

STREET GREENERY FOR OUTDOOR THERMAL COMFORT.

A CASE STUDY IN PORTO, PORTUGAL.

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Dedicated to every single person who has encouraged me along the way.

“The best time to plant a tree is twenty years ago.

The second-best time is now”

Chinese proverb

RESUMO

O objectivo desta investigação é indagar como o verde urbano pode mudar a sensação térmica exterior em termos de temperatura fisiológica equivalente (PET) num caso de estudo no Porto, Portugal, que consiste numa rua canyon e duas praças (Rua de Pinto Bessa, Largo da Estação, Alameda de Cláudio Carneiro), alterando o microclima da área. O estudo começa com uma revisão bibliográfica sobre o tema do conforto urbano, especificamente sobre alterações climáticas, clima urbano, ambiente exterior (espaços públicos e conforto térmico) e estratégias de atenuação do calor através do verde urbano. Em seguida, o programa de simulação micrometeorológica ENVI-met V4.4.5 Summer20 (com licença científica) é utilizado para simular o efeito do verde urbano sobre a sensação térmica numa rua (Rua de Pinto Bessa) e numa praça (Largo da Estação) do Porto. Diferentes configurações de árvores são testadas em dois dias de Verão (o dia mais quente de agosto e o dia médio de Verão). Os resultados mostram que, em todos os casos, o verde urbano melhora o conforto térmico ao ar livre, baixando os valores de PET (até 12 °C) sob a sombra das árvores, ao mesmo tempo que piora o estresse térmico em regiões ensolaradas (até 6 °C). Este estudo pretende acrescentar aos conhecimentos atuais sobre o potencial do verde urbano para aliviar o stress térmico humano de um ponto de vista humano-biométrico, dando um novo estudo de caso que alarga o leque de aplicações.

PALAVRAS-CHAVE: conforto térmico exterior, temperatura fisiológica equivalente (PET), espaços públicos verdes, ilha de calor urbano (UHI), resiliência urbana, simulação ENVI-met, estudo de caso do Porto.

ABSTRACT

The purpose of this research is to investigate how street greenery can change outdoor thermal sensation in terms of physiological equivalent temperature (PET) in a case study in Porto, Portugal, which consists of one canyon street and two squares (*Rua de Pinto Bessa*, *Largo da Estação*, *Alameda de Cláudio Carneiro*), by altering the microclimate of the area. The study begins with a literature review on the topic of urban comfort, specifically on climate change, urban climate, outdoor environment (public spaces and thermal comfort) and green heat mitigation strategies. Then, the micrometeorological simulation programme ENVI-met V4.4.5 Summer20 (with science licence) is used to simulate the street greenery effect on thermal sensation in a street (*Rua de Pinto Bessa*) and a square (*Largo da Estação*) of Porto. Different tree configurations are tested in two summer days (the hottest day of August and the average day of summer). The results show that for all cases street greenery improves outdoor thermal comfort by lowering PET values up to 12 °C under tree shadow, while worsening the heat stress in sunny regions (up to 6 °C). This study wants to add to current knowledge of the potential of urban greening to relieve human heat stress from a human-biometeorological standpoint by giving a new case study that expands the range of applications.

KEYWORDS: outdoor thermal comfort, physiological equivalent temperature (PET), greening public spaces, urban heat island (UHI), urban resilience, ENVI-met simulation, Porto case study.

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ACRONYMS

ABL - atmospheric boundary layer

C - convective heat flow

CO_2 - carbon dioxide

E_D - latent heat flow to evaporate water into water vapour diffusing through the skin

E_{Re} - amount of heat flows used to heat and humidify the inspired air

E_{Sw} - heat flow due to evaporation of sweat

GHG - greenhouse gas

GHGs - greenhouse gases

$\text{H}_2\text{O}_{(g)}$ - water vapour

IPCC - Intergovernmental Panel on Climate Change

M - metabolic rate

PET - Physiologically Equivalent Temperature

PMV - Predicted Mean Vote

Q_A - net horizontal heat advection

Q_E - convective sensible heat

Q_L - latent heat

Q_r - net radiation

Q_S - stored energy

Q_T - anthropogenic heat

R - net radiation of the body

RCP - Representative Concentration Pathways

RH - relative humidity

S - storage heat flow for heating or cooling the body mass

SET* - Standard Effective Temperature

T_a - air temperature

T_{mrt} - mean radiant temperature

UBL – urban boundary layer

UCL – urban canopy layer

UHI - urban heat island

UTCI - Universal Thermal Climate Index

v - wind speed

VP - water vapour pressure

W - physical work output

$\Delta T_{(u-r)}$ - urban heat island intensity

1

INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

The concept of seeing the city as a living organism in which all elements communicate with one another leads us to study the city in its dynamics in order to comprehend, in a critical and analytical way, how its metabolism works through material and energy flow analysis. Following the living organism metaphor, the components of the urban environment—urban atmosphere, urban biosphere, urban hydrosphere, urban pedo- and lithosphere (soils and geology, respectively), and built system—compose the urban ecosystem and can create ecosystem services (**Error! Reference source not found.**). The urban biosphere, for example, formed of flora and fauna, generates ecosystem services such as regulatory services related to the influence of the city's microclimate and cultural services related to recreation.

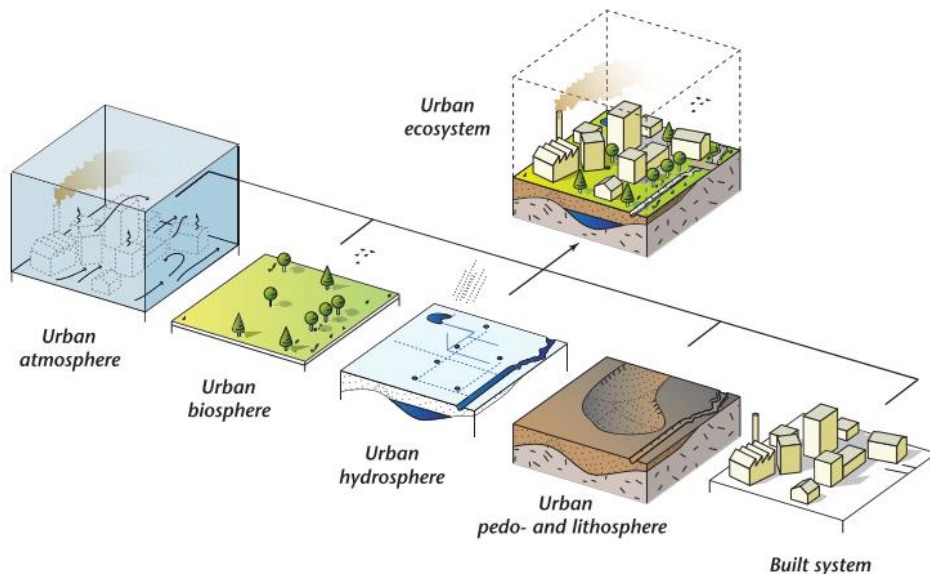


Figure 1. Components that compose the urban ecosystem. Source: (Oke et al., 2017)

Recent climatic changes hastened by human influence have resulted in an increase in the occurrence of extreme events such as heat waves, high sea levels, and heavy precipitation, as well as an increase in global temperatures, influencing the climate situation of cities. Furthermore, cities, which are typically

subject to higher temperatures than surrounding areas due to the heat island effect, are seeing an increase in urban construction and densification, which coincides with the trend of urban population growth, exacerbating the intensity of the urban heat island. During the summer, this additional heat increase caused by climate change exacerbates the already high thermo-climatic conditions in cities, resulting in decreased outdoor human thermal comfort and related public health risk.

Due to the close relationship between the thermoregulatory and circulatory systems, climatic variables such as air temperature, humidity, wind speed, and short and long wave radiation have a thermo-physiological effect on human health. High summertime temperatures in urban areas degrade outdoor comfort conditions and have a detrimental effect on the wellbeing of citizens, placing vulnerable people—children and elderly—under additional heat stress. As a result, cities and academics conducted studies on the topic in attempt to improve outdoor thermal comfort.

Furthermore, Matzarakis & Amelung (2008) found

that the thermal consequences on humans of climate change should have been underestimated. Changes in the overall bioclimatic conditions for humans are expected to be considerably greater than changes in air temperature alone. In most regions of the world, the projected climate change will produce bioclimatic conditions that are more stressful (a PET (physiological equivalent temperature—one of the existing human thermal comfort indices) of more than 35 means extreme hot conditions for Europeans) to people and affect their health and wellbeing. Regions with PET >35°C will be increased compared to present bioclimatic conditions and the possibility of heat waves will also increase. In addition, the changed thermal conditions will lead to higher energy consumption (and higher emissions of greenhouse gases) as a result of the increased need for cooling.

This research emphasises the importance of studying human thermal comfort as well as air temperature when generating future estimates, as well as how thermal comfort changes outdoors in order to prevent thermal stress.

High-density cities frequently suffer from a shortage of green spaces, which have been shown to have a significant impact on improving outdoor thermal comfort, particularly during the summer. Individualizing bioclimatic mitigation strategies through urban design of street greenery is thus required to adapt public outdoor urban spaces to climate change and generate a microclimatic change in order to improve the quality of urban outdoor thermal comfort.

1.2. RESEARCH QUESTION AND METHODOLOGY

A review of literature on the main subjects of urban comfort was performed, covering the most relevant papers from the last 20 years (found by the use of keywords such as outdoor thermal comfort, street greenery, urban green spaces, ENVI-met simulation) available in search engines such as Web of Science, Scopus, and Google Scholar.

The knowledge gathered from the literature research allowed to set the goal of this thesis, which is expressed by the following research question for two squares and one street canyon in Porto, Portugal:

How can street greenery influence human thermal perception modifying the urban microclimate?

The study model was created using geo-informatics systems applications, ArcGIS and QGIS, and then developed in the microclimatic simulation software ENVI-met V4.4.5 Summer20 with a Science license, which was used to simulate the microclimate of the study area and evaluate the outdoor thermal comfort conditions in terms of physiological equivalent temperature (PET) index. All details are available in chapter 4.5.

1.3. STRUCTURE OF THE THESIS

This dissertation is divided into six chapters, the contents of which are depicted in Figure 2.



Figure 2. Structure of the thesis

This study wants to add to current knowledge of the potential of urban greening to relieve human heat stress from a human-biometeorological standpoint by giving a new case study that expands the range of applications. Furthermore, assisting in the study of greenery in urban open spaces leads to regulating and organising open public areas from the standpoints of landscape and urban planning.

2

STATE OF THE ART: THE URBAN COMFORT

2.1. STRUCTURE OF THE CHAPTER

This chapter expose the existing literature on urban comfort in order to gain an overview of the topic. Science research about climate changes is reported to understand how the knowledge on climate change has evolved during the last two centuries (2.2). An insight on urban climate is shown to understand its structure and mechanisms (2.3). The outdoor human thermal comfort in urban environments is explained from the up-to-date state of the art point of view (2.4). Finally, heat mitigation strategies to face climate change and urban heat island are exposed with the focus on the influence of vegetation on the outdoor thermal comfort (2.5).

2.2. CLIMATE CHANGE

2.2.1. FACTORS THAT INFLUENCE CLIMATE CHANGE

The climate of the Earth has changed significantly over its history. The origins of these oscillations have been documented in geological records, demonstrating that the causes of climate change are linked to natural events, such as strength of the sun, variation in orbit, axial tilt and precession of the Earth, amount of greenhouse gases in the atmosphere, ocean currents and content of carbon dioxide, plate tectonics and volcanic eruptions, variation in land cover, and collisions of meteorite. These factors are interconnected: a change in one can cause an increase or decrease in one or more others (British Geological Survey, 2021).

Human activities are driving a change in the structure and functioning of the Earth System, leaving behind them new stratigraphic evidence that is generating a new geological epoch called the ‘Anthropocene’(Crutzen & Stoermer, 2000; Crutzen, 2002). Climate system is included in this human-driven change, and according to the reports of the Intergovernmental Panel on Climate Change, IPCC, “human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate” (IPCC, 2019, p. 4).

Global surface temperature is influenced by four factors: solar variability, volcanic eruptions, internal variability related to *El Niño*/Southern Oscillation, and anthropogenic forcing (U.S. Global Change

Research Program, 2017). The global mean temperature has changed since 1870. However, a sharp increase has occurred from the 1970s especially due to the anthropogenic factor (Figure 3).

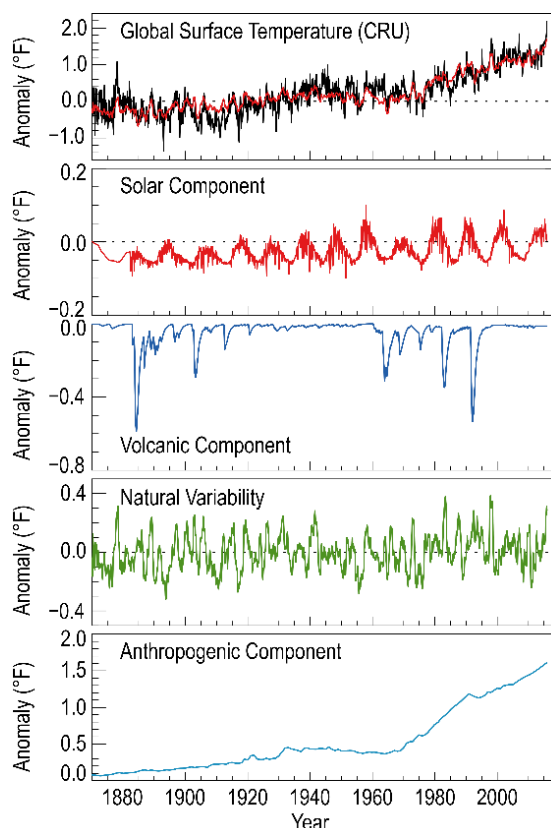


Figure 3. Graphics of temperatures anomaly (F°) in global surface temperature (Climate Research Unit -CRU- data) and its factors: solar, volcanic, natural, and anthropogenic. Source: (U.S. Global Change Research Program, 2017)

Human activities associated with the increase of temperature include “the burning of fossil fuels, deforestation, land use and land-use changes, livestock production, fertilisation, waste management and industrial processes”, and produce anthropogenic emissions composed by “greenhouse gases (GHGs), precursors of GHGs and aerosols” (IPCC, 2019). GHG emission growth started with the Industrial Revolution, continues today, and is expected to increase in the future, being related to global economic and population growth. GHG emissions must be reduced to avoid a rise of the global mean surface temperature of 3.7°C-4.8°C by 2100 if no further mitigation measures are put in place (IPCC, 2014b, p. 8). The IPCC (2014c) studied multiple mitigation pathways that are likely to reduce warming to less than 2°C over pre-industrial levels. These pathways illustrate potential climate future scenarios based on the amount of GHGs emitted in the coming years as a result of various levels of mitigation, which necessitate technological, economic, social, and institutional implementations.

Emissions scenarios leading to CO₂-equivalent concentrations in 2100 of about 450 ppm or lower are likely to maintain warming below 2°C over the 21st century relative to pre-industrial levels. These scenarios are characterized by 40 to 70% global anthropogenic GHG emissions reductions by 2050 compared

to 2100, and emissions levels near zero or below in 2100. Mitigation scenarios reaching concentration levels of about 500 ppm CO₂-eq by 2100 are more likely than not to limit temperature change to less than 2°C, unless they temporarily overshoot concentration levels of roughly 530 ppm CO₂-eq. (IPCC, 2014c)

Figure 4 depicts the features of emission scenarios, their CO₂-equivalent concentrations, and their likelihood of limiting warming to a range of temperature values.

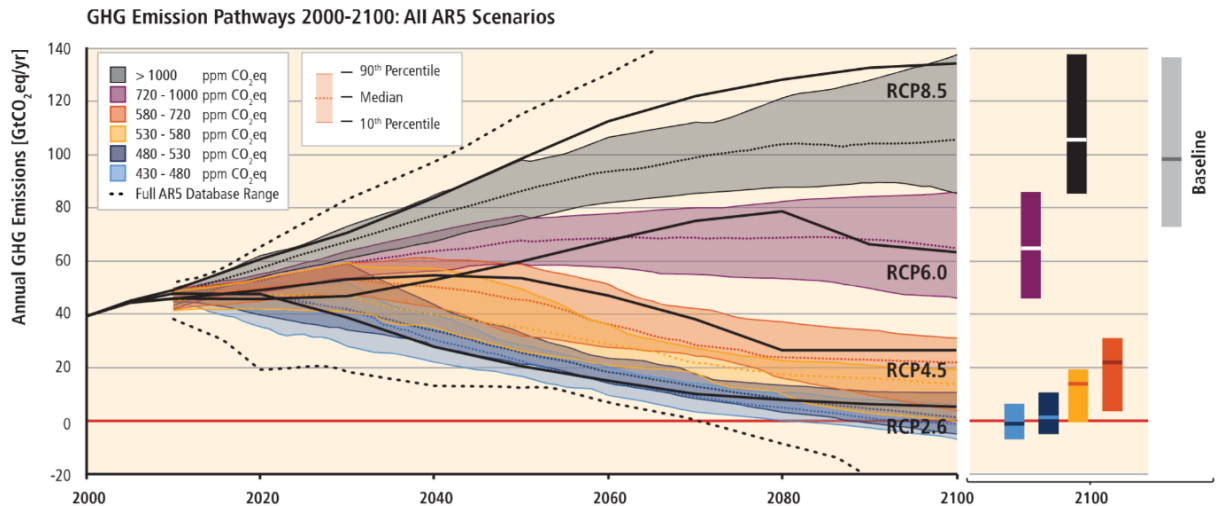


Figure 4. GHG (greenhouse gas) Emission Pathways between 2000 and 2100, with all possible scenarios of CO₂-equivalent concentrations, and their likelihood of limiting warming to a range of temperature values. The acronym RCP stands for Representative Concentration Pathways, and the number stands for the possible range of radiative forcing values (W/m²) in the year 2100. Source: (IPCC, 2014b, p. 11)

2.2.2. SCIENTIFIC RESEARCH ABOUT CLIMATE CHANGE

The research process has been going on for two centuries and is still in progress. It started in the 1820s when Joseph Fourier, a French mathematician and physicist calculated the temperature of the Earth through the fluxes of energy coming from the sun. He discovered that the temperature on the Earth is higher than it should be, and he supposed that the atmosphere might provide an insulating effect preserving the heat from being reemitted into space. For the first time in scientific history, the Greenhouse concept was proposed (ACS, 2015a). Subsequently, the Swedish chemist and physicist Svante Arrhenius (1896) demonstrated that carbon dioxide (CO₂) and water vapour (H₂O_(g)) presented in the atmosphere cause the greenhouse effect that warms the Earth. Arrhenius first sustained that the combustion of coal might expand the warming action of the greenhouse effect and increase Earth's temperature (ACS, 2015b), introducing in the scientific environment the idea that human activities might change earth dynamic equilibria.

The core of scientific research on environmental global changes had been developed during the 20th century. The environmental scientist Erle C. Ellis exposed in his book *Anthropocene: A Very Short Introduction* (2018) the major steps that brought to a worldwide consciousness of the 'human-induced global environmental changes'. The first evidence was given by Charles David Keeling (1960). Keeling

first discovered the Earth's breathing cycle and the increasing concentration in the atmosphere of CO₂ over years, studying the concentrations of the CO₂ in the atmosphere in Mauna Loa, Hawaii. The breathing cycle is the seasonal oscillations of CO₂ concentration in the atmosphere, and it is caused by plant growth cycles, while the increasing concentration of atmospheric CO₂ is principally generated by the fossil fuel combustion and it is caused by human activities. The measurements from Mauna Loa Observatory generated the *Keeling Curve*, where both seasonal oscillations and the man-driven trend are recognisable (Figure 5). The second evidence was the damage and reduction of the protective ozone layer of the Earth by the nitrous oxide gas (Crutzen, 1970), and by the chlorofluorocarbons gases (Molina & Rowland, 1974). The first is naturally produced by bacteria of the soil and present in man-made fertilizers, and the seconds are artificially produced by humans. These gases interact with the ozone layer deteriorating it. This deterioration decreases the filter capacity of the ozone layer, and the ultraviolet radiation, harmful for biological life, is able to reach Earth's surface through the *Antarctic Ozone Hole* (Farman et al., 1985; Solomon, 2019).

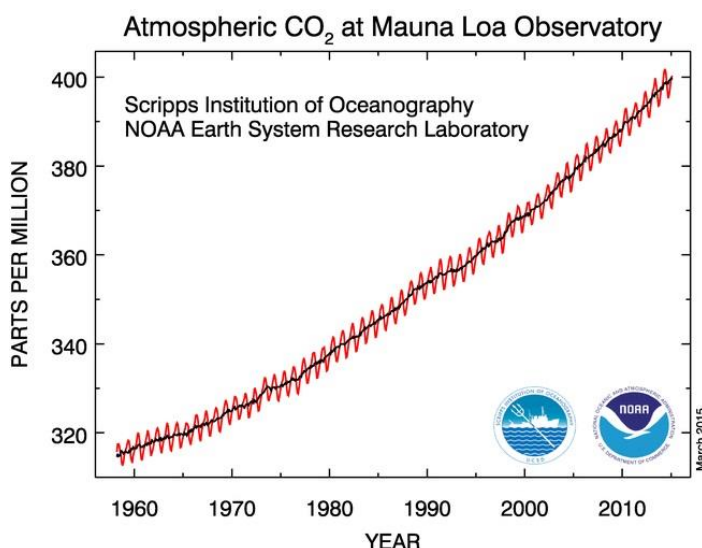


Figure 5. The Keeling Curve. Plot of atmospheric CO₂ measurement from Mauna Loa Observatory showing seasonal oscillations by plant growth cycles (red line) and increase over years by human activities (fossil fuel combustion). Source: (ACS, 2015a)

The increasing awareness in the scientific community of the risks associated with the increasing concentration of carbon dioxide and the disruption of the ozone layer led to the formation of international research coordination for global and regional changes. Conferences, programmes, and organizations were funded in the last second half of the XX century, from the *UN Environmental Programme*, and the *World Climate Research Programme*, to the *International Geosphere-Biosphere Programme*, and the *Intergovernmental Panel on Climate Change* (Ellis, 2018).

By the 1990s, improvements of technology and computer simulations of materials and fluxes of energy between the Earth spheres—lithosphere, hydrosphere, biosphere, and atmosphere—have provided new and robust evidence of a causal correlation between human activities and the change of climate (Ellis, 2018). “Anthropogenic global environmental change as a complex, multi-causal, system-level set of processes affecting the entire Earth system” and “Anthropogenic global environmental change was a

multidimensional process. Moreover, interactions among its many dimensions and cascading effects from the local to the regional and ultimately to the global might lead to unanticipated consequences for the Earth system as a whole” is said in the *Amsterdam Declaration on Global Change* (Pronk, 2002, as cited in Ellis, 2018). The scientific group of the International Geosphere-Biosphere Programme (Steffen et al., 2004) and W. Steffen *et al.* (2015) studied human activities for the period 1750-2010. The teams studied the trajectory of twenty-four indicators, twelve related to socio-economic human activities and twelve related to the structure and functioning of the Earth System. Their results showed that, from the Industrial Revolution, socio-economic and Earth system trends started slowly rising till the 1950s when an almost hyperbolic growth appeared (Figure 6). This ‘Great Acceleration’ provides another piece of evidence that human activities are the cause of global climate changes (Steffen et al., 2004, 2015).

