



# **Microclimatic analysis to mitigate urban heat islands using urban climatic map approach**

Toulouse, France

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A thesis submitted for the Joint programme of  
Master in Urban Climate & Sustainability

August 2021





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<b>Number of pages:</b> 123		
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<b>Title</b> Microclimatic analysis to mitigate urban heat islands using urban climatic map approach Toulouse, France		
<b>Degree:</b> Master in Urban Climate & Sustainability		
<b>Abstract</b> <p>Cities are urbanising at a fast phase to accommodate more people, which leads to global and local warming. Due to urbanisation, European cities are facing summer heatwave issues. The air temperature reaches up to 40 degrees celsius during the summer heatwave in Toulouse, France. Since the urban infrastructures are responsible for climatic issues, it is essential to inform urban planners and urban designers about it. Urban climatic maps are used to inform urban planners and designers about various urban climatic issues. But, urban planners and designers are not able to make appropriate climate responsive decisions based on the climatic information available through urban climatic maps. This is because the maps do not provide information about the urban planning and design parameters that cause the climatic issue in the city. To bridge the gap, this thesis aims to provide complementary spatialized indicators useful for climate-responsive decisions. Toulouse was chosen to build the climatic maps, and UHI is the climatic issue-focused through this thesis. This thesis is conducted in three phases. In the first phase, 17 urban planning and design indicators were identified through qualitative research methods. In the second phase, various GIS tools were explored to calculate the identified indicators, to build the urban climatic maps. The data generated under the MApUCE project, for Toulouse, was used to calculate the identified indicators. In the last phase of the research, the calculated indicators were grouped, and Geographically Weighted Regression (GWR), a local regression method, was used to find the relationship between the identified indicators and the climatic issues. Compared to the Ordinary Linear Regression (OLS), a global regression, GWR provides more spatial heterogeneity. Based on the GWR results, the indicators that are most responsible for the UHI effect around the city centre of Toulouse were identified. Since this region experiences the most summertime discomfort, it was selected to show how the results can be used for urban planning and design decisions. Overall this thesis demonstrates an urban climatic map approach that will be useful for the urban planning and design community. The indicators identified in this thesis can be used for future urban climatic research.</p>		
<b>Keywords</b> UHI, Urban climatic maps, Urban planning, Urban design, GWR		
<b>Originality statement.</b> I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	<b>Signature</b>	



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## ACKNOWLEDGMENT

I am grateful to **Dr Julia Hidalgo** for providing me with the internship opportunity at LISST, Toulouse. I thank her for her immense support and guidance during this thesis journey. I also thank **Najla TOUATI** for her timely guidance and advice on the data and GIS application.

I am very much thankful to my two supervisors **Prof. Francisco Pérez-Bernal** and **Dr Craig Thomson**, for their timely support and guidance. My sincere thanks to **Dr Rohinton Emmanuel** for his support and guidance through the entire master's journey.

Lastly, I thank my friend **Sweta Kandari** for her timely feedback and suggestions on the report. I also thank all my MURCS Colleagues and Professors for their care and support.



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## Chapter 1. INTRODUCTION

### 1.1 Rationale:

Worldwide, we are suffering from strong urbanisation. World's urban population was 0.8 billion in the year 1950, has rapidly grown up to 4.2 billion in the year 2018 (United Nations, 2019). In the year 2050, the expectation is that 68% of the world's population will live in urban areas. In France, the urban population is already 80% (Martins *et al.*, 2016). The rapid urbanisation, to accommodate more people and necessary infrastructures, stressing the natural and built environment causing global and local warming. Between the years 1900 and 2020, the year 2020 was the hottest year of France. The mean average temperature of the country increased by 2.3 degree Celsius than the normal (Ministry of Ecological Transition, 2021).

The significant changes in the natural surfaces and the built morphology alters the thermal, moisture, and aerodynamic properties of the environments. This leads to a new human-induced climate, which is called an Urban heat island (UHI) (Oke *et al.*, 2017). The cities are often warmer compared to the surrounding rural areas, in particular during nighttime. Luke Howard first identified this in the year 1833. Since then, the interest in urban climatic studies began (Cleugh H, 1995). Higher temperature means higher health, economic and environmental risk, especially the urban poor, elderly and sick people get affected easily (Parapari, Taslim and Shafaghat, 2015). Daytime and nighttime heat stress in cities aggravate the health impacts not allowing the people to restore their bodies at night, especially fragile people, resulting in such incidents (Lambert-habib *et al.*, 2013).

Due to UHI, there will be an increase in need of energy for air-conditioning and refrigeration, which directly have an impact on the living costs. 2 to 4 % more energy is required for every 1 degree Celsius increase in temperature. The increase in temperature also decreases the quality of water, which is a huge threat to certain animal and plant species existence (Parapari, Taslim and Shafaghat, 2015). On the other hand in cold regions, the urban warmth reduces the number of heating days that lowers the heating system energy needs. This helps for plant growth in those regions (Oke *et al.*, 2017).

Urban climate effects are studied to address the climatic issues in an existing urban settlement or to plan a new development that is climate-sensitive to avoid climate-related problems in the future (Oke *et al.*, 2017). However, climatic studies are not often perceived from an urban planning perspective, and they are mostly studied from a scientific perspective. Climatologists do not understand spatial planning procedures and processes. On the other hand, planners and policymakers do not understand the climatic effects. Hence, there is a huge gap between urban climatic studies and urban planning (Ren *et al.*, 2012). To make the climate knowledge available to the planners and also to connect the urban climate field with urban planning and urban design, the Urban climatic map (UC-Map) was introduced (Ren, Ng and Katzschner, 2010).

Ren *et al.*, (2012) mentions that the UC-Map is a fragile bridge connecting the scientific and practical world of spatial planning. Johansson (2006) points that it would be difficult for urban planning professionals to use the map without any prior knowledge or experience in climatic issues. It is very much evident from these statements that the purpose of introducing UC-Map was not met. Therefore, this thesis attempts to strengthen the connection between the scientific and practical world by making the urban climatic maps useful for the urban planning and urban design community, who does not have any knowledge or experience in climatic issues.

To fill the identified gap, the parameters that need to be present in the UC-Maps were identified through a qualitative research approach, and they were prepared using GIS tools. The prepared parameters were then analysed in GIS to provide useful information to the urban planning and urban design community for mitigating or reducing UHI.

## **1.2 Aims & Objectives:**

Based on previous research done on the framework of *MApUCE*<sup>1</sup> and *PAENDORA*<sup>2</sup> research programs in France, this research aims to complement the urban climatic mapping approach to support urban planners and urban designers for climate-responsive decisions adopted to the French operational and scientific practices and legal framework.

To achieve the aim, the formulated objectives are:

---

1 <http://www.umr-cnrm.fr/ville.climat/spip.php?rubrique120&lang=en>

2 <https://www.umr-cnrm.fr/spip.php?article1119>

1. To make urban climatic maps useful for urban planning & urban design community.
2. To identify meteorological and urban planning & urban design parameters to feed the ensemble of maps composing the UC-Maps framework.
3. To explore the GIS tools to calculate the identified urban planning & urban design parameters.
4. To find the relationship between the identified meteorological and urban planning & urban design parameters.
5. To provide recommendations for future research related to urban climatic mapping.

### **1.3 Structure of the report:**

This report starts with a rationale behind this thesis, followed by its aim and objectives. The key issue identified that lead to this thesis is discussed briefly in the next chapter.

Chapter 2, literature review, explains the concept of urban climatic maps and describes various issues and limitations of climatic maps. Different analytical studies establishing the relationship between urban elements and UHI are also described in this chapter. Along with various urban climate map limitations, a critical examination of the climatic maps that lead to this thesis is presented.

Chapter 3 contextualises Toulouse and provides information regarding the urban climatic research activity taking place in France. This chapter also presents a brief overview of the data available and their sources.

Chapter 4 explains the research design adopted to fulfil the identified research gap. An overview of different methodological approaches followed during a different phase of the research, and the reason behind choosing those approaches are also explained.

Chapter 5, Chapter 6, and Chapter 7 are the main chapters of this thesis and represents phases 1, 2, and 3 of this thesis, respectively. These chapters present a detailed explanation of different research techniques and procedures, results, and associated discussion of each phase. Chapter 5 provides the list of parameters identified, followed by Chapter 6 explaining various GIS techniques and tools used to calculate the identified parameters. Chapter 7 presents the analytical results, in the form of maps, done using the identified parameters.

Chapter 8 consists of limitations and further research possibilities. This leads to Chapter 9, the conclusion.

## Chapter 2. LITERATURE REVIEW

The urban form has a greater impact on the outdoor environment (Yuan *et al.*, 2020). Oke *et al.*, (2017), in “Urban climate” book, states that buildings, streets, parks, and gardens, are created by the arrangement of facets, and each of them creates distinctive microclimates. The assemblage of these urban elements forms an urban block and different urban blocks put together became a neighbourhood. This creates a diversified microclimate within the neighbourhood.

Ng and Ren, (2015), based on a desktop study of UC-Maps worldwide, concludes that appropriate strategies related to Albedo, Vegetation, Shading, and Ventilation, mentioned in the Table 2-1, might help to overcome the climatic issues faced by the cities.

Objectives	Aspects	Action plans and strategies	Operation and spatial scale	Climatic impact scale		
bioclimate + urban heat island + urban air ventilation + air quality situation	Albedo	Cooling of building material and pavement	Material and surface-level intervention	Meso- and micro-scale		
		Cooling of roof and façade				
		Water retention paving				
	Vegetation	Planting greenery	Material and surface-level intervention	Meso- and micro-scale		
		Parks and open spaces	Landscape/land use planning-level intervention			
		Green corridors	Landscape/land use planning-level intervention			
		Shading	Building geometric design		Building design-level intervention	Micro-scale
	Ventilation	Shading	Shelter design	Building design-level intervention	Micro-scale	
			Street orientation	Urban planning/zoning-level intervention	Meso- and micro-scale	
			Building height/street width ratio	Building design-level intervention	Micro-scale	
		Ventilation	Vegetation	Trees along both sides of streets	Landscape/land use planning-level intervention	Micro-scale
				Air path	Urban planning/zoning-level intervention	Meso- and micro-scale
				Building ground coverage and building bulks	Urban planning/zoning-level intervention	Meso- and micro-scale
			Shading	Building height/street width ratio	Building design-level intervention	Micro-scale
				Street orientation	Urban planning/zoning-level intervention	Meso- and micro-scale
Layout of building dispositions				Urban planning/zoning-level intervention	Meso- and micro-scale	
Open spaces and greenery areas				Landscape/land use planning-level intervention	Meso- and micro-scale	

Table 2-1: Strategies to improve the urban climate environment (Ng and Ren, 2015).

Since urban elements are responsible for the urban climatic issues in the cities, and urban planning and design professionals are responsible for the selection and configuration of these urban elements. Hence it is important to inform them about this issue. But how to transfer the climatic data and information into design principles? (Johansson, 2006). Urban climatic maps seem to be the right answer for this question.

Urban planners and designers use cartographic representation in their day to day work. This is the reason the urban climate research community is exploring the cartographic representation of climatic information to make urban planners and designers understand the climatic issues the cities are facing today. The climatic maps do not always provide detailed advice to the planners and designers to overcome the climatic issues (Johansson, 2006). Hence, it is important to understand and analyse the deficiency of maps to make them useful for the urban planning and design community for climate-responsive decision making. It is also important to understand the relationship between the urban elements and the urban climatic issues. Therefore, this chapter presents the explanation of urban climatic maps with few examples and also a few studies that established the relationship between UHI and the urban elements.

## **2.1 What is an Urban Climate map?**

Urban climatic maps are two-dimensional spatial map that provides climatic information, and also acts as an evaluation tool for climatic phenomena and problems (Ren, Ng and Katzschner, 2010).

Urban Climatic maps (UC-Map) were first initiated by German researchers in the year 1970, and it was known as the “Synthetic Climate Function Map” during that period. UC-Map consists of two major components, the Urban Climate analysis map (UC-AnMap) and the Urban Climatic recommendation map (UC-ReMap) (Ren *et al.*, 2012).

The Figure 2-1 illustrates the general UC-Map processing structure and different pieces of information required for the same. UC-AnMap is an analytical map generated through quantitative or qualitative techniques. It provides a climatic understanding and evaluation, which is used to identify climate-sensitive areas. UC-Maps also provides some measures to solve the identified problems. Those are represented through UC-ReMap (Ren *et al.*, 2012).

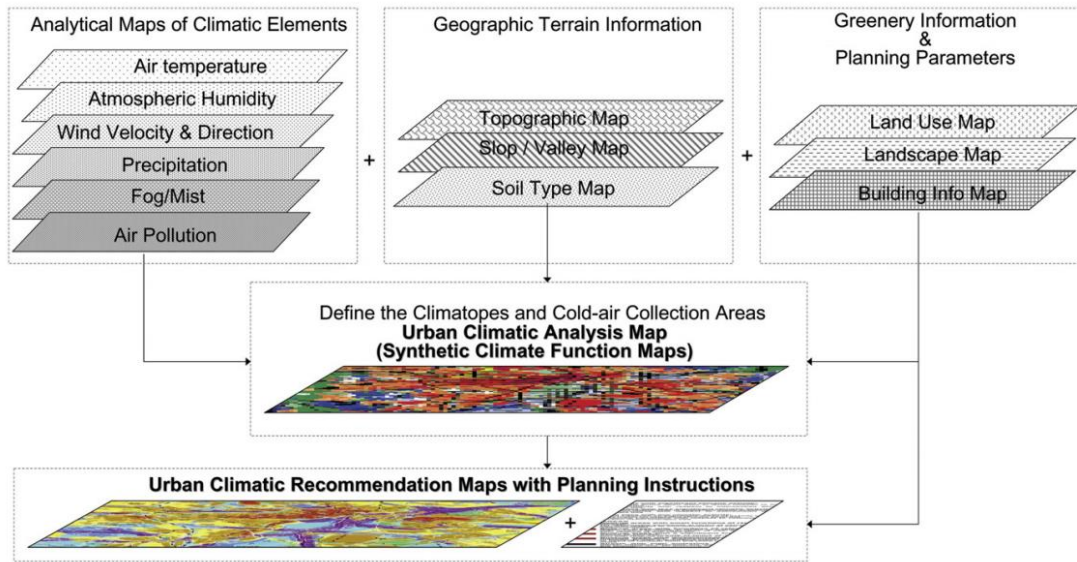


Figure 2-1: Urban climatic mapping structure (Ren, Ng and Katzschner, 2010).

### 2.1.1 A critical examination of UC-Map, through few examples, to understand their defect:

In this section, two urban climatic maps, Arnhem and Tokyo, were critically examined to understand urban climatic maps limitations and defects.

#### 2.1.1.1 Arnhem, Netherlands:

The city Arnhem, Netherland intended to identify different Climatopes for urban climatic analysis. Hence the city gathered different physical and climatic data. The gathered data were classified and calculated based on thermal load contribution and Dynamic potential (Ren *et al.*, 2012).

The intra air temperature differences might be due to Building density and other urban building geometrical differences (Ren *et al.*, 2012). Heat capacity of the area increases when the sky view factor (SVF) decreases. Higher the building density, the larger the heat capacity. Therefore, along with building volume density and land use maps, SVF for five selected

locations with varied building densities were calculated. The collected pieces of information was synthesized for urban morphological understanding. On top of the urban morphological information, the analysed wind information, and the topographical condition, are overlapped to create UC-AnMap. Three built-up area climatops, two greenery area climatopes, one water climatope, and one transport area climatope were identified from UC-AnMap for further analysis and to generate UC-ReMap. Based on the analysis high to low sensitive zones concerning urban climatic issues were identified, and appropriate recommendations suitable for each zone were provided (Ren *et al.*, 2012). Figure 2-2, Figure 2-3, Figure 2-4, and Figure 2-5 illustrate Arnhem’s UC-Map structure and relevant data used, information used to generate UC-Map, the UC-AnMap, and the UC-ReMap respectively.

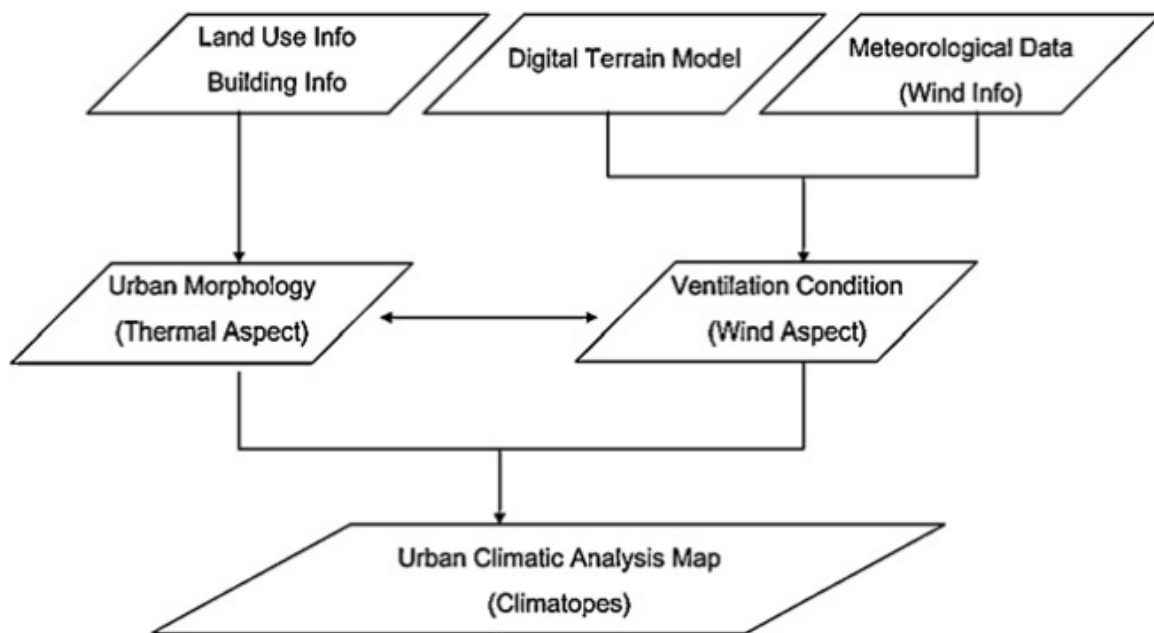


Figure 2-2 : Arnhem’s UC-Map structure (Ren *et al.*, 2012).

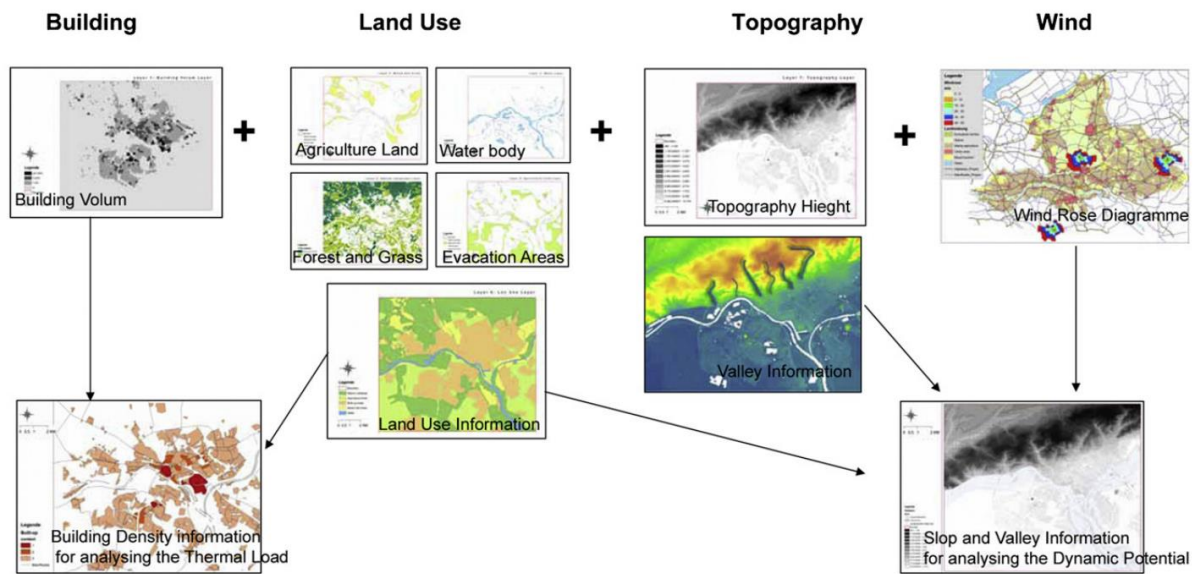


Figure 2-3: Parameters used to build UC-Map (Ren et al., 2012).

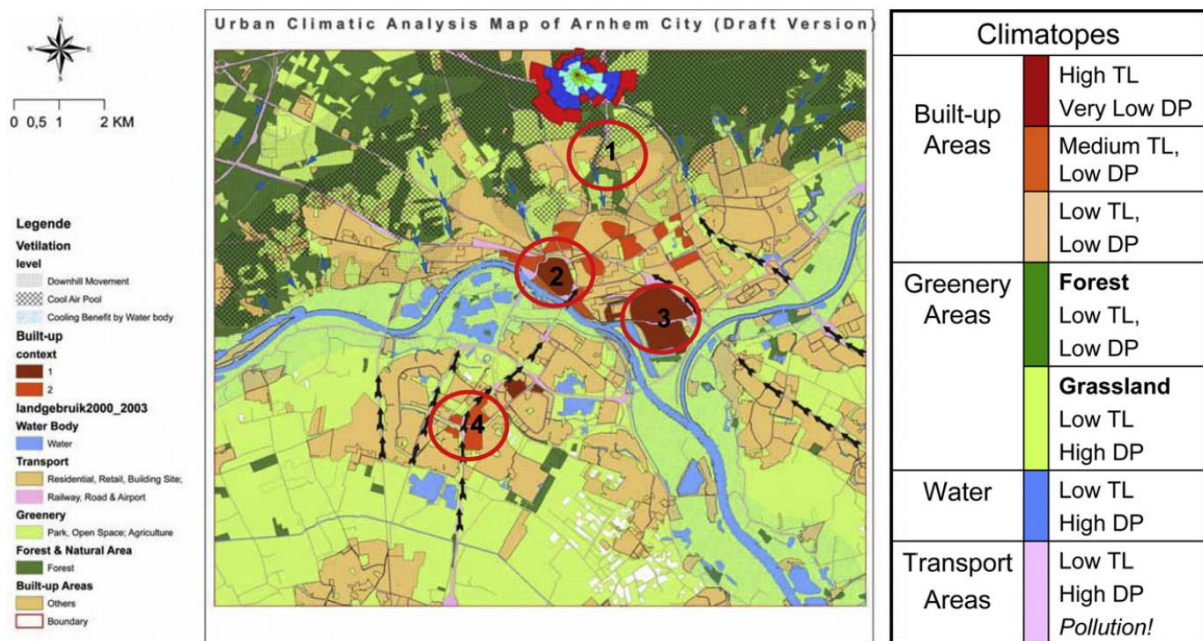


Figure 2-4: Arnhem's UC-AnMap (Ren et al., 2012).

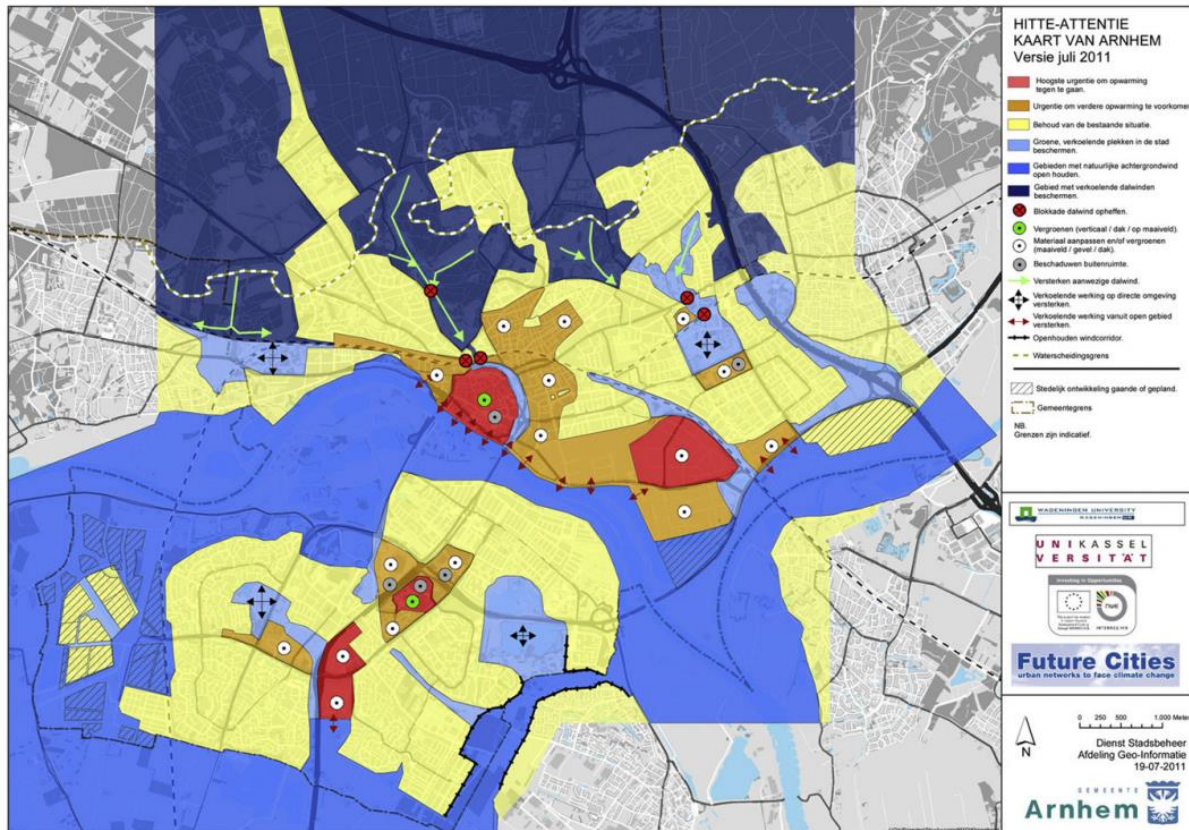


Figure 2-5: Arnhem's UC-ReMap (Ren et al., 2012).

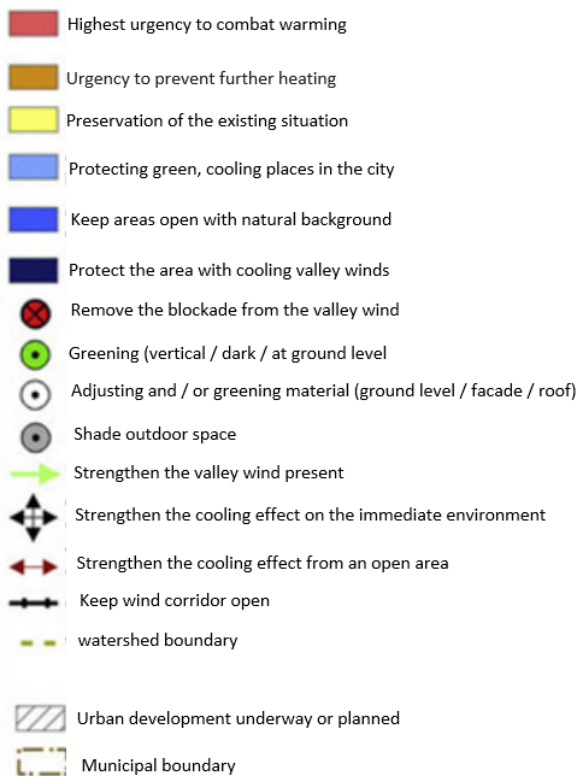


Figure 2-6: Arnhem's UC-ReMap legends translated to English (Author)

The Figure 2-6 is the English translation of the legends in the UC-ReMap of Arnhem. As it can be noticed, the provided recommendations are too generic, and it could be difficult for an urban planner and designer to address the same since the recommendations are not linked with the urban planning and design elements.

For example, a particular area was identified where the valley winds have to be strengthened to overcome the climatic issue. But urban planners and designers, without any climatic knowledge, do not know how to achieve this recommendation. This applies to most of the recommendations represented through the UC-ReMap of Arnhem.

### 2.1.1.2 Tokyo, Japan:

Apart from the necessary meteorological and planning parameter, heat release data such as anthropogenic heat release, vaporization latent heat, and surface cover sensible heat, were also considered in the UC-Maps of Tokyo. The generated UC-AnMap is overlapped with the heat release data to derive reasons for the particular urban climatic effect for the selected zone. Figure 2-7 and Figure 2-8 illustrates the information used to build Tokyo's UC-Map and the city's thermal environment map respectively (Ren, Ng and Katzschner, 2010).

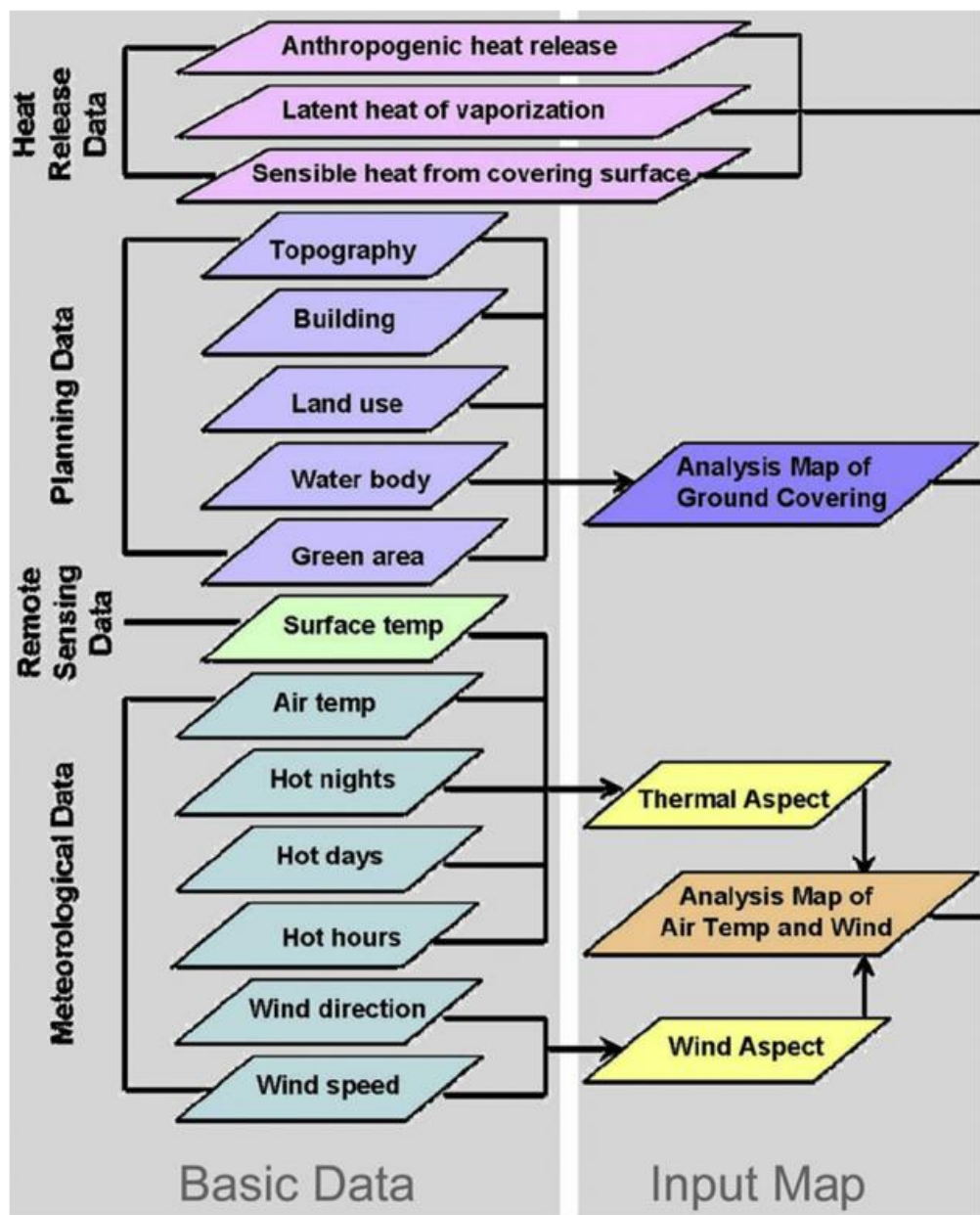


Figure 2-7 : Parameters used to build UC-Map (Ren, Ng and Katzschner, 2010).

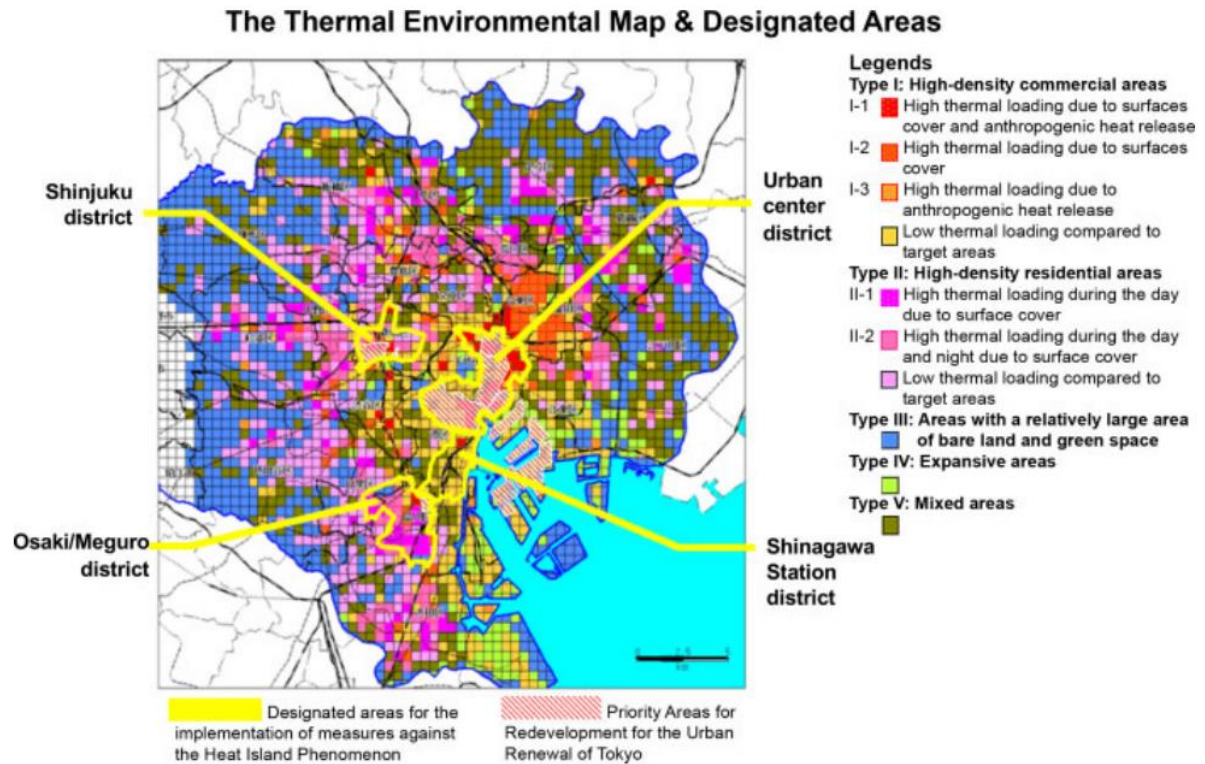


Figure 2-8: Tokyo's Thermal environmental map (Ren, Ng and Katzschner, 2010).

The thermal environment map of Tokyo (Figure 2-8), also has similar issue identified in the UC-ReMap of Arnhem. The thermal environment map explains the level of thermal load at different areas and the reason behind them. But these reasons are not linked with the urban planning and urban design elements, which makes it difficult for the urban planner and designer to understand, who do not have a climatic knowledge. This agrees with Johansson, (2006) argument, that the climatic maps do not provide detail advice to planners and designers.

### 2.1.2 Research question:

The critical understanding and examination of Arnhem's and Tokyo's UC-Map, lead to two important questions, that should be addressed through urban climate maps to make them useful for climate-sensitive planning and design decisions.

1. Who / What is responsible for the urban climatic issue in a particular place?
2. How to reduce or mitigate the climatic issue in a particular place?

