the city scale, likeliness towards further growth and extreme temperature patterns in parallel with vulnerable populations and lack of planning and guidelines in case of informal situations unanimously distinguish it as the most critical LCZ. Therefore, further simulations and mitigations will be studied specific to this LCZ class. The most common mitigation scenarios have been appropriated according to the contextual limitations. And even though green elements as a mitigation scenario are unlikely given the above-mentioned considerations, a hypothetical scenario of green roof is still simulated for comparative purposes.

## 6.2. ENVI-met Simulations Results- Comparison of Mitigation Strategies

The ENVI-met process and protocols specific to LCZ3 are explained in 3.4. The simulated cases identify the following observations:

- The largest day and nighttime  $T_{Air}$  decrease occur with the density manipulations followed by high albedo strategies leading to the second lowest  $T_{Air}$ . While no noticeable improvement is seen with the green scenario.
- The most significant  $T_{Air}$  differences during peak day hours are observed in the ‘Medium Density’ scenario with the difference of 3+°C from the ‘Base Case’, however, the night-time temperatures show lesser effects i.e., almost 1°C lesser temperature than that of ‘Base Case’ and all the other mitigation scenarios.
- The second most significant  $T_{Air}$  differences during peak day hours are observed in the ‘High albedo’ scenario with the difference of 1+°C, however, at night-time, there was no considerable difference.
- Meanwhile, greater variation was observed in terms of daytime MRT. The lowest spread of MRT occurred in the ‘Medium Density’ scenario. While during the daytime, the ‘High albedo’ scenario strikingly accentuated the effect of MRT up to 14-15°C greater than that of the base case making the thermal comfort situation much over the comfort zone (extreme danger state). However, the night-time results of the ‘High albedo’ showed slight increase in the thermal comfort intensity.
- The MRT variations in the ‘Medium density’ scenario at peak day hours was up to 4-5°C lesser than the base scenario. While as observed in case of  $T_{Air}$ , no noticeable MRT improvement is seen with the green scenario. Generally, the overall night-time MRT variations were small but the ‘Medium Density’ scenario performed the best.

Generally, it appears that density enhancement has a positive mitigating effect, although more pronounced on MRT than  $T_{Air}$ . With this implication for lower thermal discomfort in the heavily built sections of the city and given the likeliness towards such future trends, the density manipulation might prove as a viable UHI mitigation



choice. However, the entirety of these interventions i.e., the associated adverse effects like air circulation and pollution distribution need to be assessed further to allow well-rounded recommendations. Alternatively, high albedo leads to significantly lower daytime temperatures, but holds extreme consequences in terms of thermal comfort. Moreover, the practical utility of high albedo interventions is dubious, hence it may serve as an alternative strategy (Emmanuel & Fernando, 2007) for reducing temperatures. This study further endorses that the approaches that lead to better  $T_{Air}$  may not automatically have synonymous effects on the thermal comfort (Emmanuel & Fernando, 2007; Emmanuel, et al., 2007).

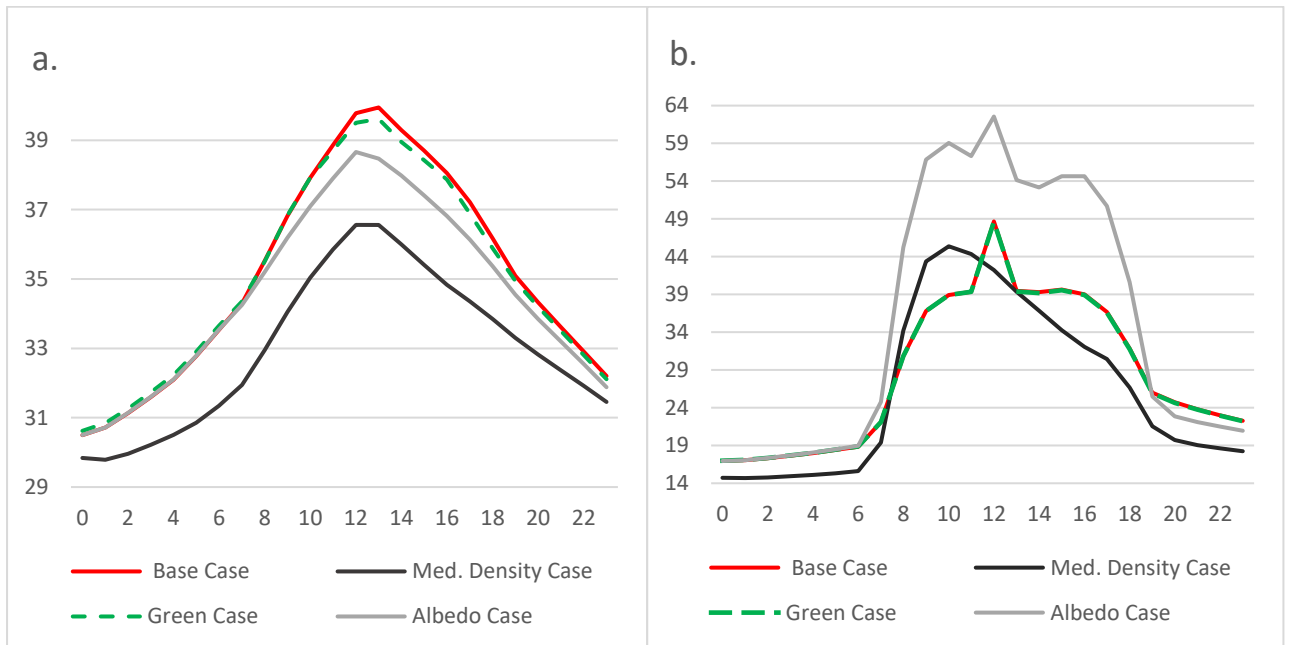


Figure 22. Comparison of (a) Air temperatures and (b) Mean Radiant Temperature for different UHI mitigation scenarios measured at 1.5 m above the street. The x-axis is hrs. of the day, the y-axis is the temperature in °C.

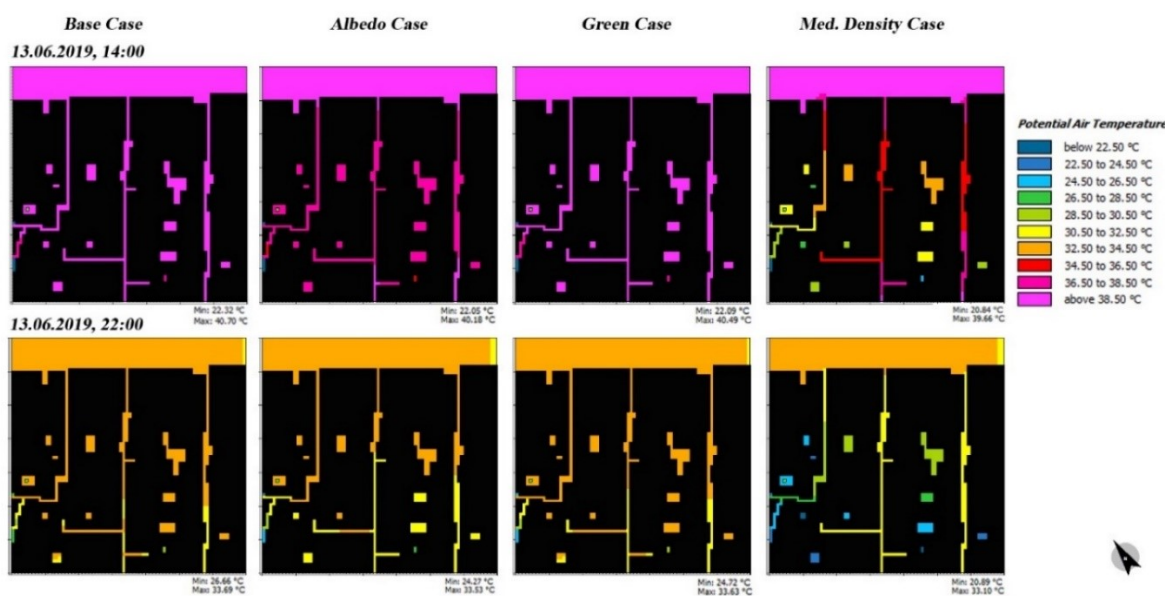


Figure 23. Air Temperature patterns (1.5 m above street surface) for the site.