Socio-economic trends

Earth system trends

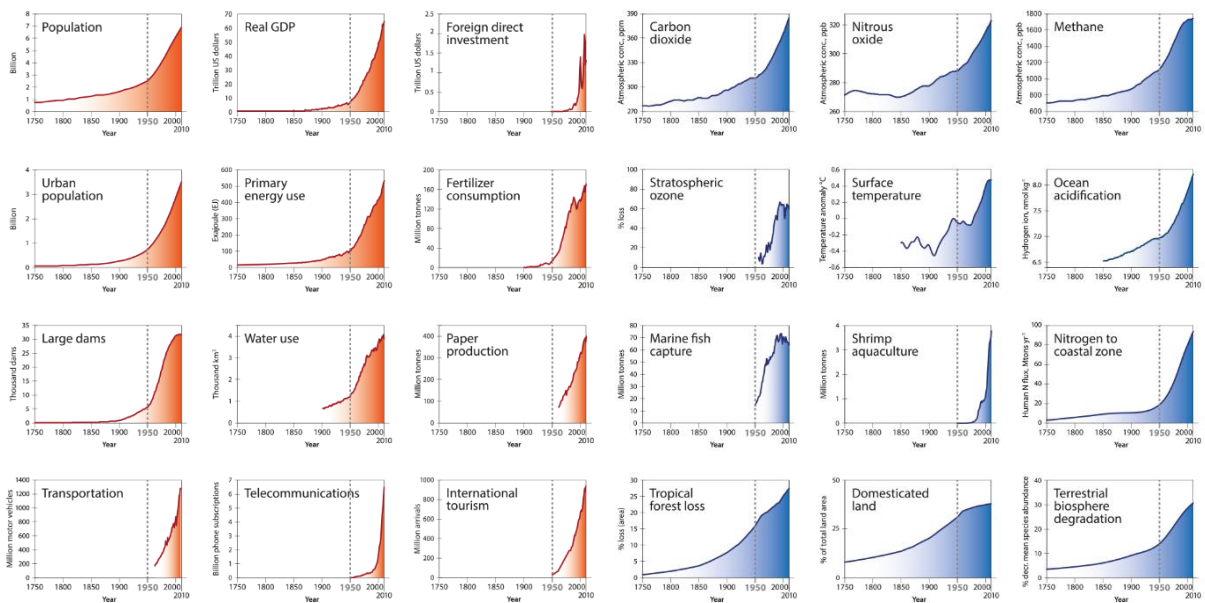


Figure 6. Graphics of the trajectory of the global socio-economic and the Earth system indicators from 1750 to 2010. Source: (Steffen et al., 2015)

Studies on the Antarctic ice cores gave us information about atmospheric GHGs concentration and temperature over the last 800,000 years. Evidence showed that CO₂ concentration had a stable cycle over the last millennium except from the early XIX century (BAS, 2014). Since the Industrial revolution CO₂ concentration increased reaching the concentration of 415 ppm in November 2020, as shown in Figure 7 (NASA, 2020).

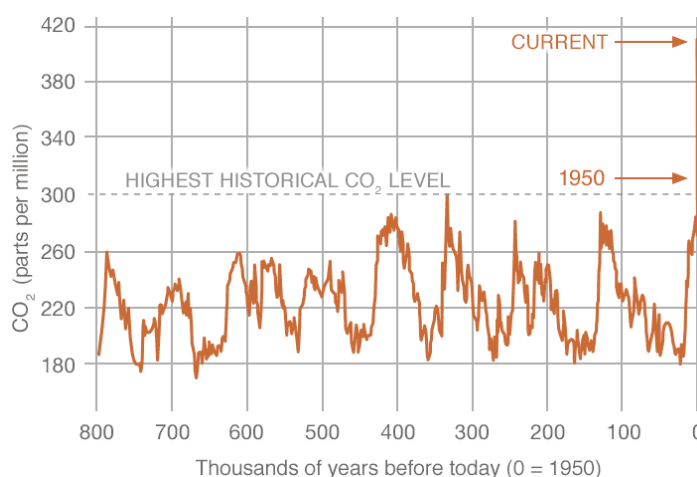


Figure 7. Indirect -by ice cores- and direct measurements of CO₂ concentration in the atmosphere from 800 thousand years before 1950 to 2020. Source: (NASA, 2020)

2.2.3. EXTREME CLIMATE CONDITIONS AND THE IMPACT ON HUMAN HEALTH

The ‘Great Acceleration’ study of Steffen *et al.* (2004, 2015) demonstrated that changes in structure and functioning of the Earth System happened because of human influence. These changes encompass extreme weather events and extreme climate events, such as decreasing of cold temperature extreme events and increasing of warm temperature, high sea levels, and heavy precipitation extreme events (IPCC, 2014c, p. 7) (Figure 8). In statistic terms, the extreme events of a weather variable are the values with a low probability to occur, i.e., the values located in the tails of the probability distribution (Meehl *et al.*, 2000; Viceto *et al.*, 2019).

The criteria of the Portuguese authorities for issuing a heat wave harmful to the human health are based on either the World Meteorological Organization’s definition of heat wave: a sequence of at least 6 days with more than 5 °C above the average of the homologous period (WCDMP-No 47, WMO-TD, No 1071); or the thresholds of days in Porto set by the Portuguese Meteorological Office, when the maximum temperature is between 32 °C and 36 °C (yellow), 37 °C and 38 °C (orange), and above 38 °C (red) (Ana Monteiro & Velho, 2014).



Figure 8. The manifestation of extreme weather and extreme climate events. a) Changes in temperature dried out part of Elbe River in Dresden, Germany, 9th July 2018. Source: (Schiermeier, 2018). b) Sea level will increase more than one meter of actual level by 2100, meeting coastal cities. Source: (Moore *et al.*, 2018). c) Changes in precipitation flooded the coastal city of San Juan in Puerto Rico after Hurricane Maria hit in September 2017 Source: (Bai *et al.*, 2018).

Urban areas produce 78% of the world's energy and more than 60% of CO₂ and greenhouse gas emissions (Lindberg et al., 2013), despite the surface of urban areas is just 1-3% of the Earth's surface (IPCC, 2014a). Europe surface with 4 million km² is populated by 446 million inhabitants—the third largest population after China and India—(European Union, 2020), and 72% of the European population lives in urban areas which constitute 4% of the European surface (European Environment Agency, 2015). Portugal has 65% of its population living in urban areas (United Nations, 2018b), mostly concentrated in the metropolitan areas of the city of Lisbon and Porto, 28% and 17%, respectively (PORTDATA, 2020).

The worst heat wave of the Northern Hemisphere occurred in the summer of 2020, outpacing the previous hottest summers of 2019 and 2016 (NOAA, 2020). Studies report that the frequency and the intensity of heat waves have increased in the last years and will increase even more in the future in Europe (Klein Tank & Können, 2003; Ouzeau et al., 2016; Morabito et al., 2017; Bador et al., 2017; Lhotka et al., 2018), especially for the Iberian peninsula (Easterling et al., 2000; Reay et al., 2007; Marengo et al., 2010; Fonseca et al., 2016; Pereira et al., 2017; Viceto et al., 2019; EEA, 2020). This would bring to low humidity levels, low wind speed, and minimal cloud cover in cities (Blocken & Carmeliet, 2004).

The future climate prediction for the city of Porto have been illustrated in the Municipal Climate Change Adaptation Strategy (*Estratégia Municipal de Adaptação às Alterações Climáticas*) (Câmara Municipal do Porto, 2016). Climate projections for the municipality of Porto, which are resumed in Table 1, hint to a potential drop in total annual precipitation and an increase in temperatures, notably in the summer and autumn, enhancing the likelihood of hotter and drier summers, among other changes. Heat waves and intense or very intense precipitation events are expected to become more common.

The heat wave of August 2003, which claimed the lives of over 70 000 people, mostly in Europe (Robine et al., 2008), sparked a growing interest in the impact of extreme heat events on population morbidity and mortality even not meeting the official criterion of the required sequence of daily temperatures (A. Monteiro et al., 2017). Various studies have demonstrated that there is a connection between the increase in temperature and the increase in death and disease for human health. Heat stress, morbidity, and mortality are direct effects of the heat waves especially in urban areas (Harlan et al., 2006; Kovats & Hajat, 2008; Gosling et al., 2009; D'Ippoliti et al., 2010; Mora et al., 2017), where the susceptible population is mainly elderly, impoverished populations, people with chronic health conditions, including diabetes, people using certain medications, the mentally ill, outdoor workers, and young children (Balbus & Malina, 2009; Wilhelmi & Hayden, 2010). IPCC (2013) and World Health Organization (2014) proposed to intensify research studies about the correlation of human heat stress to heat waves to have more supporting evidence, especially for urban areas, which are vulnerable to the effects of extreme temperatures (Marengo et al., 2010; Carter et al., 2015).

In Portugal, research have revealed a link between heat and death for the city of Porto (A. M. Monteiro et al., 2012; Silveira et al., 2019; Rodrigues et al., 2020), where a link between socioeconomic and environmental deprivation zones and yearly temperature ranges has been discovered, resulting in an example of environmental inequality or injustice (A. Monteiro et al., 2017).

Table 1. Summary of the major climate change projections for the Porto municipality till the end of the century.

Source: translated from (Câmara Municipal do Porto, 2016)

Climate variable	Summary	Projected changes
	 Decrease in average annual rainfall	Annual average Decrease in average annual rainfall could vary between 3% and 25% by the end of the 21st century.
		Seasonal precipitation In the winter months there is no clear trend (between -19% and +17%), and a decrease is projected for the rest of the year, which may vary between 10% and 35% in spring and between 9% and 6% in autumn.
		More frequent and intense droughts Decrease in the number of days with precipitation, between 12 and 29 days per year. Increased frequency and intensity of droughts in southern Europe.
	 Increase in the average annual temperature, in particular the maximum temperatures	Annual and seasonal average Increase of the average annual temperature, between 1°C and 4°C, at the end of the century. A sharp increase of the maximum temperatures in autumn and summer (between 2°C and 5°C).
		Very hot days increase in the number of days with very high temperatures ($\geq 35^{\circ}\text{C}$), and of tropical nights, with minimum temperatures $\geq 20^{\circ}\text{C}$.
		Heat waves More frequent and intense heat waves.
	 Rise in the average sea water level	Average Mean sea level rise between 0.17 m by 2050, and between 0.26 m and 0.82 m by the end of the 21st century (global projections) (IPCC, 2013). Other authors indicate an increase of up to 1.10 m by 2100 (global projections) (IPCC, 2013).
		Extreme events Mean sea level rise with more severe impacts when combined with storm surge (global projections) (IPCC, 2013).
	 Increase in extreme rainfall events	Extreme events Increase in extreme phenomena, in particular of intense or very intense precipitation (national projections) (Soares et al, 2015). More intense winter storms, accompanied by heavy rain and wind (global projections) (IPCC, 2013)

2.3. URBAN CLIMATE

2.3.1. URBAN CLIMATOLOGY

From 2007, people living in urban areas reached 50% of the world population (WorldBank, 2019) and this percentage is expected to grow up to 68% by 2050 (United Nations, 2018a). Construction and urban densification follow the urban population growth leading to increasing urban temperatures (Adachi et al., 2012; Chapman et al., 2017) that decrease the thermal comfort level (Emmanuel, 2005; Morris et al., 2017), which depends on factors of urban climates, such as air temperatures and wind speed (Givoni, 1998, p. 241). It follows that the study of the urban climate—urban climatology—is a key point to understand how to improve the thermal comfort of citizens by developing green mitigation strategies.

Urban climatology studies the influence the urban surface has on physic, chemist, and dynamic phenomena of the atmosphere with the aim to plan and design climate-adapted cities (Gerald Mills, 2014); it encompasses aspects of disciplines from meteorology to climatology, and from engineering to social science and medicine (Oke, 2006). The horizontal spatial scale studied in urban climate covers a range from macro to micro, focusing on the *mesoscale* (tens of kilometres; whole city), *local scale* (some kilometres or less; neighbourhoods) and *microscale* (few centimetres up to one kilometre; a square, a street, a building, or a terrace) (Oke, 2006) (Figure 9). Despite the rapid growth of the professional body of urban climatology in recent decades, its incorporation into urban planning remains a difficult problem in many cases due to the difficulty of communication between various academics and planning agents (Eliasson, 2000; G. Mills et al., 2010).

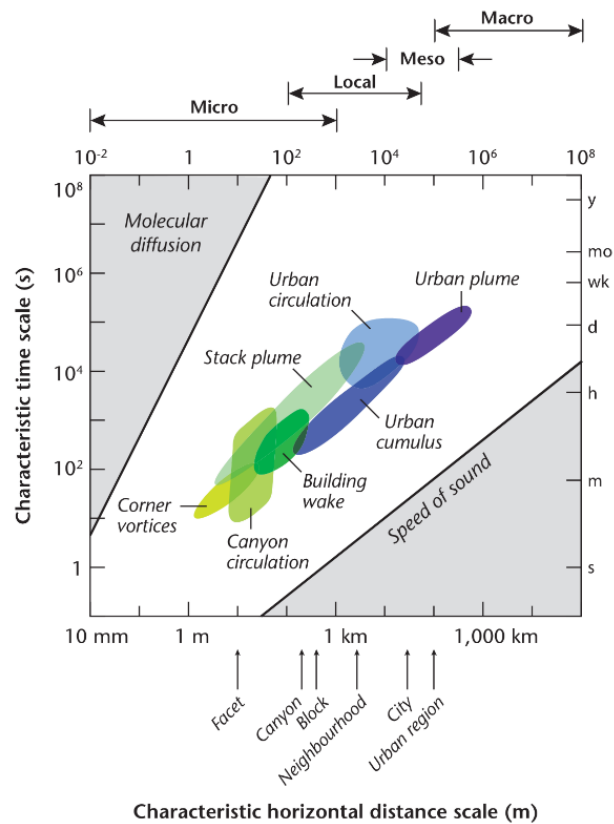


Figure 9. Selected urban climate patterns and wind phenomena on time and horizontal space scales. Source: (Oke et al., 2017)

2.3.2. CLIMATIC URBAN LAYERS

The concept of urban layers was first introduced in the 1970s by the meteorologist T.J. Oke that he describes as layers of air delimiting the area where urban heat island influences the atmosphere. In his work, Oke (1976) introduces the concepts of *urban boundary layer*—defined as the atmospheric layer above urban atmospheric phenomena that act at the local or mesoscale; and *urban canopy layer*—described as the atmospheric layer of urban atmospheric phenomena that act at the microscale. Further works from the same author and colleagues (Taesler, 1980; Oke, 1984, 1988; Bailey et al., 1997) have brought to a deeper knowledge of the climatic urban layers, and, in the book *Urban Climates* (Oke et al., 2017, p. 30), the authors divide ‘the vertical structure of the urban Atmosphere’ as follow (Figure 10).

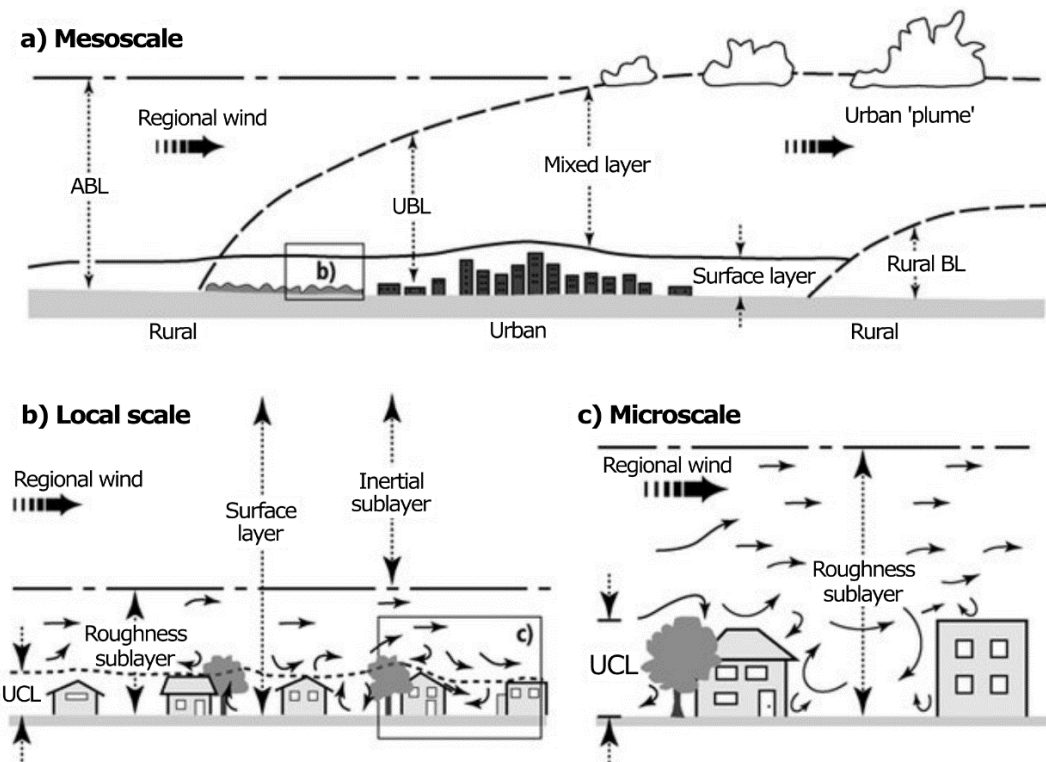


Figure 10. View of the scales of the climatic urban layers. ABL – atmospheric boundary layer, UBL – urban boundary layer, UCL – urban canopy layer. Source: adapted from (Oke, 2004)

The layer that limits the *troposphere*—part of the atmosphere affected by roughness, temperature, moisture, and pollutants of the Earth’s surface—is called *atmospheric or planetary boundary layer*.

At the mesoscale, the urban boundary layer can be divided into the lower part (10%)—the so-called *surface layer*—characterised by friction with the Earth’s surface and the upper part (90%)—the so-called *mixed layer*—characterised by almost uniform vertical profiles of potential temperature, water vapour, wind speed and direction along the height. The shape of the urban boundary layer changes depending on the presence of the regional wind: an *urban ‘dome’* when the regional wind is absent (Figure 11a); and an *urban ‘plume’* when the regional wind flows (Figure 11b). Through the plume, the

regional wind carries the thermal, moisture and kinematic effects and air pollutants of the city, for tens and hundreds of kilometres.

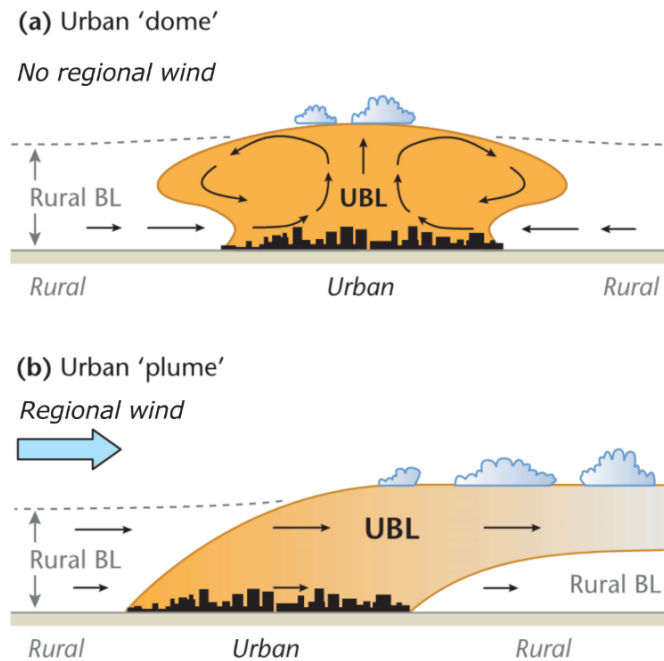


Figure 11. Mesoscale view of the urban boundary layer (UBL). The two shapes depend on the presence of the regional wind: (a) urban 'dome' – no presence of regional wind; (b) urban 'plume' – presence of regional wind.

Source: adapted from (Oke et al., 2017)

At the local scale, the *surface layer* is divided into the upper part—*inertial sublayer*—where the urban neighbourhoods directly influence the atmosphere, and the lower part—*roughness sublayer*—where the roughness of the urban elements influences the airflow.

At the microscale, the *urban canopy layer* extends its height up to the main urban elements—buildings and/or trees. The volume of air of the urban canopy layer is composed of an 'interior' part—air of the indoor built environment—and an 'exterior' part—air of the outdoor built environment—connected between each other by “the transmissivity of the windows and the porosity of the building membranes (walls and roofs)” (Oke et al., 2017, p. 30). Finally, the *subsurface layer* is the part of the city that stays under the surface, it includes “urban soils and the below-ground portions of buildings, tunnels and pipes, collectively exchange heat, water and air pollutants with the urban canopy layer above” (Oke et al., 2017, p. 30).

2.3.3. URBAN THERMAL BALANCE

Climatologists study the *transfer*, *conversion* and *storage* of mass and energy between the surface of the Earth and the atmospheric layer above. The main forms of energy exchanged between the surface of the Earth and the atmosphere are *thermal*, *kinetic*, and *potential* and are exchanged via conduction, convection, and radiation (Oke, 1988, pp. 7–17) (Figure 12). *Conduction* is the process by which the heat is transported within the matter due to the collision of molecules moving in a fast random motion.

Convection is the vertical motion of mass and energy of a fluid—liquid or gas—within the fluid itself; the energy is transported both as *sensible heat*—it varies the temperature of a body when added or subtracted to it—; and *latent heat*—it allows a substance to change state without a temperature change. *Radiation* is the transfer of energy by electromagnetic fields.

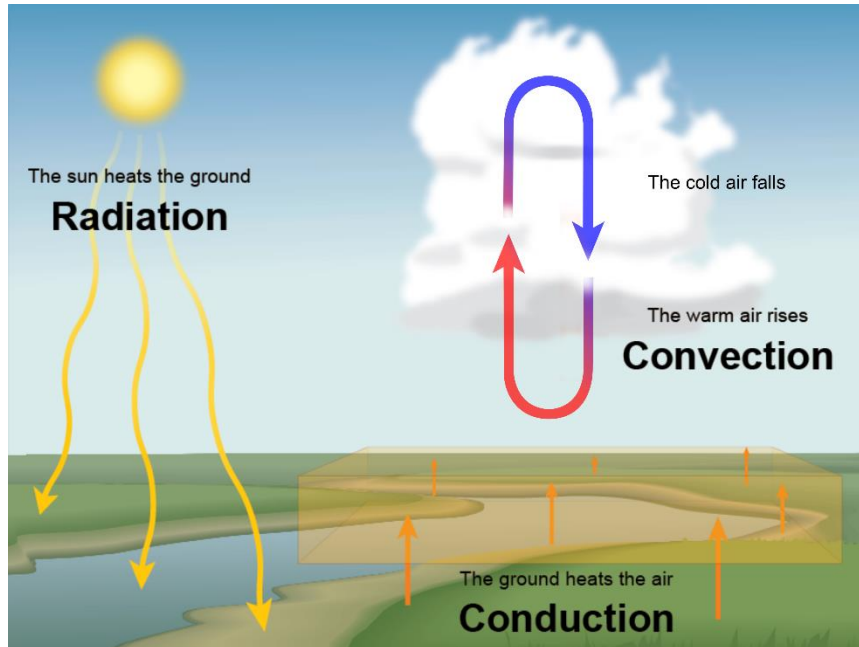


Figure 12. In the Earth-Atmosphere system, the energy can be exchanged in three modes: conduction, convection, and radiation. Source: adapted from (National Weather Service, 2016)

The energy balance connects energy flow and climate (Oke, 1988, pp. 7–17) and has its roots in the first law of thermodynamics, energy can neither be created nor destroyed, but only converted from one form to another—conservation of energy—, and can be written as follows:

$$\text{Energy gains} = \text{Energy losses} + \text{Energy storage} \quad (1)$$

The urban environment gains energy through solar power and anthropogenic heat, and loses energy through convection, evaporation and heat storage/transfer (Gartland, 2012, p. 16; P. Lin et al., 2017); the thermal balance can be written as follows (P. Lin et al., 2017) (Figure 13):

$$Q_r + Q_T = Q_E + Q_L + Q_S + Q_A \quad (2)$$

Where Q_r = net radiation

Q_T = anthropogenic heat

Q_E = convective sensible heat

Q_L = latent heat

Q_S = stored energy

Q_A = net horizontal heat advection

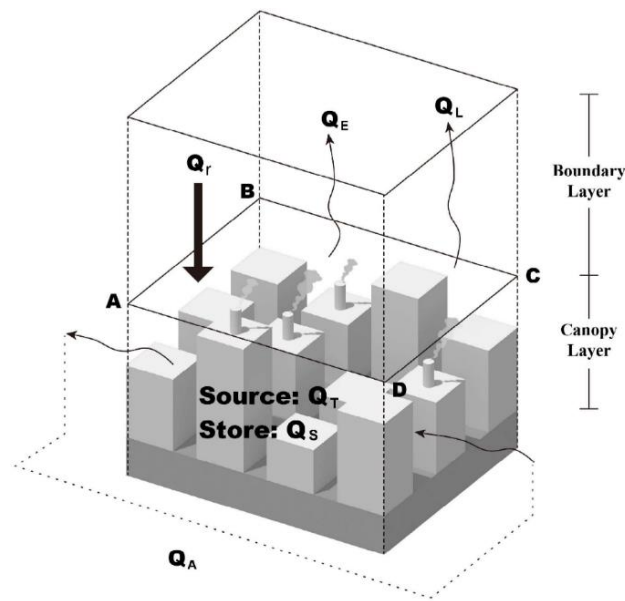


Figure 13. Graphic representation of the energy flows in the urban environment. Source: (P. Lin et al., 2017)

The *net radiation* (Q_r) is the energy absorbed by the urban surface resulting from four radiative processes occurring at the urban surface (Gartland, 2012, p. 16):

$$\begin{aligned} \text{Net radiation} = & \text{Incoming solar} - \text{Reflected solar} + \\ & + \text{Atmospheric radiation} - \text{Surface radiation} \end{aligned} \quad (3)$$

The *incoming solar* is the energy emitted by the sun and just a portion of this energy reaches the surface of the Earth depending on the season, time of the day, level of cloud cover, and level of atmospheric pollution. The *atmospheric radiation* is the energy coming from particles of the atmosphere, the emission is proportional to the air temperature and the number of particles present in the atmosphere. The *reflected solar* is the quantity of solar energy reflected at the Earth's surface, depends on the capacity of the material to reflect radiative energy—reflectance property—and can be calculated by albedo—"ratio of reflected flux density to incident flux density, referenced to some surface" (American Meteorological Society, 2012). Bright white colour materials have a high reflectance, while dark colour materials have low reflectance and absorb a major part of the radiation received. The *surface radiation* is the energy emitted by the surface and depends on the temperature of both the surface itself and the environment nearby. Conversely to incoming solar and atmospheric radiation, the reflected solar and surface radiation are controllable by the design of the urban environment. Urban planners and designers can manipulate the amount of energy reflected and emitted by choosing materials with specific reflection levels and/or thermal emittance property (P. Lin et al., 2017).