## **2.2 Relationship between UHI and urban elements:**

This section summarises a few research conducted to establish the relationship between the urban elements and UHI.

Urban heat island (UHI) is the most widely known and studied urban climatic effect, responsible for various extreme weather events (Hidalgo, Lemonsu and Masson, 2018). Atmospheric variables such as temperature, rainfall, humidity, and airflow, which define climate, are directly modified by cities (Cleugh H, 1995). This disrupts the atmospheric features by altering the surface-air heat exchange, moisture, mass, and momentum (Hidalgo, Lemonsu and Masson, 2018). These modifications are due to the city's urban form and function (Oke *et al.*, 2017).

The major cause of the UHI is due to the thermal properties of surface material in the mesoscale and urban geometry in both meso and micro scales (Emmanuel and Fernando, 2007). Apart from urban geometry and urban surface thermal properties, other factors responsible for UHI are anthropogenic heat release, low albedo materials, loss of evapotranspiration, air pollution, and wind shelter (Emmanuel and Fernando, 2007).

The Use of air conditioners for interior cooling purposes releases the absorbed heat from inside to the atmosphere. That increases the outdoor temperature (Nuruzzaman, 2015). Low albedo urban surfaces will absorb and store more solar energy, leading to temperature increase in urban areas. Depending on various factors such as the selection of roof materials, pavements, orientation, etc., the cities albedo will vary (Nuruzzaman, 2015). Pollutions due to vehicles and industries are responsible for the increase in longwave radiation. (Parapari, Taslim and Shafaghat, 2015). The other reason for the city becoming warmer is due to the lack of vegetation in the cities. Due to which there is a reduction in evapotranspiration, shade and cooling effect (Parapari, Taslim and Shafaghat, 2015). Reduction in the wind velocity due to dense building fabric decreases the conventional cooling effect, thus traps the heat leading to an increase in temperature (Nuruzzaman, 2015). The non-geometric cause, such as anthropogenic heat release, can also be related to urban geometry. Extensive land use due to higher building density increases human activity, which increases the amount of heat waste (Emmanuel and Fernando, 2007).

The UHI effects and urban geometry are studied in the following ways, 1. Density/compactness/Ground coverage, 2. Building height and street width ratio (H/W), 3. Sky view factor (SVF), 4. Orientation, 5. Local climatic zone (LCZ) classification (Maharroof, Perera and Emmanuel, 2017).

The research article, “Street design and urban canopy layer climate” by T.R. Oke, in the year 1988, can be considered as a theoretical base to understand the relationship between urban geometry and Urban climate. The results presented in this article are obtained based on observed data in the mid and high-latitude cities. To overcome the climatic issues in cities, maximise shelter, maximise dispersion of pollution, maximise urban warmth, and maximise solar access, should be the street design objectives (Oke, 1988). But, designing a street canyon for providing maximum shelter would maximise the urban warmth. However, it won't favour the other two objectives. Similarly, designing a street canyon to increase pollution dispersion will increase solar access to the street, but maximum shelter and warmth, cannot be achieved. The author concludes with some quantitative numbers,  $H/W \sim 0.65$  provides considerable shelter from the sun,  $H/W \sim 0.65$  and built density  $\sim 0.25$  might help towards satisfactory dispersion. Maximum solar radiation can be gained if the  $H/W = 0.6$  to  $1.2$  for cities located at  $45^\circ$  latitude.  $H/W = 0.4, 0.7,$  and  $1.0$  are viable to gain one-third, half, and two-thirds of heat island intensity, respectively. Figure 2-9, Figure 2-10, Figure 2-11, Figure 2-12, and Figure 2-13 describes the relationship between different urban geometrical parameters and climatic aspects (Oke, 1988). In Continuation to this work, Swaid and Hoffman, (1990) established the relationship between urban canyon orientation and urban climate effects through experimental methods using the CTTC model.

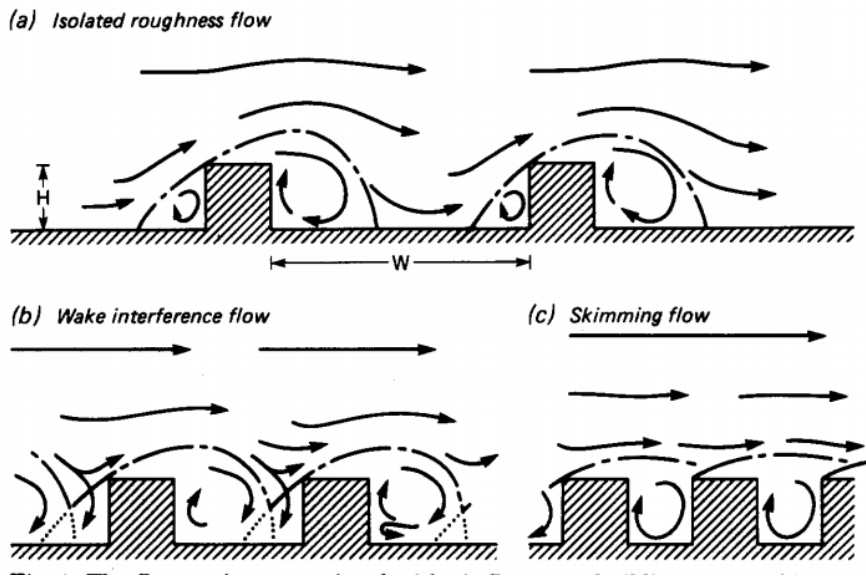


Figure 2-9: Air flow over Building arrays of increasing  $H/W$  ratio (Oke, 1988).

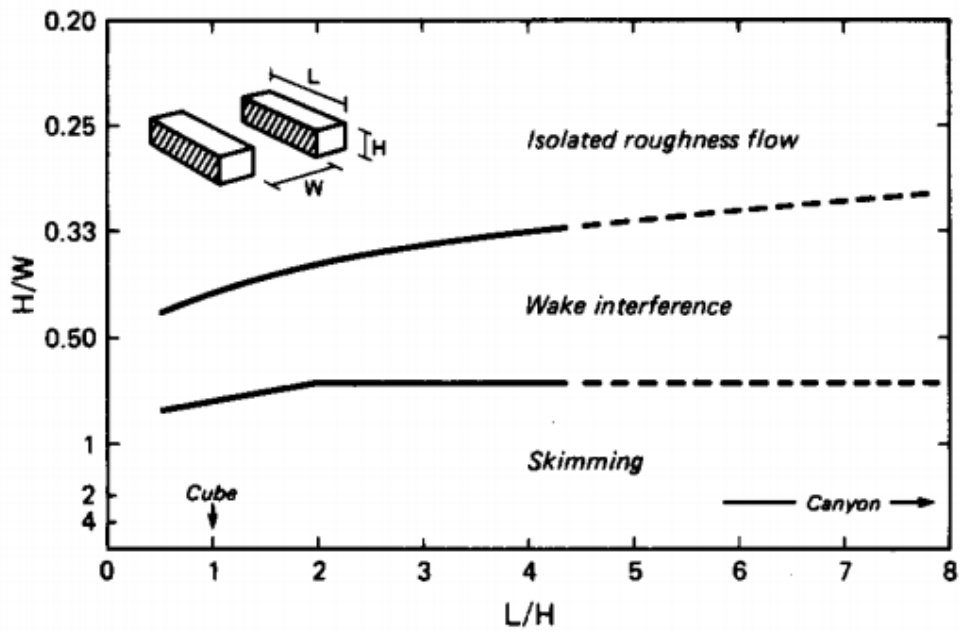


Figure 2-10 : The flow is divided in to three regimes Building, canyon, and geometry (Oke, 1988).

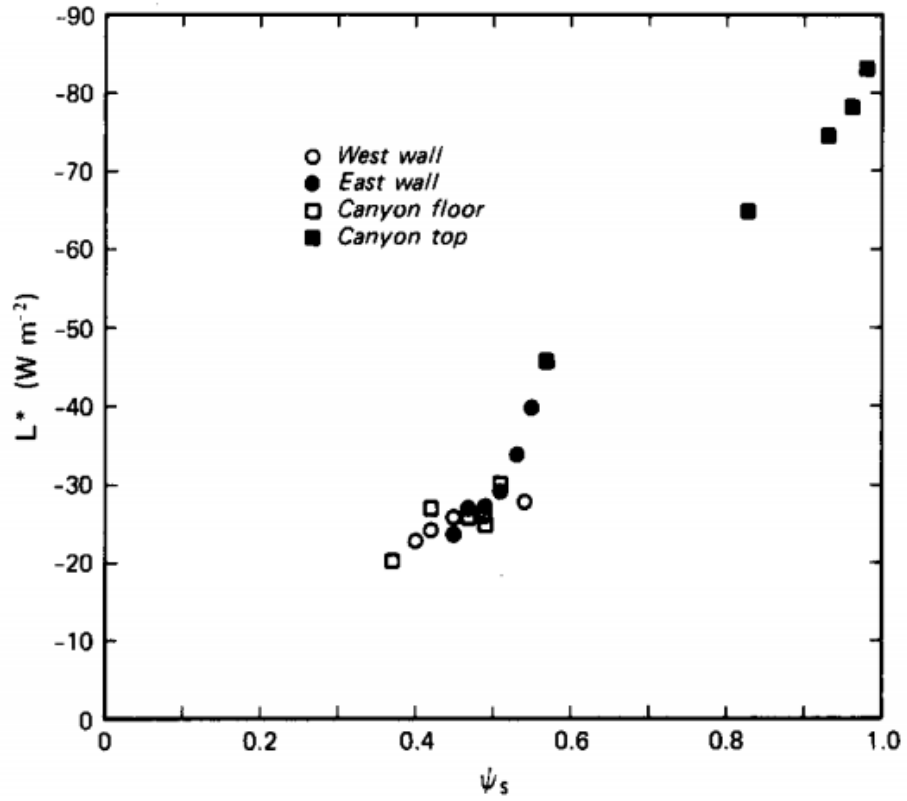


Figure 2-11: Relationship between net long wave radiation and Sky view factor (Oke, 1988)

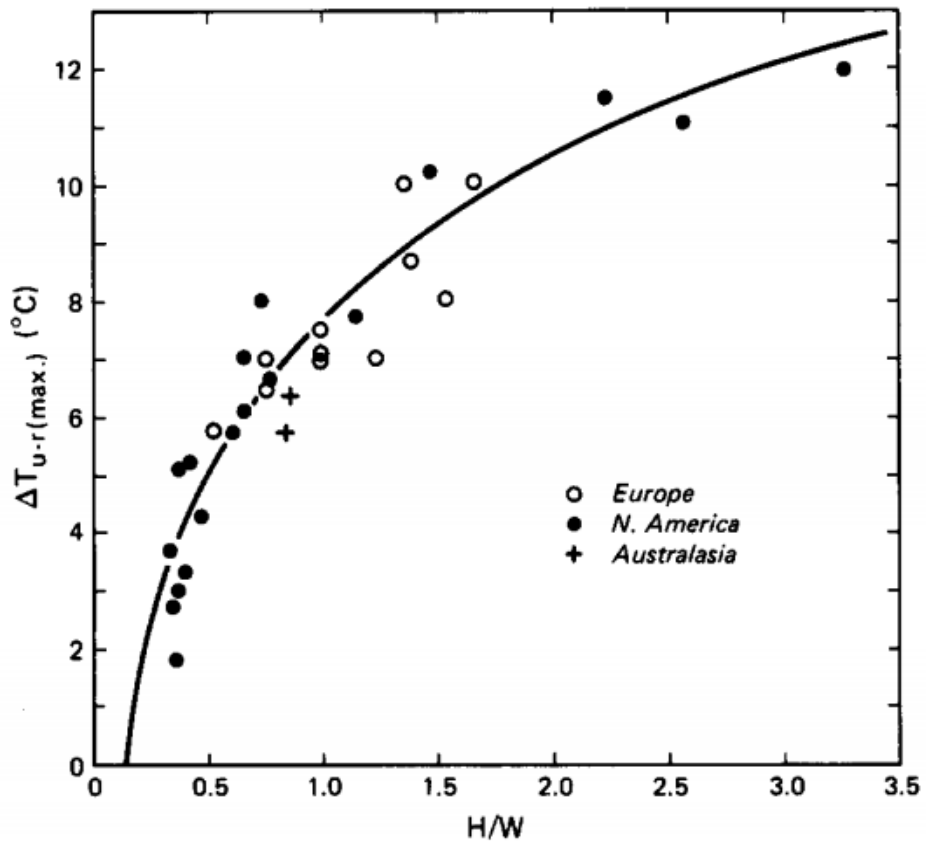


Figure 2-12: Relationship between UHI and  $H/W$  ratio (Oke, 1988).

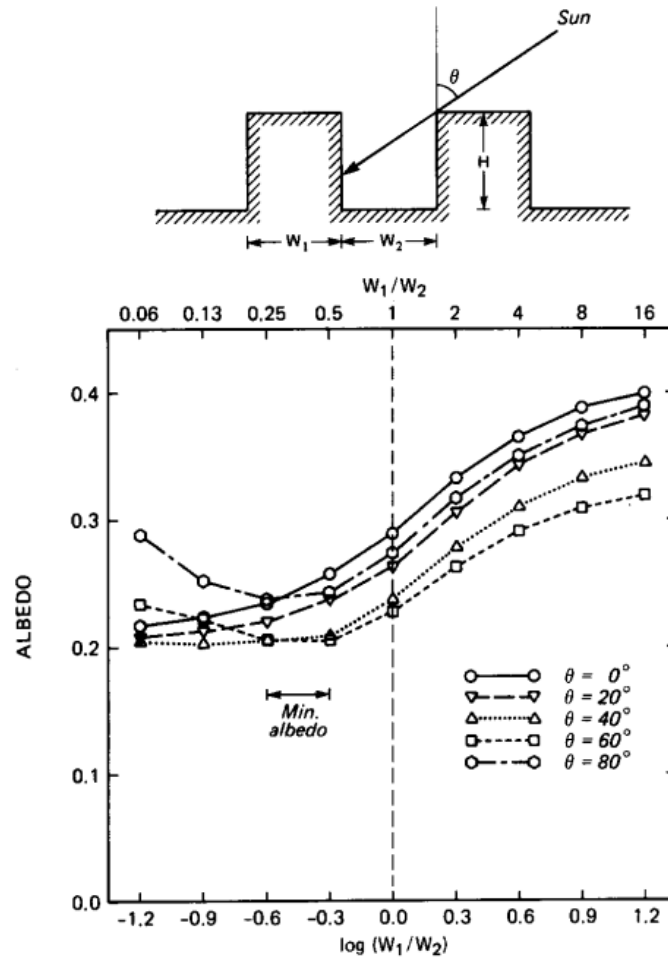


Figure 2-13: Relationship between Urban building geometry and albedo (Oke, 1988).

To understand the relationship between UHI and built density, an experiment was initiated through parametric modelling by Hu, White, and Ding in 2016. Higher built density means lower SVF and higher UHI intensity. Hence floor area ratio (FAR) and SVF were considered for creating different parametric model variables for the experiment. The study concludes that proper distribution of density through proper layout is fundamental for mitigating UHI. Compact urban form with greater SVF and low SVF at local places might also lower the UHI intensity (Hu, White and Ding, 2016).

Farhadi, Faizi and Sanaieian, (2019) found that urban form has a larger impact on UHI mitigation compared to urban vegetation cover. The author concluded these results based on investigating the role of vegetation, urban materials, and orientation of the buildings in Tehran's residential precinct. However, the urban vegetation cover has a greater share of improving thermal comfort. The author also points out that improvement of thermal comfort and UHI mitigation does not have any relationship. Air temperature, SVF, mean radiant

temperature, wind speed, surface temperature, and physiological equivalent temperature were the parameters used for the analysis. Six models, the Base model, Green roof model, Rotation model, Green model, Cool pavement model, and Cool roof model, were created and analysed using ENVI-MET to find their relationship with UHI (Farhadi, Faizi and Sanaieian, 2019).

The urban form of 150 urban areas in the Jing-jin-Ji region, China, were analysed to understand their relationship with UHI intensity. Eight urban form indicators in respect to anthropogenic heat flux, thermal capacity, surface albedo, traffic flow, greenhouse gas emissions, pollutant concentration, aerodynamic roughness, horizontal ventilation, and evapotranspiration were analysed through different numerical methods. These eight indicators fall under three broad classifications, urban size, urban geometry, and urban vegetation. The study results showed that urban size indicators had a strong positive relationship with the UHI intensity, followed by urban geometry (Liang *et al.*, 2020).

Similarly, a neighbourhood scale parametric study was conducted in a residential area of Singapore to investigate the effect of urban morphology on anthropogenic heat dispersion. The computational fluid dynamics (CFD) method was used to validate the parametric study results. The study aimed to support the practices in urban planning to mitigate anthropogenic heat's negative effect on the microclimate (Yuan *et al.*, 2020).

### Chapter 3. FRANCE AND TOULOUSE

Similar to the two examples presented in the literature review Chapter 2, worldwide different cities are trying to produce and visualise climate data to integrate them into the urban planning framework. This includes French cities as well.

Fight against climate change and adaptation to this change, saving fossil fuel resources, control of energy and the production of energy from renewable resources, and reduction of greenhouse gas emissions is one among the eight objectives present in the Town planning code (Article L101-2) of France, introduced in the year 2015 (Republique, 2021). To achieve this objective, MApUCE (Modelling applied to town planning Law: Urban climate and Energy) project was initiated and funded by France research funding agency ANR (National research agency). This project was carried out with the partnership of seven research laboratories and coordinated by CNRM (National centre for Meteorological Research) and LISST (Interdisciplinary Solidarity, Societies, Territories Laboratory) (MApUCE, 2019).

The main aim of this MApUCE project was to produce data and identify methods to improvise the climatic issue integration into French urban policies. The first piece of work, under this project, was to generate urban microclimate, climate, and residential energy consumption quantitative data through numerical simulation and to generate an urban database for the panel of forty cities. Exploration of different methodologies to integrate the generated information into the French legal documents was the second piece of work carried out under this project. Cartographic visualisations of urban and climatic information were part of the second piece of work, and Toulouse was chosen for this exploration (Hidalgo et al, no date).

This thesis is part of the internship program offered at LISST, concentrating on the second section of the MApUCE Project. The objective of this internship is to make the climatic data, produced under MApUCE project, useful for the urban planners and designers to make climate responsive decisions. Since Toulouse was the city chosen to explore different cartographic representations, the same city data was considered for this thesis as well.

This chapter provides an overview of the two-piece of work carried under the MApUCE project and contextualises Toulouse.

### 3.1 Data Generated under MApUCE project:

This subchapter presents the overview of the first section of work carried under MApUCE project, generating climate data and urban database.

#### 3.1.1 Urban database:

In total 64 urban indicators values were generated in three spatial scales, building, block and islet scale. These 64 indicators can be grouped into 5 categories, Number of elements, Surface characteristics, Distance, shape, and others. Apart from this, building typologies and local climatic zone classifications were also prepared. The islet level data, of around 40 cities, can be accessed through this link <http://mapuce.orbisgis.org/#> (Hidalgo et al, no date).



Figure 3-1: The three scales of urban data available (Hidalgo et al, no date)

Figure 3-1 illustrates the three different spatial scales, building, block and islet, also known as spatial reference unit (USR) (Hidalgo et al, no date).

#### 3.1.2 Climate data:

There are two categories of climatic information produced. The first set of climatic information is related to the sequence of meteorological situations, called local weather type classification (LWT). The number of local weather type classification varies for different cities. The second climatic information comes from SURFEX numerical simulation, providing spatialized microclimate data. The numerical simulation provides three pieces of information, thermal stress (UTCI), urban heat island intensity (UHI), and wind information. The summer time

nocturnal UHI data for more than 40 French cities can be accessed through this link <http://mapuce.orbisgis.org/#> (Hidalgo et al, no date).

The numerical simulation produced 8670 maps in total, for each meteorological variable at an hourly time step. A decision was made, by the team of researchers involved in MApUCE project, to analyse only the summer time situation since the climatic issues experienced by French cities are associated to summer season (Hidalgo et al, no date).

### **3.2 Toulouse:**

Toulouse is the sixth largest metropolitan city in France, located in the south western octane region, holding a population of 0.7 million people in 460 sqkm area approximately. Like any other city in the world, Toulouse is also urbanising in a fast rate due to increase in population every year. For the past 20 years, every year more than 8,000 new inhabitants were recorded. To accommodate this population over 170 ha of rural land were converted in to urban lands, from 2007 to 2013 (Shi et al, no date).

Toulouse is located on a relatively flat plane with the elevation numbers ranging from 102m to 273m. Since the city is located on the flat plane and because of its large distance from the sea, the city has a very limited benefit from the valley and sea breeze. The city experiences a degraded oceanic climate, with a daily temperature ranging from 15 deg C to 30 deg C. 40 deg C was the highest recorded temperature during summer season heat wave. The city experiences heat wave frequently. Hence, it is important to understand the climatic and environmental condition of the city, and appropriate planning mitigation measures has to be provided (Shi et al, no date).

Figure 3-2 displays the location of Toulouse in France, and the city's metropolitan region.

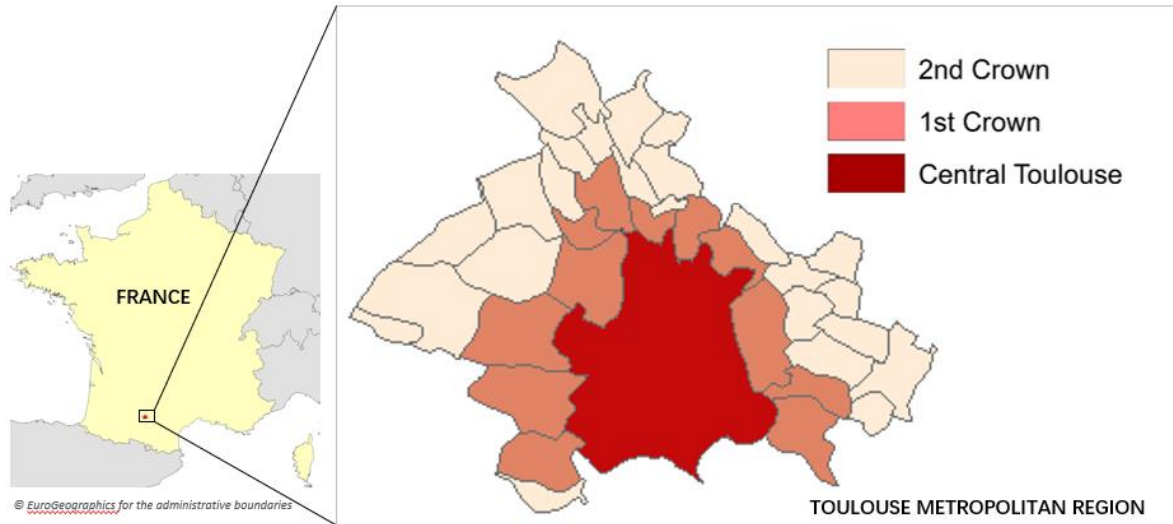


Figure 3-2: Toulouse (Shi et al, no date)

### 3.2.1 Local weather type classification of Toulouse:

The urban climatic studies are often based on stable weather conditions, monthly or annual climate indicators. But depending on the meso-scale weather situation, the depth of the urban boundary layer and thermodynamic properties might vary. Hence, a good understanding of weather situation and climatological context is necessary for a local scale analysis. This gave rise to Local weather type (LWT) classification. Based on the meteorological situation that frequently occurs with similar effects at the atmospheric boundary layer the LWT classification were performed, using the climatic data (Hidalgo and Jouglu, 2018).

For different cities, the number of LWT varies. Toulouse in total has 11 LWTs, the Table 3-1 presents LWT cluster number and their corresponding climatic variables value.

**Table 1. Variable values for the cluster centroids.**

Cluster number	$\Delta T = T_{max} - T_{min}$ (°C)	FF (m.s <sup>-1</sup> )	DD (quadrants)	PP (mm.h <sup>-1</sup> )	q (g.kg <sup>-1</sup> )
0	5.60	1.43	3.7	0.071	5.07
1	7.31	2.59	2.0	0.297	8.42
2	6.19	6.25	2.1	0.016	7.09
3	3.43	4.27	3.9	0.065	5.07
4	6.44	3.13	3.6	1.003	9.42
5	9.75	2.37	1.9	0.012	5.67
6	5.05	4.56	3.7	0.436	7.21
7	11.08	2.62	1.9	0.014	10.45
8	7.23	2.38	3.8	0.089	10.82
9	12.49	1.80	3.8	0.059	7.03
10	4.15	5.01	3.1	1.938	9.03

Diurnal amplitude of air temperature ( $\Delta T$ ) and daily mean values for wind speed (FF), wind direction (DD) expressed in quadrants 1 to 4 for ranges [1–90]; [91–180]; [181–270] and [271–360] respectively direction, precipitation (PP), and specific humidity (q) (adapted from [22])

*Table 3-1: LWT of Toulouse and corresponding climatic variable numbers (Hidalgo and Jougla, 2018)*

The list of LWT condition corresponding to the cluster number, from 0 to 10, is presented in the Table 3-2.

Cluster	Local weather types (LWT)
0	Typical winter day with low rainfall
1	Rainy day with south easterly wind
2	Autan wind day
3	Day with strong north westerly wind typical of intermediate seasons and winter
4	Rainy day
5	Typical sunny winter day with weak south easterly wind
6	Cloud day with strong NW wind and precipitation
7	Typical sunny summer day with weak south easterly wind
8	Typical sunny summer day with westerly-north westerly wind
9	Sunny day, very hot in summer, with north westerly wind
10	Very heavy rain day

*Table 3-2: Local weather type classification of Toulouse (Hidalgo and Jougla, 2018)*

In Figure 3-3 the occurrence frequency of 11 Toulouse LWT and each LWT’s seasonal distribution are explained. Since, 86.7% of LWT 7, 8, and 9 represents summer season, they are considered as summer time LWT of Toulouse (Hidalgo and Jougla, 2018).

LWT 9 was used for the urban climatic study, since it is the hottest summer LWT and Toulouse summer time temperature sometimes rise up to 40 deg C, which is responsible for the heat wave in the city (Shi et al, no date).

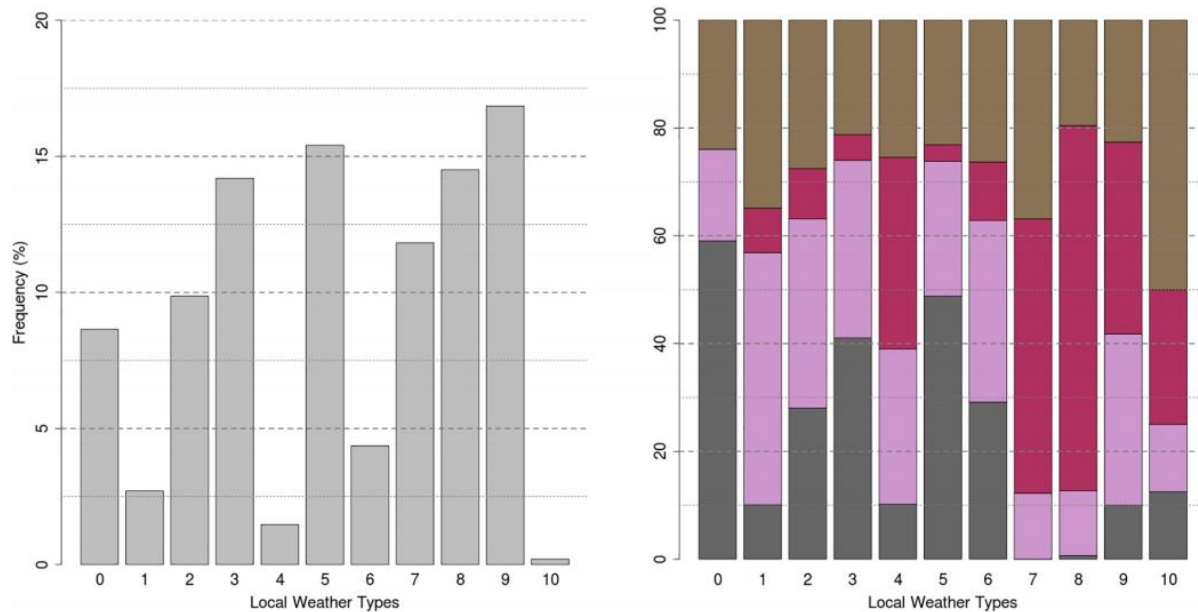


Fig 1. Cluster frequency occurrence in total percentage (left) and per season (right). Spring, summer, autumn and winter seasons are in brown, pink, purple and grey respectively. (adapted from [22]).

Figure 3-3: LWT frequency occurrence per season (Hidalgo and Jouglu, 2018)

### 3.2.2 Urban and climatic data of Toulouse:

This subsection presents the urban and climatic data produced for Toulouse, produced under MApUCE project. This data was used for different cartographic exploration, and the same has been used for this thesis.

#### 3.2.2.1 Toulouse urban data:

As mentioned in Chapter 3.1.1, data for 64 urban indicators at 3 different scales are available. Two vector shape files, building and islet, with attribute values of different urban indicators are available for Toulouse. Appendix 11.1 lists the data available in the islet scale shape file, for more than 40 French cities, including Toulouse. Apart from this, building polygon vector shape file with building height, building area, building typology information etc., is also available for Toulouse.

#### 3.2.2.2 Toulouse climate data:

As mentioned in Chapter 3.1.2, three piece of climatic information is available, thermal stress (UTCI), UHI, and wind information. Since LWT 7, 8, and 9 are the summer LWTs, nocturnal UHI data (3 to 6h local time), day time UTCI data (13 to 16 h local time), and nocturnal wind

velocity ratio (3 to 6 h local time), for these three LWTs are available, in grid point format with 250m horizontal spacing. Each grid point has a meteorological value. The UTCI and UHI values are available at a vertical distance of 2m above ground level. “Thiessen polygon” a saga tool was employed in QGIS to convert the grid points into 250 m x 250m polygons and the polygons within the Toulouse boundary were clipped. These clipped polygon shape file was used for further analysis in this thesis.

Apart from this, hourly UHI (at 2m and 10m vertical heights above ground level) and wind (U and V) values for 24 hours for two typical summer days (ETE1 and ETE2) that represents the three summer LWTs are available. These data were stored in binary R files.

UTCI:

The universal thermal climate index has 10 categories of thermal stress from, extreme heat stress to extreme cold. Each of this 10 categories were further classified into three categories, low, medium, and high, and this modified classification was used for classifying the thermal stress data produced by numerical simulation. The UTCI index categories with their corresponding temperature value and the modified UTCI index, for French cities, and their corresponding temperature values are presented in the Figure 3-4.

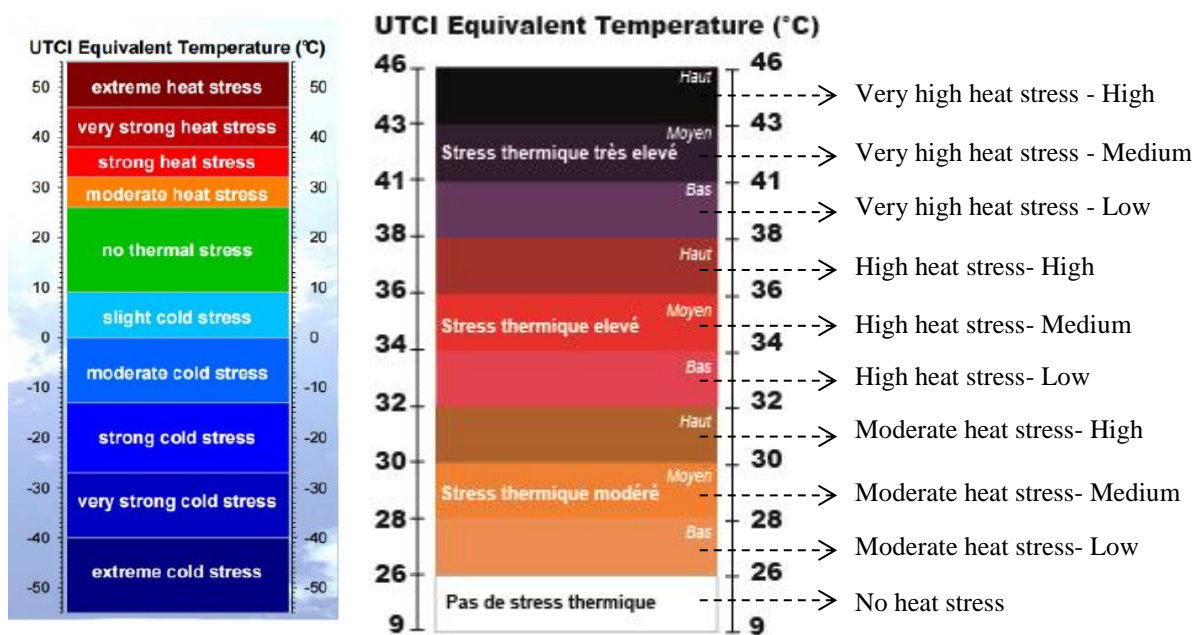
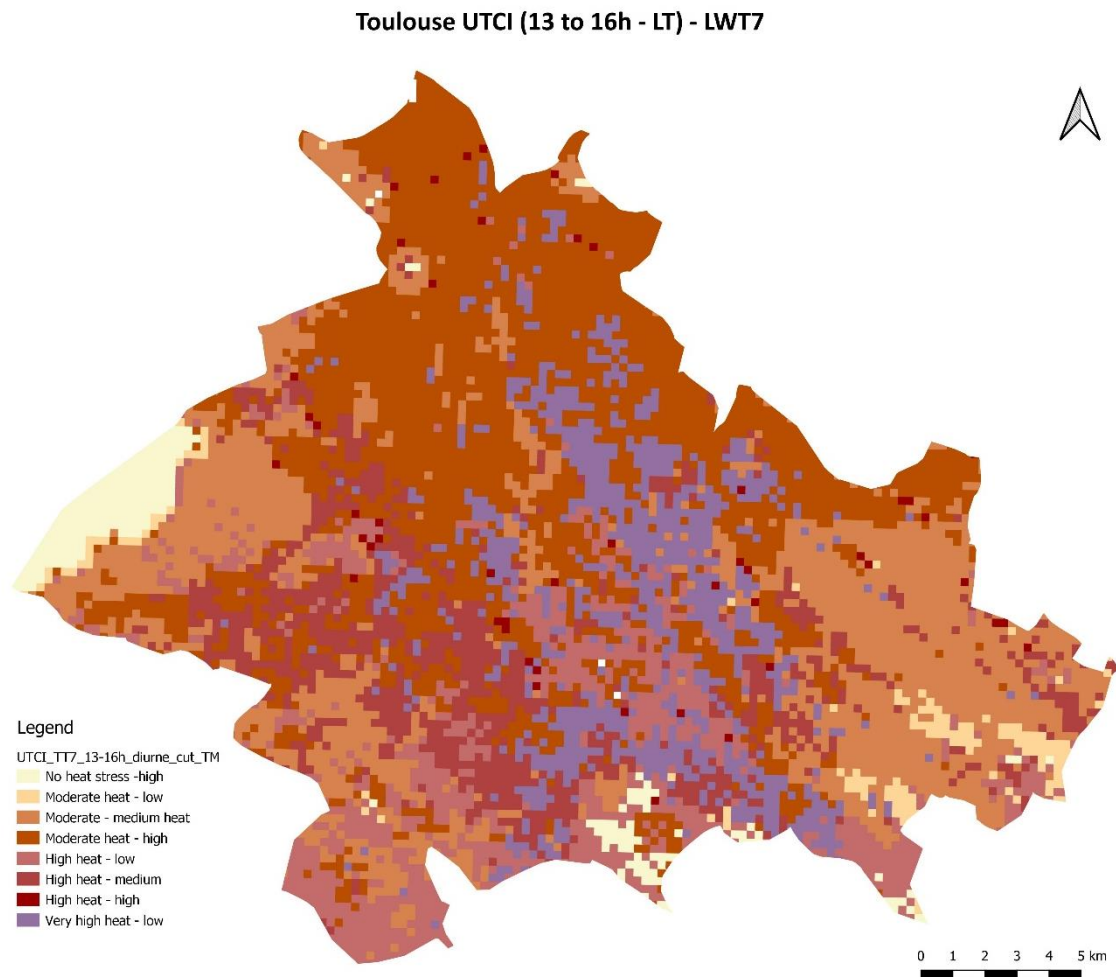


Figure 3-4 : UTCI classification. The classification used for MApUCE project is on the right

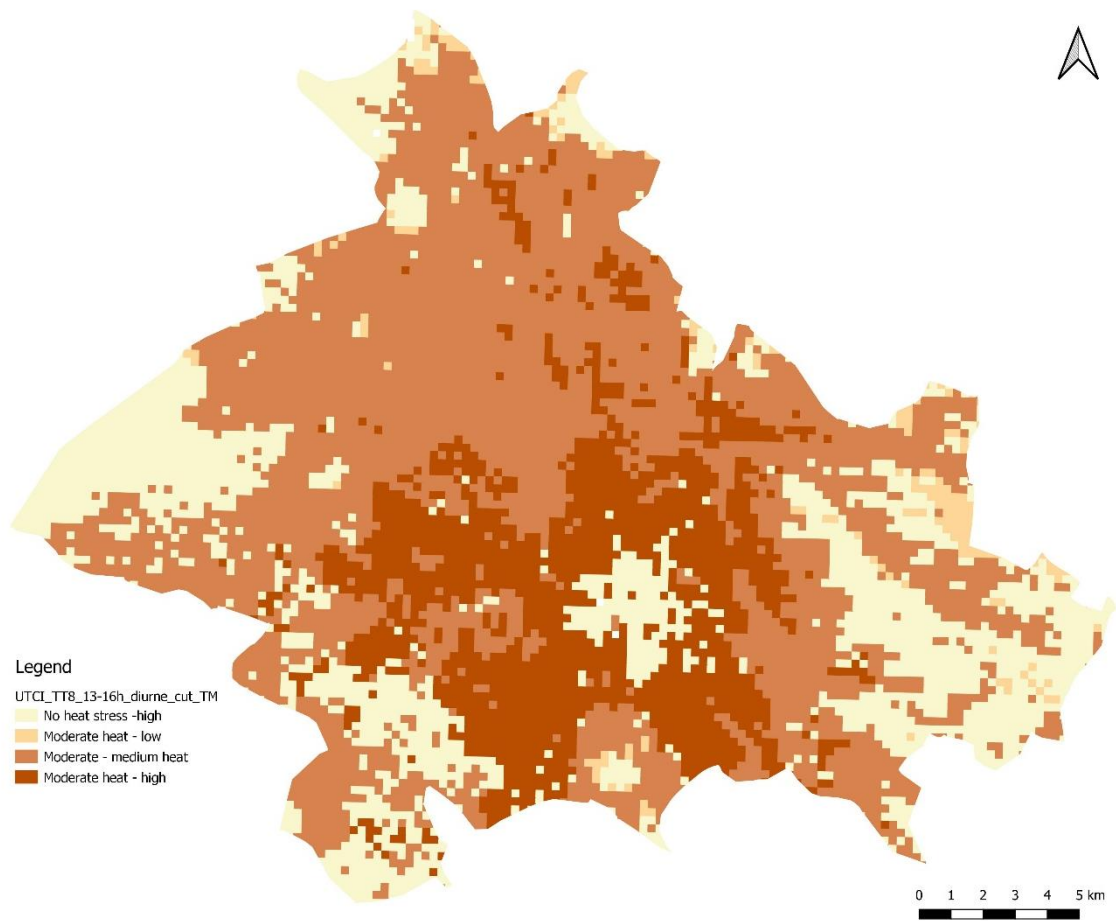
The three maps below Map 3-1, Map 3-2, and Map 3-3 Illustrates Toulouse's LWT 7, 8, and 9, day time thermal stress (UTCI) values respectively. All the three maps are in 250m X 250m horizontal resolution.