#### **7.1. Results**

The scope of urban climate studies, particularly UHI investigations, is nascent in Karachi. As a pioneer study, this thesis appropriates the application of LCZ framework along with LST analysis and traverse surveys and delivers a multidimensional process within a complex urban fabric to study UHI and its effects to facilitate climate-sensitive urban planning and mitigations.

For LCZ classification, although the WUDAPT method offered a simple process and yet established an accuracy of 68% in the data-scarce developing context of Karachi, for future studies local customisation/subclassification is proposed to fit to the local realities which could enhance the assessment. However, in this study the LCZ mapping results highlighted the presence of all 17 LCZ classes with a significant mix of built-up LCZ classes in the city's urban core along with a terrible lack of blue-green infrastructure. Further, the LST maps identified the SUHI differences among various LCZ classes forming the summer SUHI magnitude across the city of approximately 15°C at daytime. While the small dataset of traverse surveys established the temporal effect of these LCZ classes on the street level. In both the methods, the intra-zone UHI differences were coherent and relate well with previous studies attesting the common drivers such as spatial arrangement/ landcover, building density, green cover and vegetation, among others. The LST maps identified compact low-rise(LCZ3) and open mid-rise (LCZ5) as the warmest among the built-up classes (1-6) for the daytime, while the traverses identified a more accentuated role of the high-rises (LCZ1 and LCZ4) as cold spots on the street level. However, for nighttime, the high-rises (LCZ1 and LCZ4) served the opposite role. The traverse survey method was more apt for not only establishing temporal temperature changes associated to the standard LCZs defined by Stewart and Oke (2012), but also provided an introspection into unique combinations and subclasses of these LCZs in creating cooler spots and vice versa. This is a relevant consideration bearing in mind the formal/informal nature as well as mixed built typologies of Karachi's development and may offer better practical utility than examining standard LCZ classes. However, a bigger dataset along with a comprehensive understanding of these mixtures would be vital in facilitating future research. The inconsistencies within the same LCZ were also observed which may be attributed to the formal and informal development patterns, vegetation distribution, the spatial arrangements, and the coastal vicinity. Generally, the temperatures contrasts between zones with large differences in surface morphology and land cover was established such as the high-rises (LCZ1 and LCZ4) in contrast with open low-rise and large buildings(LCZ6 and 8), creating the maximum nighttime UHI magnitude of 3 °C. On the contrary, the daytime UHI magnitude was relatively lesser with 1,5 °C between compact low-rise infused with lightweight low-rise (LCZ3<sub>7</sub>) and open high-rises (LCZ4).

Further, the LCZ maps' comparisons between 2009 and 2019 show a continuous increase in more built-up areas, particularly the densification of the city core with the infusion of compact low, mid-rise and high-rise blocks.

This trend towards intense densification in terms of vertical as well as horizontal expansion is shown to push the UHI effect up and insinuates a likeliness for worse climatic impacts for the coming years. But the daytime advantages via shading, etc., allow potential for appropriation towards positive energy management (Futcher, et al., 2013). Albeit, its suggested to avoid the construction of dense, airless, overpopulated communities altogether (Toy & Yilmaz, 2010), the practical utility of such suggestions in developing cities is almost impossible to ensure. However, the densification into compact mid-rises (LCZ2) has been observed to be the least harmful among all LCZ classes validated via ENVI-met and extrapolation for future scenario. However, the exploration of the wind flow dynamics in these LCZs is a relevant research area for future studies to derive holistic recommendations.

On the other hand, the way forward must also offer inclusive UHI mitigation strategies to the unprivileged and disproportionately affected (Chakraborty, et al., 2019). Thereby, implying the need for design interventions which align with the social and economic reality of the low-income settlements (Hasan & Mohib, 2003; Kotharkar, et al., 2018). Aiding this observation, one design implications of this study is that density (in terms of height) enhancement is a viable UHI mitigation option in such contexts, albeit considering the limited wind movement and other undesirable repercussions in these high-density settings, the albedo enhancement may be a suitable alternative. However, these strategies require careful consideration as they may not have a synonymous effect towards reducing air temperature and offering better thermal comfort as observed by Emmanuel, et al.(2007) and Emmanuel & Fernando (2007). Alternatively, the cooling implications of mixed LCZs may offer opportunities for policies in urban planning for new developments advocating the idea of tall irregularly positioned building with varied heights and freed up open space (Chatzipoulka & Nikolopoulou, 2018), thereby, encouraging airflow (Emmanuel, 2006) and vegetation channels. And at this point, seem like a stable middle ground for practical density requirements and local climate, energy consumption and comfort effects.

## **7.2. Conclusions**

Through this process, this thesis identifies two main perspectives. Firstly, a deeper change classification for the rapidly growing developing cities in terms of climate. This implies that the currently dominant practice of the LULC change studies needs to be elaborated into LCZ change (LCZC) classification to understand heating behaviours associated with growth/change patterns in urban settings. This is the first study to the knowledge of the author that demonstrated an LCZC comparison over the years instead of employing LULC. Such a study not only quantifies densification of land change by going beyond the traditionally simplistic descriptors of rural/urban land but also specifies precise thermal trends associated with specific land typologies to facilitate future planning. Moreover, it offers identification of actual urban growth as opposed to planned growth and hence vital for city planning and policy making, specifically for developing cities pertaining to extreme poverty (Millington, et al., 2018).

Secondly, the thesis identifies the distinction of density-based assumptions in the LCZ classification and mitigation which seem to be context specific and not synonymous in all situations. More precisely, the informal

developments in Karachi, which may be the case in other south Asian developing cities, often exhibit a combination of vertical and horizontal building densities juxtaposed with high population density and hence, require bespoke assessment and interventions. Having said that the insufficiency of LCZ framework to rightly address population density needs to be alternatively addressed. Meanwhile, UHI mitigation in response to the perspectives of disaster/risk origins being embedded in the physical environment (Gilbert, 1995) vs the societal conditions and vulnerabilities (Flint & Luloff, 2005) puts the spatial planning at a vital point in maintaining a balance between these two standpoints and may enhance the capacity towards disaster risk reduction (Rafiq & Blaschke, 2012). Both the above-mentioned perspectives aid the recognition of these debates. Hence, such an approach may be useful for contexts like Karachi with a huge chunk of illegal and informal settlements for documentation as well as identification of the scale of mitigation.

In general, Karachi, as one of the most-dense cities of the world (Hasan, 2016), requires an urgency-instinct approach for UHI mitigation for the current issues and yet offers potential to be developed with climate as an important concern considering the mitigative potential in the current scenarios.

### **7.3. Limitations**

This is a hybrid UHI study where some existing protocols along with some new methods are collectively explored. Ideally, the traverses as well as SUHI analysis were intended to synchronize for the summer season of 2020 to analyze summer UHI effects, however, due to the Covid-19 restrictions associated to travel/field data collection, the small winter dataset was utilized for traverses. Due to the limited data, a new experimental method was devised for data assessment which may serve other data poor situations to build preliminary investigations. However, in exercises such as 5.1.3., it would have been ideal to employ values verified with a bigger data set inclusive of summer season. And due to the mentioned limitations merely, the available data has been utilized.

Further, as an architect, my exposure to remote sensing and statistics is new. Therefore, some of the assessment methods may have been based on simple, well-established and convenient approaches, none the less, have served the purpose of this thesis in my opinion.



[20Addenda/55\\_2013\\_g\\_20160920.pdf](#)

[Accessed August 2020].