Human activities such as transport, heating/cooling buildings, industrial activities, and human metabolism contribute to generating heat in the urban environment—*anthropogenic heat* (Q_T). The intensity of anthropogenic heat is related to per capita energy use, population density, and the type of climate, industrial activity, and urban transport system; and varies temporally—within the day and the season—, and spatially—within the urban area (Erell et al., 2012, pp. 54–59).

The *convective sensible heat* (Q_E) is the energy exchanged between air and the adjacent urban surface and depends on the magnitude of the temperature difference and the resistance to heat transfer between the two parts (Erell et al., 2012, p. 37).

The process of *evapotranspiration* refers to the simultaneous processes of evaporation and transpiration carrying energy away—from the surface of the Earth to the atmosphere—in the form of *latent heat* (Q_L) by water vapour. *Evaporation* is the physical process able to transform water—liquid—into vapour—gas—due the energy of the sun. *Transpiration* is the physical process with which plants regulate their internal temperature: the plant transports the water of the soil from the roots to the leaves where the water is expelled as vapour through pores—the stomata. The latent heat is affected by the amount of moisture and vegetation available in the urban environment (Erell et al., 2012, p. 43).

The *store* of energy in ‘opaque elements’—buildings, roads, etc.—is related to the properties of materials: thermal conductivity—capacity of materials to conduct heat; and heat capacity—capacity of materials to store heat. The *transfer* of the energy within the city is called *horizontal heat advection* (Q_A) and occurs between zones of different temperatures due to differences in land use, build and green area density (Erell et al., 2012, p. 59).

Rafael and colleagues (2017) studied, for the Greater Porto area, how energy fluxes would change in the future scenario 2046-2065—of the Representative Concentration Pathway RCP8.5 which is the worst scenario from IPCC—compared to the reference scenario 1986-2005. Results show that increase in sensible heat flux (40%) and reduction in latent heat flux (15%) will lead to higher surface temperatures and lower occurrence of precipitation increasing magnitude and severity of the urban heat island phenomenon which Porto suffers from. The authors stress the need for more studies on green infrastructure measures to mitigate climate change influence on the energy fluxes.

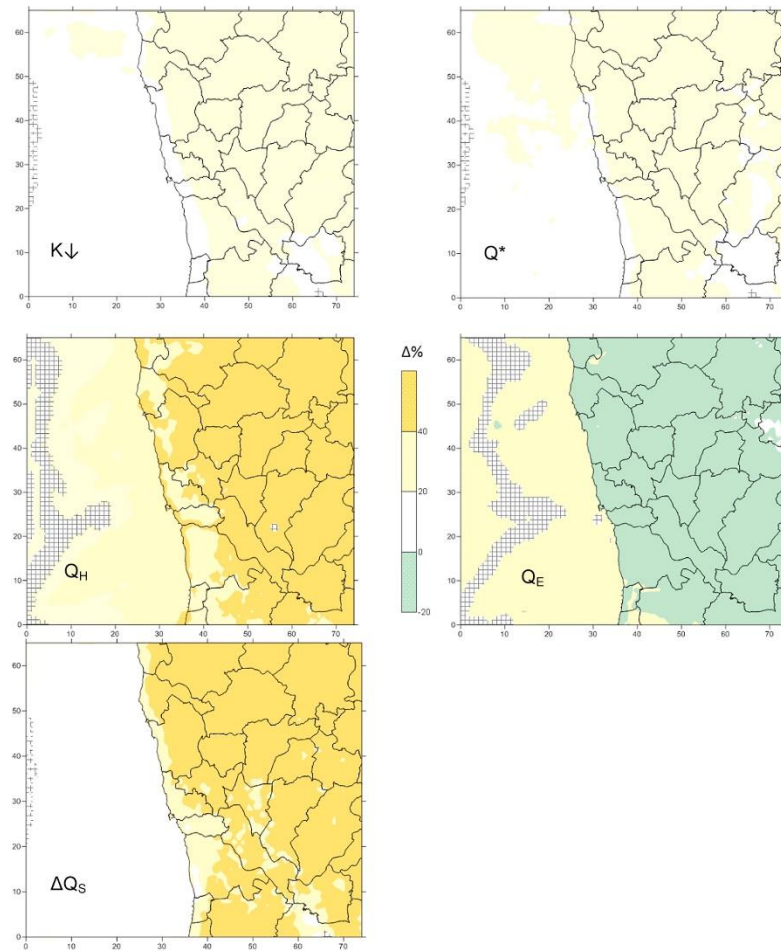


Figure 14. Visualisation of the spatial differences (%) between the future and the reference scenarios for the sensible heat flux (Q_H), latent heat flux (Q_E), net storage heat flux (ΔQ_S), the incoming shortwave radiation ($K_{\downarrow}$) and the net all-wave radiation (Q^*). Source: (Rafael et al., 2017)

2.3.4. URBAN HEAT ISLAND

The *urban heat island* (UHI) phenomenon was discovered in the early XIX century by the chemist Luke Howard (1818). During his studies on the climate of London, Howard detected a difference in air temperature between the urban area and its surrounding rural area, ΔT_{u-r} . He sustained that the urban climate differs from the climate around the city for an ‘artificial warmth’ generated by the structure, population and fuel consumption of the city (Howard, 1818). Howard first analysed “the urban ‘contamination’ of meteorological records and the magnitude and cause of the urban effect” (Gerald Mills, 2008).

After Howard, the geologist and meteorologist Renou (1855, 1862, 1868) and scholar Schmidt (1917, 1929) made similar observations for Paris and Wien, respectively. The characteristic difference in air sensation between urban and rural areas was already witnessed in the ancient Rome: writers Horatius (65-8 B.C.) and Seneca (4 B.C.-65 A.C.) hinted at it with the sense of smell and sight (Landsberg, 1981).

The UHI phenomenon influences multiple factors of city climate including air temperature, humidity, fog, and duration of sunshine (Chandler, 1965). Researchers have shown that the UHI increases energy

consumption (Hirano & Fujita, 2012; Magli et al., 2015; X. Li et al., 2019), worsen air pollution (Lai & Cheng, 2010; Feizizadeh & Blaschke, 2013; H. Li et al., 2018) and increases the burden on public health (Tan et al., 2010; Tomlinson et al., 2011; Heaviside et al., 2016) of the urban environments.

Changes in the heat balance of the Earth's surface lead to a different temperature between rural and urban environments, with the consequent formation of the UHI (Santamouris, 2001, p. 7). These changes are (Givoni, 1998, p. 244; Gartland, 2012, p. 15): evaporation reduction, heat storage increase, net radiation increase, convection reduction, and anthropogenic heat reduction. Table 2 lists the characteristic contributing to heat island formation and their relative effect on the energy balance in urban and suburban environments.

Table 2. Characteristic contributing to heat island formation and their relative effect on the energy balance in urban and suburban environments. Source: (Gartland, 2012, p. 16)

Characteristic contributing to heat island formation	Effect on the energy balance
Lack of vegetation	Reduces evaporation
Widespread use of impermeable surfaces	Reduces evaporation
Increased thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases net radiation
Urban geometries that trap heat	Increases net radiation
Urban geometries that slow wind speeds	Reduces convection
Increased levels of air pollution	Increases net radiation
Increased energy use	Increases anthropogenic heat

The section of a 'typical heat island' follows the geomorphology of an island (Figure 15a): from the 'cool sea' of the rural surroundings, the UHI first grows rapidly with a 'cliff', then slowly with a 'plateau', to finally reach the 'peak' in correspondence with the highest recorded temperature in the city; to notice, the variations in the plateau are due to the influence of natural cool areas—parks, lakes, and open areas—and warm areas—commercial, industrial, or dense building areas (Oke, 1988, p. 288). The shape of the UHI can also be visualised on a map by isotherms: the lines close themselves in concentric circles of higher temperature with the centre located in the zone of the city with the highest density (Erell et al., 2012, p. 67) (Figure 15b).

The UHI intensity, ΔT_{u-r} , is measured as the difference between the value of the rural surrounding temperature and the value of the urban 'peak' temperature (Oke, 1988, p. 289; Givoni, 1998, p. 243) (Figure 15a), and depends on *meteorological* (cloudiness, humidity, and wind speed), *geographic* (location and topography), and *man-made* (size of the city, density and distribution of the buildings, characteristics of the artificial surfaces, and amount of anthropogenic heat) *factors* (Oke, 1988, p. 288; Givoni, 1998, p. 243; Erell et al., 2012, pp. 70–75). During the day, the ΔT_{u-r} can value 1–2°C, while can reach values of 3–5°C up to 8–10°C during 'clear and still-air' nights (Figure 16). It follows that UHI and UHI intensity are nocturnal phenomena (Givoni, 1998, p. 243; Erell et al., 2012, p. 70).

The difference between heat waves and UHI should be noted; while the former is due to large, stagnant high pressure systems that cause a temporal temperature anomaly across an entire region (urban and/or rural), the latter is a local phenomenon caused by the differences in topographical characteristics between urban and rural areas (albedo, heat capacity and fluxes, land use). Heat waves and UHI episodes are inextricably linked, with heat waves not only increasing ambient temperatures but also amplifying UHI effects (Cheval et al., 2009; Basara et al., 2010; Founda et al., 2015).

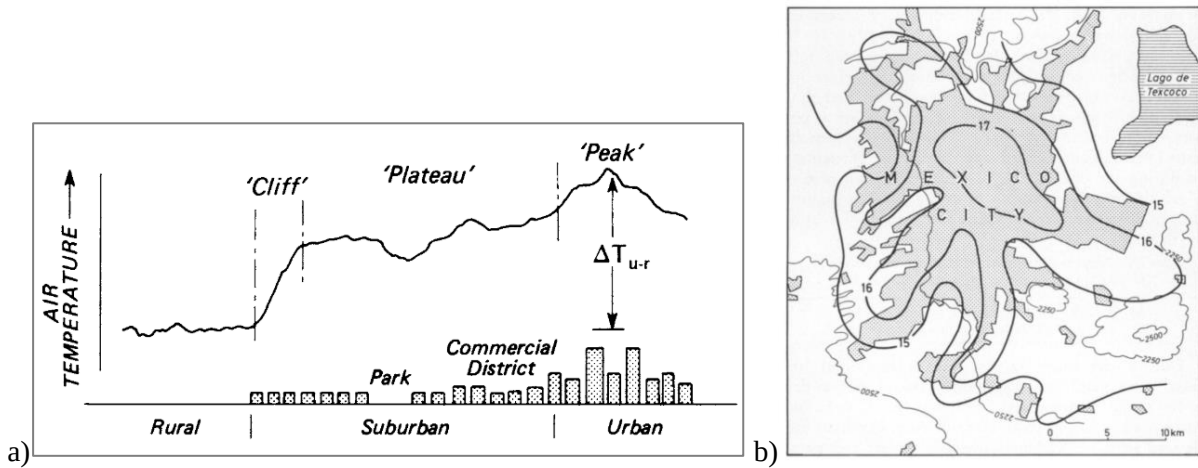


Figure 15. a) Section of a 'typical urban heat island'. Source: (Oke, 1988, p. 288). b) The isotherms ($^{\circ}\text{C}$) show the urban heat island of Mexico City by concentric circles, with a difference of 2°C between urban and rural area.

Source: (Jauregui, 1973).

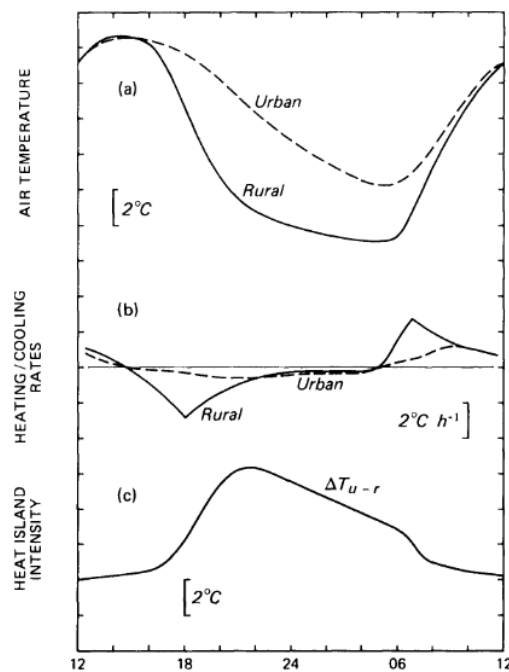


Figure 16. Urban and rural temporal trend of (I) air temperature, (II) cooling/warming rates, and (III) heat island intensity ΔT_{u-r} under 'ideal' weather conditions. Source: (Oke, 1988, p. 290)

2.4. OUTDOOR ENVIRONMENT: PUBLIC SPACES AND THERMAL COMFORT

2.4.1. OUTDOOR PUBLIC SPACES

During summer, overheating in cities can have a significant effect on the outdoor environment and, as a result, quality of life; high summertime temperatures in urban areas degrade outdoor comfort conditions and have a detrimental effect on citizens' wellbeing, placing vulnerable people under additional stress (Santamouris et al., 2017). Meteorological factors such as air temperature, air humidity, wind velocity, and short and long wave radiation, thermo-physiologically affect human health due to the close interaction between the thermoregulatory systems and the circulatory system (Matzarakis & Amelung, 2008). So, in order to maintain citizens' wellbeing, cities must provide well-designed outdoor public spaces able to generate comfortable outdoor thermal condition.

Outdoor public spaces encourage human activity and offer physical, environmental, economic, and social benefits to city dwellers (Hakim et al., 1998; Hass-Klau, 1993; Woolley, 2003). Studies show that outdoor leisure activities, such as cycling and walking, enhance physical and psychological wellbeing (Niu et al., 2015), and outdoor public spaces with green areas minimize feelings of depression and tension while also improving health (Maas et al., 2009; Kondo et al., 2018).

The physical environment and the microclimate of the outdoor public spaces influence outdoor activities of the city dwellers, such as social interaction, commercial trade, entertainment and sport (Zacharias et al., 2001; Spagnolo & de Dear, 2003; Thorsson et al., 2004), which means that thermally uncomfortable outdoor spaces will discourage people from engaging in outdoor activities (Martinelli et al., 2015; Shooshtarian et al., 2018). Gehl (1971), for example, counted people sitting on sunny and shady benches, demonstrating for the first time that the local environment, whether sunny or shady, influences people's decisions to stay or leave.

It follows that people will enjoy their time in outdoor public spaces if they are thermally comfortable, and more events and social encounters will take place, attracting more and more people (Nikolopoulou & Lykoudis, 2006); as an old Scandinavian proverb goes, “people come where people are” (Gehl, 2011). For these reasons, in recent decades, urban planning and design have concentrated on providing high-quality outdoor public spaces (Maruani & Amit-Cohen, 2007; Das, 2008; Jalaladdini & Oktay, 2012), i.e., places planned and evaluated based on thermal comfort (Lenzholzer & van der Wulp, 2010; Coccolo et al., 2016; Shooshtarian & Ridley, 2017).

2.4.2. OUTDOOR THERMAL COMFORT

Human thermal comfort is a subjective feeling that varies from person to person: a satisfied person is neither too hot nor too cold and has no need to adjust their clothes, activity levels, or the atmosphere to which they are exposed (Nikolopoulou & Lykoudis, 2006). Thermal comfort relates with the human aspects of psychology, thermo-physiology, and energy flow. It can be expressed as: (i) the state of mind that expresses satisfaction with the surrounding thermal environment (ASHRAE, 2004, 2010); (ii) thermo-physiological processes (biological reactions and thermal receptor processes) that contribute to the thermal adaptation of the skin to the external environment; and (iii) heat flows from and to the human body that balance the internal temperature (Schellen et al., 2013).

Thermal comfort studies were only based on physiological aspects (*thermal sensation*) until, for the first time, in the 1980s, the bioclimatologist Auliciems (1981) introduced psychological aspect into studies

of human indoor thermal comfort, modifying the concept of thermal sensation into *thermal perception*. Around twenty years later, Nikolopoulou *et al.* (2001) included the concept of thermal perception in studies of human outdoor thermal comfort through the use of questionnaires that, by asking questions to understand the psychology of the respondents, enriched the knowledge obtained from environmental measurements.

The study of outdoor thermal comfort has seen worldwide surge in interest in the 2010s (Kemar & Sharma, 2020; Potcher *et al.*, 2018), after being the subject of very few studies in the 1990s (Hoppe, 2002). Recently, Lenzholzer and de Vries (2020) reviewed the state of the art and developed the *physical/physiological–psychological model for outdoor thermal perception (PhyPsy model)* to provide an up-to-date overview of outdoor thermal comfort. The model represents the factors that affect thermal perception (boxes A–L) and the relationship of influence (arrows) on a conceptual diagram, classifying them by realm—physical and psychological—and time scale—short and long term (Figure 17).

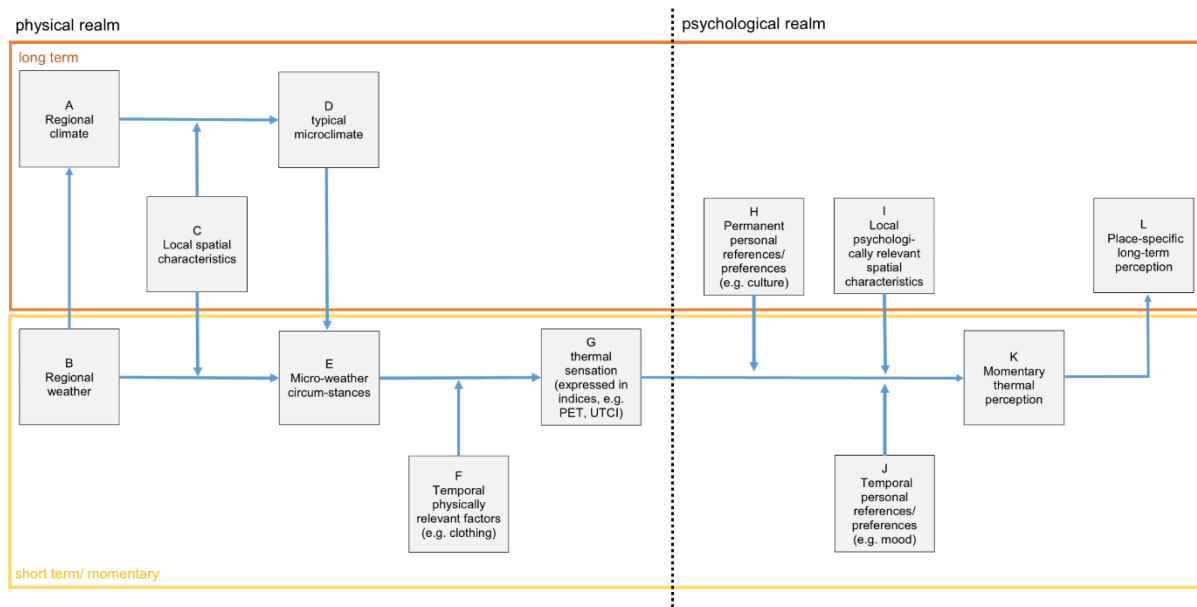


Figure 17. The physical/physiological–psychological model (PhyPsy model) describes factors and relationships of outdoor thermal perception. Source: (Lenzholzer & de Vries, 2020).

The analysis of the factors influencing thermal perception begins considering regional climate (long term stable characteristics) and weather (short term unstable characteristics) (boxes A and B), and local spatial characteristics (such as the size and shape of buildings and open areas, the amount of vegetation, and the amount of water in the environment) (box C) that together influence changes on micro- climate and weather characteristics (boxes E and D). Momentary variations in micro-weather (air temperature, wind speed, relative humidity, solar radiation, mean radiant temperature) and personal factors (human activity/metabolic rate, clothing level) (box F) influence people on their thermal sensation (box G) (Coccolo *et al.*, 2016; Olgyay, 1963; 15; Matzakaris *et al.*, 2008; Thelegani *et al.*, 1999; Kleerekoper *et al.*, 2017; Hoppe, 1999), which refers to the physiological aspect of thermal perception (Humphreys and Hancock 2007; Knez *et al.* 2009) and is expressed in indices, such as, Physiologically Equivalent

Temperature (PET), Predicted Mean Vote (PMV), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET*), which are explained in detail in section 2.4.3.

Lenzholzer and de Vries (2020) also analysed momentary and permanent physiological/physical factors that affect momentary thermal perception (box K) with a shift in thermal comfort level, i.e., “permanent personal references/preferences” (e.g., culture, climate zone, personal habits...) (box H), “local psychologically relevant spatial characteristics” (e.g., elements that influence thermal perception through senses, such as vision: shape and material of the environment, presence of natural and artificial elements...) (box I), and “temporal personal references/preferences” (e.g., the mood at the moment). Finally, the team explains that this momentary thermal perception may evolve into a permanent thermal perception for particular locations (box L) over time because the mind develops a memory of how to act in similar environments.

When the above-mentioned factors (boxes A-L) influence human thermal perception, people can adjust their thermal comfort level to a neutral zone—nor too cold, nor too hot—by using psychological, physiological, and/or behavioural/physical adaptation. (Nikolopoulou, Lykoudis, & Kikira, 2003). Nikolopoulou *et al.* explained that psychological adaptation manifests as a shift in how we perceive and respond to sensory feedback and is the product of experiences and expectations, physiological adaptation manifests as a shift in physiological response and aims to reduce the strain of thermal environment parameters exposure, and physical adaptation, which is related to the human body's heat balance, manifests as an intentional change in posture for managing comfort level.

2.4.3. OUTDOOR THERMAL COMFORT INDICES

The thermal sensation has been studied since 1960s. First, for military purposes first, then for public health, medicine, physiology, biometeorology, and engineering, with more than a hundred thermal indices developed over the years to value heat or cold human conditions (Potchter *et al.*, 2018). Indices express the level of thermal sensation and use meteorological and human physiologic parameters derived from measurements and/or simulations.