*Map 3-1: LWT 7 UTCI data*

Under LWT 7 weather condition, some areas around the city centre experience low level – very high thermal stress, corresponds to 38 deg C to 41 deg C. The northern area of the city majorly experience high - moderate thermal stress and the eastern areas experience medium – moderate heat stress. Medium – High thermal stress and Low- High thermal stress is experienced by city centre and some western areas respectively. No thermal stress was recorded in very less areas near the metropolitan boundary.

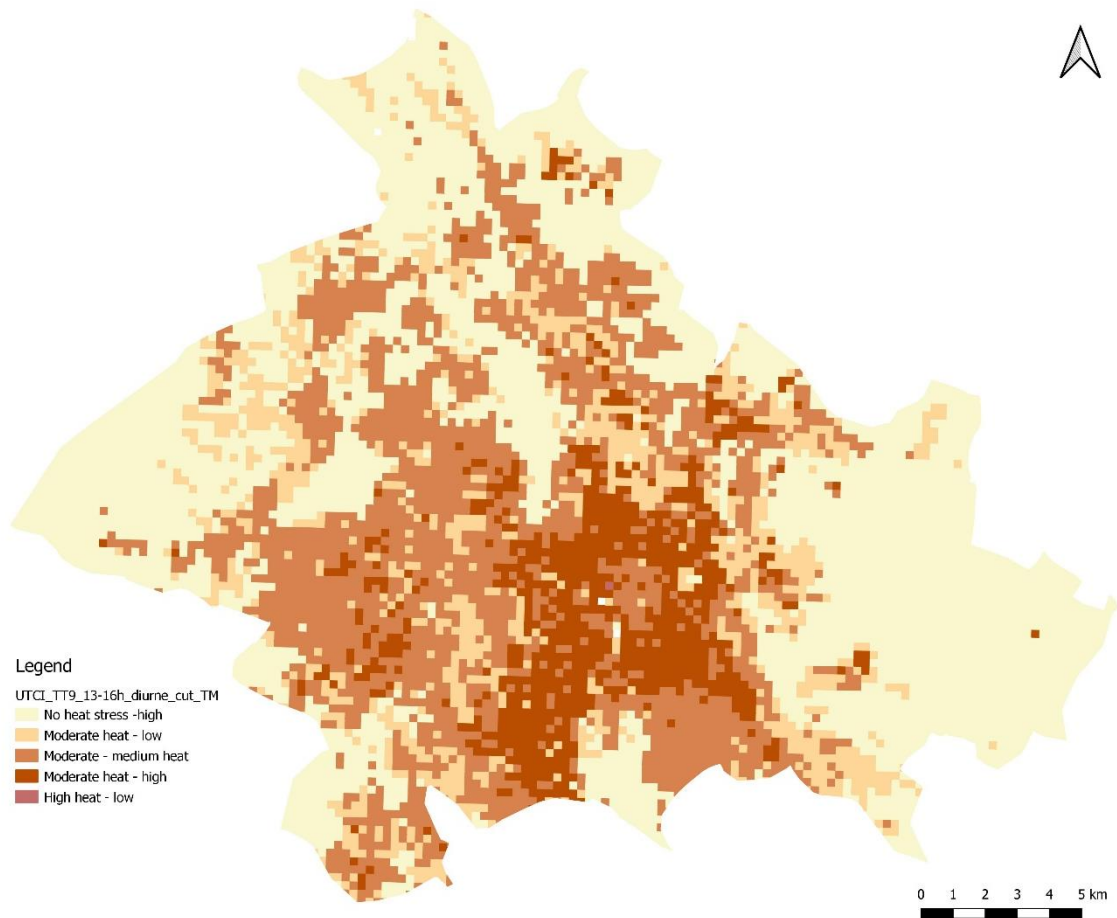
### Toulouse UTCI (13 to 16h - LT) - LWT8



*Map 3-2: LWT 8 UTCI data*

Under LWT 8 weather condition, no thermal stress was recorded in the city centre and in some areas near the metropolitan boundary. The surrounding areas of the city centre experience high – Moderate thermal stress and the area around it experience medium – moderate thermal stress. Overall majority of the Toulouse areas experiences Medium – moderate thermal stress under LWT 8 weather condition.

### Toulouse UTCI (13 to 16h - LT) - LWT9



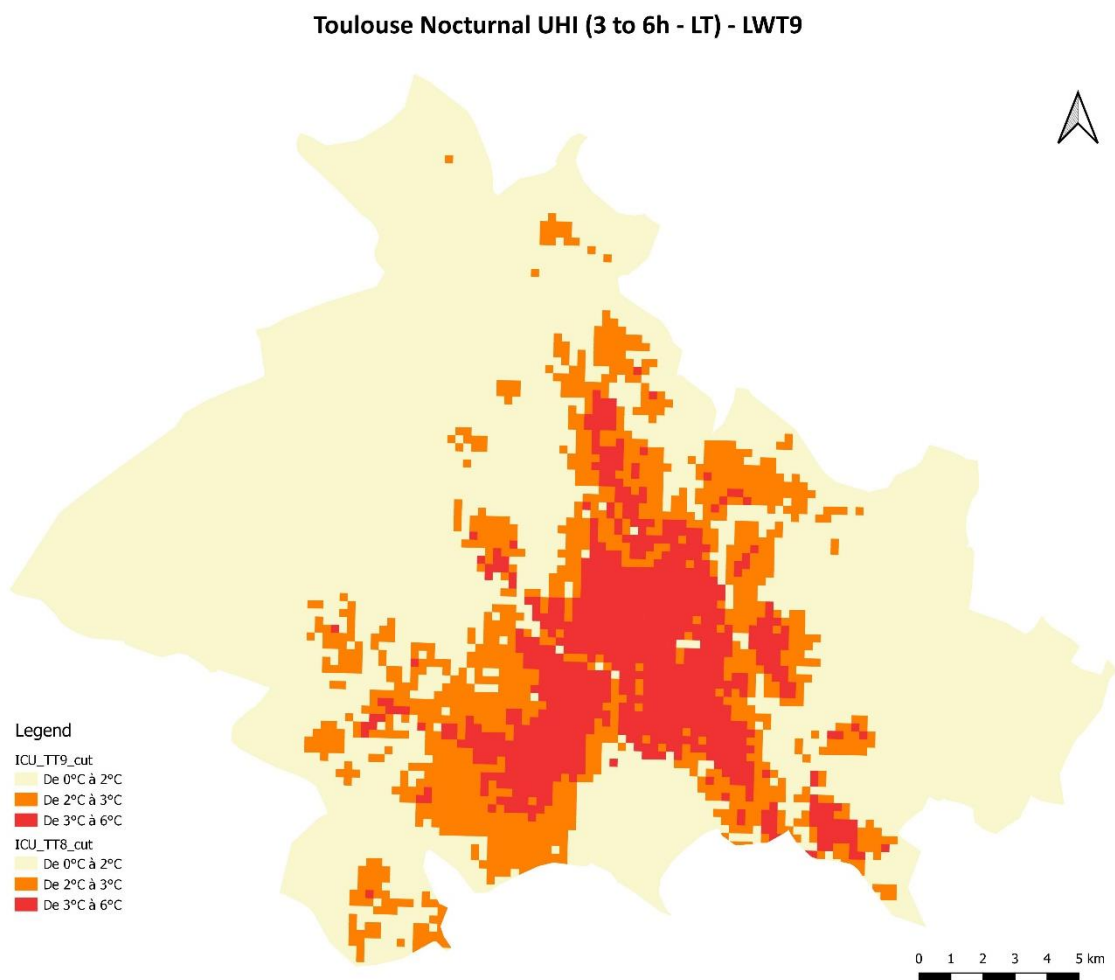
*Map 3-3: LWT 9 UTCI data*

Although LWT 9 is classified a very hot summer weather type, majority of the area experience no thermal stress. Including city centre and some more areas experience a Medium – moderate thermal stress and the areas around the city centre experiences a high – moderate thermal stress.

Overall the numerical simulated results states that, Toulouse experiences higher thermal stress under LWT 7 weather condition compare to the other two summer LWT 8 and LWT 9.

UHI:

Map 3-4 illustrates nocturnal UHI of Toulouse under LWT 9 weather condition. Among all the three summer LWTs, LWT 9 is described as very hot summer weather type. The nocturnal UHI value in this weather condition raises up to 6 deg C in the city centre and in its surrounding areas. The orange areas, with UHI number 2 deg C to 3 deg C, are described as switchover zones. These areas quickly switches to higher exposure levels (Hidalgo et al, no date). The Nocturnal UHI value of remaining areas are between 0 deg C to 2 deg C.

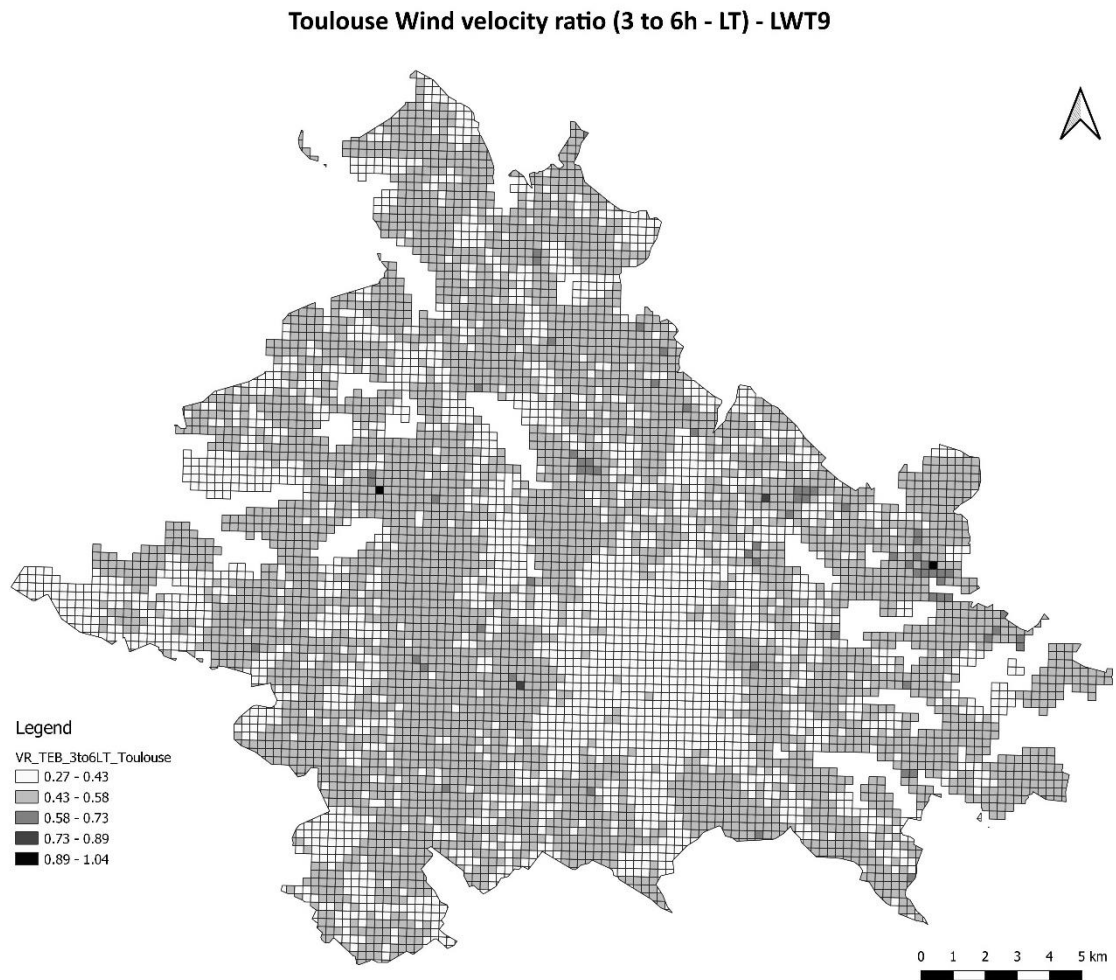


Map 3-4: Nocturnal UHI data

Wind velocity ratio:

The ratio between the wind speed at the pedestrian level (2m) and a reference point at roof level is described as wind velocity ratio. Wind velocity ratio is commonly used meteorological parameter for climatic studies.

Map 3-5 illustrates the nocturnal wind velocity ratio of Toulouse, under LWT 9 weather condition. As it can be noticed the city centre, where the nocturnal UHI value increases upto 6 deg C, has very less wind velocity ratio compare to the surrounding areas.



Map 3-5 : Wind velocity data

## Chapter 4. RESEARCH APPROACH:

This chapter presents the research approach and philosophical stand taken to answer the question, identified through literature review in Chapter 2. Followed by the explanation of different research phases and a methodological overview.

### 4.1 Research Design:

Different research choices made to conduct this research are underlined in red colour on the research onion developed by Saunders, Lewis and Thornhill (2011) (Figure 4-1).

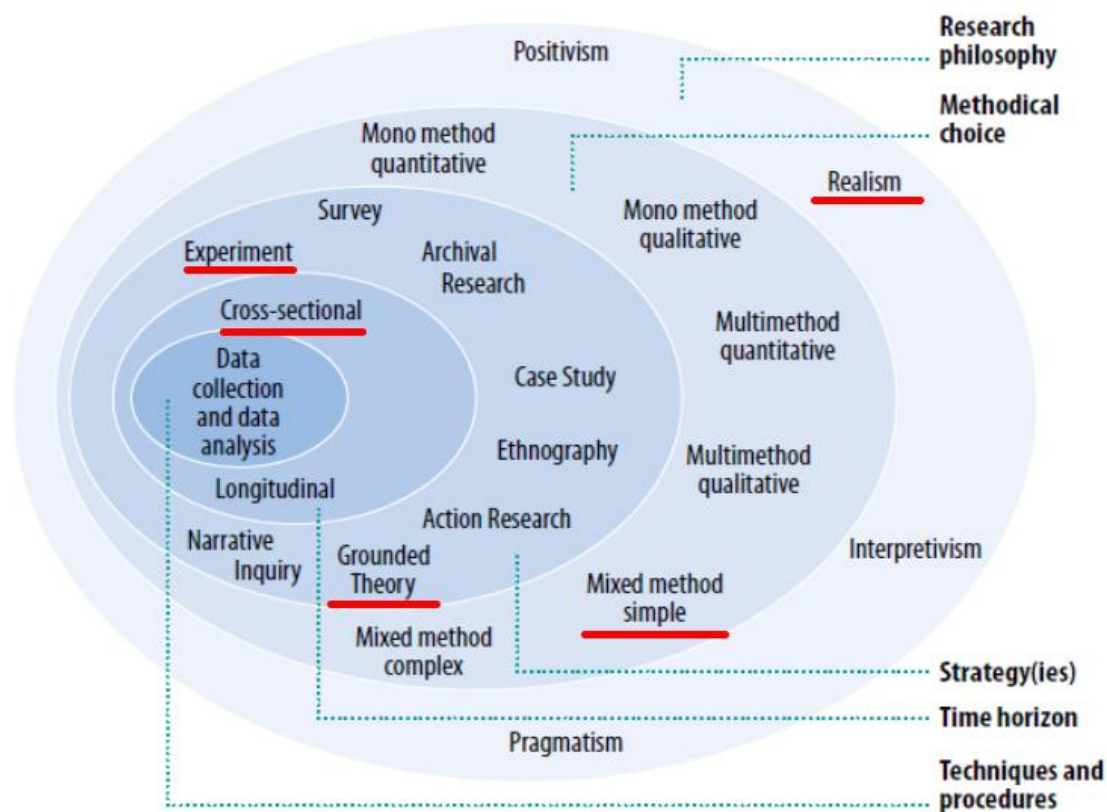


Figure 4-1: Research onion (Saunders, Lewis and Thornhill, 2011). Different research choices of this thesis are underlined in red

This research is trying to strengthen the fragile bridge of cartographic representation, to connect the scientific and practical world by answering the two questions identified in Chapter 2. This thesis aims to showcase an approach to construct an urban climatic map for the urban planning and urban design community for climatic responsive decisions. Therefore this research thesis demonstrates a “Realism” research philosophical stand.

Parameters shape the urban climatic map outcome and its creation process (Chapter 2). To answer the two research questions, it is essential to identify the parameters first. Therefore, this thesis travels from an inductive to deductive research approach. A “Sequential exploratory design – Mixed method” methodology was followed, where qualitative research further leads to quantitative research. Parameters are identified first, followed by urban climatic map creation.

## **4.2 Different Research Phases and their methodology overview:**

To fulfil the identified research gap, the thesis was conducted in three phases. The first phase was the qualitative research phase, and the other two phases were the quantitative research phases.

In the first phase, literature study, interview, and case study were the three techniques followed to identify the parameters to build the urban climatic maps. For the second phase of the research, different QGIS and ArcGIS tools were explored to calculate the parameters using the MApUCE data and data collected from other sources. In the last phase, a geographically weighted regression (GWR) analysis method was used to analyse the relationship between the identified parameters and various meteorological variables. This provided some useful information for the urban planning and urban design community. ArcGIS was used for the third phase of this thesis.

Objectives 2, 3, and 4 were achieved through Phases 1, 2, and 3, respectively. A detailed explanation of the three phases of this research is presented in the following subsections.

Figure 4-2 presents a methodological overview of this thesis, and Table 4-1 explains different research strategies, methodological choices, and techniques and procedures applied in the three phases.

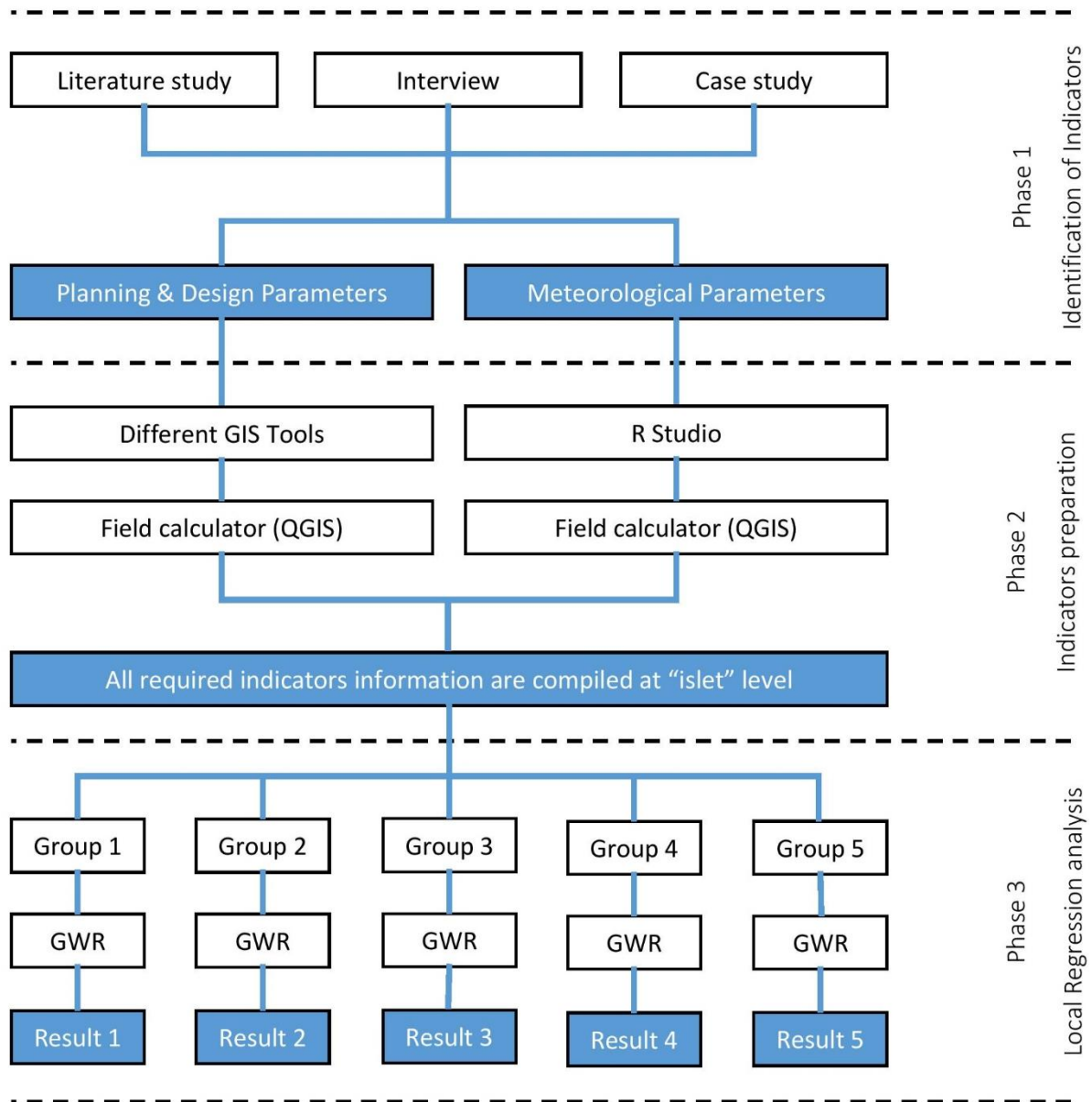


Figure 4-2: Thesis methodology (Author)

	Phase 1	Phase 2	Phase 3
<b>Research Strategies</b>	Grounded theory	Experiment using QGIS and ArcGIS	Experiment Using ArcGIS
<b>Methodological Choices</b>	Qualitative	Quantitative	Quantitative
<b>Techniques and procedures</b>	Literature study, Interviews, and International case study (Random sampling)	GIS	Geographical weighted regression analysis (Local regression)

Table 4-1: Research strategies, Methodological choices, and techniques and procedures (Author)

#### **4.2.1 Phase 1 - Identification of Urban climatic map parameters**

As mentioned in Figure 2-1, to create urban climatic maps, analytical maps of climatic elements, geographical terrain information, and greenery & planning parameters are required. Since this thesis is focused on producing urban climatic maps for climate-responsive urban planning and urban design decision making, the identified parameters are classified as meteorological parameters and urban planning & urban design parameters. These can also be called meteorological and urban planning & urban design indicators. Literature study, interviews with urban professionals, and international case studies on urban climatic maps are the three qualitative methods chosen to identify the indicators.

Most of the urban climatic maps are not providing sufficient information in the language understandable by the urban planning and urban design professionals. To overcome this issue, it is very much important to explain the causes of the climatic issues through urban planning and urban design elements (Chapter 2). To better understand the causes of the climatic issues and their relationship with urban planning and urban design elements, literature on the causes were referred.

As the thesis is trying to provide some useful information to the practical world, it is also important to understand some climate-sensitive urban planning and urban design practices. Interviewing the urban professionals involved in climate responsive practices will help to identify the linkage between various urban planning & urban design elements and the climatic issues. Interviews will also help to identify the requirements of the urban planning and urban design professionals since they are the target group of this thesis.

To understand the urban climatic map creation process better, urban climatic maps of different cities worldwide are studied. Indicators related to urban planning and urban design elements from these case studies were also included in the indicators list, prepared on the basis of literature study and interviews.

A detailed methodology and the results of Phase 1 are presented in Chapter 5.

#### **4.2.2 Phase 2 – Preparing the indicators for analysis**

Two scales of urban climatic maps were already available for Toulouse. Hence, an islet scale analysis was conducted for this thesis (Chapter 3). The islet scale analysis is extremely relevant since this thesis links different urban elements with various meteorological indicators through urban climatic maps. Since the configuration of different urban elements within an urban block creates a distinctive microclimate that contributes to the overall climatic issue (Chapter 2), islet level analytical information will help urban planners and designers to propose mitigation strategies for each urban block. However, the MApUCE project provides urban data at three different scales and climatic data at 250m horizontal resolution. Therefore, all the required information has to be transferred to islet polygons to perform islet level analysis.

While studying the urban climatic map creation processes worldwide in the first phase of this thesis, it was noticed that some indicators were combined and related with the meteorological variables to provide a better understanding. And although a rich urban database and climatic data are available under the MApUCE project, some of the identified indicators information is either unavailable or they have to be calculated using the available data.

Hence, in this second phase, different studies were referred to find appropriate GIS tools and methods to combine the necessary indicators and to calculate some of the identified indicators using the available data. Some alternatives were also explored to replace certain indicators that do not have any data or are difficult to calculate. It was made sure that all the required information was generated in the islet polygons.

A detailed methodology and the results of Phase 2 are presented in Chapter 6.

### **4.2.3 Phase 3 – Relationship between meteorological indicators and urban planning & urban design indicators**

There are various approaches to generate the urban climatic maps. Many studies, including Toulouse, have tried to identify different Climatopes, to provide planning recommendations. Although this gives a general overview of the climatic issue in a particular area and their intensity, detailed relationship information between the variables seems missing. To understand the reason behind the climatic issue, it is important to provide information about the relationships between different variables. This helps the urban planners and designers to identify appropriate mitigation strategies (Chapter 2).

Correlation techniques and statistical regression were generally used to understand the relationship between two variables. One of the well-known statistical regression methods is Ordinary Least Squares (OLS) global regression. But the spatial relationship in this global model is ignored. It is assumed that the relationship between the two variables is constant in the entire study area. Hence, a Geographically Weighted Regression (GWR) analysis was performed using ArcGIS in this thesis. GWR is a local regression model that has higher explanatory powers. Using GWR, the spatial heterogeneity of the statistical regression can be explored. Different urban climatic studies have acknowledged that GWR provides better results compared to the OLS.

While referring to the different urban climatic mapping processes, in the first phase, it was noticed that certain identified indicators were analysed only with certain meteorological variables. And also, since not all the identified indicators data were available, some alternative data from different sources were acquired and processed during the second phase of this thesis. Considering these two aspects, the indicators were grouped into five groups. Each group has dependent and independent variables, and a local regression analysis was performed for each group separately.

A detailed methodology and the results of phase 3 are presented in Chapter 7.

## **Chapter 5. LIST OF URBAN CLIMATIC MAP INDICATORS**

This chapter presents phase 1 of this research thesis in detail. It explains the qualitative research conducted to identify the urban climatic map indicators for urban planning and urban design climate responsive decisions. This chapter also provides a detailed explanation of the link between the identified indicators and their relationship with climatic elements.

To understand the causes of UHI, the book “Heat Island – Understanding and mitigating heat in urban areas” authored by Lisa Gartland was referred. This book was chosen for the literature study since it provides a concise summary of the UHI causes. In this book, Gartland also explains the relationship between the UHI causes and the urban planning & urban design elements.

Under the MApUCE project, a report on the best climate responsive urban planning and urban design practices was prepared, based on grey literature, city network exploration, and interviews of urban professionals involved in the best projects. Since the thoughts and reflections of the urban planning and urban design professionals are already summarised in this report, this report was referred instead of performing interviews again. Since this report presents the best urban planning and urban design climate responsive practices of French cities, it also helped to understand the climatic issues of cities in France.

Edward Nd and Chao Ren edited a book called “The urban climatic Map – A method for sustainable urban planning” in the year 2015. This book is composed of different urban climatic map summaries of various cities worldwide. These summaries explain the process followed to build the climatic maps and the indicators used in the creating process. Along with this book, few other Journal articles related to urban climate maps were also referred to understand the process of urban climatic map making. The seminar series, organised by the LISST laboratories, on “Urban climate appliances to urban planning” also helped to understand the urban climatic mapping process. Different researchers from different parts of the world were invited to this seminar to present their urban climatic research approaches and results.

## 5.1 Literature study:

In the book “Heat island – understanding and mitigating heat in urban areas”, Lisa Gartland mentions there are five causes for the UHI. They are reduced evaporation, Increased heat storage, Increased net radiation, reduced convection, and increased anthropogenic heat. These five causes are associated with seven urban planning and urban design elements. They are vegetation, impermeable surfaces, thermal diffusivity of materials, solar reflectance, urban geometry, air pollution, and energy use (Gartland, 2008).

According to Lisa Gartland, reduced evapotranspiration is due to lack of vegetation in the urban areas and due to widespread use of impermeable surfaces. Higher the urban material’s thermal diffusivity number, the higher the heat storage. Net Radiation increases when solar reflectance of the urban materials is less and when the air pollution level increases. Urban geometry is also responsible for the increased net radiation because it traps heat. Urban geometry also slows the wind speed and becomes responsible for reduced convection. Increase anthropogenic heat is due to the increased energy use. However, the mentioned urban planning and urban design elements are interlinked (Gartland, 2008).

The Figure 5-1 illustrates the causes of UHI.

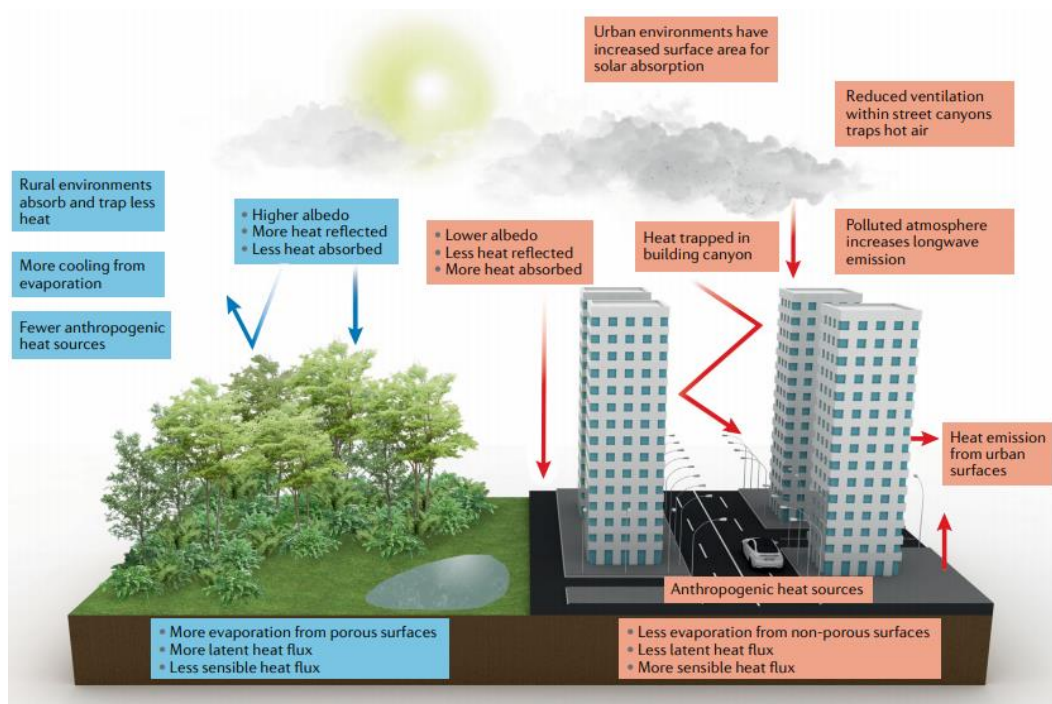


Figure 5-1 Causes of UHI effect. Warming and cooling mechanisms are indicated in red and blue coloured boxes respectively (Wong N.H., Tan C.L., 2021)

## 5.2 Best Climate responsive urban planning and urban design practices report:

Six French cities, four cities for their best climatic responsive urban planning practice and two cities for their best climate responsive urban design practice were identified to develop the best practices report under the MApUCE project. One report for each city was prepared, describing the climatic issues faced, method of analysis, tools used for the analysis and policy, and design decisions made to overcome the identified issues. The six reports also explain the urban planning and urban design elements used in the analytical process. Since these reports were in French, they were translated using ‘Google translator’ and then summarised to identify the indicators.

A summary table was prepared, containing the list of actions taken to mitigate climatic issues in the six projects and the list of parameters used in the process. This table was used to identify different indicators relevant to this thesis. The summary table can be found in the Appendix 11.2.