Auer, A. H., 1978. Correlation of land use and cover with meteorological anomalies. *J. Appl. Meteor.*, Volume 17, p. 636–643.

Avdan, U. & Jovanovska, G., 2016. Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data. *Journal of Sensors*, Volume 2.

Azeem, A., Butt, M., Nisar, K. & Anwar, H., 2016. Assessment of Urban Heat Island (UHI) using Remote Sensing. *Global Journal of HUMAN-SOCIAL SCIENCE: B Geography, Geo-Sciences, Environmental Science & Disaster Management*, 16(2).

BBC, 2015. *Why did so many die in Karachi's heatwave?*. [Online] Available at: <https://www.bbc.com/news/world-asia-33358705> [Accessed 7 July 2019].

Bechtel, B., 2019. *Generating WUDAPT Level 0 data – current status of production and evaluation*. [Online] Available at: <http://pure.iiasa.ac.at/id/eprint/15568/1/2017-WUDAPT-L0-QC-R1-fin-clean.pdf> [Accessed April 2020].

Bechtel, B. et al., 2015. Mapping Local Climate Zones for a Worldwide Database of the Form and Function of Cities. *SPRS Int. J. Geo-Inf.*, 4(1), pp. 199-219.

Bechtel, B. & Daneke, C., 2012. Classification of Local Climate Zones Based on Multiple Earth Observation Data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, 5(4), pp. 1191-1202.

Bertaud, A. 2., 2009. “*Urban Land Supply: Real Resource Constraint or Man Made Shortage?*”. Washington, DC, Presentation at World Bank, March 9–10..

Bhugio, M., Schuetze, T. & Mahar, W., 2020. Comparative Analysis of Indoor Environmental Quality of Architectural Campus Buildings’ Lecture Halls and its’ Perception by Building Users, in Karachi, Pakistan. *Sustainability*, 12(7).

Blazejczyk, K., Epstein, Y., Jendritzky, G. & Staiger, H. & T. ., B., 2012. Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, Volume 56, p. 515–535.

Bradnock, R. & William, G., 2002. *South Asia in a globalizing world*, Edited by: Bradnock, R. and William, G.. Harlow: Edinburgh Gate: s.n.

Brazel, A., Selover, N. V. R. & Heisler, G., 2000. The tale of two cities: Baltimore and Phoenix urban LTERs. *Climate Research*, 15(2).

Butera, F. M., 2010. (2010). Climatic change and the built environment.. *Advances in Building Energy Research*, 4(1), pp. 45-75.

Cai, M. et al., 2017. Investigating the relationship between local climate zone and land surface temperature using an improved WUDAPT methodology – A case study of Yangtze River Delta, China. *Urban climate*, Volume 24, pp. 485-502.

Cai, M. et al., 2017. Investigating the relationship between local climate zone and land surface temperature using an improved WUDAPT methodology – A case study of Yangtze River Delta, China. *Urban climate*.

Campbell-Lendrum, D. & Corvala’n, C., 2007. Climate Change and Developing-Country Cities: Implications For Environmental Health and Equity. *Journal of Urban Health: Bulletin of the New York Academy of Medicine*, 84(1).



- Cardoso, R. D. S., Trindade, A. & Cristiane, M., 2018. Urban heat island analysis using the ‘local climate zone’ scheme in Presidente Prudente, Brazil. *Investigaciones Geográficas (Esp)*, Volume 69.
- CDKN, 2015. *Karachi Heat Wave 2015: A Visual Guide*, s.l.: Commissioner Office, Karachi, personal communications..
- CDKN, 2017. *Response, Karachi Heat Action Plan: A Guide to Extreme Heat Planning and Response*. [Online] Available at: <http://www.lead.org.pk/attachments/HeatwaveManagementPlan.pdf> [Accessed July 2020].
- Chakraborty, T., Hsu, A., Manya, D. & Sheriff, G., 2019. Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective. *Environmental Research Letters*, 14(10).
- Chatzipoulka, C. & Nikolopoulou, M., 2018. Urban geometry, SVF and insolation of open spaces: London and Paris. *Building Research & Information*, 46(Issue 8: Urban form, density & microclimate).
- Cheema, A. R., 2015. A. High-rise buildings worsened heatwave. *Nature*, 524(35).
- Chen, L. & Ng, E., 2012. Outdoor thermal comfort and outdoor activities: A review of research in the past decade.. *Cities*, 29(2), p. 118–125.
- Climate-data.org, n.d. *Pakistan Climate*. [Online] Available at: <https://en.climate-data.org/asia/pakistan-127/>
- climatemps.com, 2020. *Karachi*. [Online] Available at: [Karachi Climate Graph. Source: http://www.karachi.climatemps.com/graph.php](http://www.karachi.climatemps.com/graph.php) [Accessed March 2020].
- Collins, M. et al., 2013. Long-term climate change: projections, commitments and irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. NY, USA: Cambridge University Press Cambridge, United Kingdom and New York.
- Coutts, A., Beringer, J. & Tapper, N., 2007. Impact of increasing urban density on local climate: Spatial and temporal variations in the surface energy balance in Melbourne, Australia.. *J Appl Meteorol.*, Volume 46, pp. 477-493.
- Danylo, O. et al., 2016. Contributing to WUDAPT: A Local Climate Zone Classification of Two Cities in Ukraine. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(5), pp. 1939-1404.
- Davis, M., 2006. *Planet of Slums*. New York: Verso publisher.
- DAWN, 2015. *Heatwave devastates Karachi, other parts of Sindh; at least 136 dead, Hasan Mansoor*, Karachi: Dawn News.
- DAWN, 2016. *Concern over 100 high-rises under construction in Karachi*. [Online] Available at: <https://www.dawn.com/news/1261075> [Accessed 8 June 2020].
- DAWN, 2019. *128,000 deaths occur in Pakistan due to climate change every year, Senate body told*. [Online] Available at: <https://www.dawn.com/news/1525374> [Accessed August 2020].
- De Souza, K. et al., 2015. Vulnerability to climate change in three hot spots in Africa and Asia: key issues for policy-relevant adaptation and resilience-building research. *Reg. Environ. Change.*, Volume 15, pp. 747-753.
- Demuzere, M., Bechtel, B., Middel, A. & Mills, G., 2019. Mapping Europe into local climate zones. *PLoS ONE*, 14(4: e0214474).

- Dolney, T. & Sheridan, S., 2006. The relationship between extreme heat and ambulance response calls for the city of Toronto, Ontario, Canada.. *Environ Res.*, Volume 101, pp. 94-103.
- Drach, P., Kruger, E. L. & Emmanuel, R., 2018. Effects of atmospheric stability and urban morphology on daytime intra-urban temperature variability for Glasgow, UK. *Science of the Total Environment*, Volume 627, p. 782–791.
- Economist Intelligence Unit, 2015. *Liveability ranking and overview*. [Online] Available at: <https://media.heraldsun.com.au/files/liveability.pdf> [Accessed 03 July 2019].
- Eliasson, I., 1990. Urban geometry, surface temperature and air temperature. *Energy and Buildings*, 15(1-2), p. 141–145.
- Ellis, P. & Roberts, M., 2016. *Leveraging Urbanization in South Asia: Managing Spatial Transformation for Prosperity and Livability*. *South Asia Development Matters*. Washington, DC: World Bank Group.
- Emmanuel, R., 1993. A hypothetical “shadow umbrella” for thermal comfort enhancement in the equatorial urban outdoors. *Archit Sci Rev*, 36(4), pp. 25-36.
- Emmanuel, R., 2006. ‘Quality-Of-Life’ Enhancement Through Urban Heat Island Mitigation: Street Design and Transportaion Implications for the Equatorial Tropics. Singapore, Conference: 4th Great Asian Streets Symposium (GASS4).
- Emmanuel, R., 2016. Urban climate challenges in the tropics: Rethinking planning and design opportunities. In: R. Emmanuel, ed. London: Imperial College Press.
- Emmanuel, R. & Fernando, H., 2007. Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. *Climate Research*, Volume 34, p. 241–251.
- Emmanuel, R. & Kruger, E., 2011. *Urban microclimate study in Glasgow*. [Online] Available at: [http://www.cicstart.org/userfiles/file/IR7\\_24-28.pdf](http://www.cicstart.org/userfiles/file/IR7_24-28.pdf) [Accessed March 2020].
- Emmanuel, R. & Loconsole, A., 2015. Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley region, UK.. *Landsc. Urban. Planning*, Volume 138, p. 71–86.
- Emmanuel, R., Rosenlund, H. & Johansson, E., 2007. Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka. *International Journal of Climatology*.
- Emmanuel, R. & Steemers, K., 2018. Connecting the realms of urban form, density and microclimate. *Building research and Information*, 46(8), pp. 804-808 .
- ENVI-met®, 2020. [Online] Available at: <https://www.envi-met.com/> [Accessed June 2020].
- Erell, E., Pearlmutter, D. & Williamson, T., 2011. *Urban Microclimate: Designing the Spaces Between Buildings*.. London: Earthscan/James & James Science Publishers.
- Express tribune, 2020. *Climate change deaths*. [Online] Available at: <https://tribune.com.pk/story/2130975/6-climate-change-deaths> [Accessed August 2020].
- Faroughi, M. et al., 2020. Computational modeling of land surface temperature using remote sensing data to investigate the spatial arrangement of buildings and energy consumption relationship. pp. 254-270.