In the last two decades, the most widely used indices in scientific research have been Physiologically Equivalent Temperature (PET) (Mayer & Höppe, 1987; Höppe, 1999), Predicted Mean Vote (PMV) (Fanger, 1970; Gagge, A. P., Fobelets, A. P. and Berglund, 1986), Universal Thermal Climate Index (UTCI) (G. Jendritzky *et al.*, 2009; Gerd Jendritzky *et al.*, 2012), and Standard Effective Temperature (SET*) (Gonzalez *et al.*, 1974; Gagge, A. P., Fobelets, A. P. and Berglund, 1986), all of which share the property of being universal indices that cover a broad range of thermal sensation and physiological stress categories, are simple to measure with readily available tools and produce empirical results from the same set of meteorological and thermo-physiological parameters—namely, air temperature, air humidity, wind velocity, mean radiant temperature, activity of humans and clothing insulation (Matzarakis, 2001; Potchter *et al.*, 2018; Kumar & Sharma, 2020) (Table 3).

PET and UTCI were created specifically for outdoor use, whereas PMV and SET* were created for indoor use and then applied outdoors. Except for SET*, which is only applicable in moderate/hot climates, PET, PMV, and UTCI can be used in all climates; however, it is important to note that outdoor thermal environment conditions affect thermal comfort indices, changing their range according to the climatic zone; thus, adjusting the range according to the climate is important to have significant results (Potchter *et al.*, 2018). For the Mediterranean climate, Pantavou *et al.* (2014) calibrated the thermal

sensation scales of a large number of thermal indices in order to have greater success during their application in outdoor urban environments of Mediterranean climatic zones. The results of the team revealed that “the calibrated scale of UTCI showed better agreement with the original than the rest of the studied indices” and “the calibrated scale of PET was in better agreement with the original one applied in Western/Central Europe than with the Mediterranean scale presented by Cohen *et al.* (2013)”. As a result, the original scales of the outdoor thermal indices were taken into account for this thesis.

The PET index, which was developed in Europe at the end of the twentieth century (Mayer & Höppe, 1987; Höppe, 1999; Matzarakis *et al.*, 1999), is based on the Munich Energy-balance Model for Individuals (MEMI) (Höppe, 1984, 1994):

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \quad (4)$$

Where M = metabolic rate

W = physical work output

R = net radiation of the body

C = convective heat flow

E_D = latent heat flow to evaporate water into water vapour diffusing through the skin

E_{Re} = amount of heat flows used to heat and humidify the inspired air

E_{Sw} = heat flow due to evaporation of sweat

S = storage heat flow for heating or cooling the body mass

PET links micrometeorological factors (calculated at the height of 1.1m, which is the average centre of gravity of a European standing person) that regulate individual heat flows—air temperature, T_a (°C): C , E_{Re} ; air humidity, RH (%): E_D , E_{Re} , E_{Sw} ; wind speed, v (m/s): C , E_{Sw} ; mean radiant temperature, T_{mrt} (°C): R —to thermo-physiological parameters of the human body—heat resistance of clothing (clo units); activity of humans (Watt) (Höppe, 1999). PET is equal to the air temperature (°C) of a standardised indoor environment—with $T_{mrt} = T_a$, water vapour pressure $VP = 12 \text{ hPa}$ (roughly equal to a relative humidity of 50% at $T_a = 20^\circ\text{C}$), $v = 0.1 \text{ m/s}$ —at which the heat balance of the human body is balanced at the same core and skin temperature as in the actual outdoor environment—with varying T_a , T_{mrt} , VP and v values— and is defined for a typical Central-European subject—a 35-year-old male of 1.75 m height and 75 kg with basic metabolism of 84 W, performing a light activity with an active work metabolism of 80 W and wearing a typical suit with thermal insulation of 0.9 clo (Höppe, 1999) (Figure 18). PET values are divided into nine ranges from "very cold" to "very hot" and from "extreme cold stress" to "extreme hot stress" for thermal sensation and physiological stress level of the human thermal comfort, respectively (Figure 18 and Table 3).

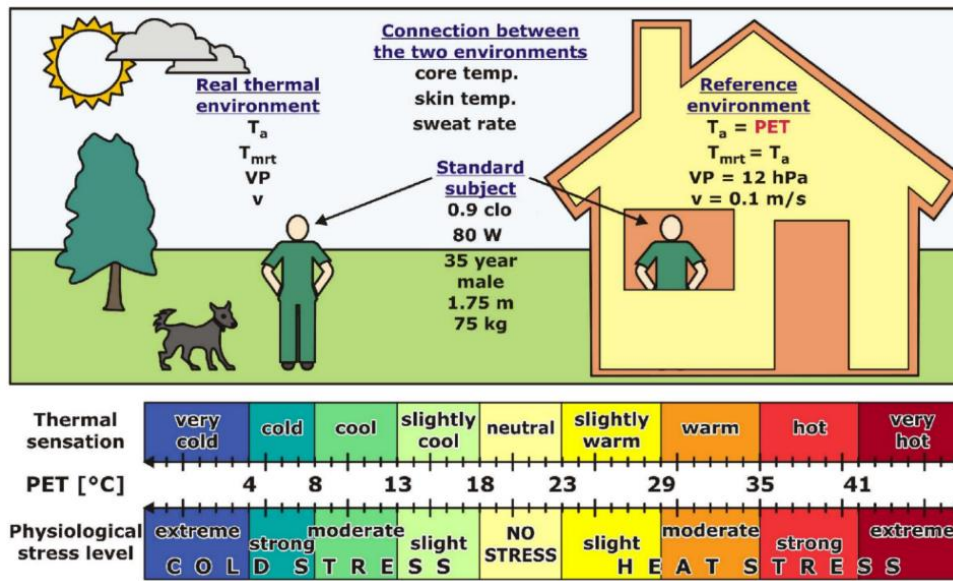


Figure 18. Graphical display of the Physiological Equivalent Temperature (PET) index and its thermal sensation and physiological stress level ranges. Where T_a air temperature – T_{mrt} mean radiant temperature – VP water vapour pressure – v wind speed. Source: adapted from (Kántor et al., 2016)

The PMV index, established in the second half of the twentieth century (Fanger, 1970), forecasts the collective experience of a group of people who are in the same place and calculates human thermal sensation by dry temperature, mean radiation temperature, relative humidity, wind speed, metabolic rate, and clothing insulation. PMV is measured on a seven-point scale ranging from -3 ("very cold" and "extreme cold stress") to +3 ("very hot" and "extreme hot stress") for thermal sensation and physiological stress level of the human thermal comfort, with 0 being the ideal value representing neutrality (Table 3).

The UTCI index, established in the first decade of the twenty-first century (G. Jendritzky et al., 2009; Gerd Jendritzky et al., 2012), is the corresponding air temperature in the reference setting—with relative humidity $RH = 50\%$, vapour pressure $VP < 20 \text{ hPa}$, still air and $T_a = T_{mrt}$ (°C)—that produces the same strain index value as the reference individual's reaction to the real environment and is determined by dry temperature, mean radiation temperature, the pressure of water vapour or relative humidity, and wind speed (at the elevation of 10 m), and is independent of the person's characteristics such as age, gender, specific activities, and clothing. Its values are divided into 10 ranges from "extreme cold stress" to "extreme heat stress" (Table 3).

The SET* index, established in the second half of the twentieth century (Gagge et al., 1971; Gonzalez et al., 1974; Gagge, A. P., Fobelets, A. P. and Berglund, 1986), is the equivalent air temperature of an isothermal environment—with $RH = 50\%$ —in which a person experiences the same heat stress and thermoregulatory pressure—respectively, skin temperature and skin wettedness (which are the limiting conditions)—as in the actual environment when wearing clothing standardized for the activity in question. Its values are divided into 5 ranges from "cool" to "very hot" and from "No danger" to "Danger" for thermal sensation and physiological stress level of the human thermal comfort, respectively (Table 3).

Table 3. Thermal sensation and physiological stress range comparison for Physiologically Equivalent Temperature (PET), Predicted Mean Vote (PMV), Universal Thermal Climate Index (UTCI, and Standard Effective Temperature (SET*) indices. Source: adapted from (Zare et al., 2018).

Thermal sensation (Grade of physiological stress)	Indices			
	PET (°C)	PMV (7-point scale)	UTCI (°C)	SET* (°C)
Very cold ¹ (Extreme cold stress ^{1,2})	<4	-3	<-40	
(very strong cold stress ²)			-40 to -27	
Cold ¹ (Strong cold stress ^{1,2})	4-8	-2.5	-27 to -13	
Cool ^{1,3} (No thermal stress ^{1,2} /No danger ³)	8-13	-1.5	-13 to 0	<17
Slightly cool ¹ (Slightly cold stress ^{1,2})	13-18	-0.5	0 to +9	
Comfortable ^{1,3} (No thermal stress ^{1,2} /No danger)	18-23	0	+9 to +26	17-30
Slightly warm ¹ (Slight heat stress ¹)	23-29	0.5		
Warm ^{1,3} (Moderate heat stress ^{1,2} /Caution ³)	29-35	1.5	+26 to +32	30-34
Hot ^{1,3} (Strong heat stress ^{1,2} /Extreme caution ³)	35-41	2.5	+32 to +38	34-37
(very strong heat stress ²)			+38 to +46	
Very hot ^{1,3} (Extreme heat stress ^{1,2} /Danger ³)	>41	3	> +46	>37

¹PET and PMV; ²UTCI; ³SET*

2.5. HEAT-MITIGATION STRATEGIES: IMPACT OF STREET GREENERY ON OUTDOOR THERMAL COMFORT

Climate change and urbanization have an impact on the urban microclimate, raising the urban heat island effect, which causes human thermal discomfort and related health problems, preventing year-round use of outdoor spaces. According to Döll and Romero-Lankao (2017), there are two risk management approaches to climate risks: one aims to reduce climate change-related risks through mitigation, while the other aims to reduce hazard and exposure impacts through adaptation. *Heat-related climate-responsive urban design* aims to construct outdoor spaces that are thermally comfortable throughout the year and in every potential future climate by maximizing the positive aspects of the microclimate while minimizing the negative ones (Eliasson et al., 2007; Brown, 2011; Lenzholzer & Brown, 2013). *Green infrastructure* is an effective adaptation method for reducing urban heat and discomfort in the context of the urban microclimate (Klemm et al., 2015).

The European Commission (2013) defines *Green Infrastructure* as “a strategically planned network of high-quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and to protect biodiversity in both rural and urban settings”. With the rise in urban studies, the concept of Green Infrastructure has evolved into *Urban Green Infrastructure*, which is defined as a network of planned and unplanned natural and built environment, both public and private, with the goal of generating benefits (Young et al., 2014; Demuzere et al., 2014; Norton et al., 2015a). Urban Green Infrastructure encompasses green spaces from small

scale, such as private gardens and street greenery, up to large-scale, such as city parks and green belts (Table 4).

Table 4. *Urban green Infrastructure* scale levels and its influence on urban climate. Street trees are the focus of this thesis. Source: adapted from (Klemm, 2018).

URBAN GREEN INFRASTRUCTURE			URBAN CLIMATE
Scale levels	Built features	Green features	Meteorological layers and scales
City	Urban areas	City parks, green belts, urban forests	Urban Boundary Layer, meso climate
Neighbourhood	Residential district	Parks, woods	Urban Boundary Layer, Urban Canopy Layer, meso and local climate
Street	Building, street canyon	<u>Street trees</u> , front gardens	Urban Canopy Layer, microclimate, human thermal comfort

Impact

The ability to regulate the microclimate is one of the environmental services that Urban Green Infrastructure brings to the built environment (Andersson et al., 2014; Norton et al., 2015b). The impact of vegetation on air temperature, relative humidity, wind pattern, and precipitation varies with time, season, and the urban built environment (Byrne et al., 2008; Perini & Magliocco, 2014; Tong et al., 2017).

Via evapotranspiration, vegetation is able to influence the radiation flux by increasing latent heat (Q_L) and decreasing stored energy (Q_S) and convective sensible heat (Q_E) (Pearlmutter et al., 2009). Studies showed that trees decrease surrounding air temperature of 3.1°C up to 5°C via evapotranspiration (Meerow & Black, 2003; Georgi & Dimitriou, 2010). Via shading, vegetation can reduce the amount of direct solar radiation reaching building and outdoor ground surfaces—because of the higher albedo of the leaves compared to the built surfaces—, influencing air temperature, mean radiant temperature, longwave radiation and consequently human thermal comfort (Shashua-Bar & Hoffman, 2000; Picot, 2004; Matzarakis et al., 2007). ENVI-met simulation studies of street canyon at pedestrian level showed that the shadow of new proposed trees in São Paulo, Brazil, reduced mean radiant temperature and PET of 24°C and 12°C, respectively, while proposed trees in Thessaloniki, Greece, reduced the mean radiant temperature of 40°C (Chatzidimitriou et al., 2005; Spangenberg et al., 2019). Shade and evapotranspiration of trees are determined by their total height and canopy geometry, as well as their foliage properties and mature shape (Santamouris, 2001). Via tree geometry (height, canopy and leaf size, and structure of the tree) and placement in the outdoor space, vegetation is able to influence the wind favouring the channelling of air or slowing down its passage (Akbari & Taha, 1992; Bonan, 1997)—a deciduous tree, for example, can reduce wind speed by 30-40% (Ali-Toudert & Mayer, 2007). However, depending on the surrounding environment, such as the geometry, arrangement, and orientation of its surrounding buildings, a decrease in wind speed and an hourly shift in the location of the sun by trees can reduce thermal comfort (B. Lin et al., 2008).

The impact of vegetation on thermal comfort is determined by the amount and type of vegetation (Figure 19), as well as the quantity and type of surrounding materials (Baris et al., 2009; Jamei et al., 2016). The cooling effect of vegetation is greater on surface temperature than on air temperature (Bowler et al., 2010; Cohen et al., 2012). In summer daytime conditions, trees perform better than alternative greening arrangements in producing comfortable thermal environments (Ng et al., 2012; Lee et al., 2016; Wu et al., 2016).



Figure 19. Type of vegetation in an urban environment. Source: adapted from (J. Li & Liu, 2020)

3

PREVIOUS INTERNATIONAL PROGRAMMES, PLANS AND STUDIES

3.1. STRUCTURE OF THE CHAPTER

This chapter provides some examples of how cities and academics around the world have been developing plans, programmes, and studies involving Urban Green Infrastructure to combat climate change, increasing heat waves, and the urban heat island effect, all of which will have an impact on human health and urban living in the near future by increasing air temperature and thermal stress. Some of the research methods that have been studied over the years include numerical modelling, subjective surveys, objective measurements, and the assessment of outdoor thermal comfort for current or future projects (Coccolo et al., 2016). Some green international programs/plans and projects are proposed first (3.2), followed by two international studies on how vegetation effects human outdoor thermal comfort (3.3 and 3.4), both of which use the ENVI-met software to model the urban environment.

3.2. CITY PROGRAMMES, PLANS AND PROJECTS

One example of a green programme can be seen in the city of Paris, France. Citizens and the mayor of the city of Paris—one of the densest city in the world—co-participated in the development of the *Greening Paris Programme* that aim to enlarge the number of green spaces and streets in the city tackling the urban heat island effect and increasing the number of outdoor public spaces for socialising by planting 20,000 trees, opening around 160 hectares of new green spaces, green facades/roofs, and urban agriculture in 2020, and granting *Green Licences* to Parisians (C40 Cities, 2015; Mairie de Paris, 2016a, 2016b). Since June 2015, through "le permis de végétaliser" (the permit to plant), the municipality of Paris, France, grants individuals or groups of citizens—who apply for—small public areas to cultivate with flowers and plants giving back green areas to the grey city and increasing the involvement of the population in the maintenance of the city (Figure 20) (BCC, 2018; Mairie de Paris, 2021).



Figure 20. Photos of two green areas in Paris, France, managed by Parisians through the "le permis de végétaliser" (the permit to plant) programme (the permit to plant). Source: (Mairie de Paris, 2021)

Another example is the city of Medellín in Colombia, which, as reported by the United Nations Environment Programme, has employed natural-inspired measures to regulate high summer temperatures in the face of rising temperatures and the impact of urban heat islands. Considering as natural solutions, actions that protect, sustainably manage, and restore natural or modified ecosystems while providing human well-being and biodiversity benefits, as well as addressing societal challenges in an effective and adaptive manner (ONU News, 2019). The Medellín Municipality's *30 Green Corridors Programme* converted 18 streets, 12 waterways, and three tutelary hills into green corridors by planting 308 trees, 240 palms, and over 90,000 plant species. The programme successfully enhanced landscaping, reduced ambient temperatures by up to 2°C, improved air quality, and offered shade and habitat for a variety of insect species (ACI Medellín, 2019). In 2019, the Ashden organization—a UK-based organisation that sponsors and supports creative projects aimed at hastening the transition to a future powered by clean, affordable energy—awarded the initiative with the *Nature-Based Cooling Award*, which provides assistance in sharing their stories, increasing awareness and reach, and influencing public policy, in addition to monetary compensation (CEIRI News, 2019; ONU News, 2019; Ashden, 2021).



Figure 21. Two of the 30 Green Corridors in Medellín, Colombia. Source: (ACI Medellín, 2019; CEIRI News, 2019)

The city of Philadelphia, Pennsylvania, developed the *GreenPlan Philadelphia* in 2016, with the goal of establishing “framework and strategic direction, created decision tools, and provided a compelling vision to guide the implementation and provision of parks, open space, and trails” throughout the city (Figure 22). The plan targets were established after a thorough analysis of resiliency, fiscal impact, and social equality and they “include a complete bicycle network, 30% tree cover, ensuring all residents live within a half-mile from a major trail, and establishing 10 acres of parkland for every 1,000 citizens”. All of the acts were categorised into one of eight different types of green infrastructure initiatives—trees, walkways, renewable energy, exterior building elements, wetlands, meadows, and urban agriculture, for example—and each was assessed to determine the distinct municipal advantages (City of Philadelphia: Office of Sustainability, 2016; WRT design, 2021).

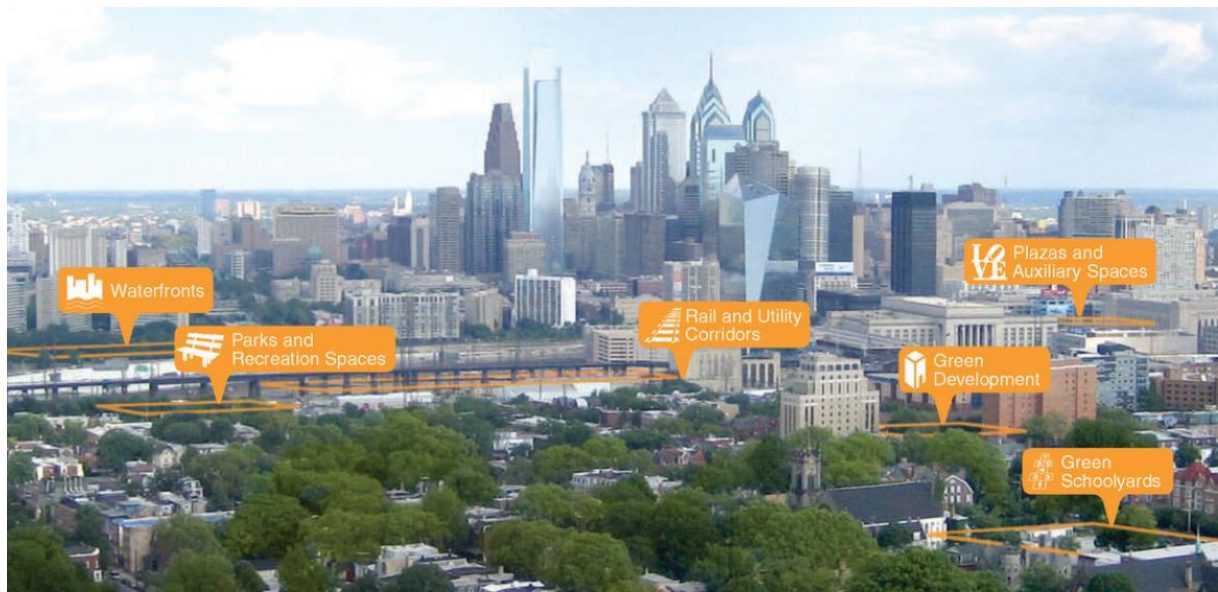


Figure 22. A depiction of some of the *GreenPlan Philadelphia* proposals for implementation in the city of Philadelphia, Pennsylvania. Source: (WRT design, 2021)

From the early 2000's, an abandoned elevated railway on Manhattan's West Side has been turned into a continuous 1.45-mile-long greenway with over 500 different plant and tree species (Figure 23). This greenway, known as the *High Line*, is a public park that is operated, maintained, and programmed by the *Friends of the High Line* a non-profit organisation that collaborates with the New York City Department of Parks and Recreation. The organisation raises approximately the total amount of its yearly budget by citizen donations and, in collaboration with local communities, organises free and open to all public activities, community and teen engagement, and world-class artwork and performances (TheHighLine, 2021).

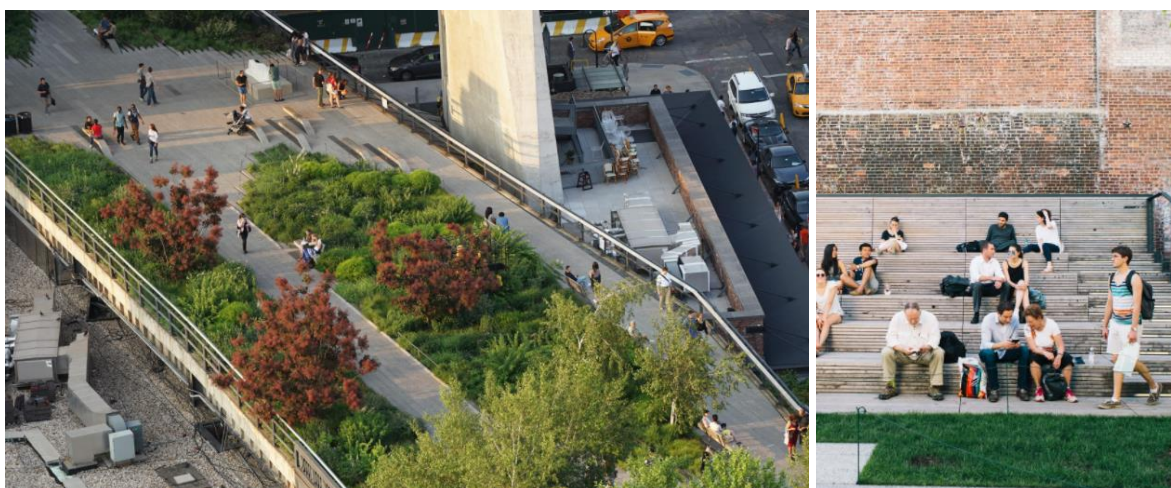


Figure 23. Photos depicting the High Line public park in New York City, New York. Source: (TheHighLine, 2021)

Forestami, which means "make me a forest" in Italian, is the project of the Metropolitan City of Milan and other local entities—the Municipality of Milan, the Lombardy Region, Parco Nord Milano, Parco Agricolo Sud Milano, ERSAF, and Fondazione di Comunità Milano—that promotes the planting of 3 million trees by 2030 in the Metropolitan area of Milan, Italy, with the aim to clean the air, improve life in greater Milan, and combat the effects of climate change (Forestami, 2021b). Trees and plants will be added in parks, along streets, squares and courtyards, on roofs and facades of homes (Figure 24). The project brings together individuals, public bodies, associations, and private companies to begin a process of census, valorisation, and implementation of all permeable and tree-filled green systems in order to encourage policies and projects that promote urban forestation activities and the construction of a Metropolitan Park in the Milan area (Forestami, 2021c).



Figure 24. Photos illustrating the *Forestami* project's tree planting in the metropolitan region of Milan, Italy.
Source: (Forestami, 2021a)

Finally, due to the lack of green and blue in the city, the Municipality of Porto has been developing and supporting projects in the last decade to implement nature-based solutions in order to promote biodiversity, respect the city's natural water cycle, increase carbon storage capacity, valorise soil, and reduce energy consumption, making the city more pleasant and comfortable for residents and visitors

(Câmara Municipal do Porto, 2021f). The projects encompass the implementation of green roofs (Câmara Municipal do Porto, 2021g), urban forests (Câmara Municipal do Porto, 2021b), ecological corridors (Câmara Municipal do Porto, 2021a), urban gardens (Figure 25) (Câmara Municipal do Porto, 2021d), and stream rehabilitation (Câmara Municipal do Porto, 2021e).