## 5.3 International case study:

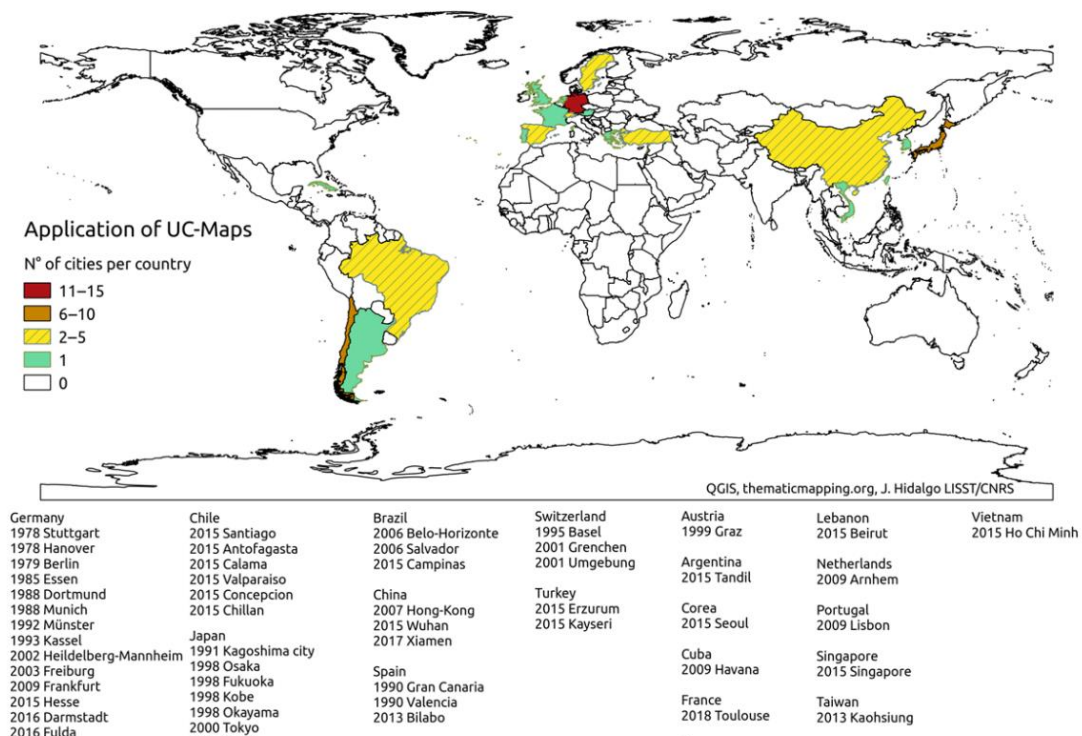


Figure 5-2: Urban climatic map studies in 2018 (Hidalgo, Lemonsu and Masson, 2018).

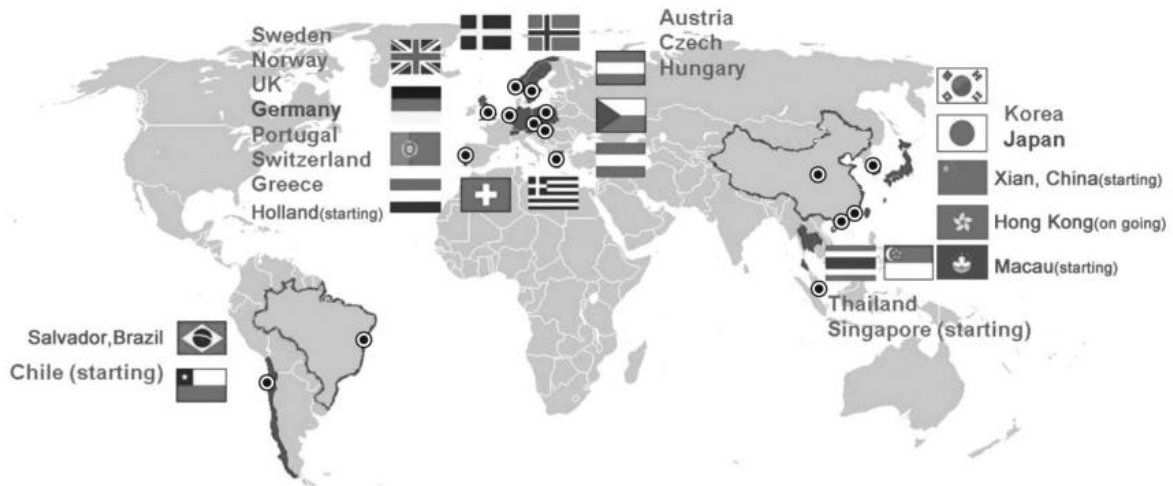


Figure 5-3: Urban climatic map studies around the world (Ng and Ren, 2015).

Depending on the climatic issue in the city and its context, different cities worldwide used different parameters to generate UC-Maps. In total, 77 cities in 29 countries conducted urban climatic map studies. Figure 5-2 and Figure 5-3 by Hidalgo et al (2019) and Ng et al (2015) respectively illustrate different countries, which performed the urban climatic map studies. Out of 77 cities, the summary of 23 cities (as shown in Table 5-1) is available in the book “The urban climatic Map – A method for sustainable urban planning”, edited by Edward Nd and Chao Ren (2015).

1. Tokyo, Japan	2. Yokohama, Japan	3. Beijing, China	4. Saka in Osaka, Japan
5. Ho Chi Minh city, Vietnam	6. Wuhan, China	7. Hong Kong, China	8. Hesse, Germany
9. Singapore	10. Salvador, Brazil	11. Berlin, Germany	12. Kaohsiung, Taiwan
13. Lisbon, Portugal	14. Campinas, Brazil	15. Frankfurt, Germany	16. Birmingham, UK
17. Greater Manchester, UK	18. Sendai, Japan	19. Stuttgart, Germany	20. Bilbao, Spain
21. Gothenburg, Sweden	22. Arnhem, Netherlands	23. Freiburg, Germany	

Table 5-1: The cities UC-Map information present in the book (Author)

12 cities were randomly chosen, and an in-depth study was conducted to understand the process, method of approach, and the indicators/parameters used to prepare the urban climatic maps.

An analysis table was prepared, with a list of parameters used by different randomly chosen cities and a summary of the process used to generate urban climatic maps, the same is attached to the appendix 11.3 for reference. This table was used to identify indicators appropriate for this thesis.

## **5.4 Urban climatic map indicators:**

Based on the three qualitative research methods, literature study, interview (Best practices report), and case studies, 19 indicators were identified, in total, and they were categorised as meteorological and urban planning & urban design indicators.

This section, is the result section of the first phase of research, introduces the identified indicators and provides a summary of each indicator based on the knowledge gained through the qualitative research process. The summary of the indicators helps to understand why these indicators are important and why they should be considered in the urban climatic maps. Under each indicator, a table presenting the overview of the indicators in the referred books and documents.

This chapter of the thesis can be used as a reference by urban planners and designers who do not have any prior knowledge about climate issues. Using this chapter as a guide will help planners and designers to think about various UHI mitigation strategies.

### **5.4.1 Meteorological indicators:**

Most of the referred urban climatic mapping processes considered the meteorological variables under two broader aspects, thermal load and dynamic potential. Thermal load is related to the heat intensity at a particular place, and dynamic potential is related to wind information to evaluate the ventilation potential of the place. This section of the chapter introduces and describes different meteorological indicators, recommended by the referred literature, considered in the best climate-responsive French practices, and used by the referred cities in their urban climatic maps.

### 5.4.1.1 Near surface temperature / UHI:

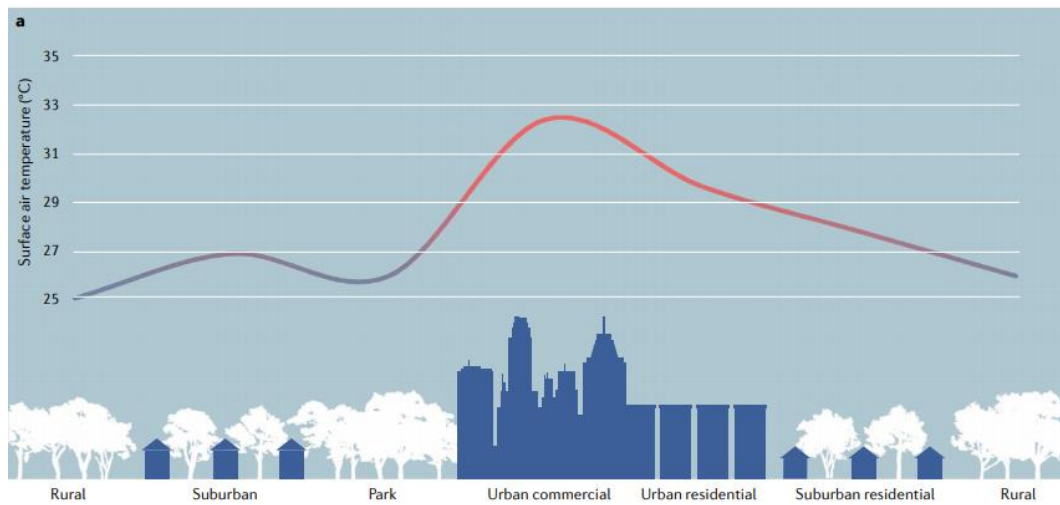


Figure 5-4: Urban heat island effect, built-up areas with high air temperature compared to the rural areas (Wong N.H., Tan C.L., 2021).

Near surface temperature data is necessary to assess the thermal load of the studied place. Among the referred urban climatic maps, some cities considered near surface temperature, and few others considered the UHI data (Table 5-2). However, both the data provides the same information. The difference in near surface air temperature in the urban and the surrounding rural areas is known as UHI. The near surface air temperature is always higher in urban areas (Figure 5-4).

Literature	Best practices (France)	International case study
Reduced evaporation, Increased heat storage, Increased net radiation, reduced convection, and increased anthropogenic heat are the five causes of UHI.	<ul style="list-style-type: none"> <li>• <b>Frontignan:</b> UHI is one of the climatic phenomenon studied for an urban redevelopment</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Tokyo, Japan:</b> Surface temperature is one of the parameter considered to identify the places with high and low thermal loads.</li> <li>• <b>Osaka, Japan:</b> Land use were categorised based on the surface temperature change pattern to provide recommendation through UC-ReMap.</li> <li>• <b>Yokohama, Japan :</b> Temperature is one of the Meteorological parameter considered in the UC-Maps</li> <li>• <b>Hong Kong:</b> Air temperature data was used to analyse thermal load.</li> <li>• <b>Beijing, China :</b> UHI data was used to identify areas affected by it.</li> </ul>

Table 5-2: Temperature/UHI overview, in the referred books and documents (Author).

### 5.4.1.2 Wind speed, Wind direction and Wind velocity ratio:

Wind speed, wind direction, and wind velocity ratio are three indicators considered by various referred studies to analyse the dynamic potential of the city (Table 5-3). Lower the wind speed, the higher the UHI intensity (Gartland, 2008).

Literature	Best practices (France)	International case study
<p>Reduced convection is one among the five causes of UHI. Slow wind speed reduces convection.</p>	<ul style="list-style-type: none"> <li>• <u>Agen</u>: Prevailing winds were overlooked to develop urban planning policies and guidelines for mitigating energy and climatic issues.</li> <li>• <u>Frontignan</u>: Aerodynamic turbulence is one of the climatic phenomenon studied for an urban redevelopment. Prevailing winds were studied to protect the site from climatic issues.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Yokohama, Japan</u>: Wind direction was considered in the UC-Maps to provide three pieces of recommendation; two among them were related to dynamic potential.</li> <li>• <u>Osaka, Japan</u>: Wind data was used to provide recommendations related to water channel restoration, green area conservation, areas where the sea breezes can be used, reducing anthropogenic heat release, and also to identify areas with psychological feeling of coolness.</li> <li>• <u>Ho Chi Minh city, Vietnam</u>: Roughness to wind speed was analysed through UC-Maps for air quality improvement.</li> <li>• <u>Hong Kong</u>: Wind speed, wind direction, and wind velocity ratio was considered in the UC-Maps for air ventilation assessment.</li> <li>• <u>Hesse, Germany</u>: Wind meteorological information was considered to generate air channel map.</li> <li>• <u>Singapore</u>: Wind meteorological information was considered to identify fresh and cool air production zones.</li> <li>• <u>Arnhem, Netherlands</u>: Wind meteorological information was overlapped with topography and urban morphology to build UC-AnMap.</li> <li>• <u>Salvador, Brazil</u>: Wind speed is one among the three charts that were used to create UC-Maps.</li> </ul>

Table 5-3: Wind speed, Wind direction, and Wind velocity ratio overview, in the referred books and documents (Author).

## 5.4.2 Urban planning and Urban design indicators:

This section of the chapter introduces and describes different urban planning and urban design indicators, recommended by the referred literature, considered in the best climate-responsive French practices, and used by the referred cities in their urban climatic maps.

### 5.4.2.1 Vegetation:

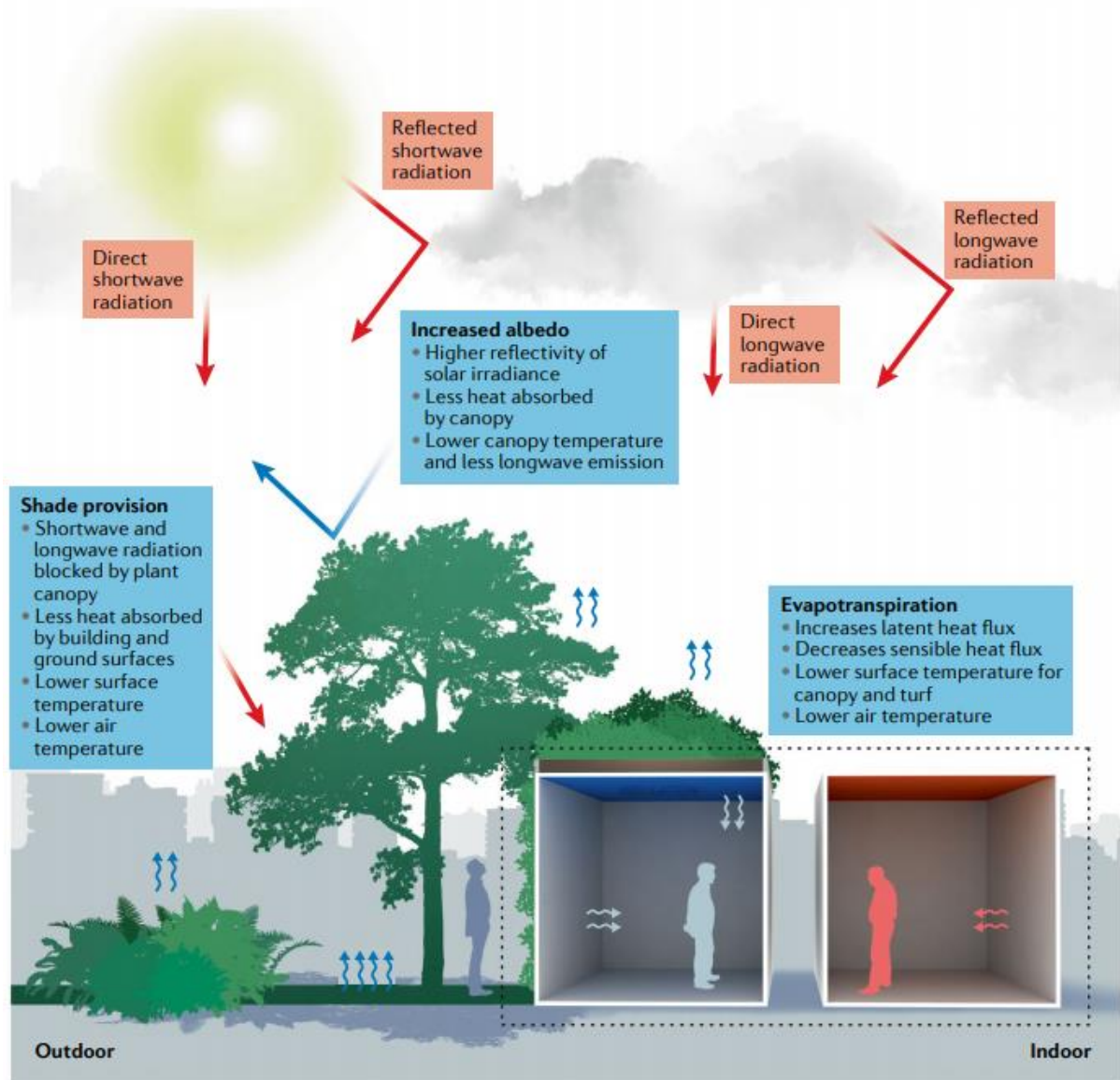


Figure 5-5: Benefits of urban Vegetation (Wong N.H., Tan C.L., 2021).

Compare to natural vegetated surfaces man-made surfaces absorb more heat. The least vegetated surfaces are the hottest due to a reduction in evaporation and evapotranspiration. On

the other hand, more soil moisture, higher wind speed and warm dry air tend to increase evaporation and evapotranspiration (Gartland, 2008).

Grass, bush and trees in an urban setup have many positive benefits such as decreasing air pollution, removing carbon dioxide, decreasing stormwater run-off, reducing building energy use, improving the outdoor thermal comfort and more. Trees around the building reduce the air temperature, which is the most summertime beneficiary (Gartland, 2008). Different benefits of vegetation in an urban area are illustrated in Figure 5-5.

Based on the purposes, the referred studies had analysed vegetation differently. Table 5-4 provides an overview of various referred studies that analysed vegetation with climatic variables. Similarly, cities Antwerp and Gdansk included ‘tall vegetation area density’ in their air quality management study (Badach *et al.*, 2020).

Literature	Best practices (France)	International case study
Lack of vegetation reduces evaporation. Reduced evaporation is one of the causes of UHI.	<ul style="list-style-type: none"> <li>• Included in all the six practices</li> <li>• <u>Lyon, Grenoble, and Agen</u>: Introduced different Vegetation strategies, guidelines, polices to mitigate UHI.</li> <li>• <u>Euromediterranee</u>: Qualification of vegetation (Sustainable concept)</li> <li>• <u>Frontignan</u>: Vegetation was included in both thermal and aerodynamic analytical studies (Urban renewal project)</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Ho Chi Minh City, Vietnam</u>: Integrated green spaces with the heat budget</li> <li>• <u>Hong Kong</u>: Green spaces and natural landscapes are the two parameters included in Thermal load and dynamic potential maps, respectively.</li> <li>• <u>Singapore</u>: Urban green information through satellite images and was included in the thermal load aspects.</li> <li>• <u>Salvador, Brazil</u>: Nine Land-use patterns identified based on building height, building density and vegetation cover, were used along with topography and wind speed to explain different levels of thermal load and dynamic potential.</li> </ul>

Table 5-4: Vegetation overview, in the referred books and documents (Author).

This indicator can be analysed with different meteorological variables such as air temperature, UHI, wind speed, and wind velocity ratio. Vegetation can also be related to other indicators such as building energy use, air pollution, and thermal comfort to understand its contribution to the climatic issue. Based on the analytical results, appropriate mitigation strategies can be decided.

### 5.4.2.2 Thermal diffusivity:

Urban materials store heat. Higher the thermal diffusivity of the material, the higher the heat storage. Thermal conductivity divided by heat capacity is Known as thermal diffusivity (Gartland, 2008).

Materials with higher thermal conductivity number transfer heat at a higher rate, and materials with higher heat capacity will store more heat. Higher heat store will lead to an increase in the material temperature. It takes a longer time to cool if the materials thermal diffusivity number is high since heat stays in the material for a longer time, and vice versa. The higher the temperature of the material, the higher the heat energy it emits to its surroundings (Gartland, 2008).

Except for two French cities, no other referred studies have considered the material properties in the urban climatic studies (Table 5-5).

Literature	Best practices (France)	International case study
Increased thermal diffusivity of the material leads to Increased heat storage. Increased heat storage is one of the causes of UHI.	<ul style="list-style-type: none"> <li>• <u>Paris and Agen</u>: Introduced strategies, guidelines, polices related to material change to mitigate UHI.</li> </ul>	None of the referred UC-Map studies have considered this indicator

Table 5-5: Thermal diffusivity overview, in the referred books and documents (Author).

The thermal diffusivity of the material also depends on the amount of radiation the material receives. Hence, the thermal diffusivity value of a particular area can be related to the sky view factor (SVF) and shadow pattern. Analysing the thermal diffusivity value of a particular area with air temperature or UHI values and also with other non-meteorological indicators (SVF and shadow) will provide an understanding of its contribution to the climatic issue to the urban planners and designers. This helps the planner and designer to think of an appropriate mitigation strategy.

### 5.4.2.3 Solar reflectance (albedo):

An increase in net radiation is another reason for urban heat island formation (Gartland, 2008).

Here Net radiation is referred to as, Net Radiation = Incoming solar radiation (radiation from the sun) – Reflected solar radiation (radiation bounced back by the surface) + Atmospheric radiation (radiation emitted by atmospheric particles) – surface radiation (radiation emitted by the surface) (Gartland, 2008).

The radiation energy and the energy from anthropogenic heat is either absorbed and stored by the urban materials or warms the air above the surface. The urban materials mostly have low albedo value, leading to an increase in net radiation. That means the urban materials absorbs and stores more energy compared to rural materials. The stored energy will get emitted at night-time, which increases the nocturnal urban temperature. Different urban materials have different reflectance values that depend on their colour and other properties (Gartland, 2008). Figure 5-6 illustrates the reflectivity values of different urban materials. It is advisable to use materials with high albedo value to reduce the high nocturnal temperature.

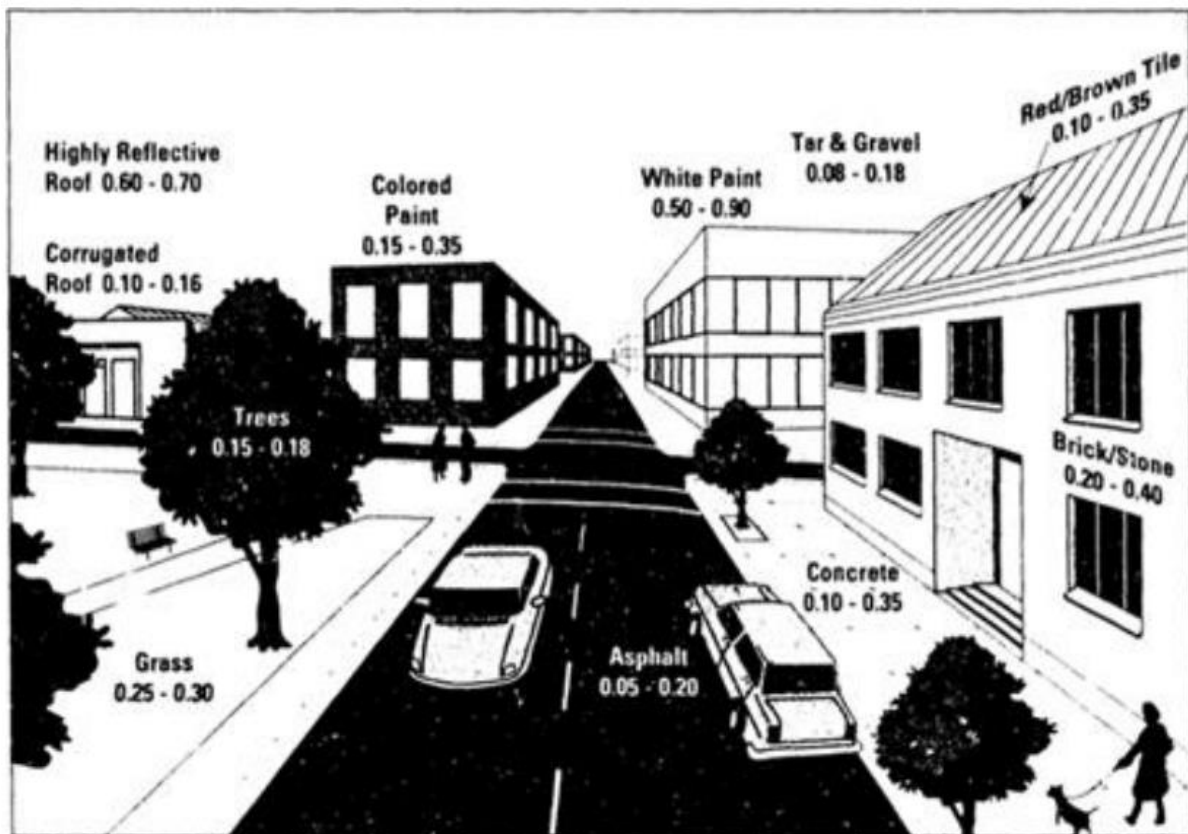


Figure 5-6: Albedo value of different urban materials (Jacobs and Delaney, 2015).

Similar to thermal diffusivity, solar reflectance of a particular area can be related to air temperature or UHI and also with other non-meteorological indicators (SVF and shadow). The relationship between the solar reflectance and urban building geometry was well explained in the Journal article “Street design and urban canopy layer climate” (Oke, 1988) (Chapter 2.2).

Table 5-6 provides an overview of the referred studies that considered solar reflectance as an indicator.

Literature	Best practices (France)	International case study
Lower solar reflectance of the Urban materials, increases the net radiation. Increase in net radiation is one of the causes of UHI.	<ul style="list-style-type: none"> <li>• <u>Paris and Agen</u>: Introduced strategies, guidelines, polices related to material change to mitigate UHI.</li> <li>• <u>Lyon</u>: Albedo measures were taken to fight against UHI.</li> <li>• <u>Marseille Euromediterranee</u>: Roof and wall solar reflectance were assessed for a sustainable urban renewal.</li> <li>• <u>Frontignan</u>: Through urban forms, reduction of solar radiation and increase in diffuse radiation were achieved.</li> </ul>	None of the referred UC-Map studies have considered this indicator

Table 5-6: Solar reflectance overview, in the referred books and documents (Author).

#### 5.4.2.4 Air pollution:

Air pollution is another indicator that is responsible for increasing the net radiation apart from the solar reflectance of the urban materials. It decreases the amount of incoming solar radiation reaching the earth surface during the day, and it also increases the amount of longwave infrared radiation emitted by the atmosphere to the earth surface. 22% reduction in solar energy gain was found in Mexico City due to Aerosol pollutants. Different studies have also found there is an increase in atmospheric radiation by 15% due to air pollution (Gartland, 2008).

Analysing air pollution variables against meteorological variables will inform its contribution towards the level of climatic issues identified in the particular area. Lower wind speed holds the pollutants in its source for a longer time.

The air pollution data can be analysed with land use, sky view factor, and vegetation data, which will help urban professionals to make climate-sensitive decisions.

The relationship between the urban geometrical indicator and air pollution is explained in the following subsections. Overlapping the air pollution data with the land use data will help urban planners to identify different city functions responsible for higher or lower air pollution values. Overlapping air pollution and vegetation information might help to identify zones where vegetation has to be improved since vegetation has the potential to decrease air pollution levels (Chapter 5.4.2.1).

Table 5-7 provides an overview of referred studies that relating air pollution with climatic issues. Antwerp and Gdansk cities, combined Gross floor area ratio for residential and commercial functions, Plan area density for urban functions related to groups vulnerable to air pollution, cycling infrastructure density, and urban parks and outdoor facilities area density, using GIS, to identify the level of potential increased exposure to air pollution in different zones. These air pollution exposure zones were then correlated with actual air pollution values in each zone (Badach *et al.*, 2020).

Literature	Best practices (France)	International case study
Increased levels of air pollution, increases the net radiation. Increase in net radiation is one of the causes of UHI.	Reducing greenhouse gas emissions, reducing CO2 emissions, improve air quality, policies and guidelines on low carbon mobility, and enhancement of public transport are the actions related to air pollution that were taken to reduce the climatic issue by the six French cities	<ul style="list-style-type: none"> <li data-bbox="1023 1238 1382 1368">• <u>Beijing, China:</u> Included Air pollution as one of the parameter in both urban and sub-domain level analysis.</li> </ul>

Table 5-7: Air pollution overview, in the referred books and documents (Author).

#### 5.4.2.5 Building energy use:

The heat generated by buildings, machinery etc., known as anthropogenic heat, is another factor responsible for UHI formation (Gartland, 2008).

In a dense urban setup, the anthropogenic heat stays longer. Hence, understanding the building energy use and correlating the values with the compactness of the urban areas will help urban professionals to decide on the urban form regulations.

Trees around the building provide shade to the building walls and windows that reduces cooling energy needs during summer. But during winter, the demand for heating energy increases. Trees also act as a windshield and reduce the heat loss from the building elements. Although this is very beneficial during winter times due to reduction in heating energy needs but not beneficial during summer times. During summer times, the cooling energy demand increases (Gartland, 2008). It will be useful for the urban planning and design professionals if the building energy data is related to the vegetation cover around the building.

Table 5-8 provides an overview of how various referred studies relating building energy use to climatic issues. Analysing building energy use against meteorological variables will inform its contribution towards the level of climatic issues identified in the particular area.

Literature	Best practices (France)	International case study
Increased energy use, Increases anthropogenic heat. Increase in anthropogenic heat is one of the causes of UHI.	<ul style="list-style-type: none"> <li>• <u>Lyon, Grenoble, Marseille Euromediterranee, and Agen</u>: Different energy-related policies, strategies, guidelines etc., were introduced to reduce urban climatic issues.</li> <li>• <u>Grenoble</u>: Urban professionals insist on the importance of considering the Energy data before planning an urban project. Avoiding the use of air conditioning was one of the urban planning actions.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Tokyo, Japan</u>: included anthropogenic heat release as a parameter, to explain the reason behind the level of thermal load at each zone.</li> </ul>

Table 5-8: Building energy use overview, in the referred books and documents (Author).

#### 5.4.2.6 Building Shadow:

Building density, SVF, and H/W ratio are commonly used building geometrical indicators by many referred urban climatic map studies. The referred literature only provided a general overview of the relationship between urban geometry and the UHI effect, but no specific urban building geometrical parameter was elaborated in the literature. However, out of six French

best practices, three have tried to orient the building according to the sun path to overcome climatic and energy issues (Table 5-9).

The shade provided by the trees around the building reduces the cooling energy needs during summer (Gartland, 2008) (Chapter 5.4.2.5). Similarly, the shade provided by the surrounding building might affect the building energy needs. Due to shade, building and ground surfaces absorb less heat. It lowers the air and surface temperature (Wong N.H., Tan C.L., 2021). Hence it has positive benefits towards thermal comfort.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>• Urban geometries that trap heat, Increases net radiation.</li> <li>• Urban geometry that slow wind speeds, reduces convection.</li> <li>• Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Agen</u>: Orientation of the land parcels according to the sun path was analysed to solve climatic and energy issues. A Bio climatic study was conducted.</li> <li>• <u>Marseille Euromediterranee</u>: TEB model was used for working on the building orientation, for a sustainable urban renewal. A Bio climatic architecture was explored.</li> <li>• <u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry. A Bio climatic building approach was explored.</li> </ul>	<p>None of the referred UC-Map studies have directly considered this indicator. However, other building geometries were considered, that can be associated with shadow pattern, such as SVF, aspect ratio, building density, and building volume density.</p>

Table 5-9: Shadow pattern overview, in the referred books and documents (Author).

#### 5.4.2.7 Solar – Building exposure:

Apart from various discussed aspects, the energy demand of the building and the thermal diffusivity of the building material depends on the amount of solar energy it receives. Hence building facade sun exposure was studied in Agen, France, to solve energy and climatic issues (Table 5-10).

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, Increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Agen</u>: Sun exposure of building facades were analysed to solve climatic and energy issues.</li> <li><u>Marseille Euromediterranee</u>: TEB model was used for working on the building orientation, for a sustainable urban renewal. A Bio climatic architecture was explored.</li> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry. A Bio climatic building approach was explored.</li> </ul>	None of the referred UC-Map studies have directly considered this indicator

Table 5-10: Solar-Building exposure overview, in the referred books and documents (Author).

#### 5.4.2.8 Transportation:

As mentioned earlier in 5.4.2.4 & 5.4.2.5 sections (Air pollution and Building energy use), an increase in air pollution and an increase in anthropogenic heat contributes to UHI formation. In cities, road transportation is one of the reasons for the increase in air pollution and higher anthropogenic heat (Gartland, 2008).

Table 5-11 presents an overview of how transportation information was considered in different referred studies. It was noticed that none of the referred examples had considered transportation from an anthropogenic perspective. Lee *et al.*, (2009) used transportation data to estimate the anthropogenic heat emission in the Gyeong-In region of Kore.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Increased levels of air pollution, increases the net radiation. Increase in net radiation is one of the causes of UHI.</li> <li>Increased energy use, Increases anthropogenic heat. Increase in anthropogenic heat is one of the causes of UHI.</li> <li>Transportation is one of the reason for increase air pollution levels and increased anthropogenic heat.</li> </ul>	Reducing greenhouse gas emissions, reducing CO2 emissions, improve air quality, policies and guidelines on low carbon mobility, and enhancement of public transport are the actions related to air pollution that were taken to reduce the climatic issue by the six French cities.	Transportation data was not directly considered in the urban climatic studies, but <u>Beijing, China</u> has Included Air pollution as one of the parameter in both urban and sub-domain level analysis.

Table 5-11: Transportation overview, in the referred books and documents (Author).

Overlapping the transport data on the meteorological variable will help to understand its contribution towards climatic issues. Relating the transportation information with other indicators, vegetation, building density, sky view factor and land use will help urban planners and designers to think on appropriate mitigation strategies. The relationship between this indicator with air pollution and anthropogenic heat were discussed in 5.4.2.4 and 5.4.2.5 sections (Air pollution and Building energy use) respectively.

**5.4.2.9 Thermal comfort:**

Thermal comfort is a subjective evaluation that expresses human mind satisfaction with the thermal environment (ASHRAE, 2021).

Table 5-12 presents an overview of the referred studies that considered thermal comfort in their analysis. The referred case studies included Physiological Equivalent Temperature (PET) values in their climatic maps.

Literature	Best practices (France)	International case study
No information related to Thermal comfort in specific.	<ul style="list-style-type: none"> <li>• <u>Grenoble</u>: Solving summer comfort issue was one of the local action plan, listed as a priority interventions.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Osaka, Japan</u>: Areas of psychological feeling of coolness were included in the UC-ReMap.</li> <li>• <u>Hesse, Germany</u>: To study the influence of thermal load and dynamic potential on people, thermal comfort (PET) values were considered.</li> <li>• <u>Salvador, Brazil</u>: Topography, land use, and wind speed were the three charts considered to identify different thermal comfort conditions.</li> </ul>

Table 5-12: Thermal comfort overview, in the referred books and documents (Author).

Thermal comfort can be related to meteorological variables to understand the influence of the thermal environment on thermal comfort. Thermal comfort can also be analysed with other indicators, such as tree cover and building shadow pattern, to understand the contribution of shade on the thermal comfort levels.

#### 5.4.2.10 Sky view factor:

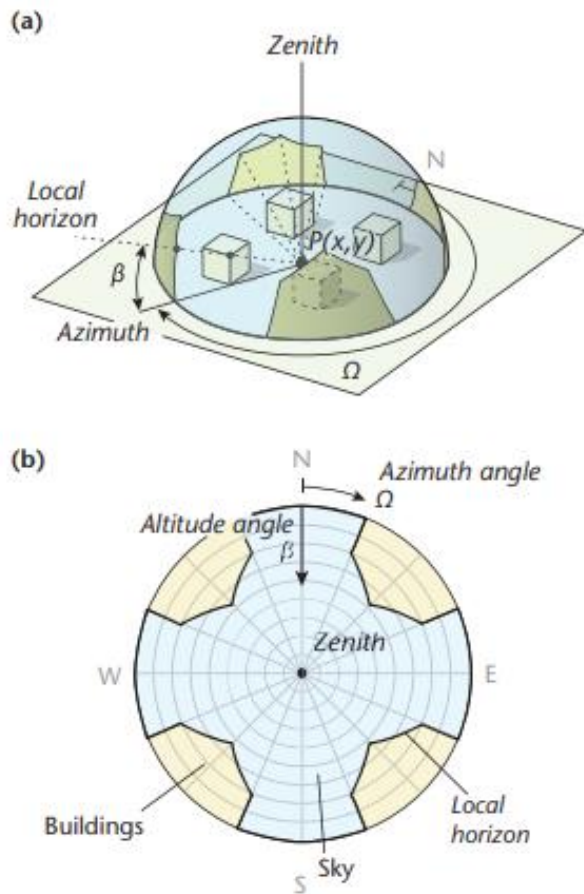


Figure 5-7: Sky view factor at point 'P' (Oke *et al.*, 2017).

The sky view factor (SVF) is a three-dimensional measurement for the given point in the surface (Figure 5-7), which explains the visibility of the sky from a particular point (Oke *et al.*, 2017). SVF is measured on a scale of 0 to 1. If SVF is 1, then the sky is 100% visible at that point.

SVF can be related to thermal diffusivity, solar reflectance and air pollution values. A 10% increase in SVF increases the wind velocity ratio by 7% to 8% (Badach *et al.*, 2020).

Thermal diffusivity value also depends on the amount of solar radiation received by the material. Higher the SVF number, the higher the solar radiation received.

On the other hand, if the sky is more visible, the energy emitted by the materials at night-time will escape to the atmosphere rather than getting trapped in the canopy layer. Thus reduces the night-time temperature. That means the higher the sky view factor, the lower the nocturnal UHI intensity. Similarly, the higher the SVF number, the more pollutants escaping the urban canopy layer.