- Field, C. & Barros, V., 2014. *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Global and Sectoral Aspects*. s.l.:Cambridge University Press.
- Filho, W. et al., 2016. *Climate Change, Hazards and Adaptation Options*. Cham, Switzerland: Springer Nature Switzerland.
- Fischereit, J. & Schlünzen, K. H., 2018. Evaluation of thermal indices for their applicability in obstacle-resolving meteorology models. *Int J Biometeorol.*, 62(10), p. 1887–1900.
- Flint, C. & Luloff, A., 2005. Natural resource-based communities, risk, and disaster: an intersection of theories.. *Society and Natural Resources*, Volume 18, p. 671–85.
- Freitas, C. D. & Grigorieva, E., 2016. A comparison and appraisal of a comprehensive range of human thermal climate indices. *International Journal of Biometeorology*, 61(3).
- Fletcher, J. A., Kershaw, T. & Mills, G., 2013. Urban form and function as building performance parameters. *Building and Environment*, Volume 62, p. 112–123.
- Gartland, L., 2008. *Heat Island: Understanding and Mitigating Heat in Urban Areas*. s.l.:Earthscan.
- Gatto, E. et al., 2020. Impact of Urban Vegetation on Outdoor Thermal Comfort: Comparison between a Mediterranean City (Lecce, Italy) and a Northern European City (Lahti, Finland). *Forests*, 11(22).
- Georgescu, M., Moustou, M., Mahalov, A. & Dudhia, J., 2011. An alternative explanation of the semi-arid urban area “oasis effect”. *Journal of Geophysical Research*, Volume 116, pp. 1-13,.
- Germanwatch, 2018. *Global Climate Risk Index 2018*. [Online] Available at: <https://germanwatch.org/sites/germanwatch.org/files/publication/20432.pdf> [Accessed 11 July 2019].
- Gilbert, C., 1995. Studying disaster: a review of the main conceptual tools. *International Journal of Mass Emergencies and Disasters*, 13, pp. , Volume 13, p. 231–240.
- Giridharan, R. & Emmanuel, R., 2018. The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. *Sustainable Cities and Society*, Volume 40.
- Giuli, V., Pos, O. & Carli, M. D., 2012. Indoor environmental quality and pupil perception in Italian primary schools. *Build. Environ*, Volume 56, p. 335–345.
- Gober, P. et al., 2012. Tradeoffs Between Water Conservation and Temperature Amelioration In Phoenix and Portland: Implications For Urban Sustainability. *Urban Geography*, 33(7), pp. 1030-1054.
- Grimm, N. et al., 2008. Global change and the ecology of cities.. *Science*, Volume 319, pp. 756-760.
- Grimmond, S., 2007. Urbanization and global environmental change: local effects of urban warming. *Geogr. Journal*, 173(1), p. 83–88.
- Guhathakurta, S. & Gober, P., 2010. Residential land use, the urban heat island, and water use in Phoenix: A path analysis. *Journal of Planning Education and Research*, 30(1), pp. 40-51.
- Hanif, U., 2017. Socio-Economic Impacts of Heat Wave in Sindh. *Pakistan Journal of Meteorology*, 3(26).
- Harlan, S. et al., 2006. Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine*, 63(11), pp. 2847-2863.
- Hasan, A., 1996. *Conserving Karachi’s Historic Architecture*. [Online] Available at: <http://arifhasan.org/articles/conserving-karachis-historic-architecture> [Accessed March 2020].

- Hasan, A., 2006. *Karachi's Development and the Principles of Urban Planning*. [Online] Available at: <http://arifhasan.org/articles/karachis-development-and-the-principles-of-urban-planning> [Accessed 8 July 2019].
- Hasan, A., 2016. *Emerging urbanisation trends: The case of Karachi*. Reference number: C-37319-PAK-I, s.l.: International Growth centre.
- Hasan, A., 2020. *The Density Debate*. [Online] Available at: <http://arifhasan.org/architecture/planning/the-density-debate> [Accessed August 2020].
- Hasan, A. & Mohib, M., 2003. *Global Report on Human Settlements 2003, The Challenge of Slums, ; Part IV: 'Summary of City Case Studies', pp195-228*, London: UN-Habitat.
- Hasan, A., Pervaiz, A. & Raza, M., 2017. *Drivers of climate change vulnerability at different scales in Karachi*, IIED, London: IIED's Human Settlements group.
- Hass, A. et al., 2016. Heat and Humidity in the City: Neighborhood Heat Index Variability in a Mid-Sized City in the Southeastern United States. *Int J Environ Res Public Health.*, 13(1)(117).
- Hassan, A., Arsalan, M. & Fatima, H., 2015. *Assessment of Urban Growth of Karachi: From a Tiny Town to a Meta City of the World*. Islamabad, Fourth International Conference on Aerospace Science & Engineering: Institute of Space Technology, Pakistan.
- Havenith, G., Holmér, I. & K., P., 2002. Personal factors in thermal comfort assessment: Clothing properties and metabolic heat production. *Energy and Buildings*, 34(6), pp. 581-591.
- He, F. et al., 2007. Assessing the effect of land use-land cover change on the change of urban heat island intensity. *J. Theor. Appl. Climatol.*, Volume 90, p. 217–226.
- He, H., Zhang, Y. & Zhang, J., 2018. *Urban local climate zone mapping and apply in urban environment study*. s.l., IOP Conf. Series: Earth and Environmental Science 113, 012055.
- Hensen, J. L. & Lamberts, R., 2019. *Building Performance Simulation for Design and Operation*. s.l.:Routledge.
- Howard, L., 1833. *The climate of London, deduced from meteorological observations made in the metropolis and various places around it*. London: Harvey and Darton.
- Huang, K., Yang, S., Matzarakis, A. & Lin, T., 2018. Identifying outdoor thermal risk areas and evaluation of future thermal comfort concerning shading orientation in a traditional settlement. *Science of The Total Environment*, Volume 626, pp. 567-580.
- Hyde, R., 2000. *Climate responsive design: A study of buildings in moderate and hot humid climates*. s.l.:Taylor & Francis.
- Ibrahim, I., Abu Samah, A., Fauzi, R. & Noor, N. M., 2016. The land surface temperature impact to land cover types. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, Volume XLI-B3, p. 871–876.
- IIED, 2015. *Focus on urbanisation issues in Karachi*. [Online] Available at: <https://www.iied.org/focus-urbanisation-issues-karachi> [Accessed March 2020].
- Im, E., Pal, J. S. & Eltahir, E., 2017. Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, 3(8).
- Imtiaz, S. & Ur-Rehman, Z., 2015. *Death Toll from Karachi, Pakistan, Heat Wave Tops 800*. *The New York Times*. [Online]

Available at: [http://www.nytimes.com/2015/06/25/world/asia/pakistan-heat-wave-death-toll-rises.html?\\_r=0](http://www.nytimes.com/2015/06/25/world/asia/pakistan-heat-wave-death-toll-rises.html?_r=0). [Accessed March 2020].