Figure 25. Photograph of an urban garden created by the *Hortas Municipais* initiative in Porto, Portugal. Source: (Câmara Municipal do Porto, 2021c)

3.3. THE CASE STUDY OF STUTTGART, GERMANY

The *Central European Programme* and the *European Regional Development Fund* are financing the *UHI Project* that seeks to establish mitigation, risk reduction, and risk management techniques for the urban heat island (UHI) phenomenon in 8 metropolitan cities of central Europe, among which the south-west German city of Stuttgart (Hungarian Meteorological Service, 2021).

From the 1990s, the various climate planning strategy of Stuttgart transformed the city into the finest example of heat island management in the world: the plan combatted issues of overheating and air pollution proposing solutions that take advantage of natural wind patterns and dense vegetation while respecting and protecting the natural environment (Jacobson, 2012; Rehan, 2016). As a result, green covers more than 60% of the city, 39% of Stuttgart area is legally protected as green belt land or nature conservation area, and the municipality engages people in greening initiatives by offering the opportunity to adopt a tree or a green area, as well as providing funding for green roofs (Municipality of Stuttgart, 2021)

The *Pilot Action Study Stuttgart* of Rinke *et al.* (2016) quantifies mitigation and adaptation possibilities for the Stuttgart-West area by analysing the city's urban heat island using air temperature and the physiologically equivalent temperature (PET) thermal comfort index. The goal of the study is to improve local climate conditions, namely better air ventilation and thermal perception, and incorporate mitigation and adaptation options into the municipality's *Development Outline Plan* for the area—*Development Outline Plan* establishes the municipality's development and planning objectives for areas of the city that exhibit urban transformation tendencies.

The city of Stuttgart is located in a valley basin characterised by low wind speed and surrounded on three sides by steep hill slopes that trap air and heat. Inadequate city ventilation, along with high build density, generates an annual mean urban heat island phenomenon of 1-2 °C. Locally, the urban heat

island phenomenon raises summer air temperature by more than 5°C, converting the core city into a hotspot of high heat stress (Rinke et al., 2016).

The Stuttgart-West area is located in the western part of the core city region, is one of the city's most densely populated areas—25 percent are young and old people, the age group most vulnerable to heat stress—and is characterized by high building density and low green and open area density, which together generate poor ventilation—the buildings block cold streams coming from the hill slopes at night—and high urban heat island intensity (Figure 26) (Rinke et al., 2016).

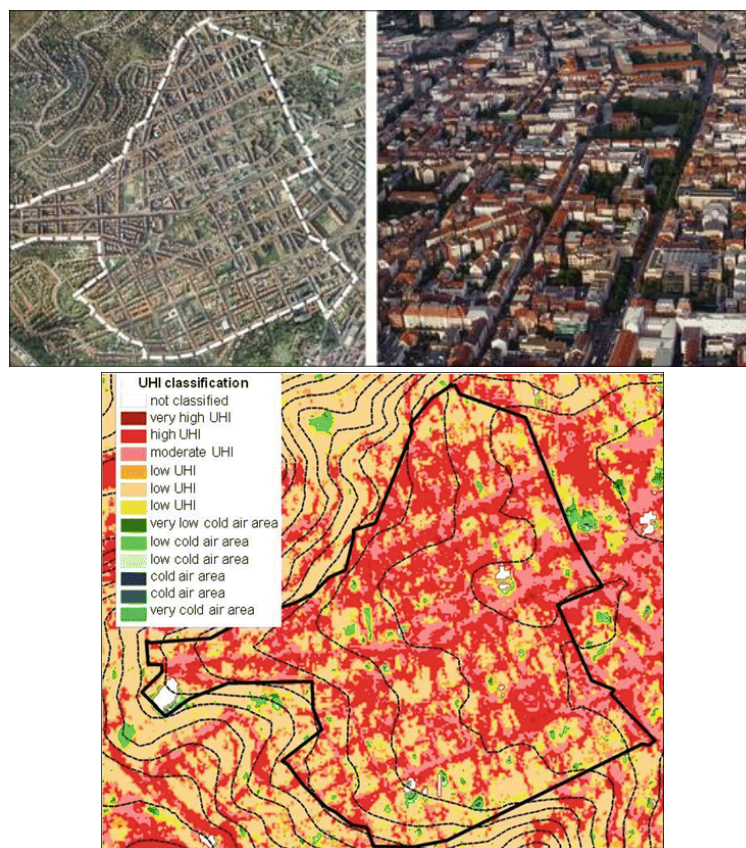


Figure 26. Photos of the Stuttgart-West neighbourhood (up-left) and typical building structures (up-right). Map of the urban heat island (UHI) classification for the Stuttgart-West area (bottom). Source: (Rinke et al., 2016)

The researchers ran simulations on both the micro and macro scales. For the microscale simulation, they chose to simulate how human thermal comfort conditions might change in different scenarios in the neighbourhood of Olga Hospital, which is no longer in use, using RayMan and ENVI-met 3.5 microscale software. Rinke *et al.* simulated the Olga Hospital area in one of the hottest clear-sky summer day (24th July 2010) for the following four scenarios (Figure 27 left):

- Case A – current situation
- Case B – park scenario
- Case C – replacement of one building by a small pond
- Case D – increase of trees along the streets

Results showed that the mean radiant temperature, which has the biggest influence on PET during the day on a sunny summer day, ranges from 23.8 °C to 75.6 °C, with the lowest value found in the tree shade in green areas. PET values (Figure 27 right) reach a maximum of 58 °C above sealed surfaces with low albedo, high solar irradiation, and low wind speed; however, PET values in green areas range from 18 to 28 °C in shaded areas, not exceeding 35 °C in unshaded areas; and PET values in streets parallel to the wind direction are 10 °C lower than other streets. Furthermore, the research discovered that PET at 1.5 m height beneath trees is lower than over green areas and asphalt—around 10°C and 25°C, respectively—and that increasing the number of trees might cut air temperature by 3.0 °C.

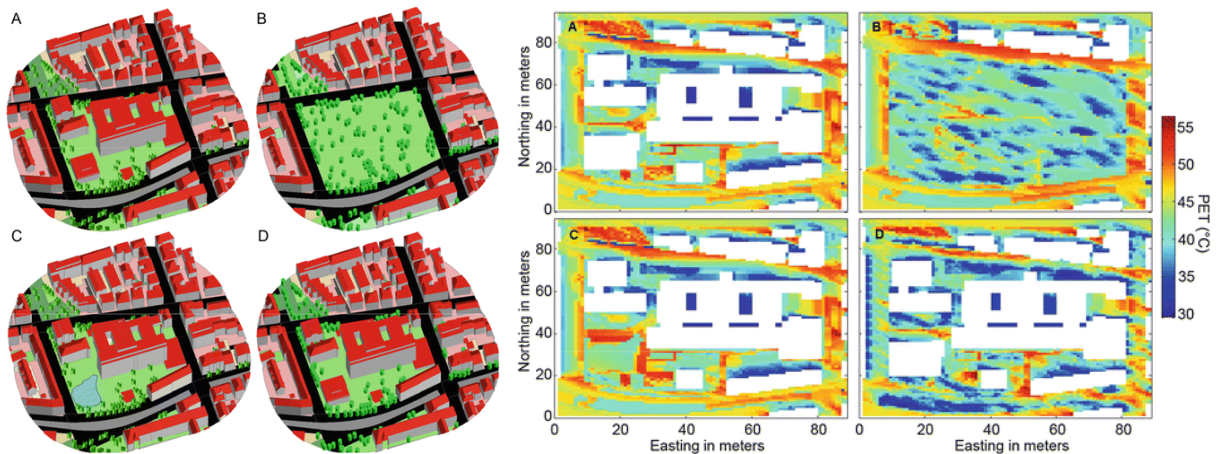


Figure 27. Left: scenarios of the microclimate simulations for the Olga Hospital area. Case A – current situation; Case B – park scenario; Case C – replacement of one building by a small pond; Case D – increase of trees along the streets. Right: physiologically equivalent temperature (PET) value results for the four scenarios of the Olga Hospital area. Source: (Rinke et al., 2016)

For the macroscale simulation, they chose to simulate how urban heat island intensity—calculated as difference between mean urban and mean rural temperature—might change in different scenarios of the city of Stuttgart. Rinke *et al.* simulated the city of Stuttgart for one day of the strong heat wave occurred in 2003 (13th August 2003) for the following five scenarios (Figure):

- Control - Current situation
- Albedo - Increase in the reflectivity of urban roof and wall surfaces
- Density – Decrease in the building density by 20 % by increasing the Sky View Factor
- Central Park – Replacement of urban surface by natural vegetation in the city centre
- Many Parks - Replacement of single urban areas scattered around the city area

Results are reported in Table 5. Temperatures drop by roughly 1–1.3 °C in both vegetation scenarios.

Table 5. Results of the macroscale simulation study. The impact on formation of urban heat island (UHI) is shown for the five scenarios (Control, Albedo, Density, Central Park, and many Parks) as the difference between mean urban and mean rural temperature for 13th August 2003 8p.m. Source: (Rinke et al., 2016)

Scenario	Control	Albedo	Many Parks	Central Park	Density	Delta [°C]			
						Albedo	Many Parks	Central Park	Density
T mean urban [°C]	33.1	31.5	32.5	32.3	32.4	- 1.60	- 0.60	- 0.80	- 0.70
T max [°C]	34.3	31.9	33.5	33.3	33	- 2.40	- 0.80	- 1.00	- 1.30
UHI; delta	2.52	0.84	1.47	1.19	1.32	- 1.68	- 1.05	- 1.33	- 1.2

The team concluded the study by converting their results into guidelines that will be included in the municipality's Development Outline Plan. They identified the hotspots of heat stress within the Stuttgart-West area, which are concentrated in the district's centre, and proposed strategies to reduce heat stress and increase ventilation. To reduce heat stress, they recommend optimising building blocks based on the Olga hospital study, such as adding greened courtyards, green roofs, and green facades, or using cool materials for roofs and facades, and optimising open public spaces by connecting existing green areas and adding trees and green/cool material facades in street canyons, particularly in the WE direction. To increase air ventilation, they propose extending stream axis by a building height limit, ideal building orientation, and building reinstatement.

3.4. THE CASE STUDY OF FREIBURG, GERMANY

The group of Lee *et al.* (2016) conducted a study in Freiburg, Southwest Germany, intending to expand knowledge of how trees and grassland decrease human heat stress in a human-biometeorological term. The study focuses on a residential district of the city where trees and grassland are already existent (Figure 28, left), and they utilize the ENVI-met simulation program to assess their influence on the environment (air temperature) and human heat stress (mean radiant temperature and physical equivalent temperature (PET) index) for a typical Central European heat wave day.

The case study of the German residential district is characterised by three-storey buildings with pitched roofs and street canyons—aspect ratio (H/W) of approximately 0.5—with asphalt surfaces, grasslands, and broad-leaved trees (Figure 28, left). The group created a 3D ENVI-met model of 1m resolution grids for four scenarios (Figure 28, right): CASE A, current situation; CASE B, current situation without trees; CASE C current situation without trees and grassland; CASE D current situation without grassland. For all scenarios, the team launch a 24h simulation on 4th August 2003, which is one of the first days of the heat wave of August 2003, to ensure that urban greening is not damaged by a lack of water and high temperatures. The team explained that comparing the simulation results of the four scenarios would calculate the effect of greening on human heat stress, namely the difference in air temperature, mean radiant temperature, and PET between:

- cases C and A could point out the total heat mitigation of the existing urban green situation;
- cases B and A could point out the influence of trees;

- cases C and B could point out the influence of grasslands;
- cases C and D could point out the human-biometeorological influence of trees located on asphalt surfaces.

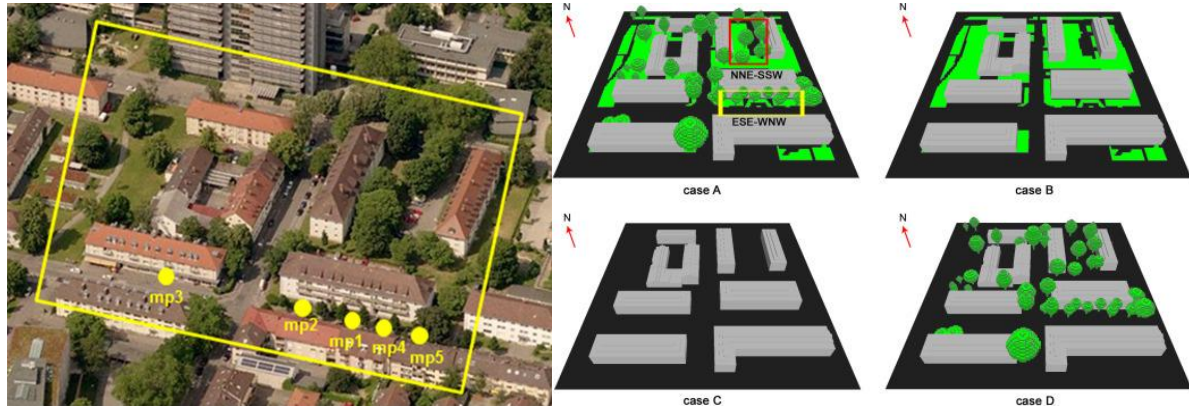


Figure 28. *Left*: Delimitation of the residential district of Freiburg, Southwest Germany, chosen as case study and locations of the human-biometeorological measuring sites (mp1-mp5) on 27th July 2009. *Right*: 3D ENVI-met model for the four scenarios: CASE A, current situation; CASE B, current situation without trees; CASE C current situation without trees and grassland; CASE D current situation without grassland. Source: (Lee et al., 2016)

To validate the human biometeorological performance of the ENVI-met simulation, the team measured air temperature, mean radiant temperature and PET at five measuring sites (mp1-mp5) (Figure 28, left) on 27th July 2009, which was a typical clear-sky summer day in Central Europe, and compared the field measurements to the results of the simulation of CASE A on 27th July 2009. The results of validation showed that, when compared to the measured values, ENVI-met overestimates air temperature (0.2 °C at any experimental air temperature value), mean radiant temperature (1.8 °C and 3.3 °C at 30 °C and 60 °C experimental mean radiant temperature value, respectively), and PET (2.8 °C and 3.6 °C at 25 °C and 40°C PET value, respectively).

Their results show that trees have a stronger heat mitigating effect than only grassland (PET difference up to 17.4 °C and 4.9 °C, respectively). The impact of having the trees in asphalt instead of grassland is minimal.

4

PORTO CASE STUDY

4.1. STRUCTURE OF THE CHAPTER

This chapter describes the process of this thesis' study conducted on a specific area in the southwest of Porto, Portugal, with the purpose of assessing thermal comfort of the study site in terms of physiological equivalent temperature index by modelling the local microclimate using ENVI-met software. An overview of the city of Porto is offered in terms of geolocation and site description (4.2), climate and thermal comfort characterisation (4.3), and vegetation characterisation (4.4). Technical aspects of the simulation investigation are exposed (4.5), from software and modelling description to simulation description and scenarios. Finally, the results of the simulations are shown (4.6).

4.2. LOCALISATION AND DESCRIPTION OF THE SITE

The case study chosen for this thesis is located in the city of Porto, Portugal, 41° N and 8.6° W. Porto faces the Atlantic Ocean in the northwest littoral region of the Portuguese Country, which is located in the extreme southwest of the European continent (Figure 30 a-b). The municipality has a uniform hypsometry, with altitudes ranging from 0 to 160 metres and a slope that faces the Atlantic Ocean (westernmost part of the city with elevations between 0 and 30m). The eastern zone is taller, and it aligns with the Northeast and Southwest alignment's marginal relief, reaching maximum elevations of 160 metres. The majority of the municipality (51%) is between 31 and 90 metres above sea level, with portions above 91 metres (37%) and portions near the ocean below 30 metres (12%) (Monteiro, et al., 2012).

To choose the Porto case study area, the path of the sun over the city of Porto during the summer period had been analysed (Figure 29). The street search began by considering streets with directions ranging from WE to NW-SE, which were shown to have the worst thermal perception range and the greatest cooling effect of tree canopies (Ali-Toudert & Mayer, 2007; Coutts et al., 2016). Then, among the selected streets, the streets considered had been the one located in the overlapping areas between the occurrence of extreme temperature values and the area with little ventilation, no trees, and a minimum width of 15 m. As a result, *Rua de Pinto Bessa* and the two adjacent squares were chosen, since they are part of the *Campanhã-Station Urban Renovation Area*.

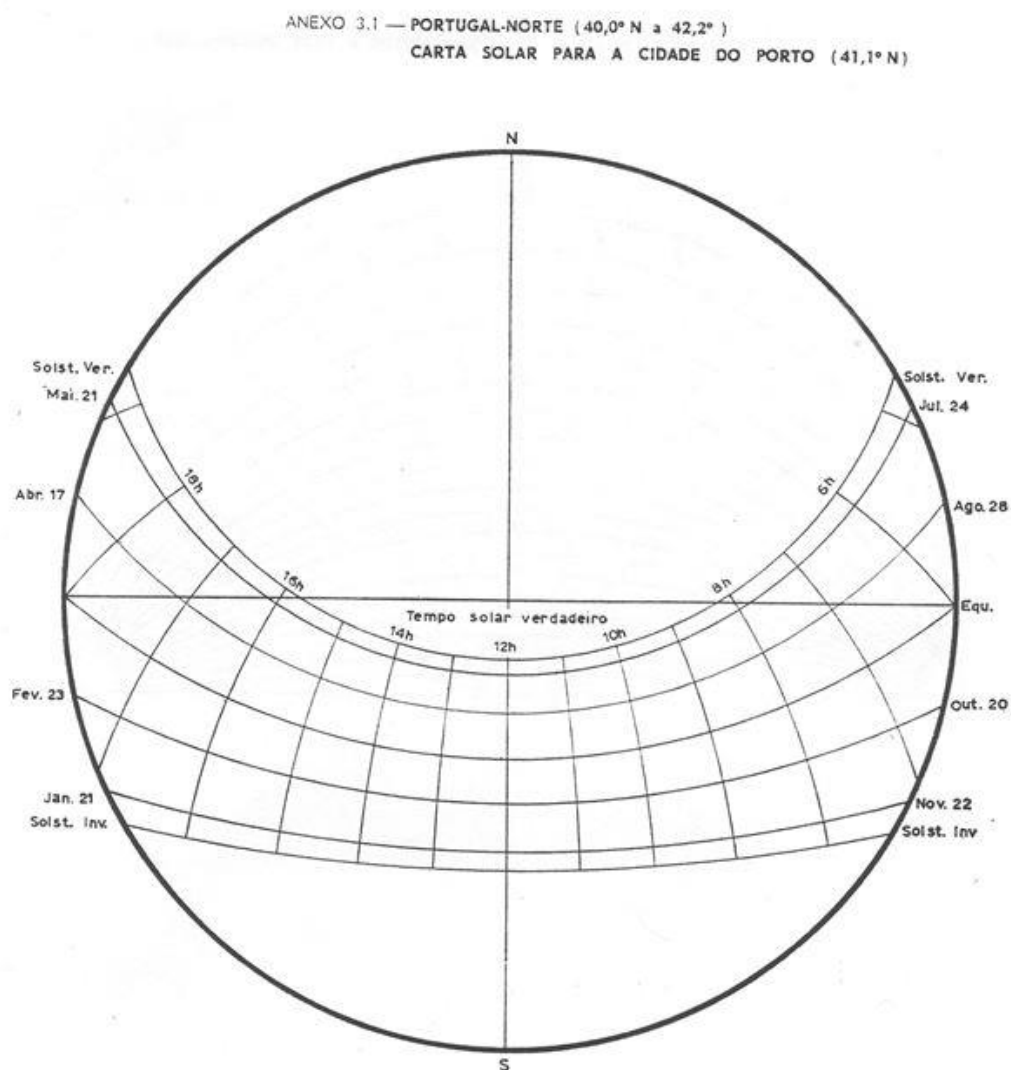


Figure 29. Sunpath diagram of the city of Porto, Portugal. Source: (Silva & Malato, 2012)

The area of the case study is located in the East part of the Municipality of Porto, on the administrative border of Campanhã and Bonfim *freguesias*, and consists of one street canyon, *Rua de Pinto Bessa*, and two squares at either end of the street canyon, *Largo da Estação* (southern) and *Alameda de Cláudio Carneiro* (northern), totalling around 15'000 m² (Figure 30 c-d).

Alameda de Cláudio Carneiro is a public square of approximately 30x35 m² and characterised by broad-leaved trees, grassland, bunches for people to sit, and concrete and granite pavements.

Largo da Estação is a parking square of approximately 35x80 m² situated in front of the metro and train station of Campanhã and is characterised by asphalt, concrete and granite pavements.

Rua de Pinto Bessa is a WNW-ESE street canyon—aspect ratio (H/W) of approximately 0.5—with a width and length of approximately 22 m and 650 m, respectively, and characterised by asphalt, concrete and granite pavements. Sidewalks and buildings of one up to seven storeys can be found on both sides of the street. The road has a difference in height of about 50 m and therefore a slope of 7.7 %.



Figure 30. Geographic localization of the Porto Case Study area in Europe (a), Northern Portugal (b), Municipality of Porto (c). The area consists of one street, *Rua de Pinto Bessa*, and two squares at either end of the street, *Largo da Estação* (southern) and *Alameda de Cláudio Carneiro* (northern) (d). Source: personal archive and (dados.gov, 2020; Eurostat, 2020; OpenStreetMap, 2021).

The area of the Porto case study is involved in the *Campanhã-Station Urban Renovation Area* (Área de Reabilitação Urbana Campanhã – Estação) programme (Câmara Municipal do Porto, 2015, 2017) for part of the territories of the Campanhã and Bonfim *freguesias*. The programme explains that the area is suffering from accelerated deterioration of a substantial portion of its structures, disqualification of public space, a lack of economic and cultural vitality, and a high level of social vulnerability, which cannot be addressed with separate sectoral policy measures. Despite these issues, the programme area has promise in terms of internal and external connections, heritage and symbolic values capable of projecting a new local identity, environmental and landscape resources, vast deactivated industrial units and urban voids with the potential for the installation of new functions and activities. As a result, the *Campanhã-Station Urban Renovation Area* intends to overcome barriers to the socioeconomic development of this territory and improve the everyday living and welfare circumstances of the population by boosting local assets and advantages and leveraging what is envisioned to be a transformation process of Porto's entire eastern area.

The Porto case study area is located inside two structuring projects, PE4 and PE6, of the *Campanhã-Station Urban Renovation Area* (Figure 31). The PE4 project intends to maintain and strengthen the ecological and environmental components of the *Campanhã-Station Urban Renovation Area*, including

the preservation and enhancement of key historic and landscape aspects, the conservation of biophysically sensitive areas, and the promotion of leisure and recreational systems. In this regard, PE4 project suggests the development of a green structure, aligned with the city's green structure, as well as the development of new green framing areas along major thoroughfares, including the Pinto Bessa street. The PE6 project encourages the requalification of public space, infrastructure, and equipment, as well as the valorisation and ultimate reunion of historically significant buildings in the territory that are in a reasonable state of preservation and have construction typologies that allow for new uses. In this regard, the PE6 project intends to requalify public space linked with the main roads of the *Campanhã-Station Urban Renovation Area*, as well as the rehabilitation of relevant dwellings and buildings that highlight historical periods in the city, with a focus on Pinto Bessa street.