Table 5-13 provides an overview of the referred studies that considered SVF as an indicator.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, Increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry.</li> </ul>	<ul style="list-style-type: none"> <li><u>Singapore and Arnhem, Netherlands</u>: SVF was considered in the UC-Maps.</li> </ul>

Table 5-13: Sky view factor overview, in the referred books and documents (Author).

#### 5.4.2.11 Canyon aspect ratio:

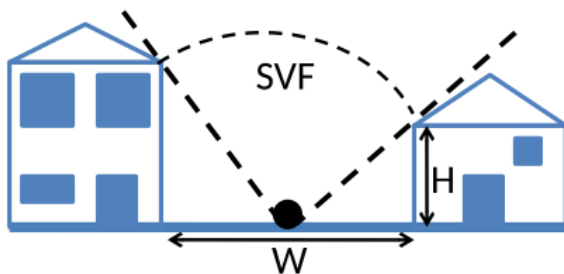


Figure 5-8: Relationship between H/W ratio and SVF (Dirksen et al., 2019).

Canyon aspect ratio is a unit less ratio that describes a two-dimensional cross-section of the street. It is also known as the H/W ratio. Where H is the average height of the building adjacent to the road and W is the width of the road. This is a universal way of describing the building density (Oke et al., 2017).

An approximate SVF can be calculated from the H/W ratio (Chen et al., 2012). The higher the value of the Canyon aspect ratio, the smaller the SVF. This indicator is used with SVF or used as an substitute for SVF (Figure 5-8).

Similar to SVF, the canyon aspect ratio can be related to solar radiation access, thermal diffusivity, solar reflectance, and air pollution dispersion. Apart from this, the H/W ratio can also be related to shade, wind effects, and thermal comfort (Oke et al., 2017). A higher H/W ratio value also lessens the wind turbulent transfer (Oke, 1988).

Table 5-14 provides an overview of the referred studies that considered H/W ratio as an indicator.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry.</li> </ul>	<ul style="list-style-type: none"> <li><u>Salvador, Brazil</u>: Included H/W ratio in its UC-Maps.</li> </ul>

Table 5-14: Canyon aspect ratio overview, in the referred books and documents (Author).

#### 5.4.2.12 Building density:

Building density, building footprint area divided by site area. The higher the building density, the lower the SVF and higher the UHI intensity. The Wind velocity in the urban areas depends on the building density. The precinct with dense building fabric reduces the conventional cooling effect due to the reduction in wind velocity, which in return traps the heat and increases the temperature. The precincts with higher building density experience increased human activity, due to which there is an increase in heat waste (Oke, 1988).

The relationship between building density and building energy use was explained in Chapter 5.4.2.5. Building density was used as one of the parameters to identify air circulation problem areas in Antwerp and Gdansk (Badach *et al.*, 2020).

Table 5-15 provides an overview of the referred studies that considered building density as an indicator.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry.</li> </ul>	<ul style="list-style-type: none"> <li><u>Tokyo, Japan and Hong kong</u>: Included building density in the UC-Maps to analyse thermal load and dynamic potential.</li> </ul>

Table 5-15: Building density overview, in the referred books and documents (Author).

#### 5.4.2.13 Building Height:

The urban precinct experience good ventilation if there is a good variability in the building height. Few studies established that if the building height varies by 33%, then there will be an 80% increase in the fresh air and a 30% chance of removing the pollutants from the precinct. Standard deviation of the building height was one of the parameter used to identify air circulation problem areas in Antwerp and Gdansk (Badach *et al.*, 2020).

Building height is an essential data, since it is required to calculate H/W ratio and SVF. Table 5-16 provides an overview of the referred studies that considered building height.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, Increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry.</li> </ul>	<ul style="list-style-type: none"> <li><u>Tokyo, Japan and Hong kong</u>: Included building height in their UC-Maps.</li> </ul>

Table 5-16: Building height overview, in the referred books and documents (Author).

#### 5.4.2.14 Roughness length:

Roughness length ( $z_0$ ) is a critical indicator that controls the wind turbulence in the city. In an urban setup more the number of taller elements, the greater the  $z_0$  value. However, beyond a certain density, the  $z_0$  value reduces. The intensity of turbulence increases when the  $z_0$  is greater (Oke, 1988).

Table 5-17 provides an overview of the referred studies that included Roughness length as an indicator to analyse the wind variables.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Frontignan</u>: SOLENE was used for urban climatic analysis to find best geometry. The urban redevelopment project, studied the aerodynamic turbulence to achieve a climate-sensitive design.</li> </ul>	<ul style="list-style-type: none"> <li><u>Ho Chi Minh city, Vietnam</u>: The wind speed was related to roughness length.</li> <li><u>Wuhan, China</u>: Roughness length was included in the UC-Maps to estimate the wind profile of the city.</li> <li><u>Hong Kong</u> : Roughness length parameter was included in the UC-Maps for accessing the dynamic potential.</li> <li><u>Salvador, Brazil</u>: . Roughness length was one of the factors which lead to the six categories of the Wind chart.</li> </ul>

Table 5-17: Roughness length overview, in the referred books and documents (Author).

#### 5.4.2.15 Urban permeability:

To improve outdoor natural air ventilation performance, potential air paths should be detected. Urban permeability is calculated to identify the potential air paths in the city (Yuan, Ren and Ng, 2014). It is calculated using three variables, frontal area density, roughness length and zero plane displacement (Ng and Ren, 2015).

Table 5-18 provides an overview of the referred studies that considered urban permeability in their ventilation studies.

Analysing the wind information with urban permeability will help urban planners and designers to think on various measures to improve the natural air ventilation in cities.

Literature	Best practices (France)	International case study
<ul style="list-style-type: none"> <li>Urban geometries that trap heat, increases net radiation.</li> <li>Urban geometry that slow wind speeds, reduces convection.</li> <li>Increase in net radiation and reduced convection leads to UHI formation.</li> </ul>	<ul style="list-style-type: none"> <li><u>Grenoble</u>: Ventilation and insulation, renovation program is one among the actions initiated as a climate responsive urban planning.</li> <li><u>Agen</u>: Prevailing winds were overlooked to develop urban planning policies and guidelines for mitigating energy and climatic issues.</li> <li><u>Frontignan</u>: Orienting the plots according to the prevailing winds is one of the main consideration in an urban redevelopment project.</li> </ul>	<ul style="list-style-type: none"> <li><u>Ho Chi Minh city, Vietnam</u>: UC-Maps were generated to improve air quality, and openness to ventilation was assessed.</li> <li><u>Wuhan, China</u>: Urban permeability was derived using urban surface roughness to detect potential air paths.</li> <li><u>Hong Kong</u>: Initiated air ventilation assessment system for better urban design guidelines. Urban permeability is one among the four issues identified in the cities and strategies were recommended to rectify the issue based on UC-Maps.</li> </ul>

Table 5-18: Urban permeability overview, in the referred books and documents (Author).

#### 5.4.2.16 Topography:

In the referred urban climatic map studies, Topography was combined with different other indicators for urban climatic analysis. In Hong Kong, it was combined with Building volume and green spaces to assess the thermal load of the city. Similarly, the building height information was summed with elevation levels, and the same was used to calculate SVF using GIS tools (Chen *et al.*, 2012). The urban climatic maps that considered topography as an indicator is listed in Table 5-19.

Literature	Best practices (France)	International case study
No information related to Topography in specific.	Topography, in specific, was not considered in any of the six best practices.	<u>Tokyo, Japan; Osaka, Japan; Ho Chi Minh city, Vietnam; Hong Kong; Hesse, Germany; Singapore; Arnhem, Netherlands; and Salvador, Brazil</u> included topography in their UC-Maps to analyse thermal load and dynamic potential.

Table 5-19: Topography overview, in the referred books and documents (Author).

#### 5.4.2.17 Land use/Building use:

The climatic modifications in the urban areas are due to their form and function (Oke *et al.*, 2017). Various indicators, such as SVF, H/W ratio, building height, and building density, explains the relationship between the urban form and the climatic issues. Similarly, including the land use or building use information in the urban climatic map will inform the relationship between the urban function and the climatic issue. This indicator can be combined with all the identified indicators for better understanding.

Land use is one of the indicators considered in the listed urban climatic map studies (Table 5-20). In Salvador, to explain the thermal and dynamic potential of the city, land use, topography, and wind speed, were superimposed.

Literature	Best practices (France)	International case study
Different examples were provided in the book, describing the relationship between different land cover /land use patterns and UHI.	Land use or building use are not directly considered in the six best practices. But overall, the proposed strategies, policies, guidelines to mitigate UHI will have an impact on the land use change. For example, improving and increasing vegetation cover is one of the mitigation measures proposed in all the six cities, that will modify the existing land use.	<u>Tokyo, Japan; Osaka, Japan; Ho Chi Minh city, Vietnam; Hong Kong; Hesse, Germany; Stuttgart, Germany; Arnhem, Netherlands; and Salvador, Brazil</u> considered land use as one of the parameter in their UC-Maps.

Table 5-20: Land use/Building use overview, in the referred books and documents (Author).

## **Chapter 6. GENERATING AND PREPARING THE IDENTIFIED INDICATORS BASED ON AVAILABLE DATA**

The assemblage of different urban elements such as buildings, streets, parks, and gardens creates a distinctive microclimate in an urban block (group of buildings surrounded by roads), and different urban blocks put together became a neighbourhood. This creates a diversified microclimate within the neighbourhood. Above the roof level of the neighbourhood, a distinct boundary layer is created and mixes with the other neighbourhood boundary layers to form an urban boundary layer (Oke et al., 2017). Therefore, an urban block scale analysis would provide sufficient information to the urban planning and design community for mitigating or reducing climatic issues at the local scale. Hence, out of the three scales of available urban data under the MApUCE project, the islet scale was chosen to generate climatic maps since each islet represents an urban block of the city.

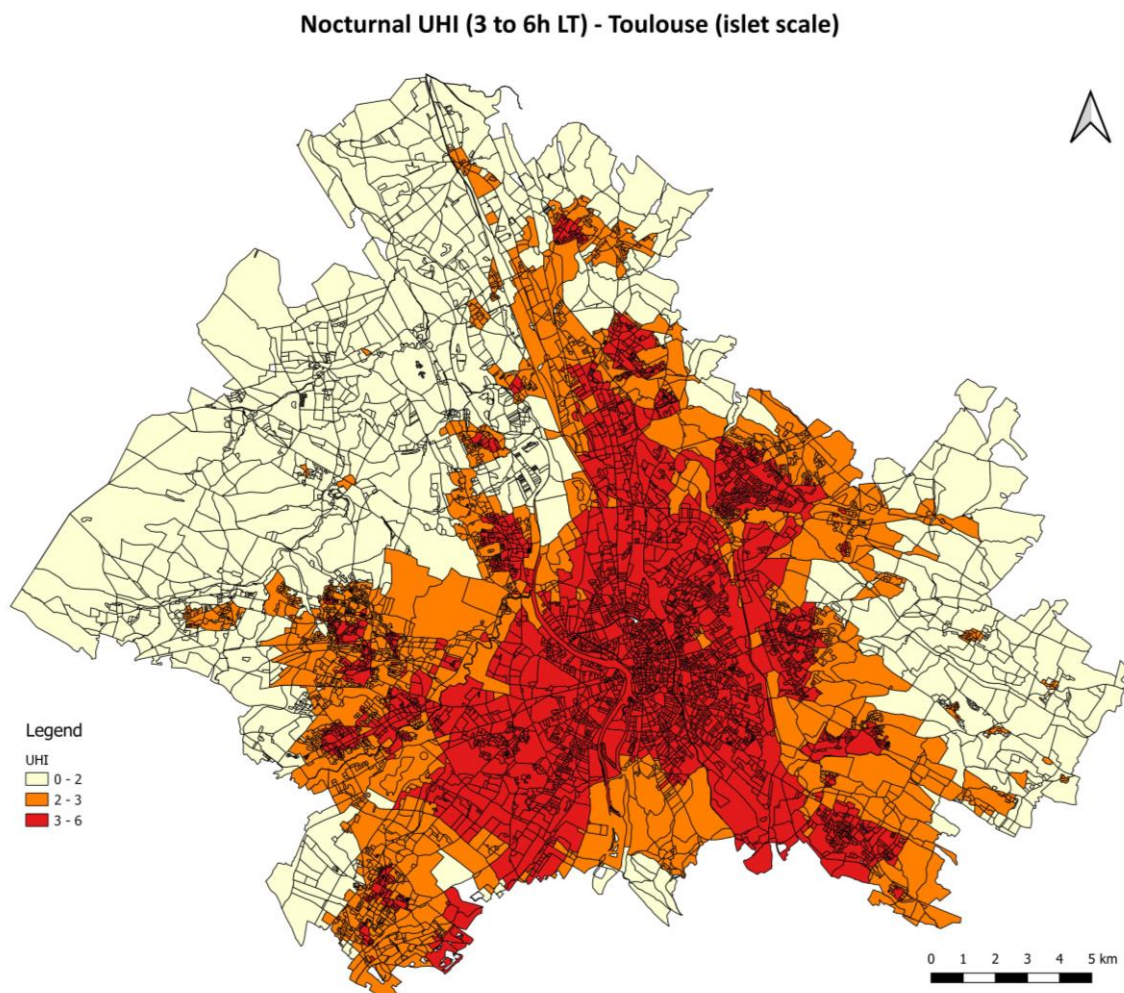
This chapter presents a detailed methodology on how an islet scale information of different identified indicators are prepared and generated, primarily using the data available under the MApUCE project.

### **6.1 Meteorological Indicators:**

This section describes how the 250m spatial resolution meteorological data produced under the MApUCE project for Toulouse were assigned to the city's islet polygons using QGIS tools.

As mentioned in Chapter 3, local time 3 to 6 hours UHI data for LWT 9 and local time 13 to 16 hours UTCI data for LWT 7 are considered for this thesis. Hence the UHI and wind velocity ratio data available at 250m spatial resolution were assigned to the islet polygons using the "Zonal statistics" majority function in QGIS. Below are the islet scale UHI and Wind velocity ratio.

### 6.1.1 Urban heat island (UHI):

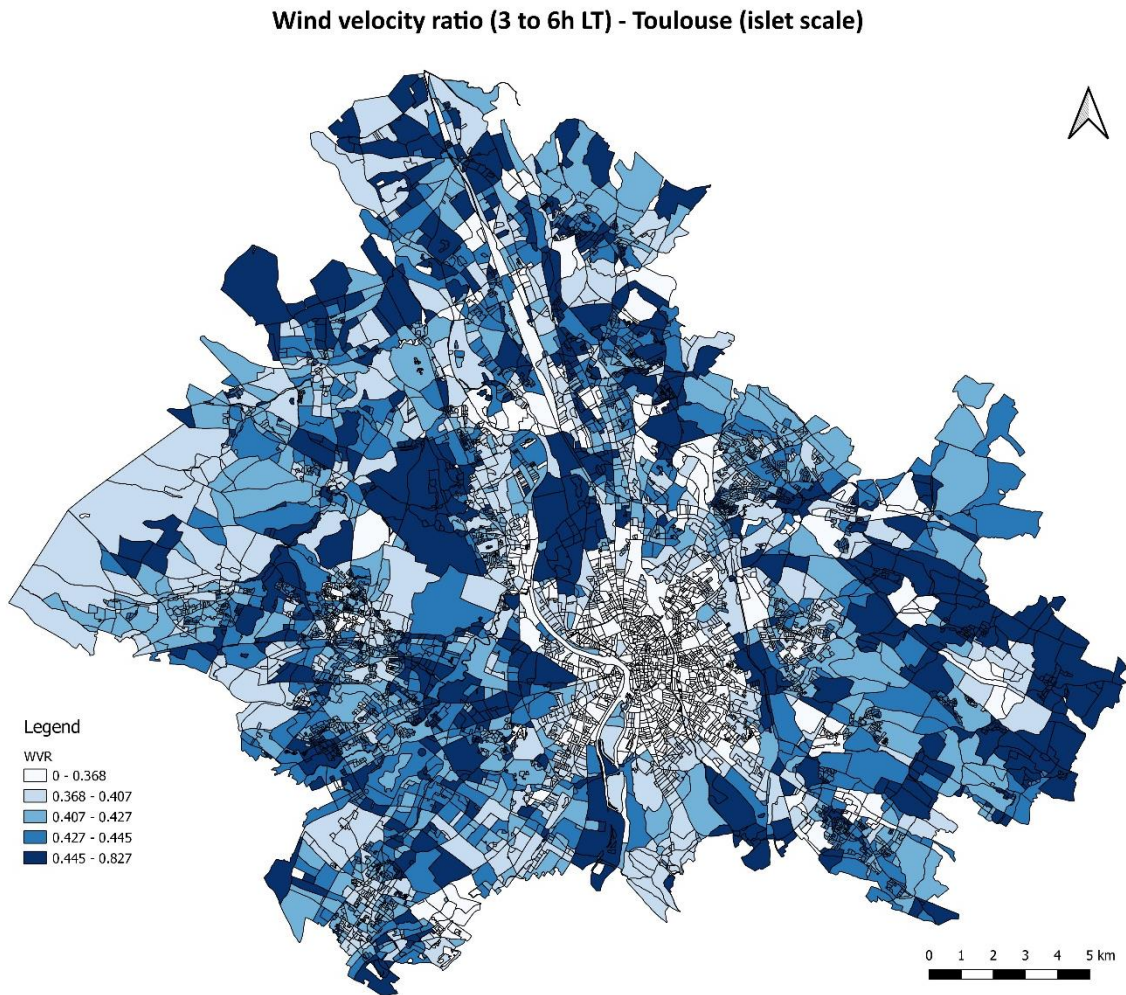


*Map 6-1: Islet scale Nocturnal UHI (3 to 6h LT) – Toulouse (Author)*

Map 6-1 is the zonal statistics outcome of the UHI data. It illustrates the islet level nocturnal UHI value of LWT 9. The classification recommended by the researchers at the LISST laboratory was used for the islet level representation.

Similar to the nocturnal UHI data of LWT9, UHI values at 13 to 16 hours local time for LWT 7 was prepared at the islet scale for analysing it with the available UTCI data.

## 6.1.2 Wind velocity ratio:



*Map 6-2: islet scale Wind velocity ratio (3 to 6h LT) – Toulouse (Author)*

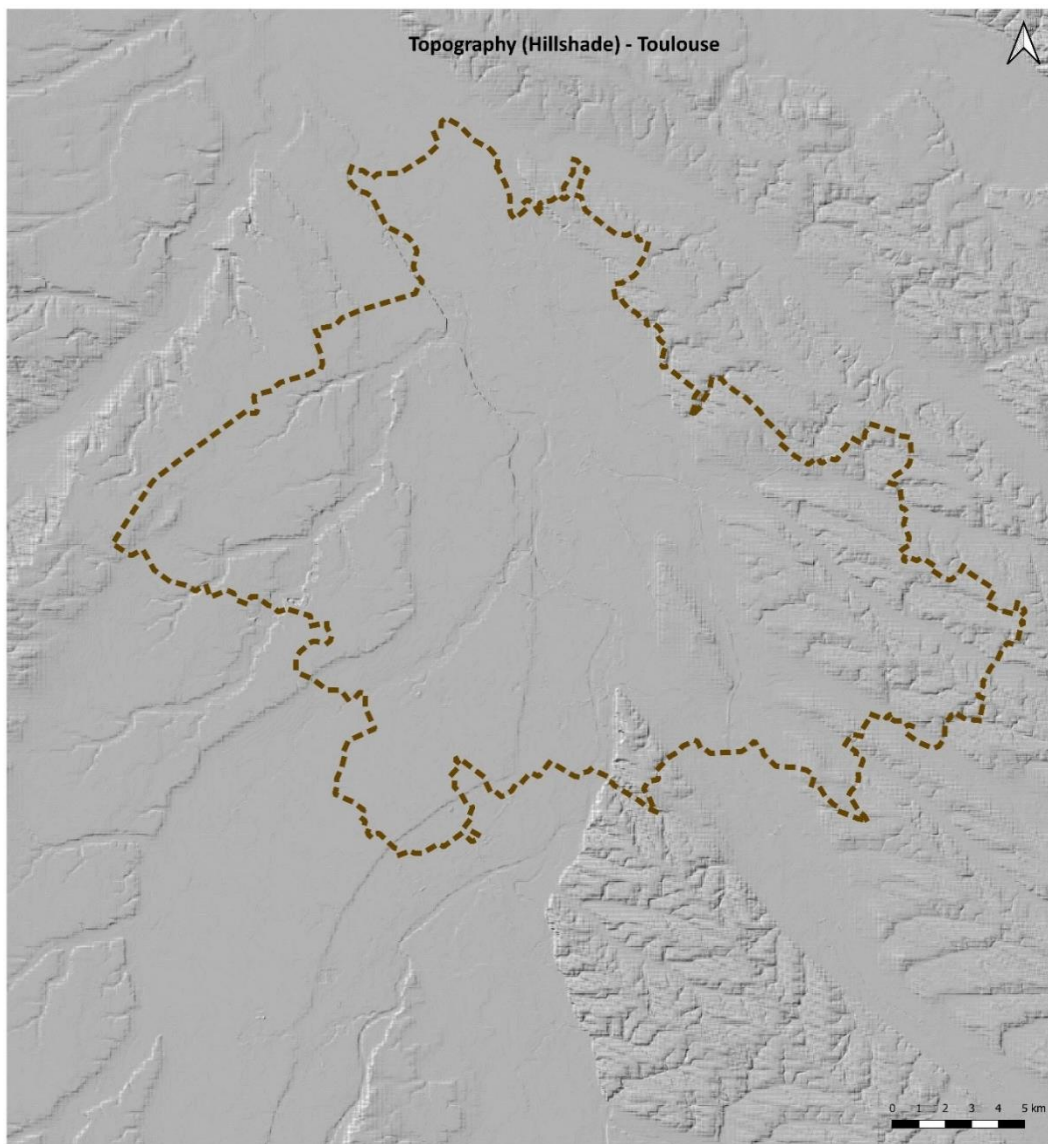
Map 6-2 is the zonal statistics outcome of the Wind velocity ratio. It illustrates the islet level nocturnal wind velocity ratio of LWT 9.

Similarly, an islet level wind speed for LWT 7 at 13 to 16 hours local time was prepared for analysing it with the available UTCI data. Before assigning the values to the islets, the wind speed data was calculated from U and V values, available for every 250m. Wind speed is equal to the square root of  $U^2 + V^2$ .

## 6.2 Urban planning and urban design Indicators:

This section of the chapter presents different GIS tools used to calculate the identified urban planning and urban design indicators, using the urban database generated under MAPUCE Project. An alternative was suggested for the indicators that require more data to prepare.

### 6.2.1 Topography:

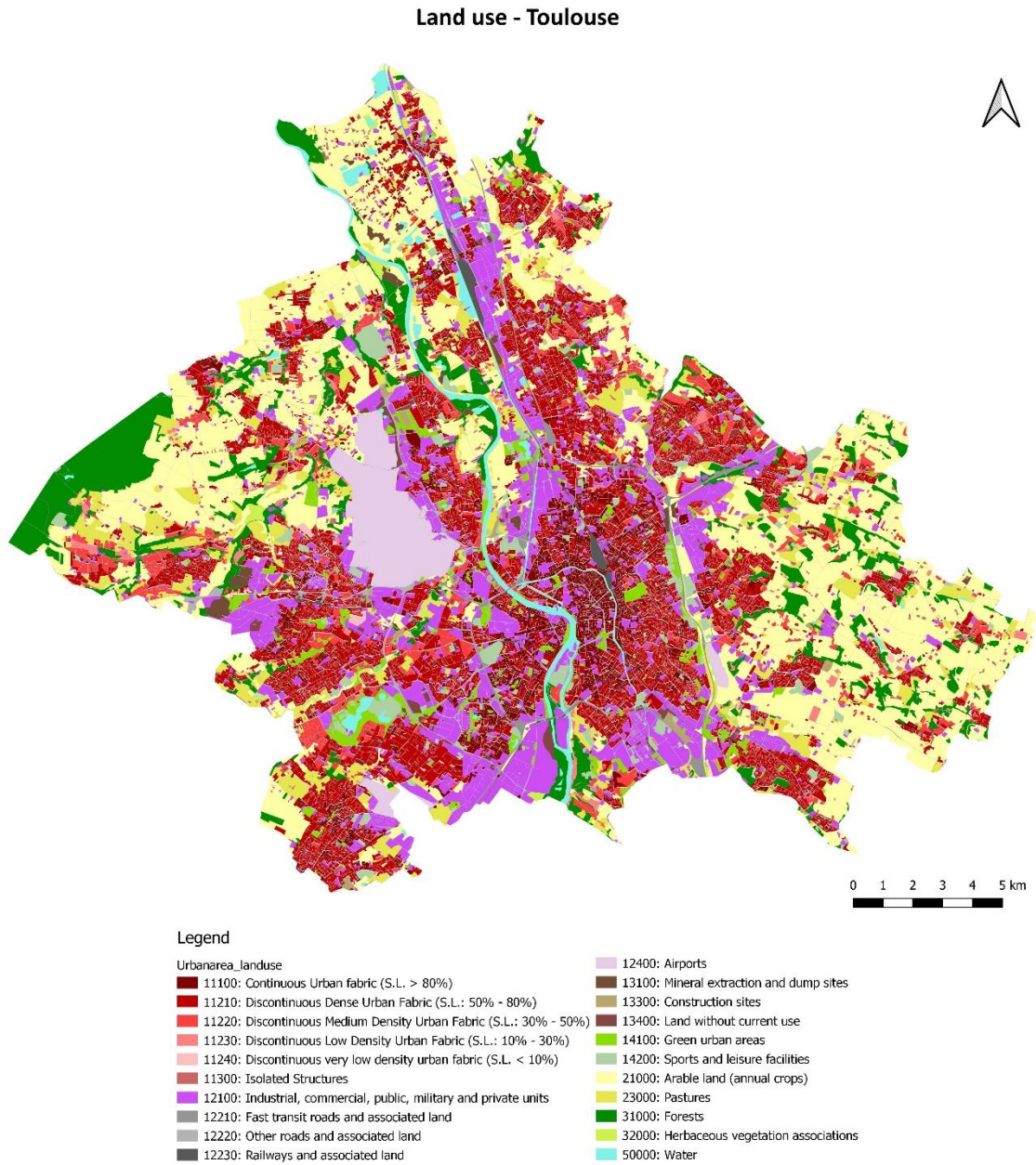


*Map 6-3: Topography of Toulouse*

Map 6-3 illustrates the topography map available at the LISST laboratories for Toulouse. Toulouse boundary was overlapped with the available topography map, and it was noticed that

the city is relatively flat. Therefore the topography information of Toulouse was not considered for this thesis.

### 6.2.2 Land use/Building use:



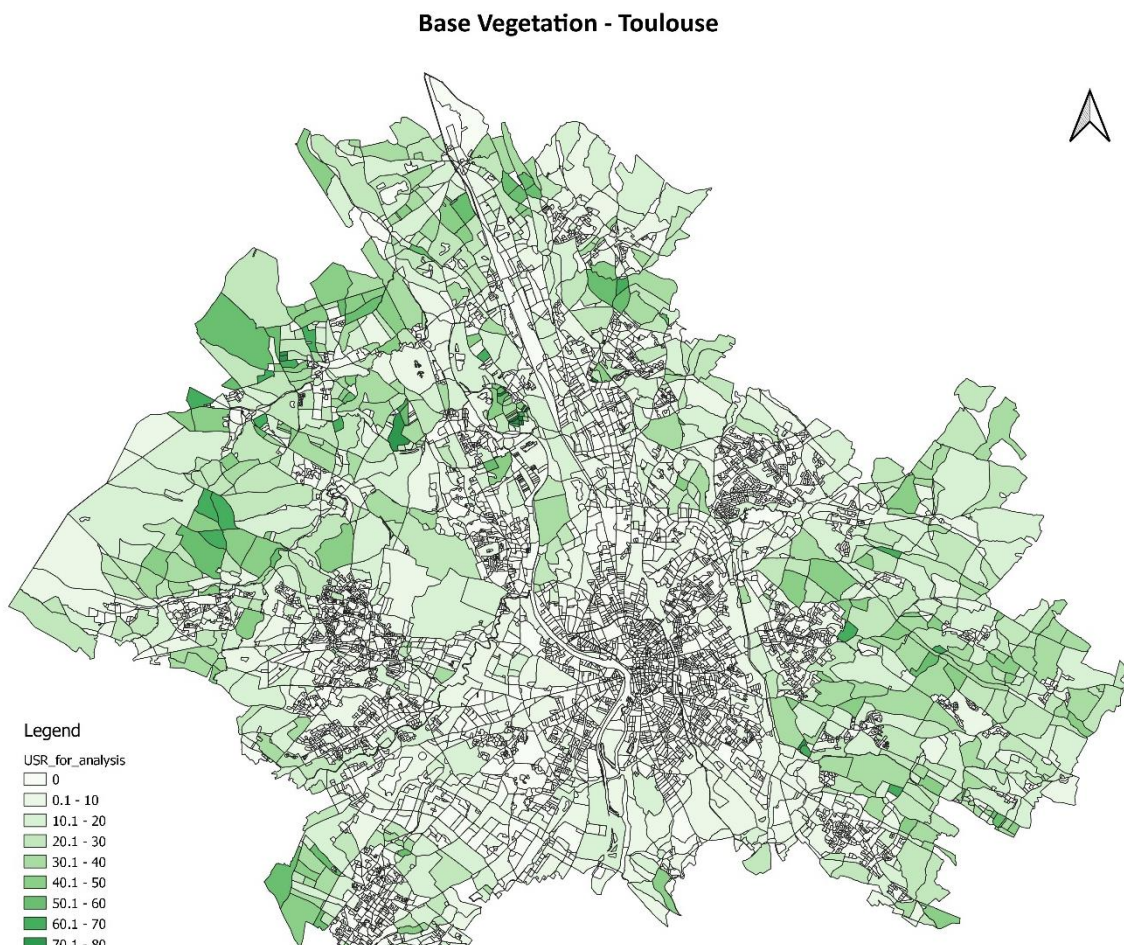
Map 6-4: Toulouse Land use (Urban Atlas, 2018).

Since the land use data was not available, it was acquired from Urban Atlas. Map 6-4 presents the land use information of Toulouse.

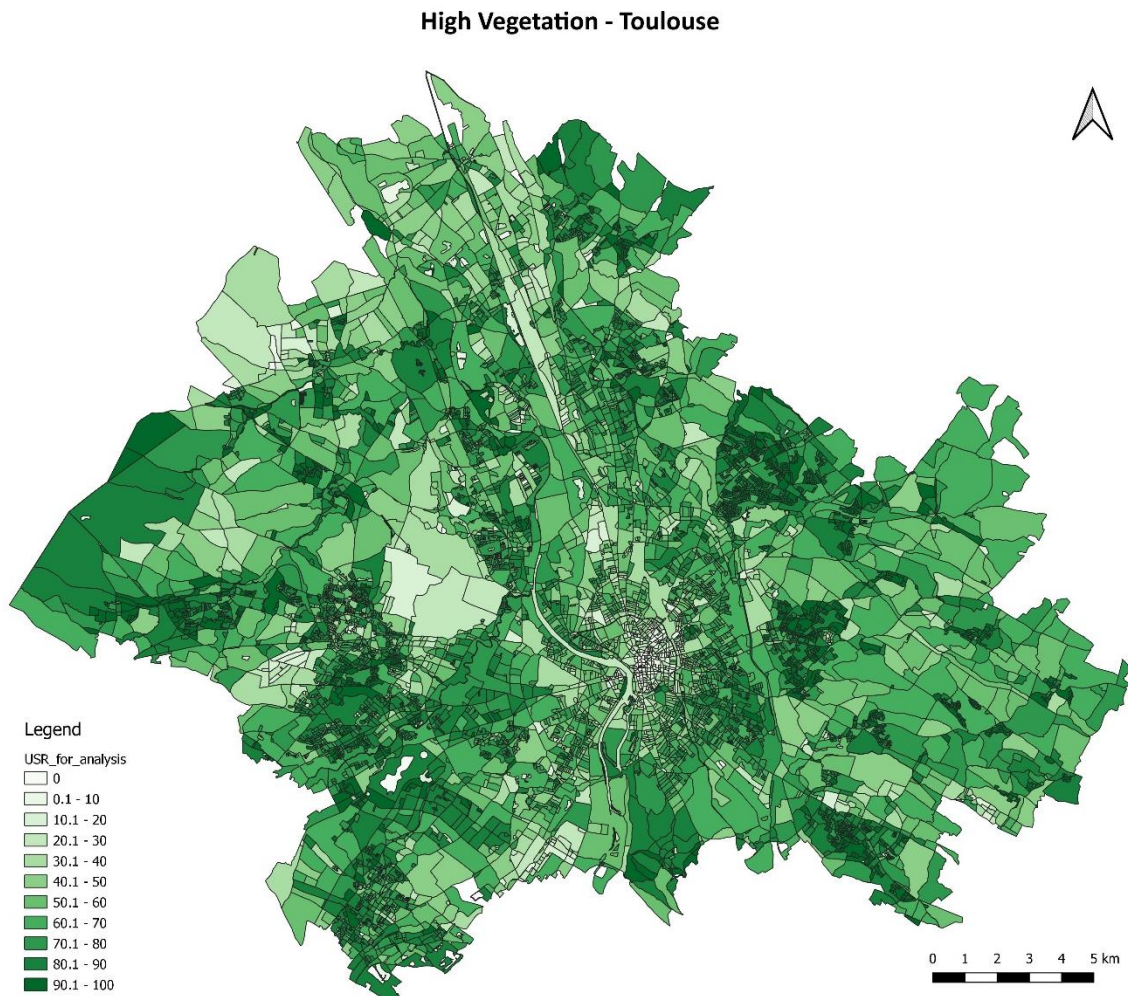
### 6.2.3 Vegetation:

For 14 French cities, including Toulouse, the percentage of Base and High vegetation data cover at islet scale are available. Base vegetation data represent grass, and High vegetation data represents bush and trees. This islet level data was prepared using SPOT 6 satellite image with 1.5m spatial resolution. Using the “Zonal statistics” QGIS tool, the pixel data were assigned to the islet scale and the vegetation cover percentage was calculated for each islet.

Map 6-5 and Map 6-6 illustrates the percentage of Base and high vegetation cover in each islet of Toulouse. However, more detailed vegetation information would be much more useful for very in-depth analysis similar to the one conducted for Melbourne. For Melbourne, eight different vegetation variables, such as grass, shrubs, trees with three different heights, etc., were correlated with temperature values to identify the best suitable vegetation type for UHI mitigation or reduction (Sun *et al.*, 2019).