IPCC, 2014. Key economic sectors and services. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In: United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge.

IPCC, 2018. *Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response*, s.l.: World Meteorological Organization, Geneva, Switzerland.

IWBI, 2019. *WELL Building Standard*, s.l.: International WELL Building Institute pbc And Delos Living LLC.

Jacobs, C. et al., 2019. Patterns of outdoor exposure to heat in three South Asian cities. *Science of The Total Environment*, Volume 674, pp. 264-278.

Jenerette, G. et al., 2007. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landscape Ecol.*, Volume 22, p. 353–65.

Jenerette, G., Harlan, S., Stefanov, W. & Martin, C., 2011. Ecosystem services and urban heat riskscape moderation: Water, green spaces, and social inequality in Phoenix, USA. *Ecological Applications*, 21(7), pp. 2637-2651.

Jonsson, P., 2004. Vegetation as an urban climate control in the subtropical city of Gaborone, Botswana. *International Journal of Climatology*, 2(10), pp. 1307-1322.

Kanwal, S., Ding, X., Sajjad, S. & Abbas, S., 2020. Three Decades of Coastal Changes in Sindh, Pakistan. *Remote Sensing*, 12(8).

Katsouyanni, K., Trichopoulos, D., Zavitsanos, X. & Touloumi, G., 1988. The 1987 Athens heat wave. *The Lancet*, 2(8610).

Khan, J. & Omar, T., 2014. *Impacts of Urbanization on Land Surface Temperature of Karachi*. University of Engineering & Technology (UET), Lahore, Conference: First International Young Engineers Convention (IYEC).

Khan, N., 2010. *Beyond Crisis: Re-evaluating Pakistan*. New Dehli, Abingdon: Routledge.

Khan, N. et al., 2019. Prediction of heat waves in Pakistan using quantile regression forests. *Atmospheric research*, 221(1), pp. 1-11.

Kolb, E., 2019. *75,000 people per square mile? These are the most densely populated cities in the world, USA TODAY*. [Online]

Available at: <https://eu.usatoday.com/story/news/world/2019/07/11/the-50-most-densely-populated-cities-in-the-world/39664259/>

[Accessed March 2020].

Kosatsky, T., 2005. The 2003 European heat waves. *Euro Surveill.*, 10(7).

Kotharkar, R. & Bagade, A., 2017. Local Climate Zone classification for Indian cities: A case study of Nagpur. *urban Climate*, Volume 24, pp. 369-392.

Kotharkar, R. & Bagade, A., 2018. Evaluating urban heat island in the critical local climate zones of an Indian city. *Landscape and Urban Planning*, Volume 169, pp. 92-104.

Kotharkar, R., Bagade, A. & A, A. A., 2019. Investigating Local Climate Zones for Outdoor Thermal Comfort Assessment in an Indian City. *Geographica Pannonica – Special Issue*, 23(4), p. 318–328.

- Kotharkar, R., Bagade, A. & Ramesh, A., 2019. Assessing urban drivers of canopy layer urban heat island: A numerical modeling approach. *Landscape and Urban Planning*, Issue [https://www.researchgate.net/publication/334050775\\_Assessing\\_urban\\_drivers\\_of\\_canopy\\_layer\\_urban\\_heat\\_island\\_A\\_numerical\\_modeling\\_approach/stats](https://www.researchgate.net/publication/334050775_Assessing_urban_drivers_of_canopy_layer_urban_heat_island_A_numerical_modeling_approach/stats).
- Kotharkar, R., Bahadure, P. & Sarda, N., 2014. Measuring compact urban form: A case of Nagpur City, India. *Sustainability*, 6(7), pp. 4246-4272.
- Kotharkar, R., Ramesh, A. & Bagade, A., 2018. Urban heat island studies in South Asia: A critical review. *Urban Climate*, Volume 24, pp. 1011-1026.
- Kotharkar, R., Ramesh, A. & Bagade, A., 2018. Urban Heat Island studies in South Asia: A critical review. *Urban Climate*, Volume 24, pp. 1011-1026.
- Kotharkar, R. & Surawar, M., 2016. Land use, land cover, and population density impact on the formation of canopy urban heat islands through traverse survey in the Nagpur urban area, India. *Journal of Urban Planning and Development*, 142(1).
- Krüger, E., Drach, P. & Emmanuel, R., 2018. Atmospheric Impacts on Daytime Urban Heat Island. *Air, Soil and Water Research*, 11(1-3).
- Krüger, E., Drach, P., Emmanuel, R. & C. O., 2012. Assessment of daytime outdoor comfort levels in and outside the urban area of Glasgow, UK. *International Journal of Biometeorology*, Volume 57, p. 521–533.
- Krüger, E., Drach, P., Emmanuel, R. & Corbella, O., 2012. Urban heat island and differences in outdoor comfort levels in Glasgow, UK. *Theoretical and Applied Climatology*, 112(1-2), p. 127–141.
- Krüger, E. & Emmanuel, R., 2013. Accounting for atmospheric stability conditions in urban heat island studies: The case of Glasgow, UK. *Landscape and Urban Planning*, Volume 117, pp. 112-121.
- Leconte, F., Bouyer, J. & Claverie, R., 2020. Nocturnal cooling in Local Climate Zone: Statistical approach using mobile measurements. *Urban Climate*, Volume 33.
- Leconte, F., Bouyer, J., Claverie, R. & Pétrissans, M., 2015. Using Local Climate Zone scheme for UHI assessment: Evaluation of the method using mobile measurements. *Building and Environment*, Volume 83, pp. 39-49.
- Lee, K. et al., 2020. Trend Analysis of Urban Heat Island Intensity According to Urban Area Change in Asian Mega Cities. *Sustainability*, 12(112).
- Lemonsu, A., Vigiúé, V., Daniel, M. & Masson, V., 2015. Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). *Urban Climate*, 14(4).
- Lin, T., 2009. Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, Volume 44, pp. 2017-2026.
- Lin, T.-P., Matzarakis, A. & Hwang, R., 2010. Shading effect on long-term outdoor thermal comfort. *Building and Environment*, 45(1), pp. 213-221.
- Li, X., Koh, T., Panda, J. & Norford, L., 2016. Impact of urbanization patterns on the local climate of a tropical city, Singapore: An ensemble study. *JGR Atmospheres*.
- Loridan, T. & Grimmond, C., 2012. Characterisation of energy flux partitioning in urban environments: links with surface seasonal properties. *Journal of Applied Meteorology and Climatology*, Volume 51, pp. 219-241.
- Loridan, T. et al., 2013. High Resolution Simulation of the Variability of Surface Energy Balance Fluxes Across Central London with Urban Zones for Energy Partitioning. *Boundary-Layer Meteorology*, Volume 147, p. 493–523.