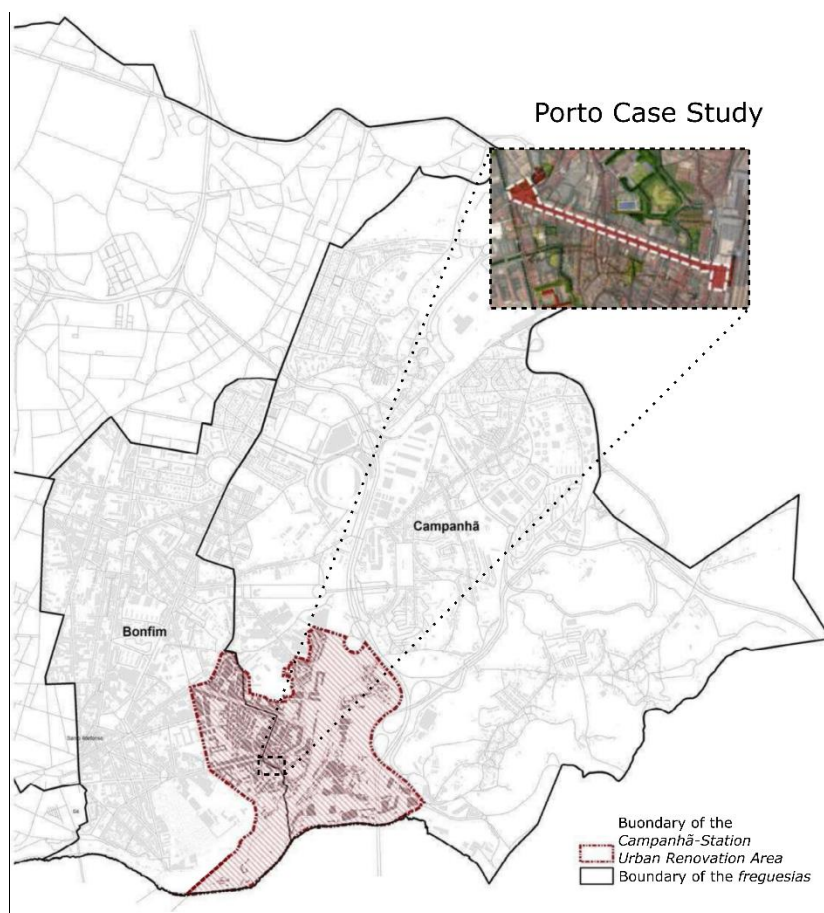


Figure 31. The Porto case study area is depicted in the *Campanhã-Station Urban Renovation Area*. Source: adapted from (Câmara Municipal do Porto, 2015, 2017)

4.3. CLIMATE AND THERMAL COMFORT CHARACTERISATION

The geographic region of Porto is characterised by a Mediterranean Climate—warm temperate climate with dry and warm summer, Cbs of Köppen-Geiger climate classification (Köppen, 1931; Kottek et al., 2006) (Figure 32)—with an Atlantic influence. From the Atlantic Ocean, the Azores Anticyclone and the movements of Polar Front drive two air masses—subtropical warm and humid and Polar colder and drier—to the emerged land affecting the atmosphere in a significant intra- and inter-annual temperature,

precipitation, and wind variability (Ana Monteiro & Velho, 2014). This climatological context provides a consistent daily cycle of competing, stressful, and demanding thermal conditions, which could influence human health (Ana Monteiro, 1993; Ana Monteiro, Velho, et al., 2012; Ana Monteiro et al., 2013).

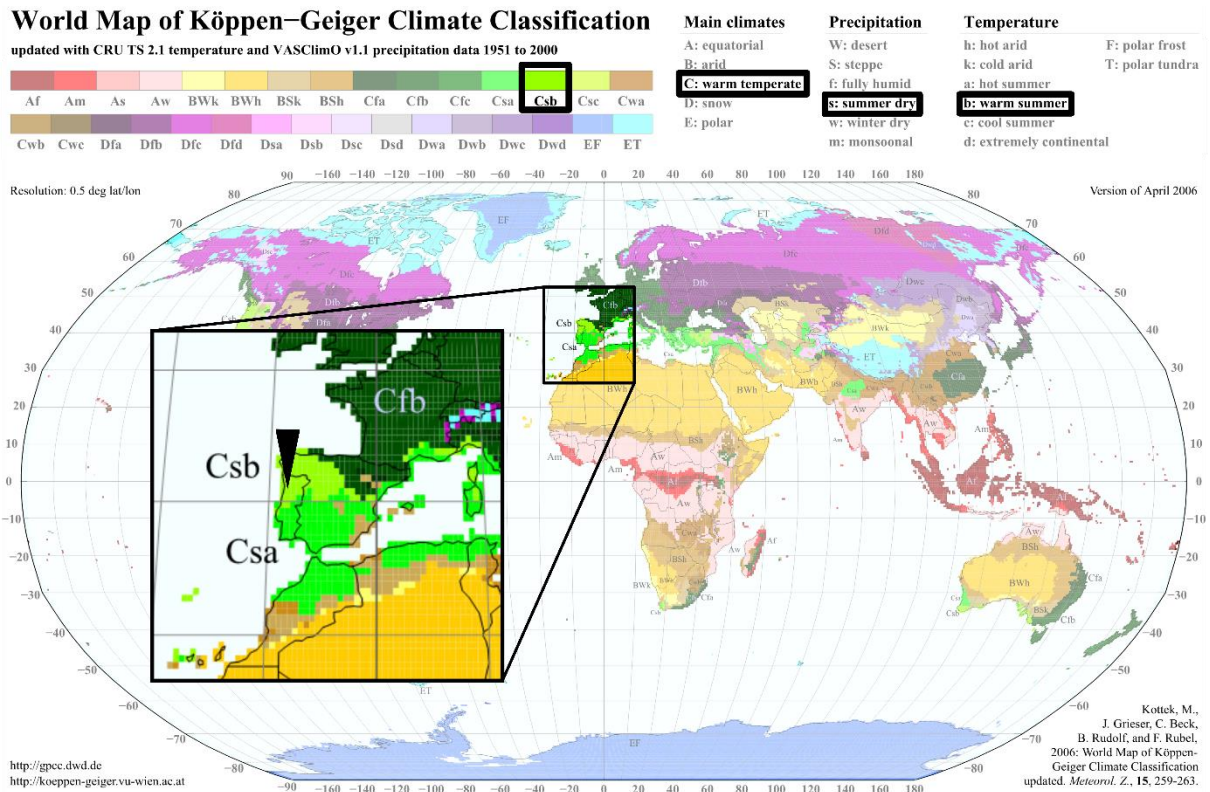


Figure 32. The city of Porto, Portugal, is depicted in the Köppen–Geiger climate classification World Map. The city is classified in the Csb climate, where C=warm temperate, s=summer dry, and b=warm summer. Source: adapted from (Kottek et al., 2006)

Porto, which has summer average temperatures ranging from 15 to 25°C and winter average temperatures ranging from 5 to 15°C (Carvalho et al., 2017; Rafael et al., 2020), is witnessing a rise in the trend of annual temperature and extreme heat occurrences throughout the summer months as a result of climate change, which corresponds to the estimates for this latitude given by the various Global Climate Projection Models (Ana Monteiro, Carvalho, et al., 2012; Ana Monteiro et al., 2018). From 1978 to 2016, summer days with maximum temperatures above 25°C were common in June, July, and September (25% of the days) and very common in August (45% of the days), and days with minimum temperatures above 20°C were uncommon and occurred only between May and September, being more frequent in August (3% of the days) (Ana Monteiro et al., 2018).

Regional winds, with an average wind speed of 5–7 m/s, blow over Porto from the North and Northwest during summer, and from the Northwest, Northeast, and Southeast during winter. Relative humidity is extremely high, with values exceeding 70%, and advection and radiation fogs are frequent along the coast and in the inland, respectively (Ana Monteiro, 1993; Ana Monteiro et al., 2018).

In the revision of the master plan of the Municipality of Porto (Biophysical Support and Environment, Ecological Structure and Biodiversity, Characterization and Diagnosis Report), Ana Monteiro *et al.* (2018) studied the thermal comfort of Porto for the period 2002-2007 using the PET index, which takes into account air temperature, humidity, wind, solar radiation, body mass, age, gender, type of clothing worn, and heat exchanges between the human body and the surrounding environment (see chapter 2.4.3). According to this study, the highest percentage of heat discomfort days occurred between June and September (>50%), as well as in August (81%), while the highest percentage of thermal comfort days occurred in June (41%) (Figure 33).

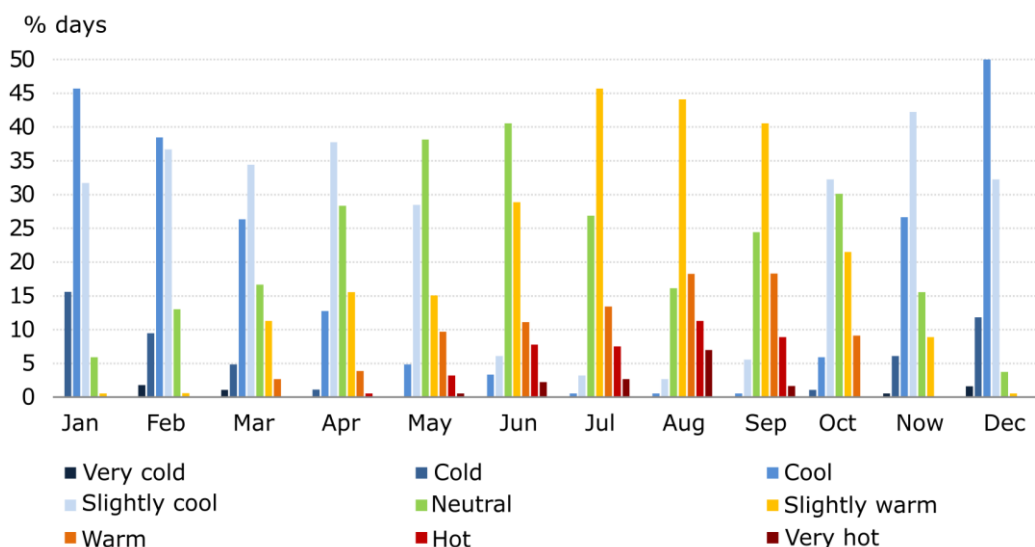


Figure 33. Analysis of the physiological equivalent temperature (PET) index for the city of Porto, Portugal, over the period 2002-2007. Source: adapted from (Ana Monteiro *et al.*, 2018)

During any season, the city of Porto is characterised by an Urban Heat Island, with temperature picks situated in the correspondence of the city's central core and central core's periphery, where the combination of high levels of urban and population density, lack of green spaces, dramatic topography, and strong traffic combine their influence (Góis, 2002). With a few exceptions, extreme summer heat is likely to occur across practically the whole city, and the entire built-up area of the city core is a low-wind zone, while the rest of the urban space is pulverised by several well-ventilated patches. The confluence of these severe summer heat occurrence zones and low-wind zones illustrates the area where urban thermal comfort needs to be enhanced (Ana Monteiro *et al.*, 2018), and it also correlates to the picks of the Urban Heat Island. Furthermore, areas of greater financial and environmental disadvantage links to the East part of the city Porto, demonstrating environmental inequity or injustice (A. Monteiro *et al.*, 2017). As a result of these considerations, the case study for this thesis has been chosen in one of these zones' confluences (Figure 34).

In the city of Porto, the revision of the Municipal Master Plan with the heat island study is part of the Municipal Climate Change Adaptation Strategy (*Estratégia Municipal de Adaptação às Alterações Climáticas*) (Câmara Municipal do Porto, 2016). This study is part of an adaptation option that aims to establish a new paradigm of structure that is an active element of climate change adaptation solutions in order to increase the city's adaptive capacity to have a better quality of human health.

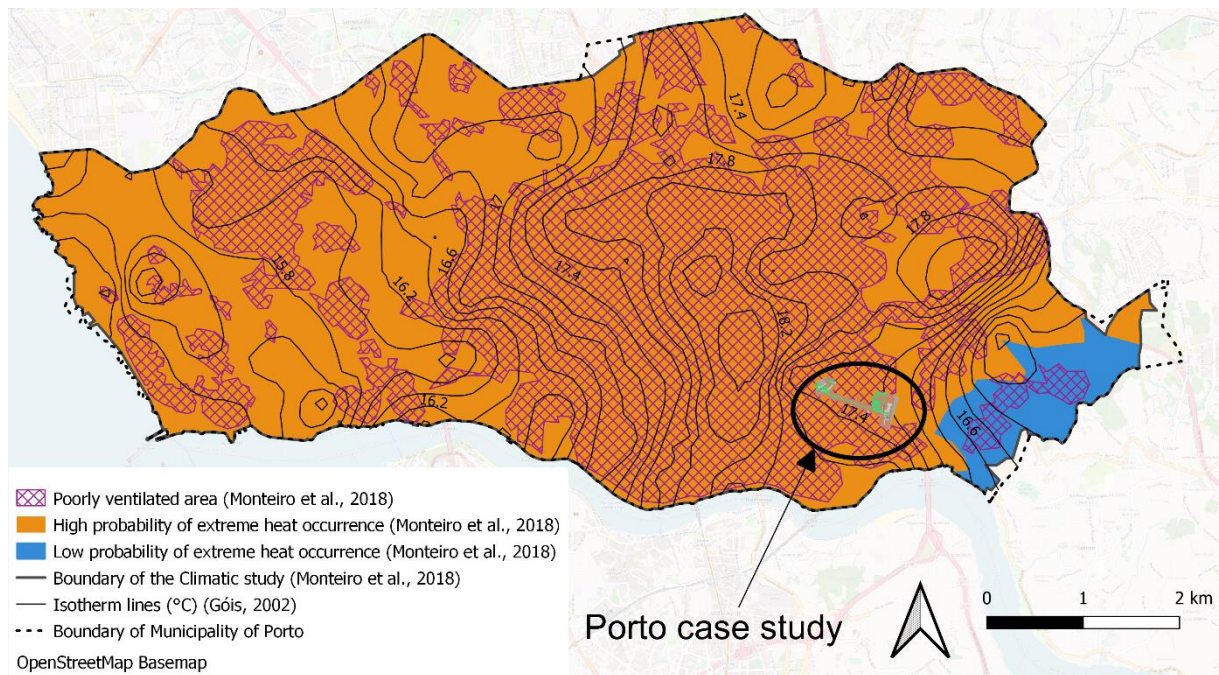


Figure 34. Maps of the Municipality of Porto depicting the Porto case study among the areas with poor ventilation, high and low probability of extreme heat occurrence, and isotherm lines indicating the Porto urban heat island phenomenon. Source: personal archive and adapted from (Góis, 2002; Ana Monteiro et al., 2018)

4.4. VEGETATION IN THE CITY OF PORTO

Porto is Portugal's second-largest urban area, accounting for 25% of national urban land use, and it is the first most densely populated area, with 215k inhabitants in 42km² (INE, 2011; PORDATA, 2020). The urban fringe expansion of Porto is one of the fastest in Europe, outpacing population growth and resulting in the loss of fertile land and forests, making it the Portuguese city with the fewest green and blue regions (EEA, 2011; Carvalho et al., 2017; Rafael et al., 2020).

In the revision of the master plan of the Municipality of Porto (Biophysical Support and Environment, Ecological Structure and Biodiversity, Characterization and Diagnosis Report), Marques *et al.* (2018) examined and categorised green areas in Porto municipality as *natural areas* and *green urban areas*, with the former operating biophysically independently of human action and the latter acting biophysically dependent on both human action and anthropic origin. They defined urban green areas as places with 50% or more green covering, with the planimetric bounds of both green space design and the vertical projection of tree and shrub canopies serving as the limit of green covering (Figure 35). Figure 36 depicts the findings of the investigation and the authors point out that the majority of urban green areas, notably the largest ones, are found on the city's outer ring, particularly in the east and west. These urban green areas has been classified accordingly to the eleven urban green area groups proposed by Marques et al. (2014), with the public square, *Alameda de Cláudio Carneiro*, falling into the group of wooded or landscaped square, which is defined as a non-built space, dominated by the presence of vegetation, ordered and designed, with direct public access and predominantly intended for recreational activities, with less than 35% permeable soil cover.

The authors split the city into three zones based on the historical period of expansion: zone 1 - historical area; zone 2 – downtown (where the Porto case study is located), and zone 3 - outside ring (Figure 37). Combining the information of Figure 36 and Figure 37, the authors highlighted a varied interaction between green areas and built places in each of these zones, with a gradual increase in the amount of green spaces towards the city's northern and northeast boundaries; especially the lack of urban green spaces in zone 1 - historical area when contrasted to zone 3 - outside ring. Table 6 summarise zoning and overall distribution of urban green areas by zones in the municipality of Porto.

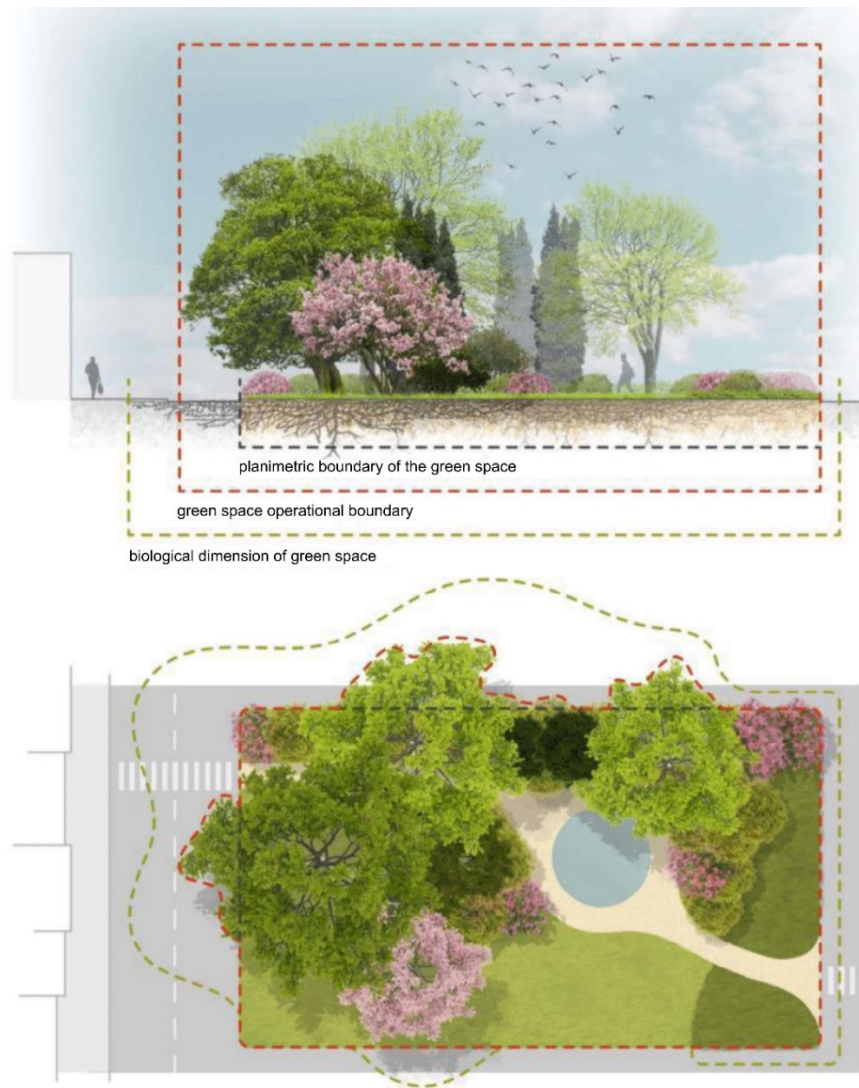


Figure 35. Representation of the method of delimitation of urban green space. Source: adapted from (Marques et al., 2018)

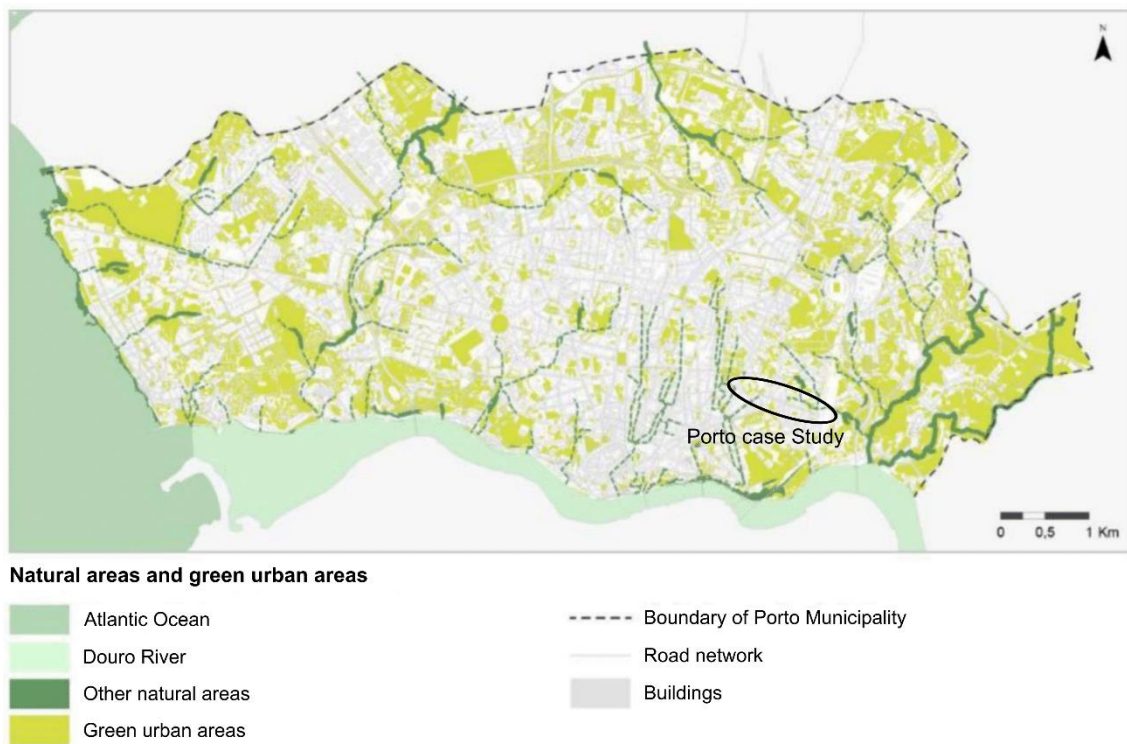


Figure 36. *Natural areas and green urban areas* in the city of Porto and localization of the Porto case study in the map. Source: adapted from (Marques et al., 2018)

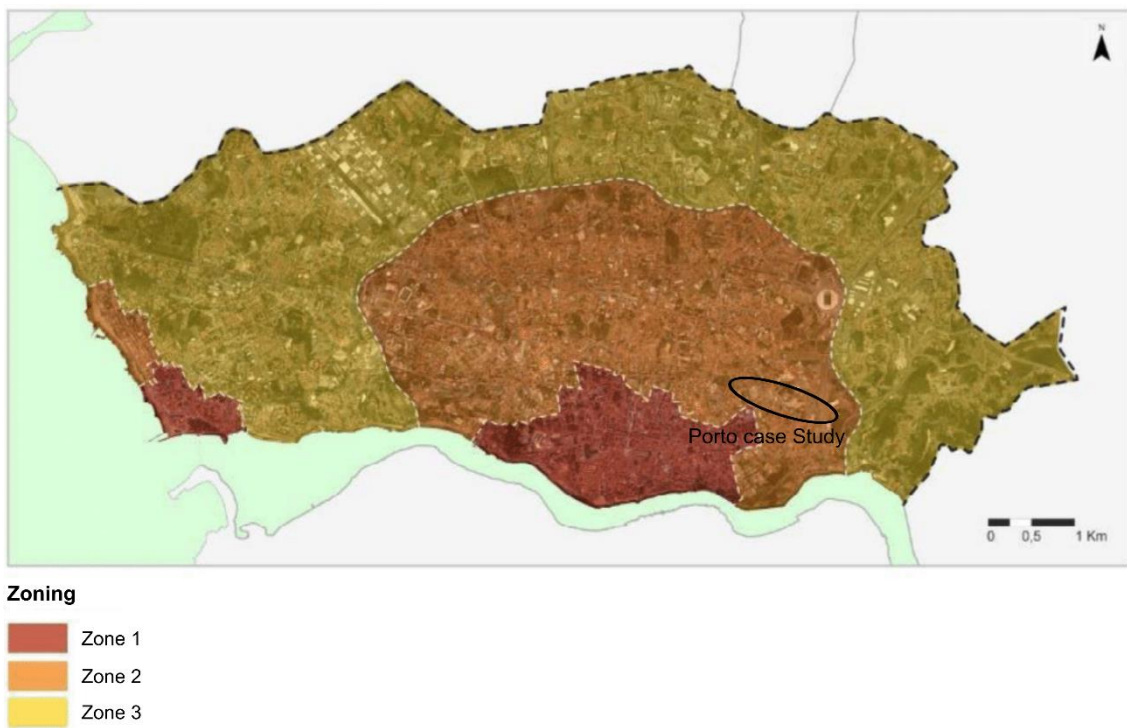


Figure 37. Map of the areas of the city of Porto corresponding to Zone 1 (historical areas), 2 (downtown) and 3 (outer ring) and localization of the Porto case study in the map. Source: adapted from (Marques et al., 2018)

Table 6. Porto's zoning and overall distribution of urban green spaces by zones. The Porto case study is located in zone 2. Source: translated from (Marques et al., 2018)

	Porto	Zone 1	Zone 2	Zone 3
Total area (ha) (concerning only the land portion of the municipality)	4035.39	360.65	1411.17	2263.57
Proportion of the zone in relation to the area of Porto (%)	100	8.9	35.0	56.1
Area of urban green areas (ha)	1313.58	58.74	335.63	919.23
Proportion of urban green areas in relation to the area of the zone (%)	32.6	16.3	23.8	40.6
Percentage distribution of the area of urban green areas (%)	100	4.5	25.6	69.9

The team indicated that urban green areas of the municipality of Porto account for nearly 32% of the total area, resulting in a total urban green space per person of 55.3 m²/inhabitant, which is decreased to 7.9 m²/inhabitant when only considering urban green areas of direct public use with a primarily recreational function - parks, gardens, and wooded or landscaped squares. The group analyses the value of urban green space with public access in Porto to cities in northern and southern Europe, finding that it is comparable to cities in southern Europe, such as Milan with 8,98 m²/inhabitant and Barcelona with 6,82 m²/inhabitant, but significantly lower than cities in northern Europe, such as Berlin with 16,82 m²/inhabitant and Bristol with 27,3 m²/inhabitant—values to consider taking into account factors such as geographical location, climatic conditions and cultural issues. The team came to the conclusion that the climate of the city of Porto, with its mild temperatures and enough rainfall, could provide a bigger plant cover.