Map 6-5: Toulouse – Base vegetation cover (MApUCE project)



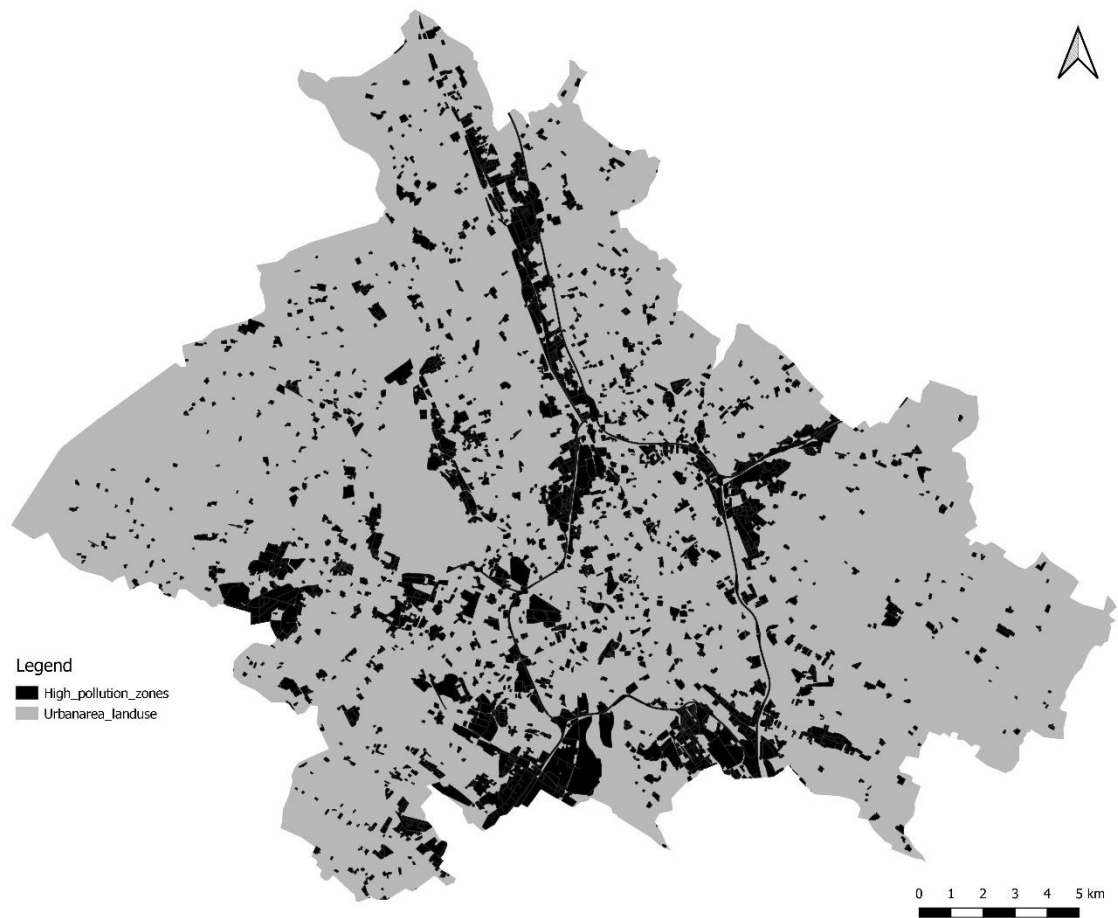
*Map 6-6: Toulouse - High vegetation cover (MApUCE project)*

#### **6.2.4 Air pollution:**

Since air pollution data is not available, High and Low air pollution zones were assumed based on the land use information acquired from the urban atlas. Out of 21 available land use categories, 12100, 1220, and 13100 were classified as air pollution potential zones. 12100 represents Industrial, commercial, public, military and private lands. 12210 represents fast transit roads and associated lands. 13100 represents mineral extraction and dumpsite. However, detailed land use would have provided precise information.

Map 6-7 illustrated the estimated air pollution zones, represented in black

## Potential Air pollution zones - Toulouse



Map 6-7: Estimated Air pollution zones (Author)

### 6.2.5 Building energy use:

Building energy use data is not available. But trees around the building will reduce the energy demand (Chapter 5). Therefore, High vegetation cover around the building was calculated and used as a substitute for the building energy use information. The higher the vegetation cover, the lower will be the energy use and vice versa.

A 15m buffer around the building polygon of Toulouse was created using GIS. The satellite

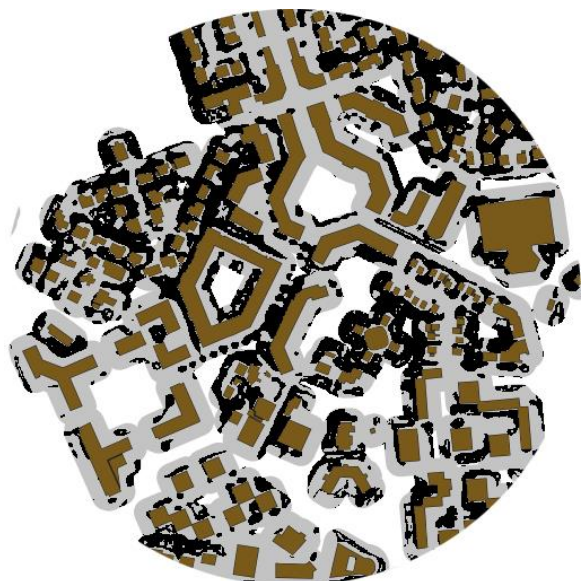
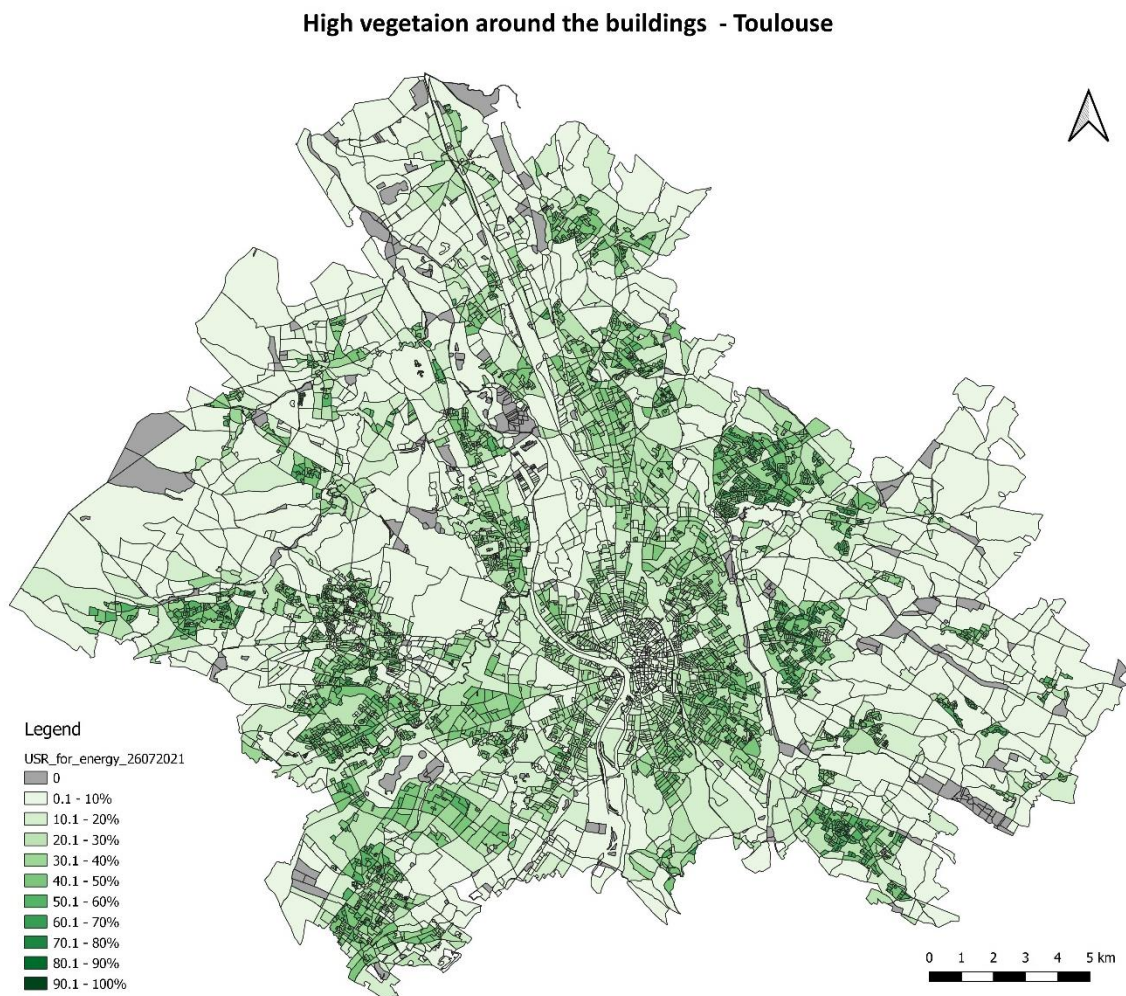


Figure 6-1: High vegetation with in 15m buffer around the building (Author)

image containing the vegetation information was clipped using the clip tool to calculate the high vegetation cover ratio around the buildings. In Figure 6-1, Brown colour represents building polygon, Grey colour represents 15m buffer around the building, and Black colour represents the High vegetation within the buffer.

The obtained information was represented at the islet scale using Zonal statistics tool. Map 6-8 illustrates the results of this process.



*Map 6-8: High vegetation cover around the building (islet scale) (Author)*

Pretzsch *et al.*, (2015) published a Journal article titled "Crown Size and growing space requirement of common tree species in urban centres, parks, and forests" to estimate and evaluate the spatial requirements of different tree species. 22 species from different parts of the world were used in this research. For France, "Platanus hispanica Münchh" was included in this research. The mean diameter of this tree is 13.6m. Using this as the reference, a 15m buffer

around the building was performed. However, to make the analysis more precise, richer vegetation information at the islet scale is necessary.

### 6.2.6 Shadow pattern:



Figure 6-2 : Shadow pattern at 13h (eft) and 14h (right) (Author)



Figure 6-3: Shadow pattern at 15h (eft) and 16h (right) (Author)

### Shadow - Toulouse

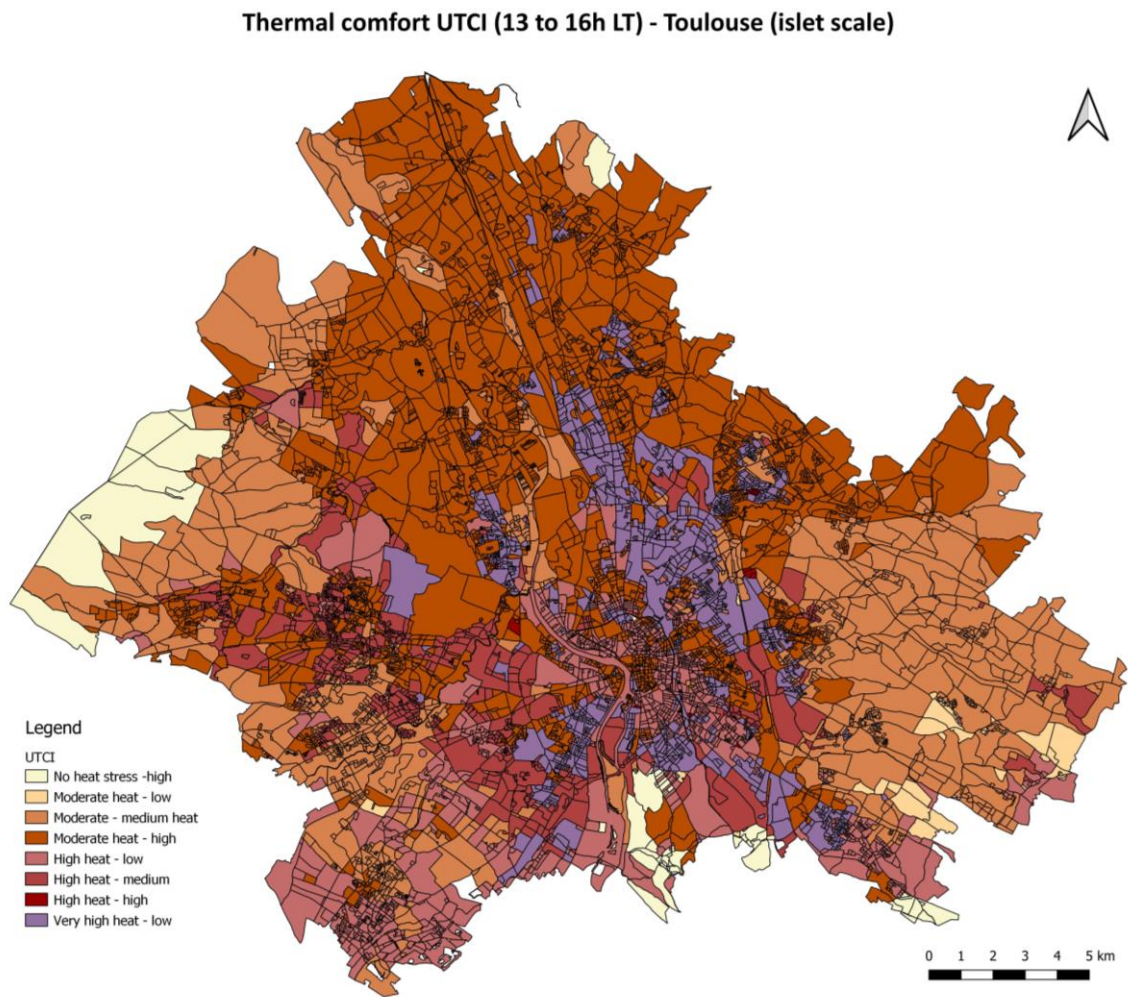


Map 6-9: shadow pattern (13 to 16h) of Toulouse (islet scale) (Author)

To analyse the relationship between building shadow and thermal comfort, a typical summer day was selected and building shadow for Toulouse was calculated. Since 13 to 16h local time UTCI data is considered for the analysis, a building shadow for the same time was performed using the QGIS tool.

The “Daily shadow pattern” tool, available under UMEP QGIS Plugin, was used to calculate the Building shadow pattern. Building polygons with the height data was rasterised and used as an input. Figure 6-2 and Figure 6-3 illustrates the results produced by the tool for 13h, 14h, 15, and 16h, respectively. Using the “zonal statistics” tool, the generated shadow pattern images, for each hour, were assigned to the corresponding islets. The percentage of the shadow cover on the open spaces, of each hour, for each islet, was calculated. The shadow cover values of each hour were averaged, and the same was considered for further analysis. Map 6-9 illustrates the islet level shadow cover percentage for 13 to 16 hours local time.

## 6.2.7 Thermal comfort:



*Map 6-10 : islet scale 13 to 16h UTCI data (LWT 7) – Toulouse (Author)*

Map 6-10 illustrates the islet level UTCI data of LWT 7 for 13 to 16 hours local time. Compare to the three summertime LWT Thermal comfort values, LWT 7 has the highest areas with “Very high heat” values. Hence, this LWT was chosen for the analysis. The 250m spatial resolution data was transferred to islet polygons using the majority function in the “Zonal statistics tool”.

### 6.2.8 Sky view factor:

In Hong Kong, a separate study on the SVF and nocturnal heat island was conducted. A 2m resolution digital elevation model (DEM) was generated using building polygons with building height values and topography. This DEM was used as an input to calculate the SVF using Arcgis. A conventional way of calculating SVF, using a fisheye lens camera, was also performed, and both the results were compared (Chen *et al.*, 2012).

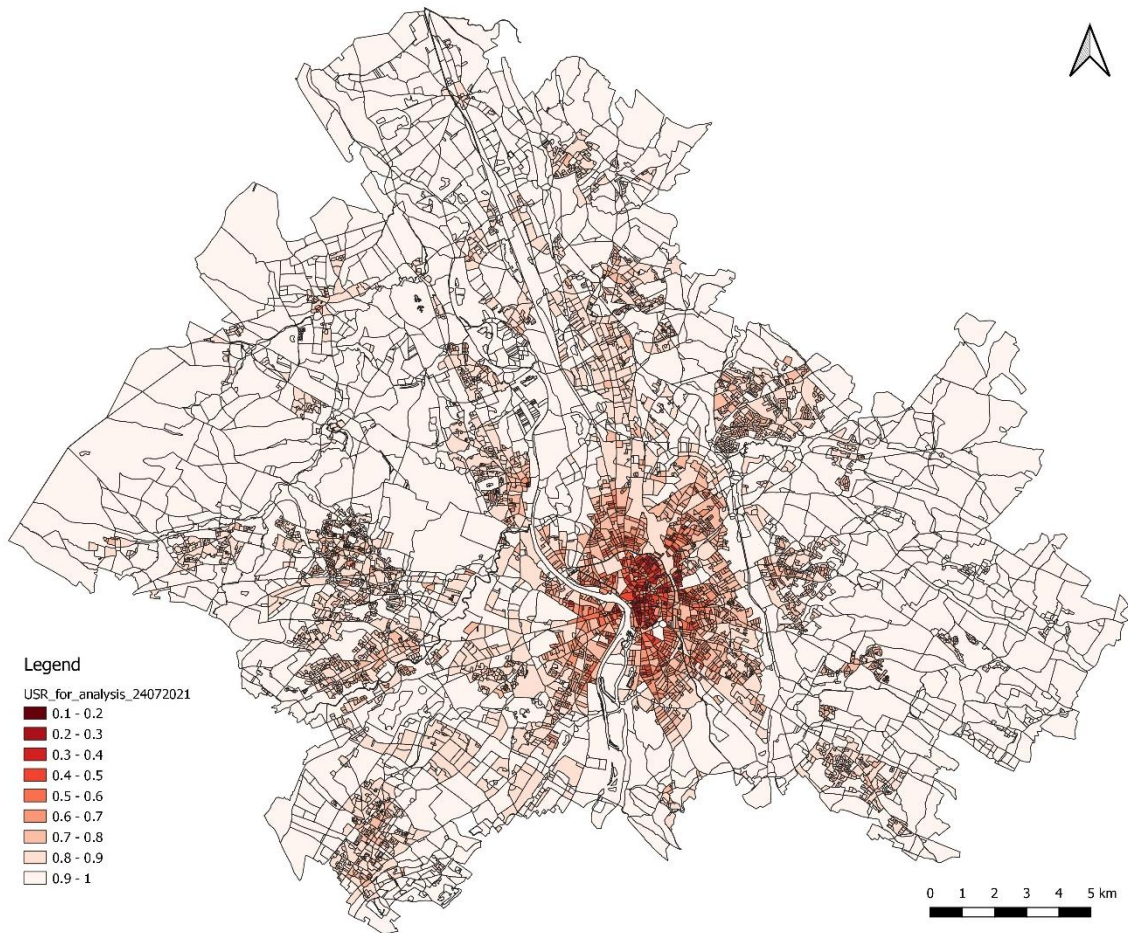
There are two open-source, free GIS tools available for the SVF calculation using raster data. One provided by OrbisGIS and the other by SAGA-GIS. For Toulouse, another freely available GIS tool called the “Ambient occlusion (sky-view factor)” tool was employed to calculate the SVF of the city. Since Toulouse is relatively flat, only the building polygon shapefile with height attribute was used to generate a 2m resolution DEM, and the same was used to calculate SVF. All the buildings in the SVF raster output, provided by the “Ambient occlusion (Sky-view factor)” tool, was assigned with ‘no data’ (Figure 6-4) and using the “Zonal statistics” tool, islet level average SVF was calculated (Map 6-11). The tool “Ambient occlusion (Sky-view factor)” can be found under “Terrain shading” in QGIS.

Sky view factor - Toulouse



Figure 6-4: Sky view factor output. Ambient occlusion tool result on the left, and on the right sky view factor values after assigning 'no data' for the buildings. (Author)

### Sky view factor - Toulouse



Map 6-11: islet scale sky view factor information (Author)

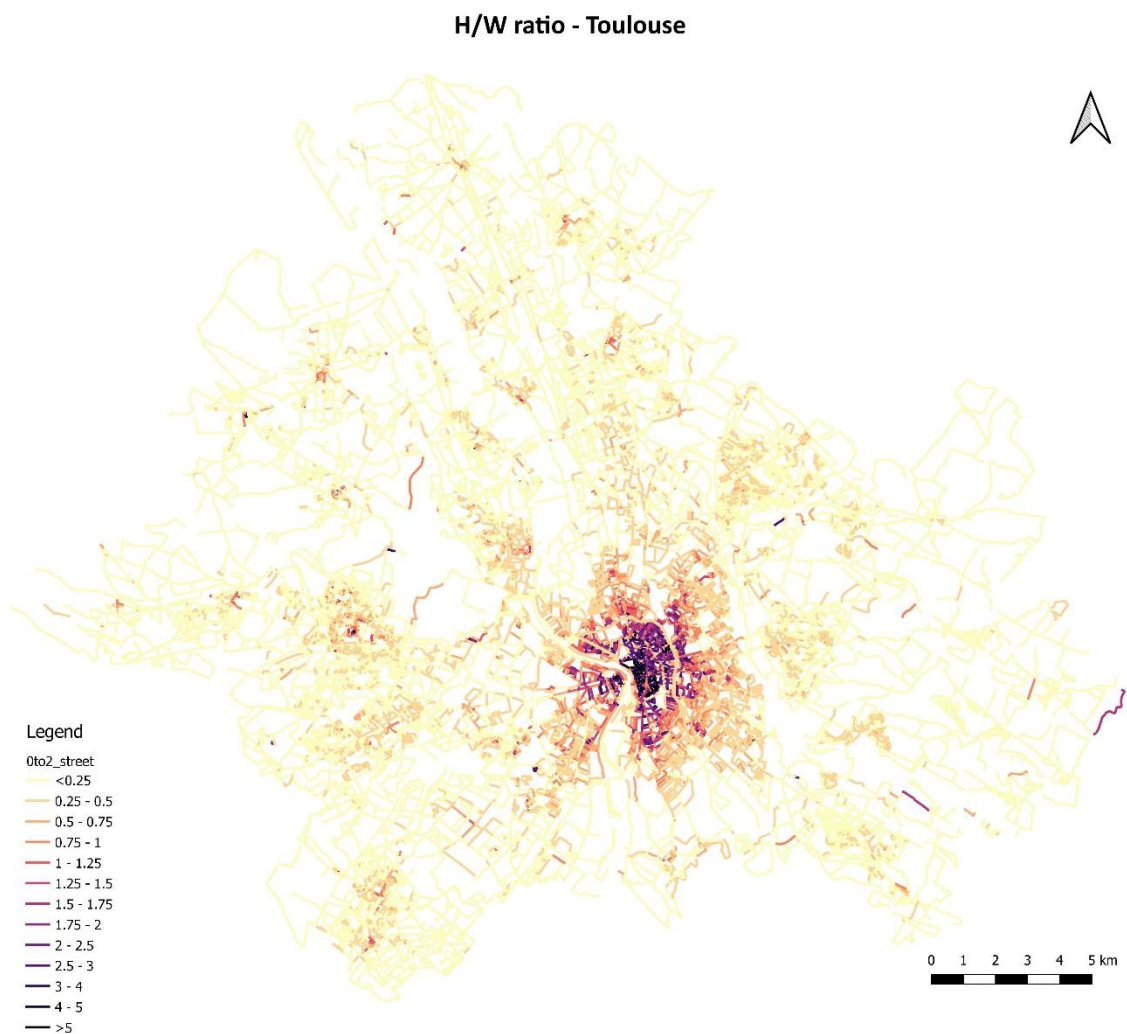
The conventional method of calculating SVF concentrates only on a particular point. However, using GIS, SVF can be calculated for multiple points. The precision of the value depends on the DEM resolution. The higher the input DEM resolution, the higher precision achieved with more SVF value points. For greater precision, it is advised to employ a vector-based method, but it consumes more time to calculate.

#### 6.2.9 Canyon aspect ratio:

Building polygons with building height attributes and road centre lines are the required data for H/W calculation. For Toulouse, an ArcGIS extension developed by CERC (Cambridge Environmental Research consultants ltd), called the ADMS-Street canyon tool was used to calculate this indicator. Street centre line and building polygons were used as input data for the

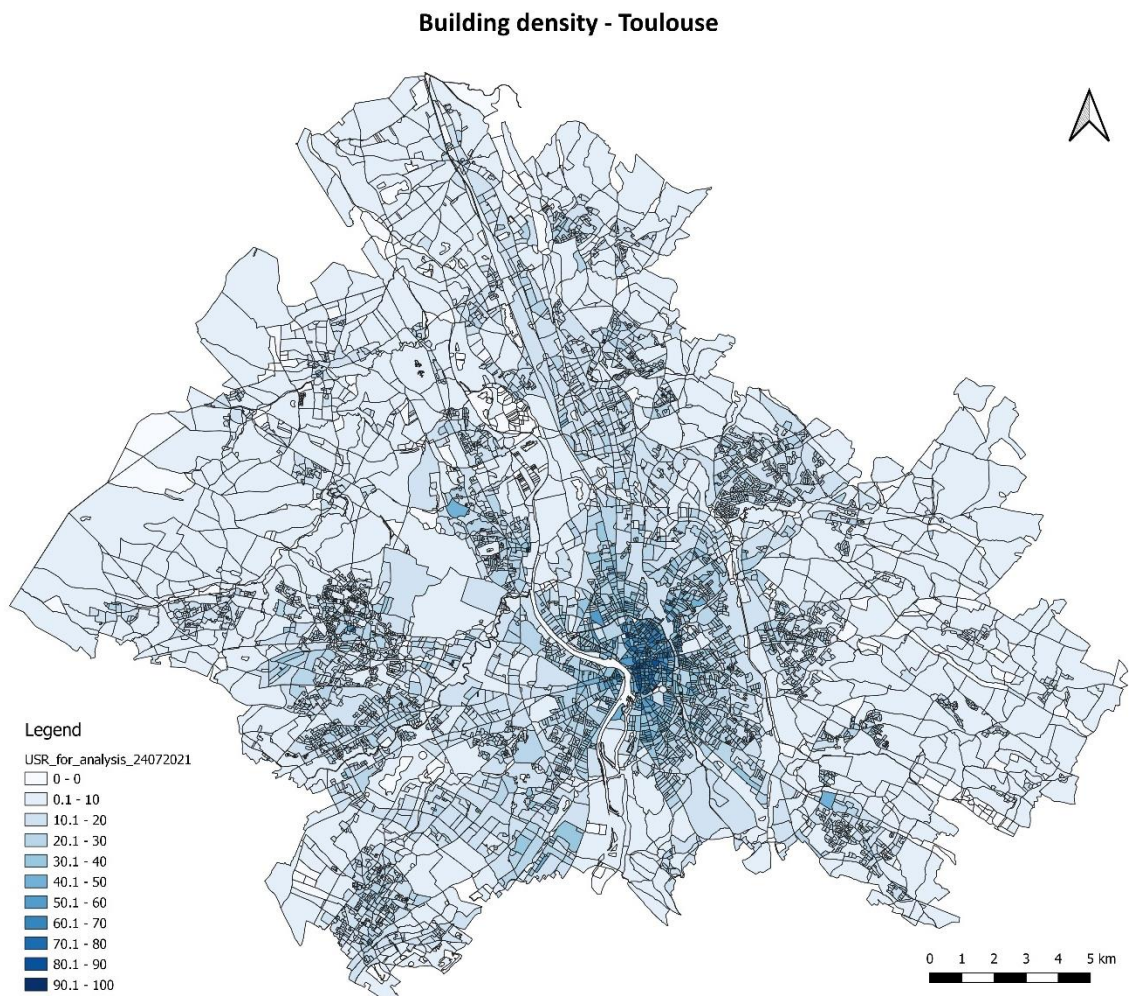
same. The islet polygons were converted into polylines, and they were used as street centre lines. For each street centreline, the tool provides three pieces of information, Canyon height, canyon widths and canyon length. The results of the same are illustrated in Map 6-12.

Since it is not possible to assign these values to the islet polygons. Since, only the buildings adjacent to islet polylines were considered for calculating the H/W ratio, but not the buildings surrounded by other public spaces within the islets, this indicator was not considered for further analysis. As discussed in Chapter 5, SVF can be a substitute for the H/W ratio, and SVF was calculated for every 2m spatial distance covering all the buildings of Toulouse. Hence, only the SVF was considered for further analysis.



Map 6-12: H/W ratio of Toulouse (Author)

## 6.2.10 Building density:



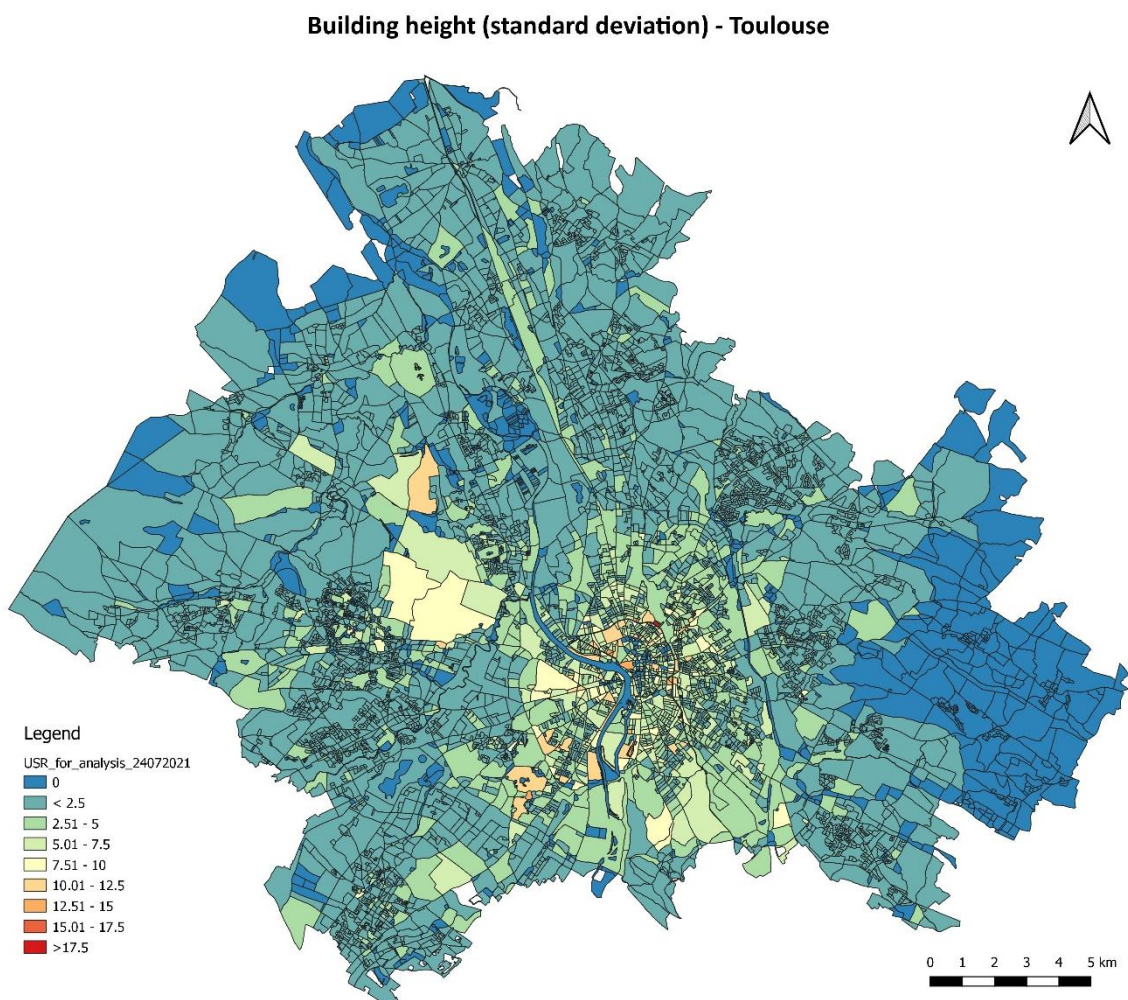
*Map 6-13: islet scale building density values of Toulouse (Author)*

Islet scale Building density data is one among the 64 urban data available under MApUCE Project. The same data was illustrated in Map 6-13.

### 6.2.11 Building Height:

Building height variability is also another indicator studied in Antwerp and Gdansk for identifying air circulation problematic areas. The standard deviation of building heights area was calculated for different areas, that represents building height variation (Badach *et al.*, 2020). Using this as a reference, building height standard deviation was considered for the analysis.

For Toulouse, Islet level building height standard deviation numbers are available, under MApUCE project. The same was illustrated in Map 6-14.



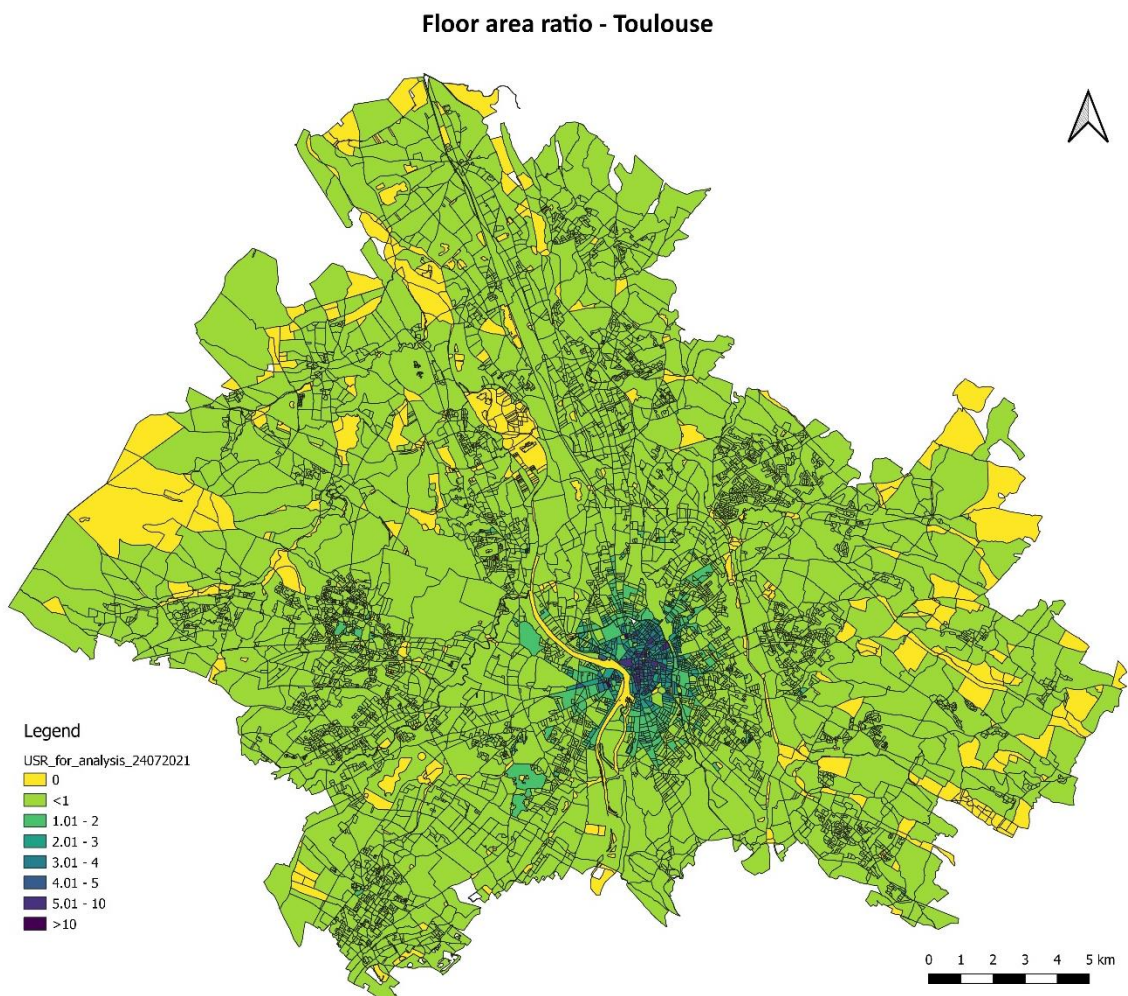
Map 6-14: islet scale building height standard deviation values (Author).

### 6.2.12 Floor area ratio an alternative for roughness length:

Wuhan-China also included Roughness length in their urban climatic maps to estimate the wind profile of the city. The morphometric surface roughness modelling method was used to calculate the roughness length. The roughness length was calculated based on the frontal area density and site coverage ratio (Yuan, Ren and Ng, 2014).

Since the frontal area density or frontal area index is based on the local wind condition, and it is not suitable for the analysis at the municipal scale. Hence, the gross floor area ratio (Gross floor area of the building divided by site area) was used as a substitute for the roughness length indicator. In Antwerp and Gdansk, to identify air circulation problematic areas, floor area ratio was used as a substitute for roughness length and sky view factor (Badach *et al.*, 2020).

Floor area ratio values are available for Toulouse under the MApuCE project, and the same is illustrated in Map 6-15.



Map 6-15: islet scale floor area ratio of Toulouse (Author).

### **6.2.13 Other Indicators:**

Apart from the above-calculated indicators, there are five more indicators identified during phase 1 of this research. They are Thermal diffusivity, Solar reflectance, Solar building exposure, Transport, and Urban permeability.

Since various factors are involved in the quantification of thermal diffusivity and solar reflectance, it is recommended to perform a TEB numerical modelling to calculate the values. Based on the building construction year, building typology, and the city region, the architectural team categorised the building materials under the MApUCE Project. Although this might provide a basic understanding of thermal diffusivity and solar reflectance, it is very much recommended to use building level material data for a more precise analysis. Hence, these two indicators are not considered for further analysis.

Similarly, it is difficult to calculate Solar building exposure using GIS tools. Therefore, this indicator was also not considered for further analysis.

Transportation data is used to understand the air pollution and anthropogenic heat of a particular place. Therefore, fast transit routes were identified from the land use data and the same were marked as air pollution zones. However, for anthropogenic heat calculation, more precise transport data is essential.