- Lotfian, M. et al., 2019. *The relationship between land surface temperature and local climate zone classification: A case study of the canton Geneva, Switzerland*. Limassol, Cyprus, Conference: AGILE 2019.
- Maharroof, N., Emmanuel, R. & Thompson, C., 2018. *Local Climate Zone Parameters for Street Design in Compact Urban Areas*. City College of New York, 10th International Conference on Urban Climate/14th Symposium on the Urban Environment.
- Maharroof, N., Emmanuel, R. & Thomson, C., 2020. Compatibility of local climate zone parameters for climate sensitive street design: Influence of openness and surface properties on local climate. *Urban climate*, Volume 33.
- Maharroof, N., Emmanuel, R. & Thomson, C., 2020. *Local Climate Zone Parameters for street design in compact urban areas*. [Online] Available at: <https://ams.confex.com/ams/ICUC10/mediafile/Presentation/Paper341691/2C.1-%20Local%20Climate%20Zone%20Parameters%20for%20Street%20Design%20in%20Compact%20Urban%20Areas.pdf> [Accessed March 2020].
- Mangi, M., Yue, Z., Kalwar, S. & Lashari, Z., 2020. Comparative Analysis of Urban Development Trends of Beijing and Karachi Metropolitan Areas. *Sustainability*, 12(451).
- Martin, P., Baudouin, Y. & Gachon, P., 2014. An alternative method to characterize the surface urban heat island. *International Journal of Biometeorology*, 59(7), p. 849–861.
- McMichael, A., 2000. The urban environment and health in a world of increasing. *Bull World Health Organ*, 78(9), p. 1117–1126..
- Meehl, G. & Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century.. *Science*, Volume 305, pp. 994-997.
- Middel, A., Brazel, A., Kaplan, S. & Myint, S., 2012. Daytime cooling efficiency and diurnal energy balance in Phoenix, AZ. *Climate Research*, 54(1), pp. 21-34.
- Middel, A. et al., 2014. Impact of urban form and design on a mid-afternoon microclimate in Phoenix Local Climate Zones. *Landsc. Urban Plan.*, Volume 122, p. 16–28.
- Millington, A., Nagendra, H. & Kopecks, M., 2018. *Urban Land Systems: An Ecosystems Perspective*. Basel, Switzerland: MDPI.
- Mills, G., 2007. Cities as agents of global change. *Int. J. Climatol.*, 27(14), pp. 1849-1857.
- Mills, G., 2008. Luke Howard and The Climate of London. *Weather*, 63(6).
- Mills, G. et al., 2015. *An Introduction to the WUDAPT project, ICUC9*. Toulouse, France, the 9th International Conference on Urban Climate.
- Mills, G. et al., 2009. *Climate and sustainable cities: climate information for improved planning and management of mega cities (Needs and Capabilities Perspectives)*. Geneva, Switzerland, World Climate Conference-3.
- Mustafa, E., Liu, G., Abd El-Hamid, H. & Kaloop, M., 2019. Simulation of land use dynamics and impact on land surface temperature using satellite data. *Geo Journal*, Issue Auer, A. H., 1978: Correlation of land use and cover with meteorological anomalies. *J. Appl. Meteor.*, 17, 636–643.
- Naveed, A., 2017. *Future proofing Karachi for Urban Heat Island*, Dubai: Dissertation submitted in fulfilment of the requirements for the degree of MSc Sustainable Design of Built Environment at The British University in Dubai.
- Nayak, S. et al., 2018. Development of a heat vulnerability index for New York State. *Public Health*, Volume 161, p. 127–37.

- Nazrul Islam, S. & Winkel, J., 2017. *Climate Change and Social Inequality\**, DESA Working Paper No. 152. New York: United Nations, Department of Economic and Social Affairs.
- Ng, E., Chen, L., Wang, Y. & Yuan, C., 2012. A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Build. Environ.* , Volume 47, p. 256–271.
- Ng, E. & Ren, C., 2015. *The Urban Climatic Map: A Methodology for Sustainable Urban Planning*. s.l.:Routledge .
- Nicol, J., Raja, I., Allaudin, A. & Jamy, G., 1999. Climatic variations in comfortable temperatures: The Pakistan projects. *Energy Build.*, Volume 30, p. 261–279.
- Nouri, A., 2015. A framework of thermal sensitive urban design benchmarks: potentiating the longevity of Auckland’s public realm Buildings. *Buildings*, 5(1), pp. 252-281.
- Nuruzzaman, M., 2015. Urban Heat Island: Causes, Effects and Mitigation Measures -A Review. *International Journal of Environmental Monitoring and Analysis* , 2(67-73), p. 3.
- Obradovich, N. et al., 2017. Nighttime temperature and human sleep loss in a changing climate. *Science Advances*, 3(5).
- Oke, T., 1973. City Size and the Urban Heat Island. *Atmospheric Environment*, 7(8), pp. 769-779.
- Oke, T., 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, Volume 108(455), pp. 1-24.
- Oke, T., 2004. *Urban observations*, s.l.: s.n.
- Oke, T., 2006. Towards better scientific communication in urban climate.. *Theoretical and Applied Climatology*, Volume 84, pp. 179-190.
- Ottel , M. et al., 2011. Comparative life cycle analysis for green faades and living wall systems. *Energy and Buildings*, 43(12), pp. 3419-3429.
- Pakistan Bureau of Statistics, 2018. *Provincewise Provisional Results of Census - 2017*. [Online] Available at: [http://www.pbs.gov.pk/sites/default/files/PAKISTAN%20TEHSIL%20WISE%20FOR%20WEB%20CENSUS\\_2017.pdf](http://www.pbs.gov.pk/sites/default/files/PAKISTAN%20TEHSIL%20WISE%20FOR%20WEB%20CENSUS_2017.pdf) [Accessed March 2020].
- Pearlmutter, D. B. A. & Berliner, P., 1999. Microclimatic analysis of “compact” urban canyons in an arid zone. *Atmospheric Environment*, 33(24–25), pp. 4143-4150.
- Perera, N., Emmanuel, M. & Mahanama, P., 2012. *Mapping “Local Climate Zones” and relative warming effects in Colombo, Sri Lanka*.. UCD, Dublin Ireland., Conference: ICUC8 – 8th International Conference on Urban Climates.
- Perera, N. & Emmanuel, R., 2016. A “Local Climate Zone” based approach to urban planning in Colombo, Sri Lanka. *Urban Climate*, Volume 23, pp. 188-203.
- Peters, J., Poppel, M. & Theunis, J., 2012. Air quality mapping in urban environments using mobile measurements. *Sensing a Changing World*.
- Qureshi, S., 2010. The fast growing megacity Karachi as a frontier of environmental challenges: Urbanization and contemporary urbanism issues. *Journal of Geography and Regional Planning*, 3(11), pp. 306-321.
- Qureshi, S., Breuste, J. & Lindley, S., 2010. Green space functionality along an urban gradient in Karachi, Pakistan: A socio-ecological study. *Human Ecology*, Volume 38, p. 283–294.