In the city of Porto, the revision of the Municipal Master Plan with the vegetation study is part of the Municipal Climate Change Adaptation Strategy (*Estratégia Municipal de Adaptação às Alterações Climáticas*) (Câmara Municipal do Porto, 2016). This study is part of an adaptation option that intends to develop a new paradigm of structure that is an active component of climate change adaptation solutions, namely, implement a tree-planting and blue infrastructure programme targeted at rescuing CO₂ and efficiently mitigating heat island phenomena, in order to reduce susceptibility and/or grasp possibilities in the city and have a better urban environment.

4.5. SIMULATION STUDY

4.5.1. ENVI-MET V4.4.5 SUMMER20

The numerical simulation is carried out using the most recent ENVI-met model V4.4.5 Summer20 (Science and Education License) and its sub-models. ENVI-met (Bruse & Fleer, 1998; Huttner, 2012) is a high-resolution computational fluid dynamics modelling software that simulates the microclimate of the urban environment. A grid-based climate model is used to simulate ground, façade, vegetation, and air relations in order to analyse and assess the effects of design and urban planning on the microclimate of outdoor spaces. The ENVI-met software can produce useful results in urban thermal

comfort research, i.e., parameters such as wind speed, air temperature, mean radiant temperature, relative humidity, wind speed and direction.

The Monde V1.0 beta sub-model allows users to import their UTM georeferenced shape files into ENVI-met software in order to transform them into the ENVI-met extension readable by the Spaces V4.4.5 sub-model, which allows users to visualise and modify the model in a 3D grid-based environment.

The BioMet V2.0 sub-model is a post-processing tool able to calculate human thermal comfort indices directly interacting with the ENVI-met meteorological output and let the users to interactively set the persons parameter (such as gender, height, weight, clothing value, and level of activity), to choose the thermal comfort index (specifically PMV, PET, UTCI, and SET) and to define the range of calculation.

The LEONARDO V4.4.5 sub-model generates coloured images of all simulation results.

4.5.2. MODELLING OF THE STUDY SITE IN ENVI-MET

The layout of the case study area is developed from a CAD drawing provided by the Faculty of Engineering at the University of Porto using QGIS and ArcGIS programs (Figure 38). The GIS model is developed in the georeferenced system of WGS 84 / UTM zone 29N (Portugal zone) in order to be able to be imported in the Monde sub-model of ENVI-met.

Due to the large area of the case study and the long simulation time needed, in the Space sub-model of ENVI-met, the area domain of the case study is divided into three sections corresponding to the public square, *Alameda de Cláudio Carneiro*, the parking square, *Largo da Estação*, and the street canyon, *Rua de Pinto Bessa* (Figure 39), which characteristics are reported in Table 7. To avoid any boundary disturbance, the spatial domain along the z-axis was set to at least twice the height of the tallest building, and the horizontal distance between the model border and the buildings was set to at least the size of the closest building height, as the ENVI-met creators recommended (ENVI-met, 2021c). As suggested by the authors (ENVI-met, 2021a), the topography of the area was not considered due to some drawbacks that were actually encountered during the simulations, then explained in the discussion section.

Owing to the pandemic's restrictions on going outside, the heights and materials of buildings and roads are obtained from Google Earth View Street observation, while tree species are obtained from an interactive geolocated tree catalogue of the Municipality of Porto (Câmara Municipal do Porto, 2020a) and the app PlantNet (Pl@ntNet, 2020). Pavement and roof materials, trees, and grass are chosen from the database of the ENVI-met software to reproduce the real materials, while building façade materials are combined to generate a new equivalent material for the various types of existing houses in the case study area. Information on the materials and trees can be found in Annex I.

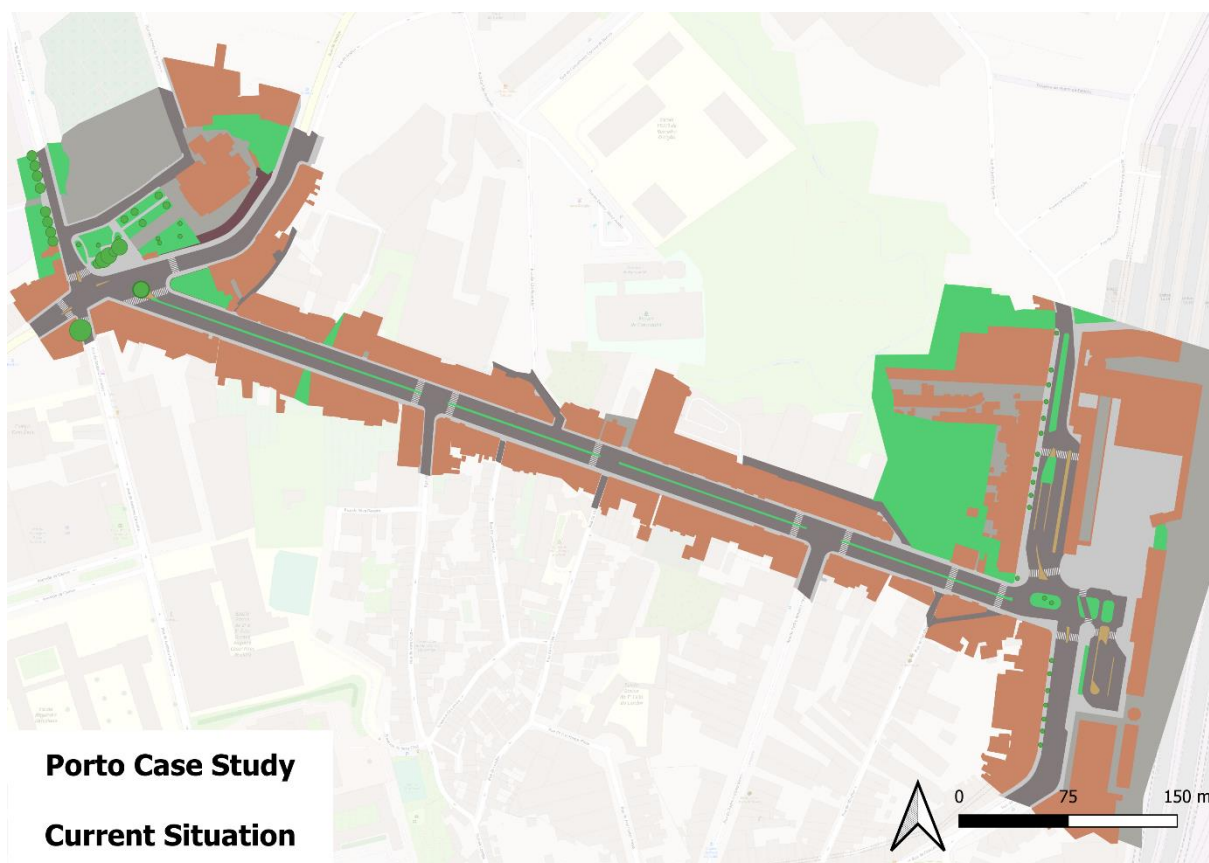


Figure 38. Layout of the Porto case study area. Source: personal archive and OpenStreetMap.

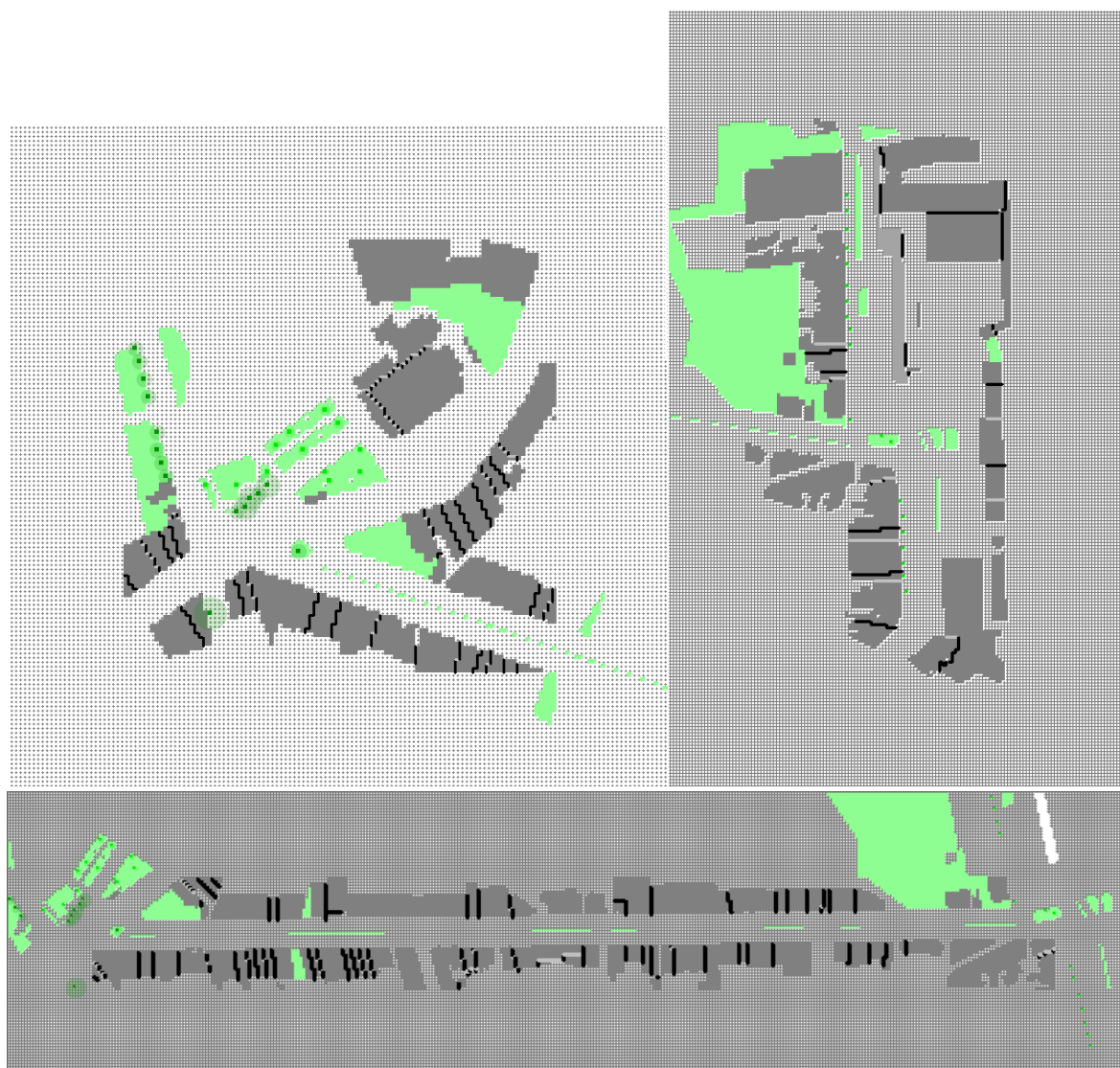


Figure 39. Layout of the three ENVI-met model domain of the Porto case study. *Alameda de Cláudio Carneiro* (up-left), *Largo da Estação* (up-right), *Rua de Pinto Bessa* (bottom). Source: generated with the ENVI-met sub-model *Spaces*.

Table 7. Domain characterisation of the three ENVI-met models of the Porto case study

Location	Alameda de Cláudio Carneiro	Rua de Pinto Bessa	Largo da Estação
Spatial Resolution	2m x 2m x 11m	2m x 2m x 11m	2m x 2m x 11m
Domain size (grids)	150 x 150 x 6	400 x 100 x 6	150 x 250 x 5
¹ <i>dz of the lowest grid box is split into 5 subcells</i>	yes	yes	yes
¹ <i>Telescoping (dz increases with height)¹</i>	yes	yes	yes
¹ <i>Telescoping factor (%)</i>	20.00	20.00	20.00
¹ <i>Start telescoping after height (m)</i>	25.00	25.00	17.00
<i>Model Rotation out of grid north (deg)</i>	00.00	20.00	10.00
<i>No Buildings at border within ... grids</i>	26	30	25

¹These characteristics are graphically represented in Figure 40

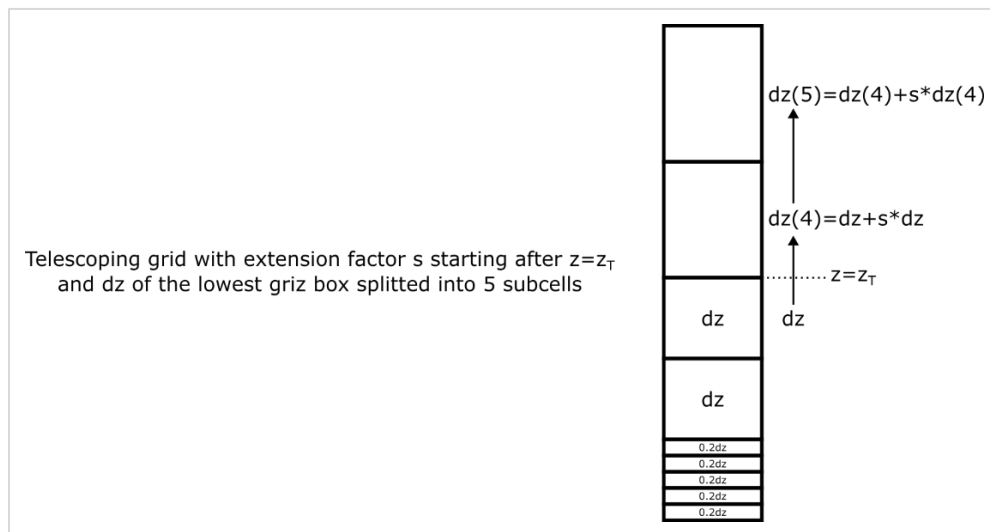


Figure 40. Graphic representation of the vertical cells of the model in ENVI-met. Source: adapted from (ENVI-met, 2021b)

4.5.3. SETUP FOR THE NUMERICAL SIMULATION

Meteorological data for the City of Porto (solar radiation, wind speed and direction, air temperature, and relative humidity) for a typical year are obtained from the EnergyPlus website (U.S. Department of

Energy, 2020). The microclimate simulations of the three ENVI-met models were set up in the following ways for the hottest day of August and the average summer day.

In order to compare the green mitigation strategies, the representative hottest day in month of August was chosen. The month of August in Porto has the highest average air temperature values of the year (Figure 41) and the highest values of thermal stress affecting humans (Figure 33) (Ana Monteiro et al., 2018). According to the typical year data obtained from the EnergyPlus website, the hottest day of August (10th) has an average air temperature of about 27 °C (with a maximum of 31°C). Then, because the ENVI-met tool requires a year to be used throughout the simulation and we are utilising typical year data, a fictitious year was selected from maps of air temperature anomalies from the preceding five years obtained from the *Portuguese Sea and Atmosphere Institute* (IPMA, 2020). August 2018 has seen the highest fluctuation in maximum, average, and lowest air temperatures over the last five years (Figure 42). As a result, the 10th of August 2018 has been selected as the simulation day for the hottest day of August.

Meteorological data for the average summer day were created by calculating the hourly mean values for each meteorological datum over the summer period (from 21st June to 22nd September). The obtained minimum and maximum air temperature values were used to select the fictitious simulation day, which happened to be July 14th, by comparing the obtained values to the typical year values. Then, as for the choice of the hottest day of august, a fictitious year was selected from maps of air temperature anomalies from the preceding five years obtained from the Portuguese Sea and Atmosphere Institute (IPMA, 2020). July 2019 has seen the highest fluctuation in maximum, average, and lowest air temperatures over the last five years (Figure 43). As a result, the 14th July 2019 has been selected as the simulation day for the average day of summer.

The start time of the simulation was set at 9:00 of both 10th August 2018 and 14th July 2019 and the total modelling time was set as 6h—minimum time needed by ENVI-met. Initial meteorological conditions were given, with fix wind and speed time considering the values at 13:00 for both the days since is the time considered for the output analysis. Then simple forcing was chosen for values of air temperature and relative humidity. Table 8 summarises the meteorological data and simulation settings utilised in the configuration files of the three ENVI-met models for both simulation days (hottest day of august and average day of summer).

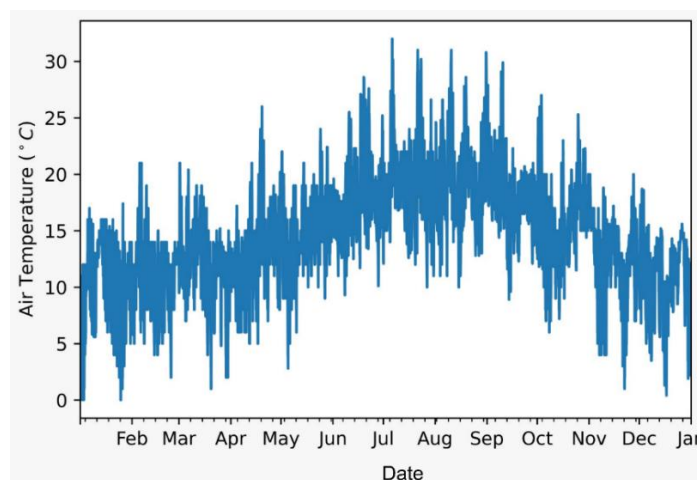


Figure 41. Plot of annual air temperature data (°C) obtained by the EnergyPlus website

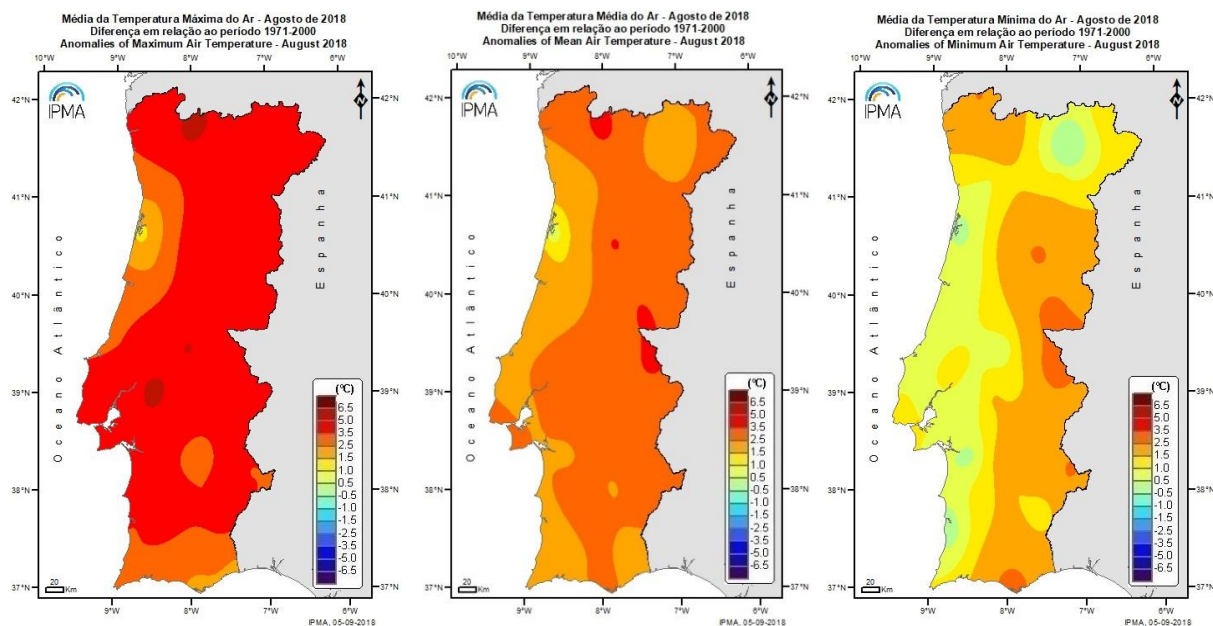


Figure 42. 10-08-2018 Source: (IPMA, 2020)

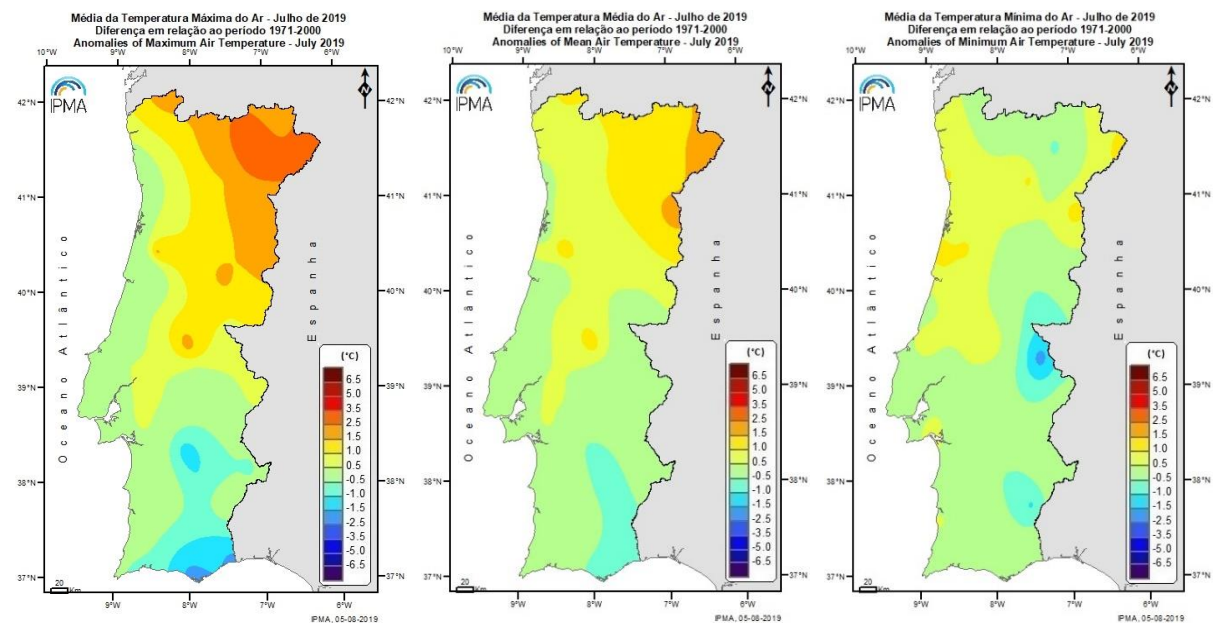


Figure 43. 14-07-2019 Source: (IPMA, 2020)