To calculate urban permeability, roughness length data is essential. Since it was found difficult to calculate roughness length, this indicator was also not considered for further analysis.



## **Chapter 7. UNDERSTANDING THE REASON BEHIND THE UHI FORMATION IN TOULOUSE**

Thermal and dynamic potential are the two primary analyses performed and represented through UC-Maps in all the referred studies. Apart from the two meteorological indicators, seventeen urban planning and urban design indicators were identified and prepared for further analysis in the first and second phases of the research, respectively. Based on the data availability, few indicators were replaced or combined with other parameters in the second phase. Overall, ten urban planning and urban design indicators were analysed with the two meteorological indicators in phase three of this thesis, using the geographically weighted regression (GWR) method. To perform the analysis, the indicators were arranged in five groups.

The chapter presents the grouping of the meteorological and urban planning & design indicators, the geographically weighted regression (GWR) methodology and results, and a description of how the results can be used for urban planning and urban design decisions.

### **7.1 Grouping the indicators:**

Urban geometry, urban surface thermal properties, anthropogenic heat release, low albedo materials, loss of evapotranspiration, air pollution, and wind are the major cause of UHI (Emmanuel and Fernando, 2007) (Chapter 2). The literature study, performed to identify the indicators during phase one, informed that there are five causes for the UHI formation in cities. The five causes are reduced evaporation, increased heat storage, increased net radiation, reduced convection, and increased anthropogenic heat (Gartland, 2008) (Chapter 5). Based on the causes of UHI, the results of the two research phases, and the availability of data, the indicators were arranged into five groups (Table 7-1).

Out of five groups, the GWR method was performed in four groups, and the overlay method was performed in the fifth group. However, all five groups are interlinked and overall trying to understand the reason behind the UHI formation in Toulouse, except group 3. Group 3 is trying to understand the impact of UHI, wind, vegetation, and building geometry on Thermal comfort. The below table illustrates the five groups and followed by a brief description of the groups.

Group 1: Nocturnal UHI	Group 2: Nocturnal Wind information	Group 3: Thermal comfort	Group 4: Building energy	Group 5: Air pollution
<b>Geographical weighted regression</b>				<b>Overlay method</b>
<ul style="list-style-type: none"> <li>• UHI (3 to 6h)</li> <li>• Wind velocity ratio (3 to 6h)</li> <li>• Vegetation</li> <li>• Sky view factor</li> <li>• Building density</li> </ul>	<ul style="list-style-type: none"> <li>• Wind velocity ratio (3 to 6h)</li> <li>• High Vegetation</li> <li>• Building density</li> <li>• Building height</li> <li>• Floor area ratio</li> </ul>	<ul style="list-style-type: none"> <li>• UTCI (13 to 16h)</li> <li>• UHI (13 to 16h)</li> <li>• Wind speed (13 to 16h)</li> <li>• Building Shadow (13 to 16h)</li> <li>• High Vegetation</li> </ul>	<ul style="list-style-type: none"> <li>• UHI (3 to 6h)</li> <li>• Vegetation</li> <li>• Building density</li> </ul>	<ul style="list-style-type: none"> <li>• UHI (3 to 6h)</li> <li>• Land use</li> </ul>

Table 7-1: Indicators grouping for the analysis (Author)

Group 1:

According to Gartland (2008), the five UHI causes can be associated with vegetation, urban material property, urban geometry, air pollution, and energy use (Chapter 5). Except, energy use and air pollution, Group one is trying to understand the other UHI causes. Due to the shortage of thermal diffusivity and solar reflectance information, SVF was used to understand the net radiation. The relationship between thermal diffusivity, solar reflectance, and SVF was discussed in Chapter 5. Apart from SVF, building density was also analysed in this group. SVF and building density represents urban building geometry. Therefore, UHI is the dependent variable, and the other four indicators are independent variables.

Group 2:

Reduced convection is one of the causes of UHI (Gartland, 2008), and to understand this, the data on wind velocity was included in group 1. However, in cities, urban building geometry reduces the wind speed (Gartland, 2008). Out of all the identified urban planning and urban design indicators, roughness length and building height variation are the two indicators that were associated only with wind information (Chapter 5). Since calculating roughness length was found difficult using GIS tools, the floor area ratio was used instead of roughness length (Chapter 6). Apart from roughness length and building height variation, building density and tall vegetation also have an impact on wind speed (Chapter 5). Hence, these four indicators become independent variables, and the wind velocity ratio will act as a dependent variable in group 2.

The study conducted to identify air circulation problem areas in Antwerp and Gdansk is the base for this grouping. Building density, Floor area ratio, Tall vegetation (Trees) cover, and Building height variation (standard deviation of building height) are the indicators used to identify the air circulation problem areas (Badach *et al.*, 2020).

#### Group 3:

Group 3 is tries to understand the impact of UHI, wind, urban building geometry, and tall vegetation on the thermal comfort of the city. Building shadow pattern represents the urban building geometry in this group. Trees and building shadows have positive benefits on thermal comfort (Chapter 5). In this group, UTCI act as a dependent variable and the other four parameters are independent variables.

#### Group 4:

Anthropogenic heat is another cause of UHI. This group tries to understand the relationship between the UHI and anthropogenic heat release. The increase in building energy use increases the anthropogenic heat (Gartland, 2008). Apart from building energy use, the heat generated by the vehicles also contributes to the anthropogenic heat numbers (Chapter 5). However, the building energy use and transportation data are not available. Instead, tall vegetation around the building was correlated with UHI. Higher the tall vegetation around the building, the lesser the energy use, and the higher the building density, the higher the energy use (Chapter 5). Since the building density and UHI were analysed in group 1, the same analysis was not repeated in this group again. The independent variable is tall vegetation around the buildings, and the dependent variable is UHI.

#### Group 5:

This group helps to understand the relationship between UHI and air pollution. Air pollution increases net radiation, and that leads to UHI formation (Gartland, 2008). But, the air pollution data was not available. The air pollution values were assumed based on land use (Chapter 6). The generated air pollution map was overlapped with the UHI map, to understand its contribution to the UHI formation. Since the air pollution map was generated based on certain assumptions, the GWR was not performed for this group.

## 7.2 GWR and ArcGIS:

As mentioned in Chapter 4.2.3, correlation and regression techniques are generally used to understand the relationship between the two variables. For this thesis, the Geographically Weighted Regression (GWR), a local regression method, was performed to identify the indicators responsible for the UHI effects at the islet level.

“Everything is related to everything else, but near things are more related than distinct things”, is the first law of geography. The influence of the independent variable on the dependent variable might be stronger in some areas compared to other areas. GWR is a linear regression technique in the spatial form to analyse the spatial relationship between the independent and dependent variables (Sun *et al.*, 2019). Compared to the global regression methods, such as Ordinary Linear Regression (OLS), GWR provides a more localised and better fit (Zhao *et al.*, 2018).

Different urban climatic studies have used this technique to identify the spatial relationship between meteorological variables and the urban elements. To inform urban planners about the local cooling effect due to the urban vegetation structure and its spatial arrangements, the GWR technique was used in Melbourne (Sun *et al.*, 2019). Similarly, GWR was used to establish the relationship between land surface temperature and different land surface properties, such as land cover and urban morphology, in Austin and San Antonio, Texas, to identify the obvious landscape property relating to the surface UHI (Zhao *et al.*, 2018). The spatial relationship between leaf area index, topography and climate variables were understood using GWR in Haihe catchment, China (Zhao, Yang and Zhou, 2010).

In ArcMap's, the GWR tool can be found inside “Modelling spatial relationship” within “Spatial statistics tools”. Toulouse islet shapefile, with all the indicators values in the attributes, was selected as the input feature. The attribute column containing values of nocturnal UHI (3 to 6h\_LT), the wind velocity ratio (3 to 6h\_LT), and UTCI (13 to 16h\_LT), were chosen as dependent variables for analysing group 1 and 4, group 2, and group 3, respectively. Based on the group that was analysed, the attributes of the listed variables in each group were selected as explanatory variables.

The GWR ArcGIS tool provides different outputs. A shapefile with attribute values of Local  $R^2$ , Coefficients and standard errors of the explanatory variable, Deviance residual, predicted, etc., is the main output generated through this tool. The  $R^2$  values of the indicators, under each group, presented as maps in Chapter 7.3.

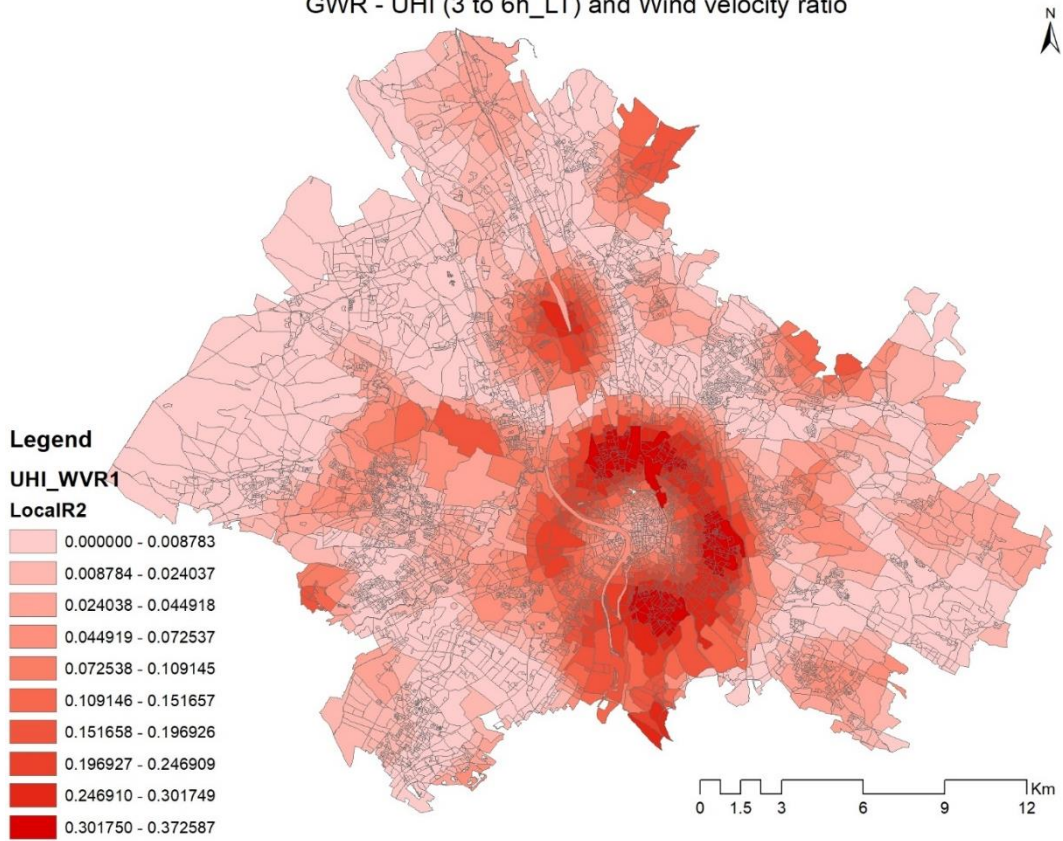
### **7.3 Results:**

This is the result section of the Phase 3 research, conducted to identify the indicators responsible for climatic issues at the islet level, using the GWR technique. The  $R^2$  value represents the percentage of the relationship between the dependent and the independent variable. The higher the  $R^2$  number, the higher the correlation between the dependent and independent variables. In the map, higher  $R^2$  islets are marked in a darker colour, and the lesser  $R^2$  islets are marked in a lighter colour. Higher the goodness of fit, if the colour is darker. The colour shade and their corresponding  $R^2$  values are present in the legends of each map.

#### **7.3.1 Group 1:**

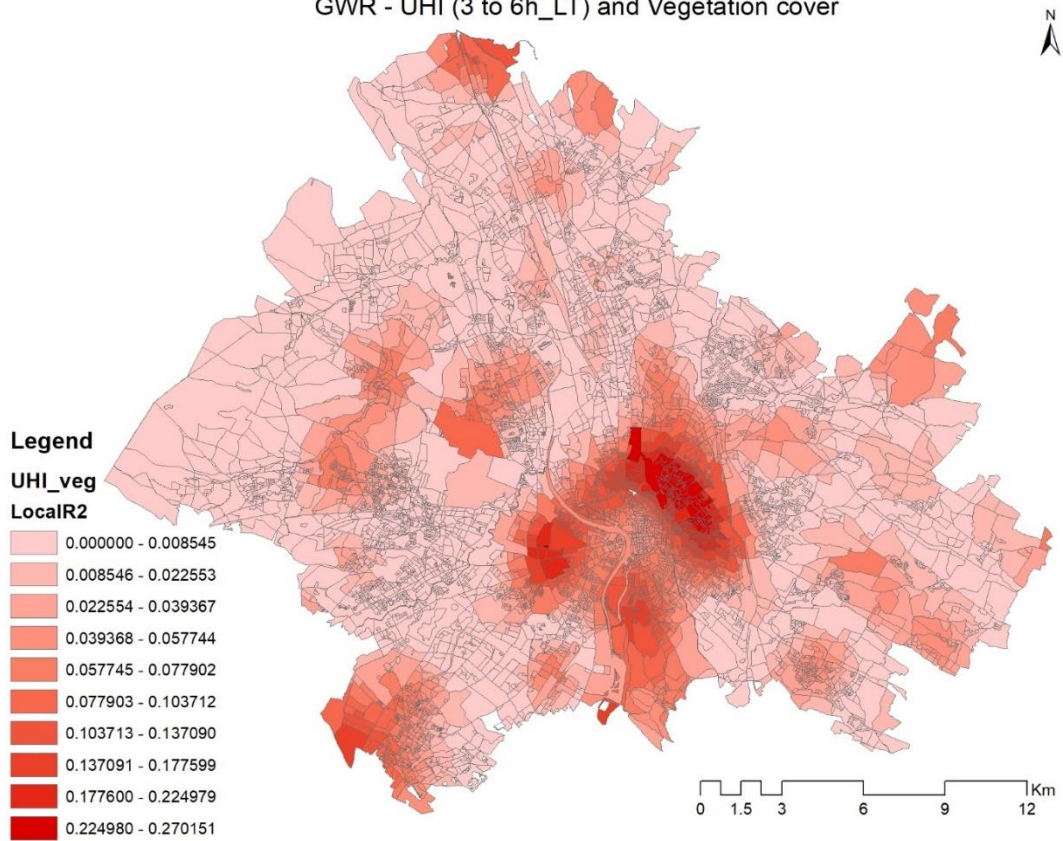
Map 7-2, Map 7-1, Map 7-4, and Map 7-3 are the GWR linear regression results, performed using group one indicators. Overall, Urban building geometrical indicators have the highest  $R^2$  values in certain islets, compare to the other two indicators. The highest  $R^2$  number of SVF and building density are 0.657 and 0.672 respectively.

GWR - UHI (3 to 6h\_LT) and Wind velocity ratio

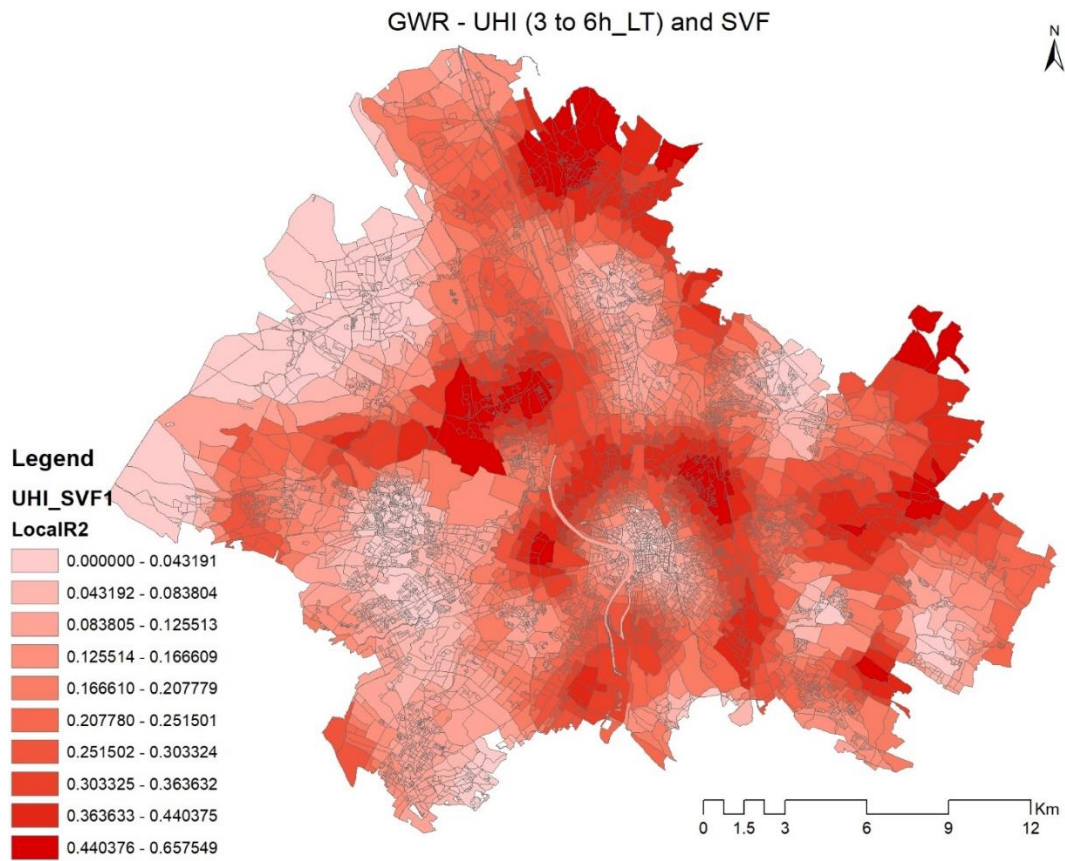


Map 7-2: GWR linear regression analysis – Nocturnal UHI and Wind velocity ratio (Author)

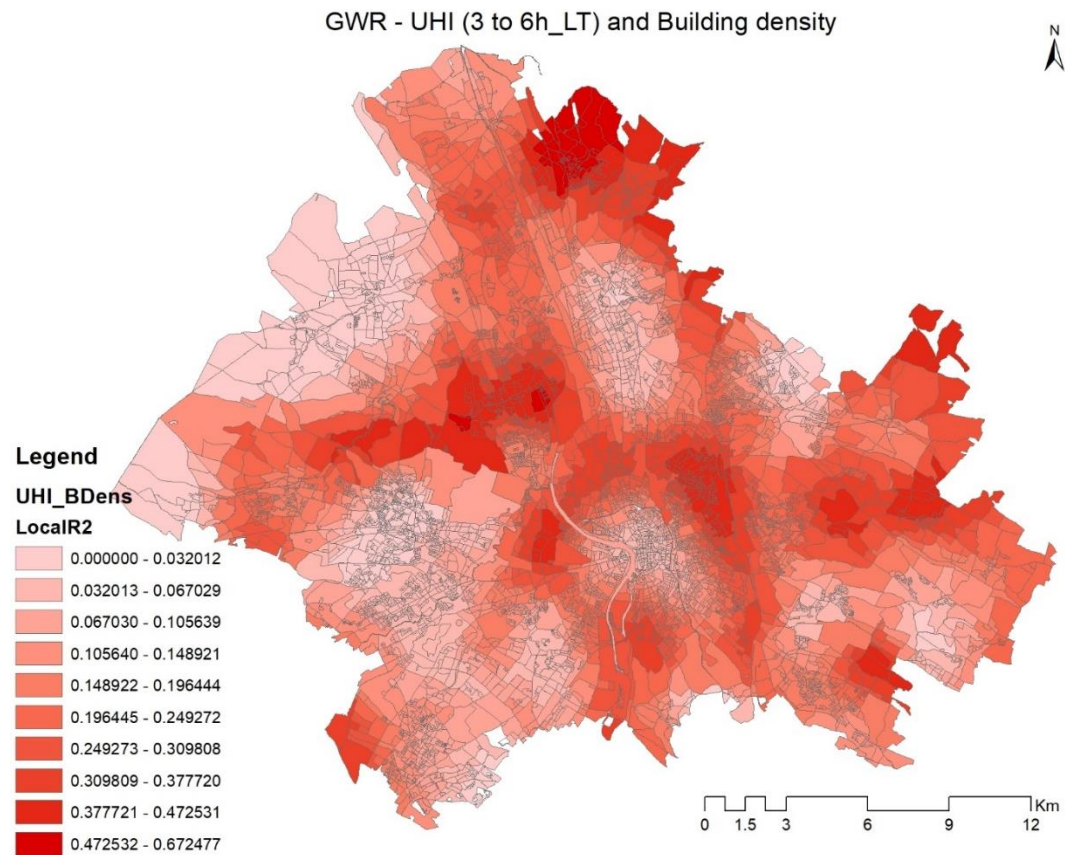
GWR - UHI (3 to 6h\_LT) and Vegetation cover



Map 7-1: GWR linear regression analysis – Nocturnal UHI and vegetation cover (Author)



Map 7-4: GWR linear regression analysis – Nocturnal UHI and Sky view factor (SVF) (Author)

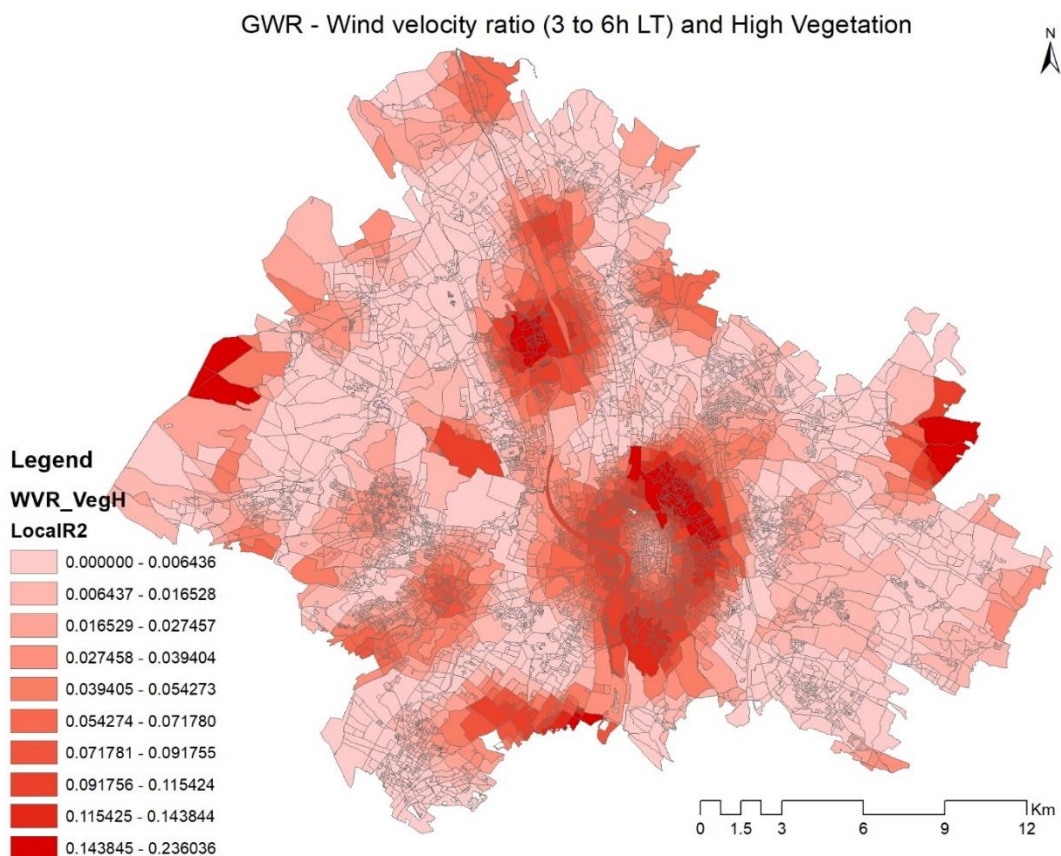


Map 7-3: GWR linear regression analysis – Nocturnal UHI and Building density (Author)

### 7.3.2 Group 2:

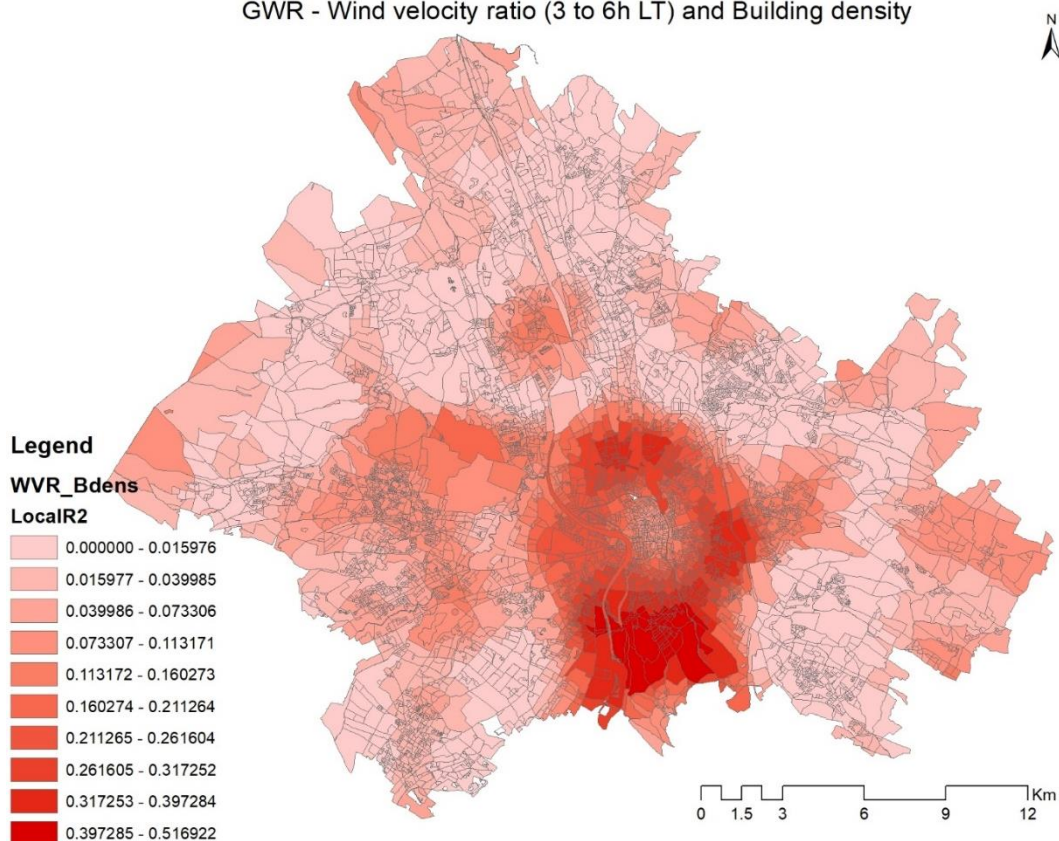
The four maps presented in this section, Map 7-5, Map 7-7, Map 7-6, and Map 7-8, are the results of GWR linear regression, performed using the listed indicators under group 2 (Table 7-1).

Overall, it can be concluded that the urban building geometry has the highest responsibility for the wind velocity ratio numbers compare to the High vegetation cover. The highest  $R^2$  values of building density, building height variation, and floor area ratio, as independent variables, are 0.516, 0.583, and 0.433, respectively.



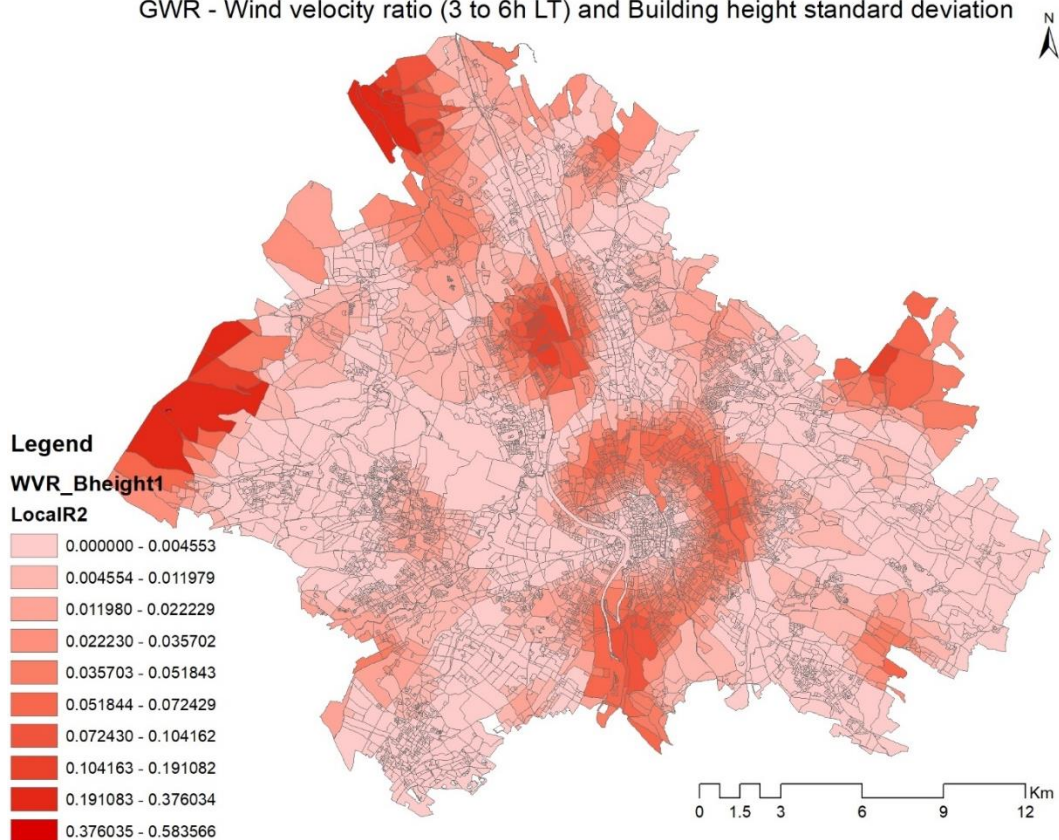
Map 7-5 : GWR linear regression analysis – Wind velocity ratio and High vegetation cover (Bush and trees)  
(Author)

GWR - Wind velocity ratio (3 to 6h LT) and Building density

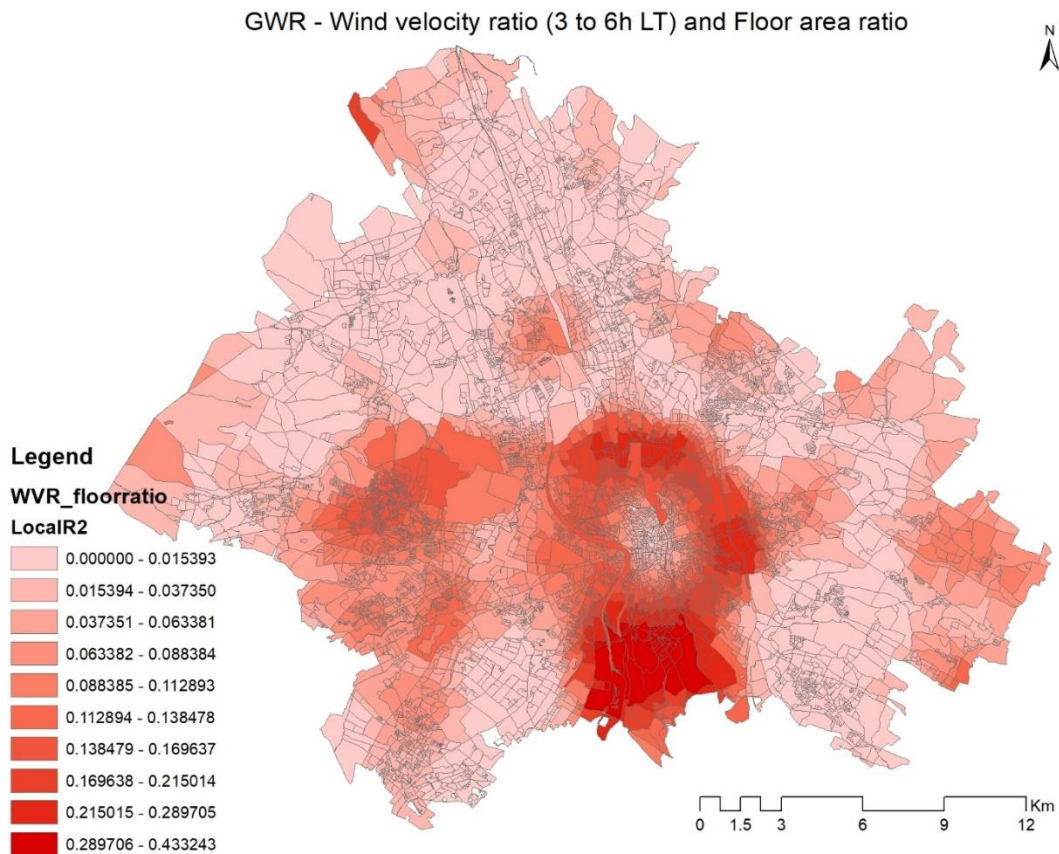


Map 7-7: GWR linear regression analysis – Wind velocity ratio and Building density (Author)

GWR - Wind velocity ratio (3 to 6h LT) and Building height standard deviation



Map 7-6: GWR linear regression analysis – Wind velocity ratio and Building height variation (standard deviation) (Author)

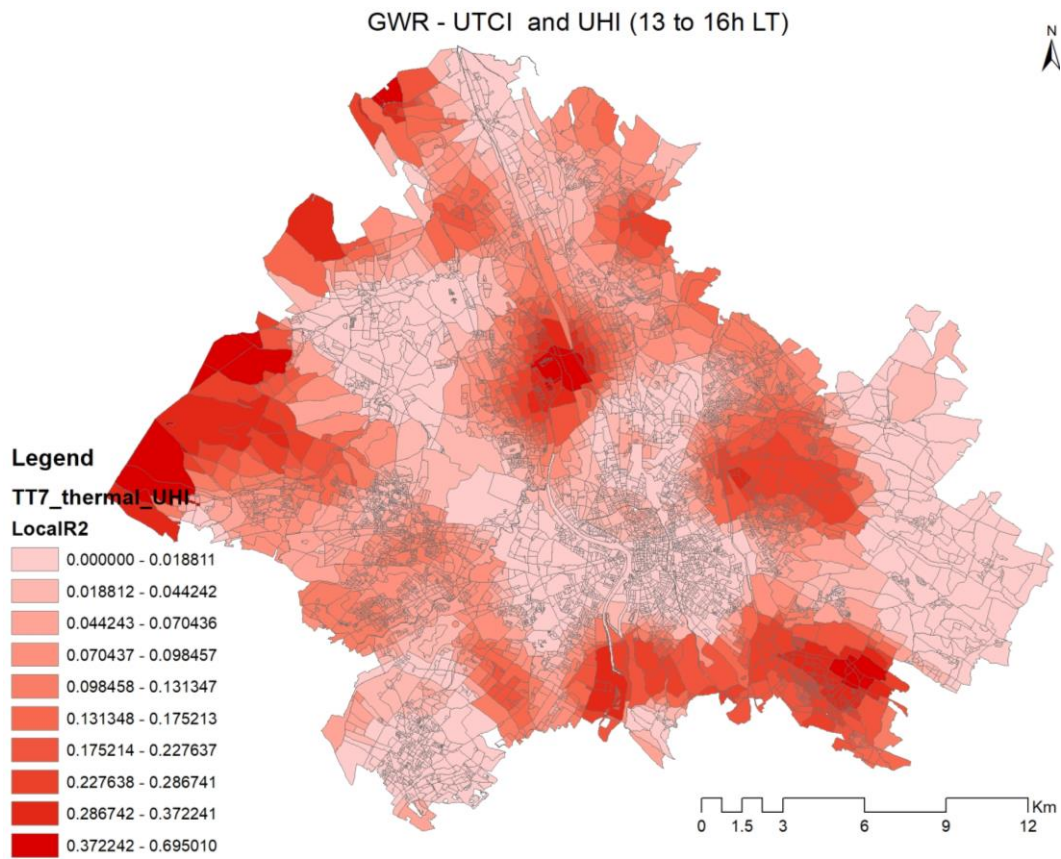


Map 7-8: GWR linear regression analysis – Wind velocity ratio and Floor area ratio (Author)

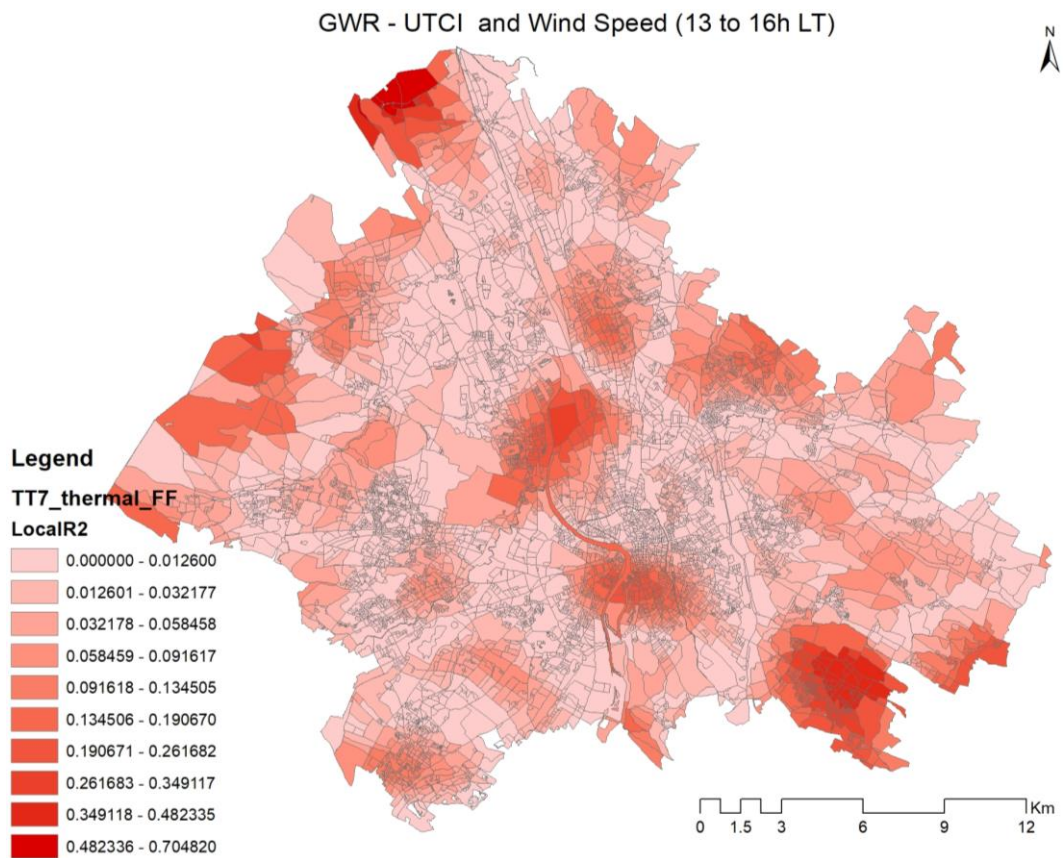
### 7.3.3 Group 3:

The impact of the indicators, listed under group 3 (Table 7-1), on the thermal comfort was understood using GWR linear regression technique and Map 7-10, Map 7-9, Map 7-12, and Map 7-11 are the results.