- Qureshi, S., Kazmi, S. & Breuste, J., 2010. Ecological disturbances due to high cutback in the green infrastructure of Karachi: Analyses of public perception about associated health problems. *Urban Forestry & Urban Greening*, Volume 9, p. 187–198.
- Qureshi, S., Umar, M. & Haase, D., 2012. Multitemporal image analyses for monitoring the dynamics of urban vegetation in response to rapid urbanization in Karachi. *Landscape Ecology lab, Humboldt University of Berlin*.
- Rafiq, L. & Blaschke, T., 2012. Disaster risk and vulnerability in Pakistan at a district level. *Geomatics, Natural Hazards and Risk*, 3(4).
- Ramakreshnana, L. et al., 2019. A qualitative exploration on the awareness and knowledge of stakeholders towards Urban Heat Island phenomenon in Greater Kuala Lumpur: Critical insights for urban policy implications. *Habitat International*, Volume 86, pp. 28-37.
- Rasul, A. et al., 2017. A Review on Remote Sensing of Urban Heat and Cool Islands. *Land*, 6(38).
- Raza, D. et al., 2019. Satellite Based Surveillance of LULC with Deliberation on Urban Land Surface Temperature and Precipitation Pattern Changes of Karachi, Pakistan. *Journal of Geography & Natural Disasters*, 9(1).
- Ren, C. et al., 2019. Assessment of Local Climate Zone Classification Maps of Cities in China and Feasible Refinements. *Scientific Reports*, Volume 9.
- Ren, C., n.d. *Census of urban Morphology: Recent Developments and Potential of the World Urban Database and Access Portal Tools (WUDAPT) Global initiative*, s.l.: Institute of Future Cities.
- Ren, C., Ng, E. & Katzschner, L., 2011. Urban climatic map studies: a review. *Int. J. Climatol.*, Volume 31, p. 2213–2233.
- Rescha, E., Bohne, R., Kvamsdalb, T. & Lohne, J., 2016. Impact of urban density and building height on energy use in cities, SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep.. *Energy Procedia*, Volume 96, pp. 800-814.
- Rizwan, A., Dennis, Y. & Liu, C., 2008. A review on the generation, determination and mitigation of urban heat island. *J. Environ. Sci.*, Volume 20, pp. 120-128.
- Romero-Lankao, P., Gnatz, D., Wilhelmi, O. & Hayden, M., 2016. Urban Sustainability and Resilience: From Theory. *Sustainability*, 8(1224).
- Roth, M., 2012. Urban heat island. In: H. Fernando, ed. *Handbook of environmental fluid dynamics, volume one: Overview and fundamentals*. s.l.:Vol. 1, CRC Press, pp. 143-159.
- Sadiq, N. & Ahmad, I., 2010. An Empirical Microclimate Analysis of the Coastal Urban City and Comparison of Vicinal Urban and Rural Areas with It. *Pakistan Journal of Meteorology*, 6(11).
- Sailor, D., Kalkstein, L. & Wong, E., 2002. *The Potential of Urban Heat Island Mitigation to Alleviate Heat-Related Mortality: Methodological Overview and Preliminary Modeling Results for Philadelphia*. s.l., 4th Symposium on the Urban Environment.
- Sajjad, S. et al., 2015. The long-term variability in minimum and maximum temperature trends and heat island of Lahore city, Pakistan. *Sci.Int.(Lahore)*, 27(2), pp. 1321-1325.
- Sajjad, S., Hussain, B. & Khan, M., 2009. On rising temperature trends of Karachi in Pakistan. *Climatic Change*, 96(4), p. 539–547.
- Salim, A., Ahmed, A., Ashraf, N. & Ashar, M., 2015. Deadly heat wave in Karachi, July 2015: negligence or mismanagement?. *The international journal of occupational and environmental medicine*, Volume 6:249, p. 678–249.

- Samaa News, April 2018. *Karachi load shedding: No one ready to take responsibility*. [Online] Available at: <https://www.samaa.tv/news/2018/04/karachi-load-shedding-no-one-ready-to-take-responsibility/> [Accessed April 2018].
- Samaa.tv, 2017. *Karachi's population could have been shown less for political reasons: Arif Hasan*. [Online] Available at: <https://www.samaa.tv/news/2017/08/karachis-population-shown-less-political-reasons-arif-hasan/> [Accessed February 2020].
- Santamouris, M., 2014. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, Volume 103, pp. 682-703.
- Shashua-Bar, L. & Hoffman, M. E., 2003. Geometry and orientation aspects in passive cooling of canyon streets with trees. *Geometry and orientation aspects in passive cooling of canyon streets with trees*, 35(1).
- Shashua-Bar, L., Pearlmutter, D. & Erell, E., 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment.. *International Journal of Climate*, Volume 31, p. 1498–1506.
- Sherwood, S. & Huber, M., 2010. An adaptability limit to climate change due to heat stress. *PNAS*, 107(21), pp. 9552-9555.
- Shinzato, P., Simon, H., Duarte, D. & Bruse, M., 2019. Calibration process and parametrization of tropical plants using ENVI-met V4 – Sao Paulo case study. *Architectural Science Review*, 62(2), pp. 112-125.
- Shishegar, N., 2013. Street Design and Urban Microclimate: Analyzing the Effects of Street Geometry and Orientation on Airflow and Solar Access in Urban Canyons. *Journal of Clean Energy Technologies*, 1(1).
- Shi, Y., Lau, K. K.-L., Rena, C. & Ng, E., 2018. Evaluating the local climate zone classification in high-density heterogeneous urban environment using mobile measurement. *Urban Climate*, Volume 25.
- Simon, H., 2016. *Modeling Urban Microclimate*, s.l.: PhD diss., Johannes Gutenberg Universitat-Mainz.
- Simon, H. et al., 2018.. “Modeling Transpiration and Leaf Temperature of Urban Trees – A Case Study Evaluating the Microclimate Model ENVI-met Against Measure Data. *Landscape and Urban Planning*, Volume 174, p. 33–40.
- Sobrino, J. et al., 2011. Impact of spatial resolution and satellite overpass time on evaluation of the surface urban heat island effects. *Remote Sensing of Environment*, Volume 117, p. 50–56.
- Solecki, W. et al., 2005. Mitigation of the heat island effect in urban New Jersey. *Global Environmental Change Part B: Environmental Hazards*, 6(1), p. 39–49.
- Soomro, T. & Soomro, M., 2018. Planning Failure of Satellite Town: A Case Study of Korangi, Karachi-Pakistan. *Mehran University Research Journal of Engineering and Technology*, *Mehran University of Engineering and Technology, Jamshoro, Pakistan*, 37(1), pp. 209-222.
- Sorensen, A. & Okata, J., 2010. *Megacities: Urban Form, Governance, and Sustainability*. Tokyo Newyork London: Springer.
- Stathopoulou, M., Cartalis, C., Keramitsoglou, I. & Santamouris, M., 2005. *Thermal remote sensing of Thom's discomfort index (DI): comparison with in-situ measurements*. SPIE Remote Sensing, Bruges, Belgium, Remote Sensing for Environmental Monitoring, GIS Applications, and Geology. Proceedings Volume 5983.
- Steadman, P., 2017. *UCL-Energy 'High-Rise Buildings: Energy and Density' research*. [Online] Available at: <http://www.conservativehome.com/wp-content/uploads/2017/07/Energy-and-Density-Philip-Steadman.pdf> [Accessed March 2020].

- Steadman, R., 1979. The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science. *J. Appl. Meteorol.*, Volume 18, pp. 861-873.
- Stewart, I. D., 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, Volume 31, p. 200–217.
- Stewart, I. D. & Oke, T. R., 2012. Local Climate Zones for Urban Temperature Studies. *Bull. Amer. Meteor. Soc.*, 93(12), p. 1879–1900.
- Stewart, I., Oke, T. R. & Krayenhoff, E., 2014. Evaluation of the ‘local climate zone’ scheme using temperature observations and model simulations. *International Journal of Climatology*, Volume 34, p. 1062–1080.
- Strømman-Andersena, J. & Sattrup, P., 2011. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. *Energy and Buildings*, 43(8), pp. 2011-2020.
- Sun, H., Chen, Y. & Zhan, W., 2015. Comparing surface- and canopy-layer urban heat islands over Beijing using MODIS data. *International Journal of Remote Sensing*, 36(21), pp. 5448-5465.
- Surawar, M. & Kotharkar, R., 2017. Assessment of Urban Heat Island through Remote Sensing in Nagpur Urban Area Using Landsat 7 ETM+ Satellite Images. *International Journal of Urban and Civil Engineering*, 11(7).
- Synnefa, A., Dandou, A., Santamouris, M. & Tombrou, M. & S. N., 2008. On the use of cool materials as a heat island mitigation strategy.. *Journal of Applied Meteorology and Climatology*, 47(11), pp. 2846-2856.
- Taleghani, M., 2018. Outdoor thermal comfort by different heat mitigation strategies- A review. *Renewable and Sustainable Energy Reviews, Elsevier*, 81(P2), pp. 2011-2018.
- Taleghani, M., Kleerekoper, L., Tenpierik, M. & Van den Dobbelen, A., 2015. Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and Environment*, Volume 83, pp. 65-78.
- The Express Tribune, 2018. *Urban planner calls for protection of fields, fruit farms in Karachi suburbs*, Karachi: The Express Tribune.
- The News, 2008. *Karachiites on Karachi*, Karachi: International The News.
- The News, 2019. *Going for high-rise buildings*. [Online] Available at: <https://www.thenews.com.pk/tns/detail/573190-going-for-high-rise-buildings> [Accessed 10 June 2020].
- The urban Unit, 2017. *Karachi Heatwave Management Plan: A Guide to Planning and Response*, ESSA Technologies Ltd. and The Urban Unit. [Online] Available at: [https://urbanunit.gov.pk/Upload/ProjectDocument/Karachi%20Heat%20Management%20Plan\\_FINAL.pdf](https://urbanunit.gov.pk/Upload/ProjectDocument/Karachi%20Heat%20Management%20Plan_FINAL.pdf) [Accessed August 2020].
- The World Bank, 2020. *Urban Development*. [Online] Available at: <https://www.worldbank.org/en/topic/urbandevelopment/overview> [Accessed July 2020].
- Thomas, G., Sherin, A. S. & Zachariah, E., 2014. Analysis of urban heat island in Kochi, India, using a modified local climate zone classification. *Procedia Environmental Sciences*, Volume 21, p. 3 – 13.
- Thom, E., 1959. The discomfort index. *Weather wise*, Volume 12, p. 57–60.
- Tomlinson, C., Chapman, L., Thornes, J. & Baker, C., 2011. Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham, UK. *International Journal of Health Geographics*, 10(42).