Certain islets have 0.695 and 0.704  $R^2$  numbers, which corresponds to UHI and wind speed, respectively. These are the highest  $R^2$  numbers compare to the  $R^2$  values of building shadow and high vegetation cover. Overall, it can be concluded that UHI and wind speed are more responsible for thermal comfort than the urban building geometry and High vegetation cover.

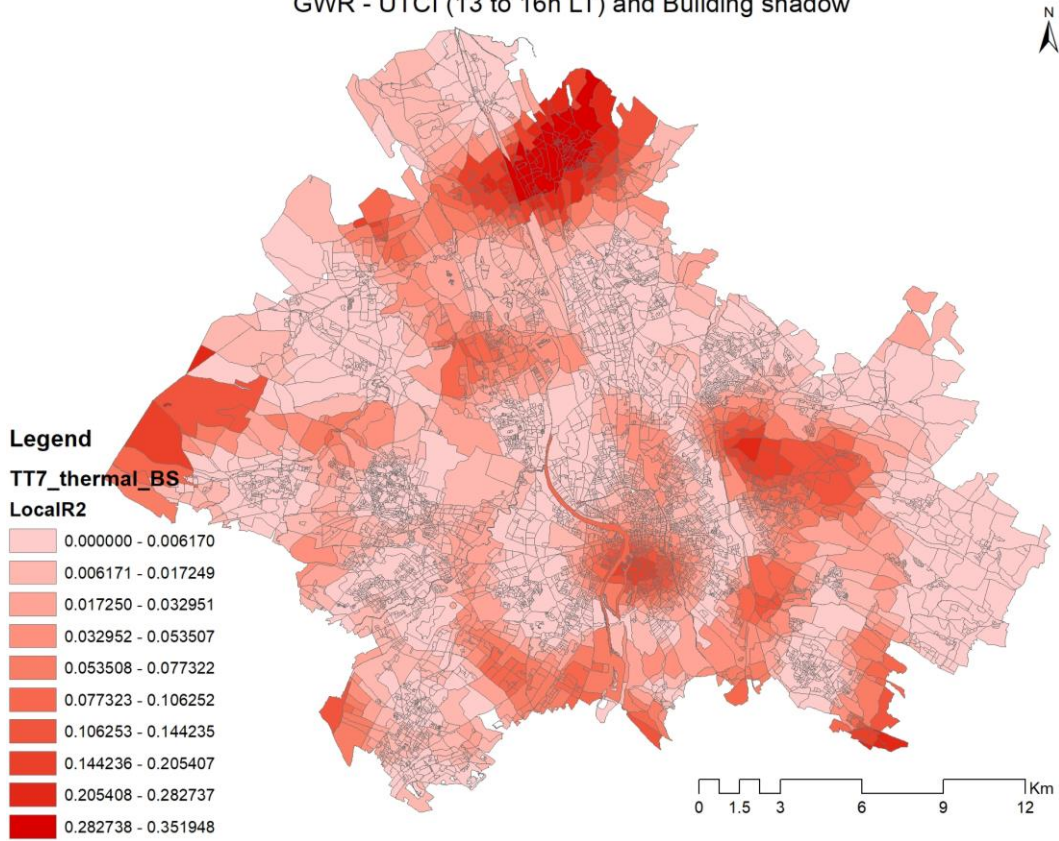


Map 7-10: GWR linear regression analysis – UTCI and UHI (Author)



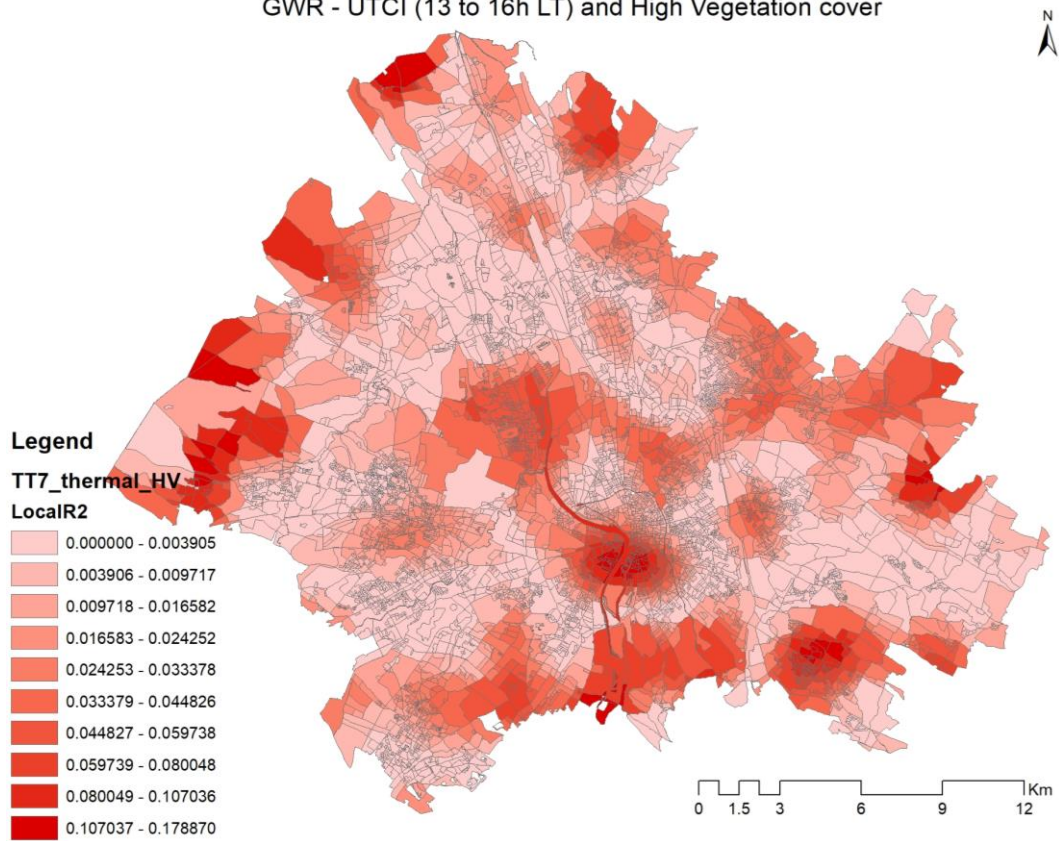
Map 7-9: GWR linear regression analysis – UTCI and Wind speed (Author)

GWR - UTCI (13 to 16h LT) and Building shadow



Map 7-12: GWR linear regression analysis –UTCI and Building shadow (Author)

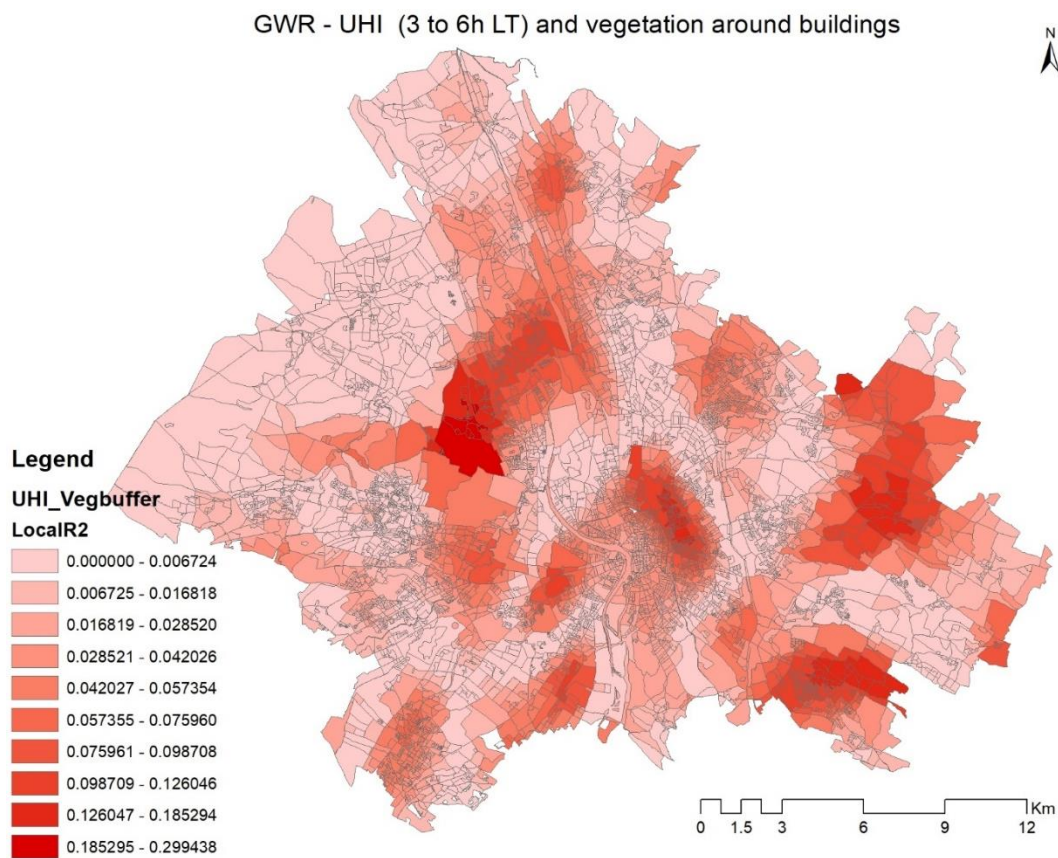
GWR - UTCI (13 to 16h LT) and High Vegetation cover



Map 7-11: GWR linear regression analysis – UTCI and High vegetation (Trees & Bush) (Author)

### 7.3.4 Group 4:

Map 7-13 is the GWR linear regression result performed using high vegetation cover around the buildings as the independent variable and nocturnal UHI as the dependent variable. The highest  $R^2$  value is 0.299. Overall, it can be concluded that this indicator is not a good fit. From this, it cannot be concluded that building energy use has the least effect on the UHI and the actual building energy use data for a more precise conclusion. But overall, the high vegetation cover around the buildings has a less impact on the nocturnal UHI.

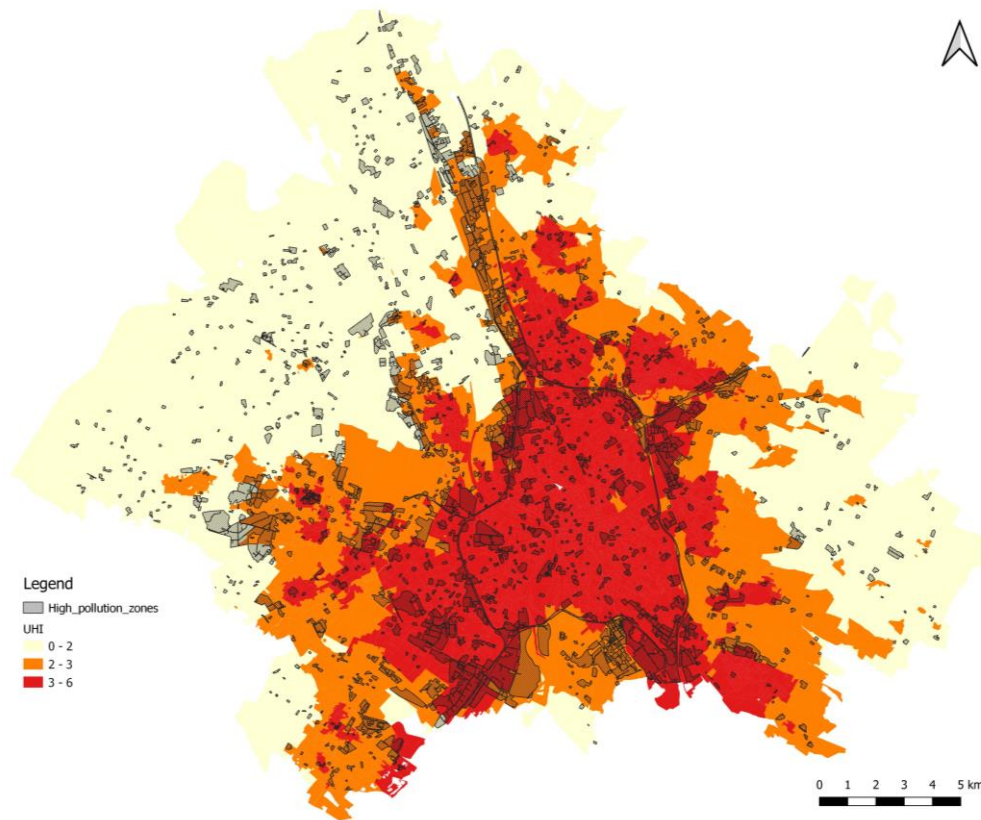


Map 7-13: GWR linear regression analysis – Nocturnal UHI and High vegetation around the buildings  
(Author)

### 7.3.5 Group 5:

The air pollution zones were overlapped on the nocturnal UHI islet scale map to understand the impact of air pollution on the nocturnal UHI effect (Map 7-14). From this, it was noticed that the majority of the air pollution zones, including the heavy mortar ways, falls within the islets with 2 to 6-degree Celsius UHI. A spatial air pollution data is required for a precise conclusion.

### Air pollution zones overlapped with Nocturnal UHI



Map 7-14: Air pollution zones of Toulouse overlapped with islet scale Nocturnal UHI data

## 7.4 Results interpretation and discussion:

Based on the climatic data produce under the MAPUCE project, researchers at LISST have already identified that the area around the city centre experiences the most thermal discomfort during summertime. The nocturnal UHI reaches up to 6 degrees Celsius under LWT 9 weather conditions (Hidalgo et al. no date). The wind velocity ratio at this particular zone is very low. Hence, this particular zone was chosen to explain, how the phase three results could be used for urban planning and design decisions.

From the group 1 GWR results, it can be concluded that the urban building geometry has a greater impact on the nocturnal UHI effects since building density and SVF  $R^2$  values are greater compared to the other two indicators in the zone around the city centre. However, compared to the other islets in the city, the  $R^2$  value of wind velocity ratio is high in the islets within the thermal discomfort zone.

According to the group 2 wind velocity ratio GWR results, the  $R^2$  value of building density and floor area ratio is high in the thermal discomfort zone, compared to the other group 2 indicators.

UHI and wind speed have a high  $R^2$  value, overall, when analysed against thermal comfort. But Building shadow has the highest  $R^2$  value in the thermal discomfort zone, compared to all the group 3 indicators. Only fewer air pollution zones fall within the thermal discomfort zone.

Therefore, it can be concluded that urban building geometry has the highest responsibility for the issue identified around the city centre area.



## **Chapter 8. LIMITATIONS AND FUTURE WORKS:**

This thesis has successfully demonstrated how to make an urban climatic map useful for the urban planning and urban design community. However, some of the identified indicators are not considered in the analysis due to a lack of data. For accurate results, the missing data has to be generated and included in the analysis.

Compare to the other climatic maps produced worldwide, the results obtained through the demonstrated approach answers the two identified research questions by pointing out the urban planning and design elements that are most responsible for the climatic issue at the urban block level. However, the reliability of these results is unknown. Hence, it is essential to devise a method or framework to assess the reliability of these results. Also, a validation of the entire approach is required. Although the thoughts and viewpoints of the target group were considered during the first phase, feedback and comments from them on the usefulness of this approach and results is very important.



## **Chapter 9. CONCLUSION:**

Overall, this research explored how to generate spatialized urban and climatic information, that can be useful for urban planning and urban design decisions.

This research act as a reference for the urban planning and urban design professionals, who do not have any climatic knowledge but are responsible for the climatic issues in the city. This research is also useful for urban climate professionals, who are trying to convey the urban climatic issues to urban planning and urban design community through cartographic representation.

The first phase of this research provides appropriate climatic knowledge to the urban planning and urban design community by providing information about the urban elements responsible for the modification of atmospheric variables. Using this part of the research as a reference, urban planners and designers can able to make appropriate climate responsive decisions. This phase also informs the urban climatic community about the relevant indicators that should be included in the urban climatic maps to make them useful for urban planning and design communities.

Different GIS tools were identified and explained to calculate the identified indicators in the second phase. This teaches the urban professionals to calculate different indicators without relying on expensive software and tedious traditional calculation techniques.

The third phase of the research demonstrated a method to explain the relationship between the indicators through cartographic representation. This phase results also provide some useful pieces of information to the French urban professionals who are trying to mitigate or reduce the climatic effects in Toulouse.



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## Chapter 11. APPENDICES

### 11.1 Appendix – Urban information available for around 40 French cities:

Attribute Column	Description
insee_individuals	Number of inhabitants
insee_menages	Number of resident households
insee_men_coll	Number of households in collective housing
insee_men_surf	Cumulative surface area of main residences (in sqm)
insee_surface_collectif	estimate of the surface area of collective housing
vegetation_surface	sum of the areas of vegetation zone intersecting the USR
route_surface	sum of road surfaces intersecting the USR
route_length	sum of road lengths intersecting the USR
sidewalk_length	sum of sidewalk lengths intersecting the USR
hydro_surface	sum of water surfaces intersecting the USR
hydro_length	sum of the lengths of the hydrographic section intersecting the USR
floor	sum of floor areas
floor_ratio	ratio between the sum of the floor areas and the area of the USR
compac_mean_nw	unweighted average of building compactness
compac_mean_w	weighted average (by the area of the buildings) of the compactness of the buildings
contig_mean	average of the adjoining buildings
contig_std	standard deviation of building adjacency
main_dir_std	standard deviation of the main direction of buildings
h_mean	average building height
h_std	standard deviation of building height
p_vol_ratio_mean	average passive volume
b_area	sum of building areas
b_vol	sum of building volumes
b_vol_m	average building volumes
build_numb	number of buildings
min_m_dist	Minimum of the minimum distance between the buildings of the USR
mean_m_dist	Average minimum distance between USR buildings
mean_std_dist	Average standard deviation of distances between buildings in USR
b_holes_area_mean	average area of holes in RSU blocks
b_std_h_mean	average height of blocks
b_m_nw_compacity	unweighted average of the compactness of the blocks
b_m_w_compacity	weighted average (by the area of the blocks) of the compactness of the blocks
b_std_compacity	block compactness standard deviation
dist_to_center	distance, in meters, between the USR centroid and that of the municipality to which it belongs
build_dens	building surface density
hydro_dens	area density in water
veget_dens	surface density of vegetation zone
road_dens	road surface density
ext_env_area	sum of exterior surfaces (free, in contact with air) of buildings
ba	percentage of "Activity Building" in the USR
bgh	percentage of "Tall Buildings" in the USR
here	percentage of "Continuous Building on Closed Island" in the USR
icio	percentage of "Continuous Building on Open Island" in the USR
id	percentage of "Discontinued Building" in the USR
local	percentage of "Local" in USR
pcif	percentage of "Continuous Pavilion on Closed Island" in the USR
pcio	percentage of "Continuous Flag on Open Island" in the USR
pd	percentage of "Discontinued Flag" in the USR
psc	percentage of "Semi-Discontinuous Pavilion" in the USR
typo_maj	majority typology in the USR
typo_second	secondary typology in the USR

## 11.2 Appendix - Best climate responsive Urban planning and Urban design practices:

Cities Known for Best Climate responsive Urban design Practices		
French Cities	Marseille Euromediterranee	Frontignan
<b>Context and Emergencies</b>	<ul style="list-style-type: none"> <li>Urban renewal</li> </ul>	<ul style="list-style-type: none"> <li>Urban redevelopment (former Sulfur refinery)</li> </ul>
<b>Summery</b>	<ul style="list-style-type: none"> <li>Sustainable development</li> <li>Low energy consumption</li> <li>Water management</li> <li>Low carbon mobility</li> <li>Access to services</li> <li>Controlled overall cost</li> </ul> <p><b><u>Sustainable development concepts:</u></b></p> <ul style="list-style-type: none"> <li>Public transport</li> <li>Public space improvement</li> <li>Qualification of vegetation</li> <li>Energy performance of buildings</li> <li>Park to solve flooding</li> <li>Street orientation and alignment</li> <li>Bio climatic architecture</li> <li>Roof and wall reflections were assessed</li> <li>Comparison between park and other areas</li> <li>TEB model used for working on the orientation.</li> </ul>	<ul style="list-style-type: none"> <li>Ecological approach</li> <li>Recapture of biodiversity</li> <li>Water management</li> <li>Low emission modes of travel</li> <li>Bioclimatic building approach</li> <li>Renewable energies</li> <li>Storm water management</li> <li>Atmospheres in urban spaces (light, wind, etc.)</li> <li>Waste management</li> </ul> <p><b><u>Major constrains:</u></b></p> <ul style="list-style-type: none"> <li>Orientation (sunshine of plots &amp; prevailing winds)</li> <li>Storm water retention</li> <li>Mobility &amp; accessibility</li> <li>Demolition of sulfur refinery</li> </ul> <p><b><u>Site climate protection:</u></b></p> <ul style="list-style-type: none"> <li>Strong sunshine</li> <li>Prevailing winds</li> </ul> <p><b><u>Climatological studies carried out:</u></b></p> <ul style="list-style-type: none"> <li>Solar study</li> <li>Aerodynamic study</li> <li>Vegetation included in both solar and aerodynamic study</li> </ul> <p><b><u>Local approach needed in scales:</u></b></p> <ul style="list-style-type: none"> <li>Urban spaces</li> <li>Islets</li> <li>Interior spaces of buildings</li> </ul> <p><b><u>Major climate phenomenon studied:</u></b></p> <ul style="list-style-type: none"> <li>UHI</li> <li>Aerodynamic turbulence (outdoor space &amp; facades)</li> </ul> <p><b><u>Amplified by certain urban forms:</u></b></p> <ul style="list-style-type: none"> <li>Low relative air humidity</li> <li>Modified wind flow fields</li> <li>Air pollution</li> <li>Reduction of solar radiation</li> <li>Increased diffuse radiation</li> </ul> <p><b>Urban geometric analysis to find the best geometry using SOLENE</b></p>

Cities Known for Best Climate responsive Urban planning Practices				
French Cities	Paris	Lyon	Grenoble	Agen
Context and Emergencies	Heat wave (2000) 2004 Heat Plan from public health perspective.	Fight against greenhouse effect Heat wave (2003) 2007 climate change energy plan	2005 local climate action plan	Integration of Energy and climate issues
Summery	<p><b>Grenelle Act:</b> Tool to collaborate climatologists and planners.</p> <p><b>Adaptation strategies to reduce UHI:</b> Vegetation program Material change Water (refreshment)</p> <p><b>EPICEA Project:</b> The objective is to quantify the impact of climate change at city and building level to propose adaptation strategies. Urban climate change Extreme heat wave situation study Link between Urban planning and urban climate</p> <p><b>MUSCADE Project:</b> Urban modelling and climate change adaptation strategies to anticipate energy demand and production.</p>	<p>Soft mobility Energy control Sustainable development</p> <p><b>Actions identified in the -</b> Companies Transport Habitat Very old energy climate plans Energy component of the energy plans</p> <p><b>General development context:</b> Renewable energy Energy efficiency Performance of the buildings Fight against fundamental changes</p> <p><b>AMICA:</b> Reduce greenhouse gas emission Global warming mitigation measures (albedo &amp; vegetation)</p> <p><b>Reports to developers to fight Heat islands:</b> Albedo Materials Plant integration</p>	<p>Reduce co2 Reduce per capita energy consumption Achieve renewable energy Solve summer comfort problems Neighborhood and building studies. Municipal buildings summer evolution – Green &amp; Concrete Energy data is important to be considered before planning an urban project</p> <p><b>Factor 4 plan (2008-2014):</b> Thermal improvement of social housing Renovation Energy rehabilitation Plans for heat improvement program Reduce greenhouse gas emission Expand tram networks Develop innovative mobility Cycle facilities Soft modes and public transport</p> <p><b>National project (eco-city):</b> City vegetation process Sustainable management</p> <p><b>Actions related to climate consideration in urban planning:</b> Easy to access water table Heat pumps to cool off summers Avoiding air conditioning Grand boulevards Thermal improvement operation of existing building Renovation program – ventilation &amp; insulation system</p> <p><b>Priority interventions:</b> Winter and summer comfort Vegetation Water cycle Mode of energy production Accessibility and parking Air quality and noise pollution</p>	<p>Components of climate Energy performance Greenhouse gas reduction Energy consumption Water and vegetation as a means of heat mitigation</p> <p><b>Development guidelines:</b> Renewable energy Eco-construction Implementation of Bio-sourced materials Building energy performance Rainwater recovery system Use of geothermal energy</p> <p><b>Possibility of valuing solar inputs:</b> Orientation of the parcel Exposure of building facades Renewable energy production needs Bio climatic design Sun light inside the building Protection against solar radiation Risk of summer over heating Collective spaces Interior of building Prevailing wind should be over looked Limiting the energy loss &amp; consumption.</p>

### 11.3 Appendix – International case studies:

S.No	Cities	List of parameters used	Summary
1	<b>Tokyo, Japan</b>	<ul style="list-style-type: none"> <li>• <i>Surface temperature</i></li> <li>• <i>sensible heat from covering surface</i></li> <li>• <i>latent heat for ventilation</i></li> <li>• <i>Land use</i></li> <li>• <i>Topography</i></li> <li>• <i>anthropogenic heat release</i></li> <li>• <i>Building Land ratio</i></li> <li>• <i>Building height</i></li> </ul>	<p><i>Through the maps, areas with high and low thermal loads were identified, and the reason behind it was also mentioned.</i></p> <p><i>Three main causes for the night time temperature that does not fall below 25 deg celsius were identified in Tokyo. They were artificial heat waste, Land cover, and Ventilation. Based on the causes, the 23 wards are categorised into ten regional types.</i></p> <p><i>The urban canopy model was developed for the analysis. As a counter measure, Water-retention paving, Rooftop greenery, grassing over the school grounds, and water sprinkling activity were carried out.</i></p>
2	<b>Yokohama, Japan</b>	<ul style="list-style-type: none"> <li>• Temperature</li> <li>• Wind direction</li> <li>• Wind velocity ratio</li> </ul>	<p>Using the urban climate map, summer patterns were analysed using the listed parameters and three pieces of advice for effective use of sea breeze, effective use of ventilation, and effective greening were provided.</p>
3	<b>Beijing, China</b>	<ul style="list-style-type: none"> <li>• Pollution percentage</li> <li>• Thermal comfort</li> <li>• Wind information</li> <li>• Temperature intensity</li> <li>• UHI</li> </ul>	<p>Providing the scientific basis for the urban planning decision-making process was set as the aim. A multiscale model approach was adopted, urban scale and sub-domain scale. Areas affected due to UHI intensity were identified, and greening was recommended for mitigation. Necessary analysis using wind information was also performed.</p>
4	<b>Osaka, Japan</b>	<ul style="list-style-type: none"> <li>• Terrain</li> <li>• Wind</li> <li>• Land use, categorised by surface temperature change pattern</li> <li>• Observed temperature</li> </ul>	<p>A three-step process was followed in the making of UC-Maps. UC-AnMap were prepared, interviews with local government officials were performed, and based on the interview response UC-Remap were produced.</p> <p>Department of Rivers and channels, Department of green space, Department of urban planning, and Department of environmental activists were the target departments for the interview. Following questions were asked to the four departments, What are all the urban climate-related work performed by the department? Under what situations the</p>

			<p>UC-Maps will be used? What kind of information should be included in the UC-Maps?</p> <p>Based on the interview responses, recommended areas for restoring water channels, conserving green areas, using sea breezes, reducing anthropogenic heat release, and areas of the psychological feeling of coolness, were included in the example UC-ReMap. A detailed map, 1:2500 scale, was prepared with information related to building, trees and associated wind patterns for the urban planning department.</p>
5	<b>Ho Chi Minh city, Vietnam</b>	<ul style="list-style-type: none"> <li>• Land use map</li> <li>• Building volume to heat storage</li> <li>• Greenery to heat budget</li> <li>• Openness to ventilation</li> <li>• Roughness to wind speed</li> <li>• Topographical information</li> </ul>	<p>The UC-Maps were generated to improve air quality and thermal conditions.</p> <p>The listed parameters are combined through weighted factors. Building volume and thermal load were added together to describe the amount of overheating. Green space distribution, air transport routes, and cooling capacity were added together to describe the needed mitigation measures for lowering the calculated heat capacity.</p>
6	<b>Wuhan, China</b>	<ul style="list-style-type: none"> <li>• Frontal area density</li> <li>• Roughness length</li> <li>• Zero plane displacement</li> </ul>	<p>The morphological modelling method was used to model urban surface roughness using a three-dimensional building database. The model results were used in different master planning and district planning stages. The surface roughness is used to estimate the wind profile.</p> <p>Using the urban surface roughness, urban permeability was derived to detect potential air paths.</p>
7	<b>Hong kong</b>	<ul style="list-style-type: none"> <li>• <i>Wind speed</i></li> <li>• <i>Wind direction</i></li> <li>• <i>Wind velocity ratio</i></li> <li>• <i>Air temperature</i></li> <li>• <i>Solar radiation</i></li> <li>• <i>Relative humidity</i></li> <li>• <i>Land use</i></li> <li>• <i>Topography</i></li> <li>• <i>Building volume</i></li> <li>• <i>Building ground coverage ratio</i></li> <li>• <i>Building height</i></li> <li>• <i>Permeability</i></li> <li>• <i>Green spaces</i></li> <li>• <i>Ground roughness</i></li> </ul>	<p>Hong kong initiated Air ventilation assessment system for better urban design guidelines. Four issues related to building morphology, Building site coverage, dispersion, height, and permeability, were identified and nine design strategies were recommended.</p> <p>Based on the positive and negative effects of the different morphological layers, they were grouped into thermal and dynamic potentials. Building volume, Topography, and available green spaces were combined to assess the thermal load and Ground roughness, site coverage,</p>

		<ul style="list-style-type: none"> <li>• <i>Site coverage</i></li> <li>• <i>Natural landscape and slopes</i></li> <li>• <i>Proximity to openness</i></li> </ul>	<p>available natural landscape on slopes, and proximity to openness were combined to assess the dynamic potential.</p> <p>Preservation zones, Maintenance zones, and zones where mitigation actions encouraged, recommended, and essential were marked. Planning guidelines related to building volume, building permeability, building site coverage, air paths and breezeways, building heights, and greenery were also provided.</p>
8	<b>Hesse, Germany</b>	<ul style="list-style-type: none"> <li>• Land use</li> <li>• Digital terrain model</li> <li>• Wind information</li> <li>• Urban morphological parameters</li> <li>• Thermal comfort (PET)</li> </ul>	<p>Using Geographical information system (GIS), thermal climatop distribution map, air channel map, and bioclimate maps were generated. Overall, two sets of analysis, thermal and dynamic, were carried. In total, eight climatopes were derived from the UC-An maps, and to study their influence on people, Physiologically equivalent temperatures (PET) were analysed against these eight identified climatopes.</p>
9	<b>Singapore</b>	<ul style="list-style-type: none"> <li>• Sky view factor</li> <li>• Leaf area index</li> <li>• Wind information</li> <li>• Topography</li> <li>• Urban morphology</li> <li>• Vegetation</li> </ul>	<p>Two stages of recommendations were done General climate-based recommendation and areal recommendations in different zones. A weighted average of different layers was used to identify six climatopes, and planning recommendations were provided accordingly. The climatopes are Fresh and cool air production zones, Cool air production zone, Mixed and transitional climate zone, Heat accumulation potential zone, Heat accumulation zone, and overheating zone.</p>
10	<b>Stuttgart, Germany</b>	<ul style="list-style-type: none"> <li>• <i>Meteorological data</i></li> <li>• <i>traffic, domestic, business, and industrial emissions</i></li> <li>• <i>land use</i></li> <li>• <i>geographical data</i></li> </ul>	<p>Climate and Air hygiene are the focus of attention. Similar to other cities, Stuttgart also prepared UC-AnMap and UC-ReMap. Climatopes were defined to help urban planners towards climate sensitive planning. Topographic maps, city maps, Land use maps, and aerial photographs were used to build the UC-AnMap.</p> <p>Cold air production areas, Cold air blockage areas, narrow valley sections, descending winds from slopes, mountain and valley winds, air passages are distinctively categorised in the climatic maps. Along with this air pollution from various sources were also included in the climatic maps.</p>

11	<b>Arnhem, Netherlands</b>	<ul style="list-style-type: none"> <li>• <i>Land use</i></li> <li>• <i>Sky view factor</i></li> <li>• <i>Building volume</i></li> <li>• <i>Digital terrain model</i></li> <li>• <i>Wind information</i></li> </ul>	<p>The listed parameters are classified and calculated based on thermal load and dynamic potential.</p> <p>Urban morphological information, wind information, and topographical conditions were overlapped to create UC-AnMap. Based on this, three built-up area climatops, two greenery area climatopes, one water climatope, and one transport area climatope were identified to generate UC-REMap.</p>
12	<b>Salvador, Brazil</b>	<ul style="list-style-type: none"> <li>• Roughness</li> <li>• Aspect ratio</li> <li>• Building volume</li> <li>• Openness</li> <li>• Green spaces</li> <li>• Exposed soil</li> <li>• Water bodies</li> <li>• Topoclimate</li> <li>• Wind corridors</li> <li>• Thermal comfort (PET)</li> </ul>	<p>Using GIS, three charts were prepared to identify different thermal comfort conditions in different urban areas. Topography, Land use, and wind speed are the three charts that were classified into three, nine and six categories, respectively. Further to generate urban climate maps, these three charts were superimposed. The UC-Map have seven different categories explaining different levels of thermal load and dynamic potential.</p>