- Toy, S. & Yilmaz, S., 2010. Evaluation of 10-year temperature differences between urban and rural areas of a well-planned, unindustrialized and medium-sized Turkish Town, Erzincan.. *Journal of Urban Planning and Development*, 136(4), p. 349–356.
- Tsilini, V., Papantoniou, S., Kolokotsa, D. & Maria, E., 2015. Urban gardens as a solution to energy poverty and urban heat island. *Sustainable Cities and Society*, Volume 14, pp. 323-333.
- Uejio, C., Wilhelm, O., Golden, J. & Samenow, J., 2010. Intra-Urban Societal Vulnerability to Extreme Heat: The Role of Heat Exposure and the Built Environment, Socioeconomics, and Neighborhood Stability. *Health & Place*, 17(2), pp. 498-507.
- UN, 2018. *68% of the world population projected to live in urban areas by 2050, says UN*. [Online] Available at: <https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html> [Accessed February 2020].
- UN-Habitat, 2017. *Forced Evictions-- Towards Solutions?: Second Report of the Advisory Group on Forced Evictions to the Executive Director of UN-HABITAT.*, s.l.: UN-Habitat.
- United Nation, 2017. *Sustainable Cities*. [Online] Available at: <https://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/11.pdf> [Accessed June 2020].
- Urban Land Institute, 2005. *Higher-Density Development, Myth and Fact*, Washington, D.C.: ULI—the Urban Land Institute.
- Veerbeek, W., 2017. *Estimating the Impacts of Urban Growth on Future Flood Risk: A Comparative Study*. s.l.:CRC Press.
- Verma, D. & Jana, A., 2019. LULC classification methodology based on simple Convolutional Neural Network to map complex urban forms at finer scale: Evidence from Mumbai.
- Vidanapathirana, M., Emmanuel, R. & Perera, N., 2017. *Microclimatic impacts of high-rise cluster developments in Colombo, Sri Lanka*. Colombo, Sri Lanka, Conference: 10th International Conference of Faculty of Architecture Research Unit (FARU). ISBN: 978-955- 9027- 66-9.
- Voelkel, J. & Shandas, V., 2017. Towards Systematic Prediction of Urban Heat Islands: Grounding Measurements, Assessing Modeling Techniques. *Climate*.
- Voogt, J. & Oke, T., 2003. Thermal Remote Sensing of Urban Climates. *Remote Sensing of Environment*, Volume 86, p. 370–384.
- Wang, C. et al., 2018. Assessing local climate zones in arid cities: The case of Phoenix, Arizona and Las Vegas, Nevada. *ISPRS Journal of Photogrammetry and Remote Sensing*, Volume 141, pp. 59-71.
- Wang, R. et al., 2017. Mapping the local climate zones of urban areas by GIS-based and WUDAPT methods: A case study of Hong Kong.. *Urban Climate*.
- Wang, Y. & Akbari, H., 2016. The effects of street tree planting on Urban Heat Island mitigation in Montreal. *Sustainable Cities and Society*, Volume 27, pp. 122-128.
- Wang, Y., Berardi, U. & Akbar, H., 2015. Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and Buildings*.
- Westgate, K. & O'Keefe, P., 1976. Some definitions of disaster. *Occasional Paper 4. Disaster Research Unit, University of Bradford*.



- Westlund, L., Puolain, F., Bage, H. & Anrooy, R., 2007. *Disaster Response and Risk Management in the Fisheries Sector*. s.l.:Food and Agriculture Organization of the United Nations .
- WHO, 2016. *Climate and Health Country Profiles 2015*. [Online] Available at: <https://apps.who.int/iris/bitstream/handle/10665/246150/WHO-FWC-PHE-EPE-15.28-eng.pdf;jsessionid=5B1D25CE1DDB052D721337310362ED4A?sequence=1> [Accessed August 2020].
- WHO, 2020. *Heatwaves*. [Online] Available at: <https://www.who.int/health-topics/heatwaves> [Accessed July 2020].
- Wilhelmi, O. & Hayden, M., 2010. Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. *Environmental Research Letters*.
- Wong, N. et al., 2007. Environmental study of the impact of greenery in an institutional campus in the tropics. *Building and Environment*, 42(8), pp. 2949-2970.
- World Bank, 2018. *Transforming Karachi into a Livable and Competitive Megacity: A City Diagnostic and Transformation Strategy. Directions in Development*, Washington, DC: World Bank.
- Wu, J. G. (., 2006. Landscape ecology, cross-disciplinarity, and sustainability science..
- Yadav, N. & Sharma, C., 2018. Spatial variations of intra-city urban heat island in megacity Delhi. *Sustainable Cities and Society*, Volume 37, pp. 298-306.
- Yamamoto, Y., 2006. Measures to mitigate urban heat islands. *Science and Technology Trends Quarterly Review*,. 2006, 18(1), pp. 65-83.
- Yamashita, S., 1996. Detailed structure of heat island phenomena from moving observations from electric tram-cars in Metropolitan Tokyo. *Atmospheric Environment*, 30(3), pp. 429-435.
- Yang, X., Zhao, L., Bruse, M. & Meng, Q., 2012. An integrated simulation method for building energy performance assessment in urban environments.. *Energy Build.*, Volume 54, p. 243–251.
- Yao, R., 2013. *Design and Management of Sustainable Built Environments*. s.l.:Springer Science & Business Media.
- Yasmeen, Z., Afzaal, M., Anjum, M. & Ahmad, B., 2017. urban heat island in changing climate (a case study of karachi heatwave, 2015). In: *World Environment Day*. s.l.:Pakistan Engineering Congress.
- Yeung, Y., 2011. Rethinking Asian cities and urbanization: four transformations in four decades. *Asian Geographer*, 28(1), pp. 65-83.
- Yokobori, T. & Ohta, S., 2009. Effect of land cover on air temperatures involved in the development of an intra-urban heat island. *Climate Research*, Volume 39, p. 61–73.
- Zaidi, A. & Zafar, S., 2018. *Karachi: An Expanding City with Rising Disasters*. s.l., World Environmental and Water Resources Congress 2018.
- Zhan, X. et al., 2002. Detection of land cover changes using MODIS 250 m data. *Remote Sens. Environ.*, Volume 336 – 350, p. 83.
- Zheng, Y. et al., 2017. GIS-based mapping of Local Climate Zone in the high-density city of Hong Kong. *Urban Climate*.
- Zhou, B., Rybski, D. & Kropp, J., 2017. The role of city size and urban form in the surface urban heat island. *Scientific Reports*, Volume 7.