Table 8. Data used in the ENVI-met model simulations

Input for numerical simulations		
<i>Total simulation duration</i>	6h	6h
<i>Date</i>	Hottest day of August	Average summer day
<i>Starting time (HH:MM)</i>	09:00	09:00
<i>Geolocation</i>	41.15 N / -8.59 W	41.15 N / -8.59 W
<i>Radiation adjustment</i>	0.87	0.72
<i>Wind speed (m/s)</i>	3.60	3.81
<i>Wind Direction (deg)</i>	300	310
<i>Lowest air temperature (°C & HH:MM)</i>	18.40 at 06:00	15.59 at 05:00
<i>Highest air temperature (°C & HH:MM)</i>	31.00 at 17:00	22.49 at 14:00
<i>Lowest relative humidity (% & HH:MM)</i>	39.00 at 15:00	64.40 at 15:00
<i>Highest relative humidity (% & HH:MM)</i>	75.00 at 06:00	90.84 at 05:00
<i>Cloud setting</i>	Clear sky	Clear sky
<i>Plant section (default)</i>	Use tree calendar CO2 background level 400 ppm	Use tree calendar CO2 background level 400 ppm

4.5.4. SIMULATION SCENARIOS

This study aims to investigate how outdoor thermal comfort conditions are currently for *Alameda de Cláudio Carneiro*, *Rua de Pinto Bessa*, and *Largo da Estação*, as well as how the addition of street greenery—street trees and grass in the tree wells—affects outdoor thermal comfort conditions in *Rua de Pinto Bessa*, and *Largo da Estação*. Since the geometry of the street canyon allows for two tree configurations—one central row and two rows at the borders—two proposals for *Rua de Pinto Bessa* were made, while one proposal for *Largo da Estação* was made. As a result, six scenarios were developed:

- *Alameda de Cláudio Carneiro* current situation
- *Rua de Pinto Bessa* current situation
- *Rua de Pinto Bessa* proposal A (two tree rows at the border of the street)
- *Rua de Pinto Bessa* proposal B (one tree central row)
- *Largo da Estação* current situation
- *Largo da Estação* proposal

To select the trees to be proposed in the new configurations of *Rua de Pinto Bessa* and *Largo da Estação*, a cross-search was conducted between the trees present in the streets of Porto—via the municipality's catalogue (Câmara Municipal do Porto, 2020a)—and the existing trees in the ENVI-met database with dimensions in line with the dimensions of both the street and the square. The following deciduous tree

species were chosen as a result of the search: *Acer Platanoides* (Norway Maple), *Acer Pseudoplatanus* (Maple), and *Ulmus Minor* (Field Elm). Deciduous trees were chosen because their leaves fall off in the winter, allowing solar radiation to penetrate through and keeping the area warm. Furthermore, both *Acer Platanoides* and *Acer Pseudoplatanus* are already present in the case study area, namely in *Alameda de Cláudio Carneiro*. *Acer Platanoides* (Norway Maple) and *Acer Pseudoplatanus* (Maple) are medium-growing species, whereas *Ulmus Minor* (Field Elm) is a fast-growing species. Medium-growth species may develop 30 to 60cm in height per year, fast-growth species 60cm, and slow-growth species 30cm; in general, a tree can take 10 to 15 years to mature, and growth rates of trees vary greatly depending on factors such as positioning, soil, fertility, and moisture, and various portions of plants grow at different rates and frequently at different times of the year (Cortês, 2013). Figure 44 depicts the existing tree species chosen for the proposals in some streets of Porto, then provided in a larger size in Annex I.



Figure 44. Existing *Acer Platanoides* (Norway Maple), *Acer Pseudoplatanus* (Maple), and *Ulmus* (Elm) trees in some streets of the city of Porto. (The images shown here are represented in a larger size in Annex I). Source: Google Earth

The **current situation of the public square, *Alameda de Cláudio Carneiro***, presents pavements of concrete and granite, green areas of grassland, shadowing trees of different species and bunches for people to sit and rest in the tree shadow (Figure 45 and Figure 66 in Annex I with plant details).

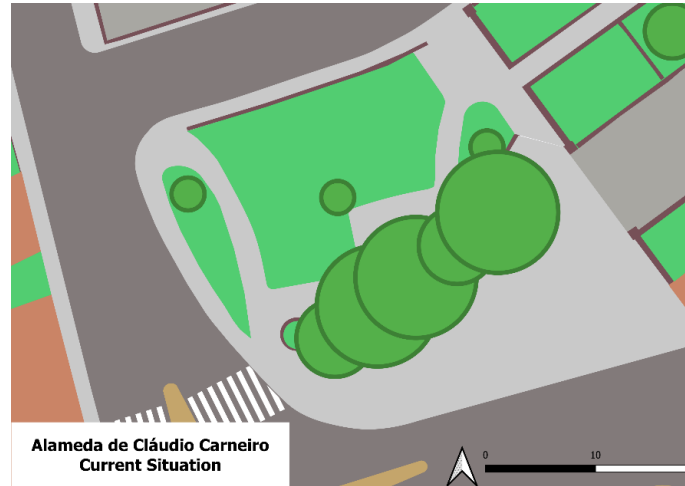


Figure 45. GIS map of the current situation of *Alameda de Cláudio Carneiro* public square. Source: personal archive

The **current situation of the street canyon, *Rua de Pinto Bessa***, includes asphalt road pavement, concrete and granite sidewalks, and a central green traffic island line that runs the length of the street (Figure 46). The structure of the street canyon is symmetrical, with sidewalks on the periphery, one car park lane, one car lane, and a central green traffic island; the transversal profile of the street canyon with dimensions is given in Figure 46 and in a larger size in Annex II. The facades of the buildings along the street are made of various materials, including granite, plaster, concrete, tiles, glass, and metal.



Figure 46. GIS map and transversal profile of the current situation of *Rua de Pinto Bessa* street canyon. (The images shown here are represented in a larger size in Annex II). Source: personal archive and OpenStreetMap

The **proposal A of the street canyon, Rua de Pinto Bessa**, differs from the current situation in the installation of street greenery, i.e., one row of *Acer Platanoides* (Norway Maple) trees in both car park lane and grass in the tree wells; the transversal profile of proposal A of the street canyon with dimensions is given in Figure 47 and in a larger size in Annex II. The tree wells dimension and tree distances had been proposed following the local ordinances of the municipality of Porto (Câmara Municipal do Porto, 2020b) and the general guide line listed in Cortesão (2013).



Figure 47. GIS map and transversal profile of the Proposal A of *Rua de Pinto Bessa* street canyon. Two rows of (The images shown here are represented in a larger size in Annex II). Source: personal archive and OpenStreetMap

The **proposal B of the street canyon, Rua de Pinto Bessa**, differs from proposal A in the installation of trees: one row of *Ulmus minor* (Field Elm) trees are installed in the central green traffic island. The transversal profile of proposal B of the street canyon with dimensions is given in Figure 48 and in a larger size in Annex II.



Figure 48. GIS map and transversal profile of the Proposal B of *Rua de Pinto Bessa* street canyon. One row of *Ulmus Minor* (Field Elm) trees is installed in the central traffic island. (The images shown here are represented in a larger size in Annex II). Source: personal archive and OpenStreetMap

4.6. RESULTS

The PET index is calculated using the BIO-met sub-model and the standard values from Höppe (1999) as input, which are already available in the program (Table 9). All simulation results (Figure 51-50) refer to a height above ground level of 1.1 m—average centre of gravity of a European standing person—at 13:00. This time is chosen because solar radiation is at its peak in Porto at this time of day, the area is almost completely sunny, and a study conducted in Bilbao, Spain,—which has the same climate classification as Porto—revealed that peak levels of PET are around this time for streets with a NW/SE orientation (Lobaccaro et al., 2019). Figure 51-50 are created using the LEONARDO sub-model of the ENVI-met software; the base areas of the buildings are shown in black, while the simulated variable results are shown in color-coded ranges. The meteorological parameters (air temperature, wind speed, relative humidity, and mean radiant temperature) used as input for the PET index calculation are shown in Annex III.

Table 9. Data used in the BIO-met sub-model for the simulation of PET index

PET input		
Body parameters	Gender	Male
	Age of person	35 years
	Weight	75.00 kg
	Height	1.75 m
	Surface area (Dubois-Area)	1.91 m ²
Clothing parameters	Static Clothing Insulation	0.90 clo
Person's metabolism	Total metabolic rate	164.46 W = 86.21 W/m ²
		1.48 met

The PET index values of the public square, *Alameda de Cláudio Carneiro*, range from 29.0°C to 54.4°C for the current situation simulation of the hottest day of August, with a total difference of 25.4°C and a thermal sensation ranging from warm to very hot. The lowest PET value is obtained under the tree shadow with a warm level of thermal sensation, as shown in Figure 51a.

The PET index values of the public square, *Alameda de Cláudio Carneiro*, range from 22.8°C to 50.2°C for the current situation simulation of the average day of summer, with a total difference of 27.4°C and a thermal sensation ranging from slightly warm to very hot. The lowest PET value is obtained under the tree shadow with a slightly warm level of thermal sensation, as shown in Figure 51b.

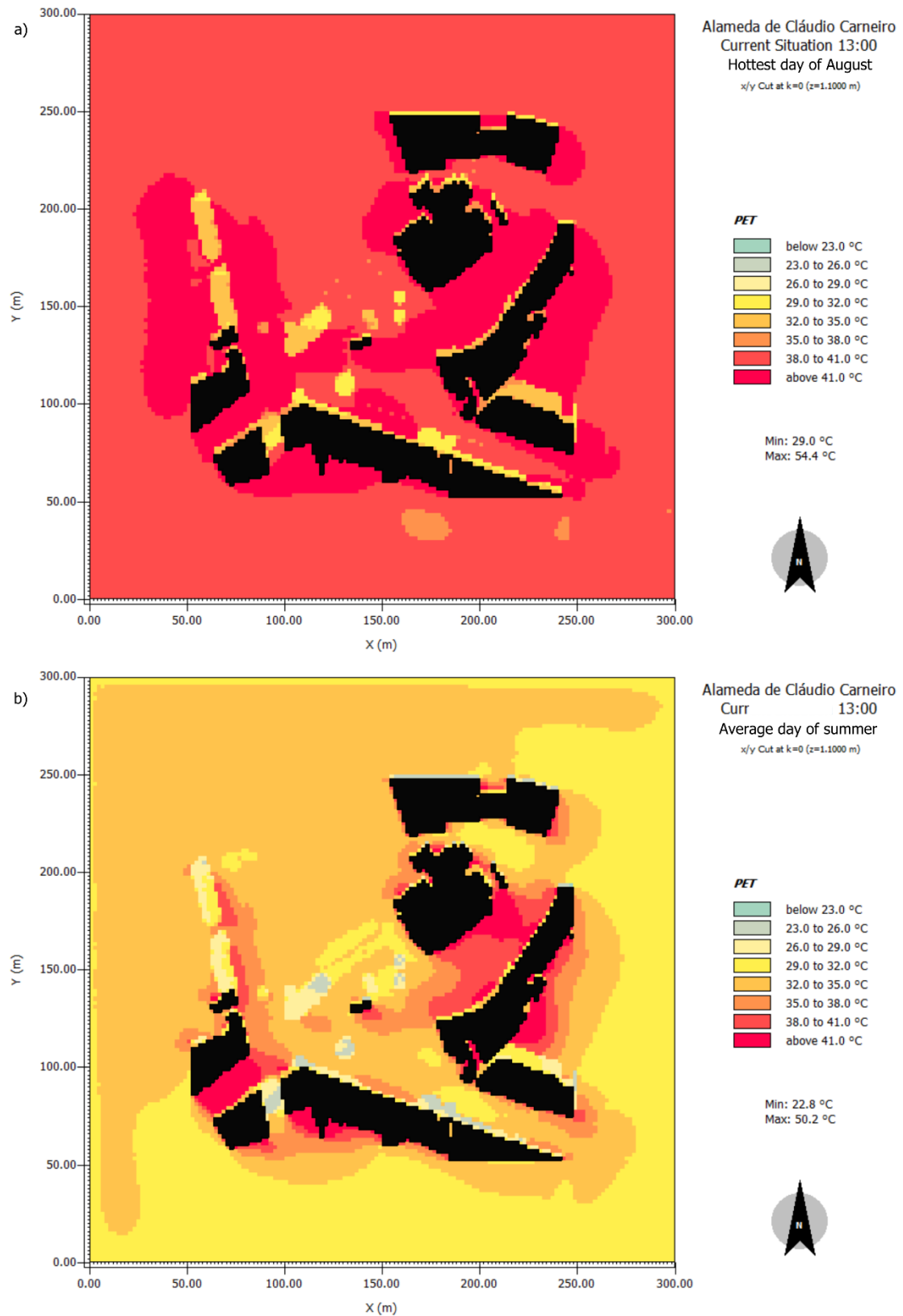


Figure 51. Results of PET values of the public square, *Alameda de Cláudio Carneiro*, for both hottest day of august and average day of summer.

The PET index values of the street canyon, *Rua de Pinto Bessa*, range from 27.4°C to 54.6°C for the current situation simulation of the hottest day of August, with a total amplitude of 27.2°C and a thermal sensation ranging from slightly warm to very hot. The lowest PET value is obtained under the building shadow with a slightly warm level of thermal sensation, as shown in Figure 52a. While for the proposal simulations of the hottest day of August, the PET index values of the street canyon, *Rua de Pinto Bessa*, range from 27.4°C to 53.0°C for proposal A and from 27.4°C to 53.4°C for proposal B, with a total amplitude of 25.6°C and 26.0°C, respectively. In both proposal situations, the lowest PET value is obtained under tree shadow with a warm level of thermal sensation, as shown in Figure 52b-c.

Comparing the current situation and the proposals for the hottest day of August, the PET value difference ranges from -17.2°C and +4.7°C for the proposal A (Figure 54a) and from -18.4°C to +3.6°C for the proposal B (Figure 54b). The influence of trees on PET values varies with spatial distribution: under the shade of trees, PET values are lower than in the current scenario, whereas in the immediate vicinity of trees but outside the shadow, PET values are higher than in the current scenario. Under the tree shadow the PET value difference ranges from -10.6°C to -4.1°C for proposal A (Figure 54a) and from -11.8°C to -0.8°C for the proposal B (Figure 54b). While outside the tree shadow, i.e., in the immediate surrounding of the trees, the PET value difference ranges from +0.3°C to +4.7°C for proposal A (Figure 54a) and from -0.8°C to +3.6°C for the proposal B (Figure 54b).

The PET index values of the street canyon, *Rua de Pinto Bessa*, range from 22.0°C to 50.0°C for the current situation simulation of the average day of summer, with a total amplitude of 28.0°C and a thermal sensation ranging from neutral to very hot. The lowest PET value is obtained under the building shadow with a neutral and slightly warm level of thermal sensation, as shown in Figure 53a. While for the proposal simulations of the average day of summer, the PET index values of the street canyon, *Rua de Pinto Bessa*, range from 22.2°C to 49.6°C for proposal A and from 22.0°C to 48.8°C for proposal B, with a total amplitude of 27.4°C and 26.8°C, respectively. In both proposal situations, the lowest PET value is obtained under tree shadow with a slightly warm level of thermal sensation, as shown in Figure 53b-c.

Comparing the current situation and the proposals for the Average day of summer, the PET value difference ranges from -16.6°C and +6.6°C for the proposal A (Figure 54c) and from -17.0°C to +4.1°C for the proposal B (Figure 54d). The influence of trees on PET values varies with spatial distribution: under the shade of trees, PET values are lower than in the current scenario, whereas in the immediate vicinity of trees but outside the shadow, PET values are higher than in the current scenario. Under the tree shadow the PET value difference ranges from -9.6°C to -0.4°C for proposal A (Figure 54c) and from -8.6°C to -2.2°C for the proposal B (Figure 54d). While outside the tree shadow, i.e., in the immediate surrounding of the trees, the PET value difference ranges from -0.4°C to +6.6°C for proposal A (Figure 54c) and from -2.2°C to +4.1°C for the proposal B (Figure 54d).

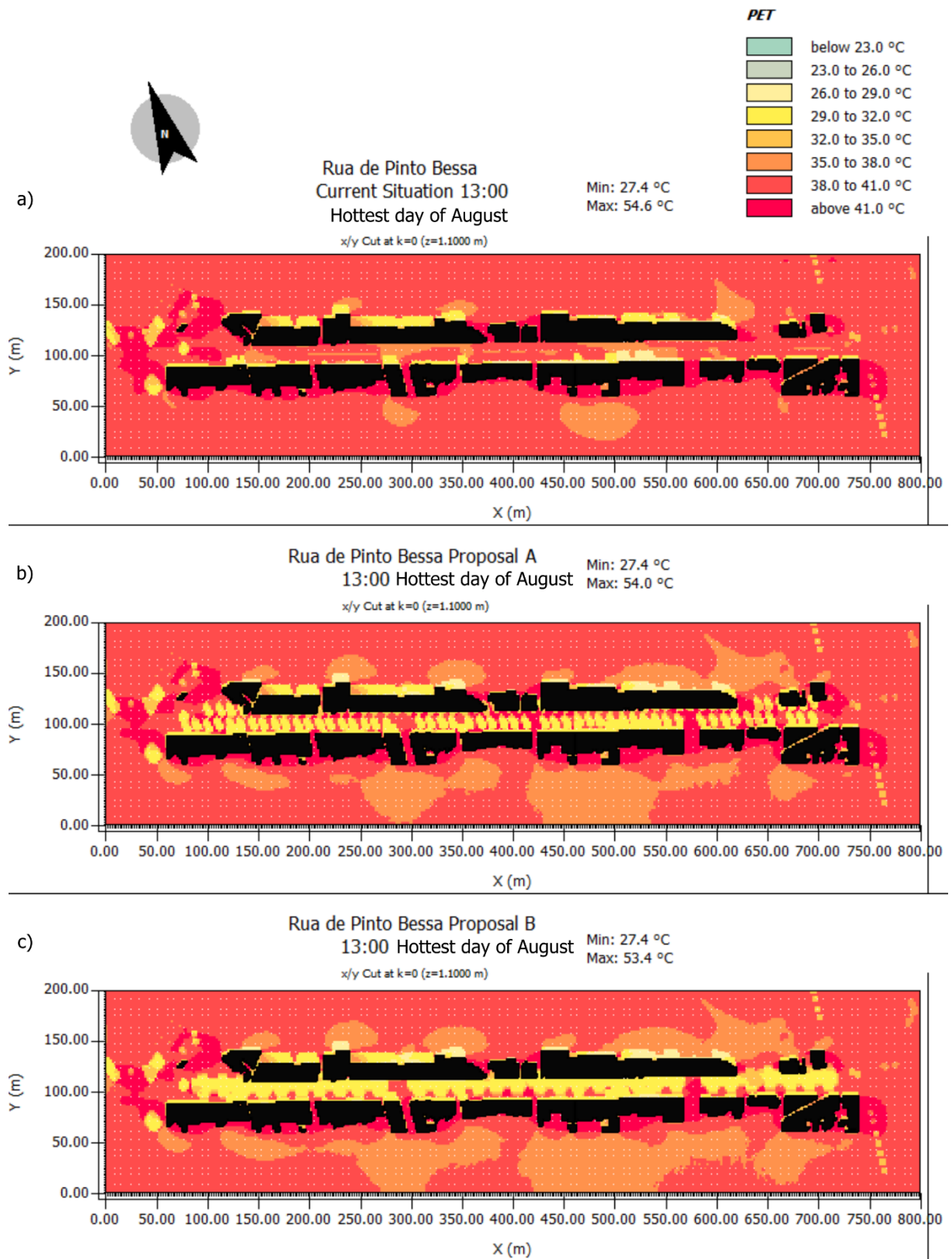


Figure 52. Results of PET values of the street canyon, *Rua De Pinto Bessa*, for hottest simulation day

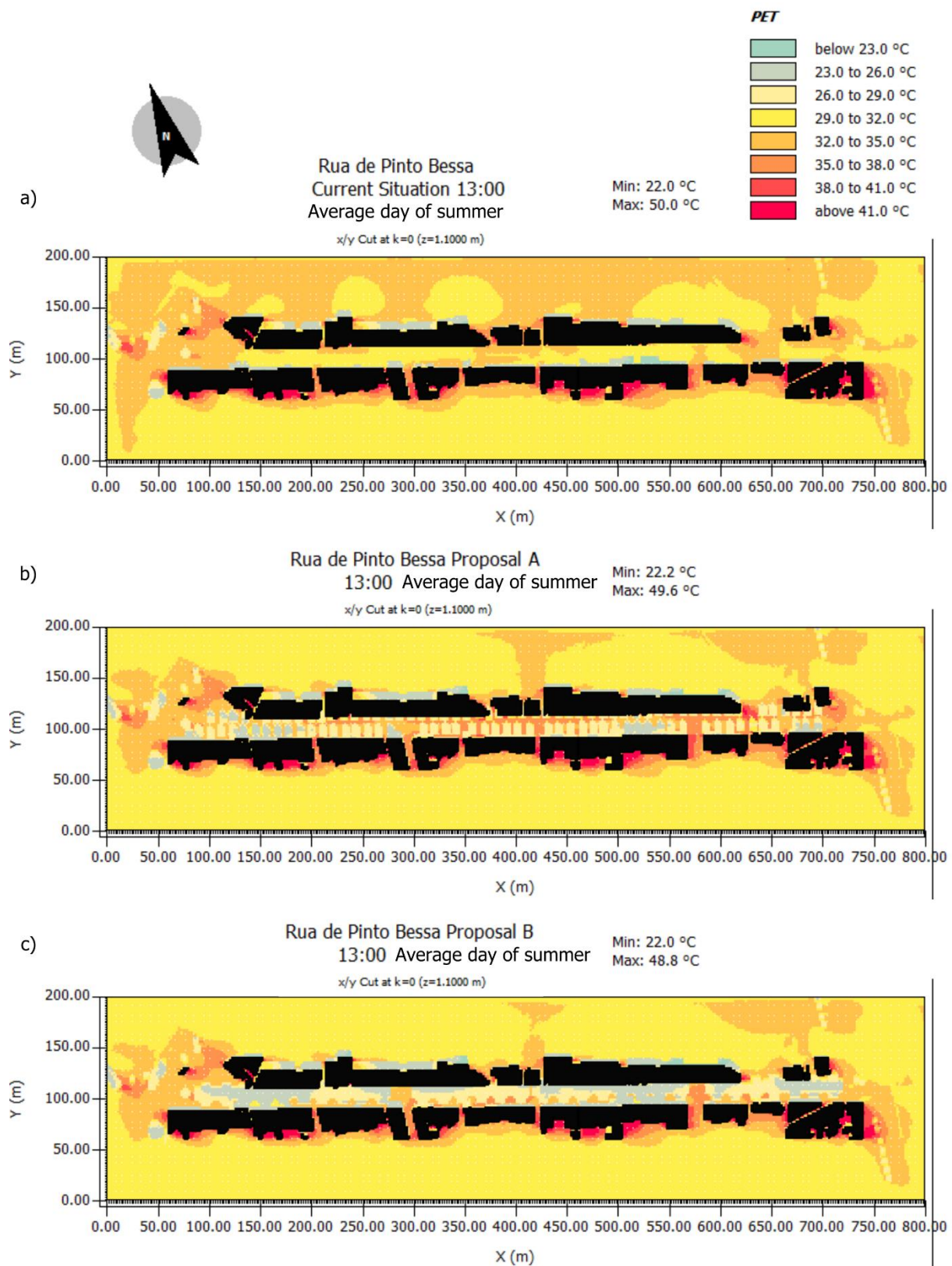


Figure 53. Results of PET values of the street canyon, *Rua De Pinto Bessa*, for average simulation day

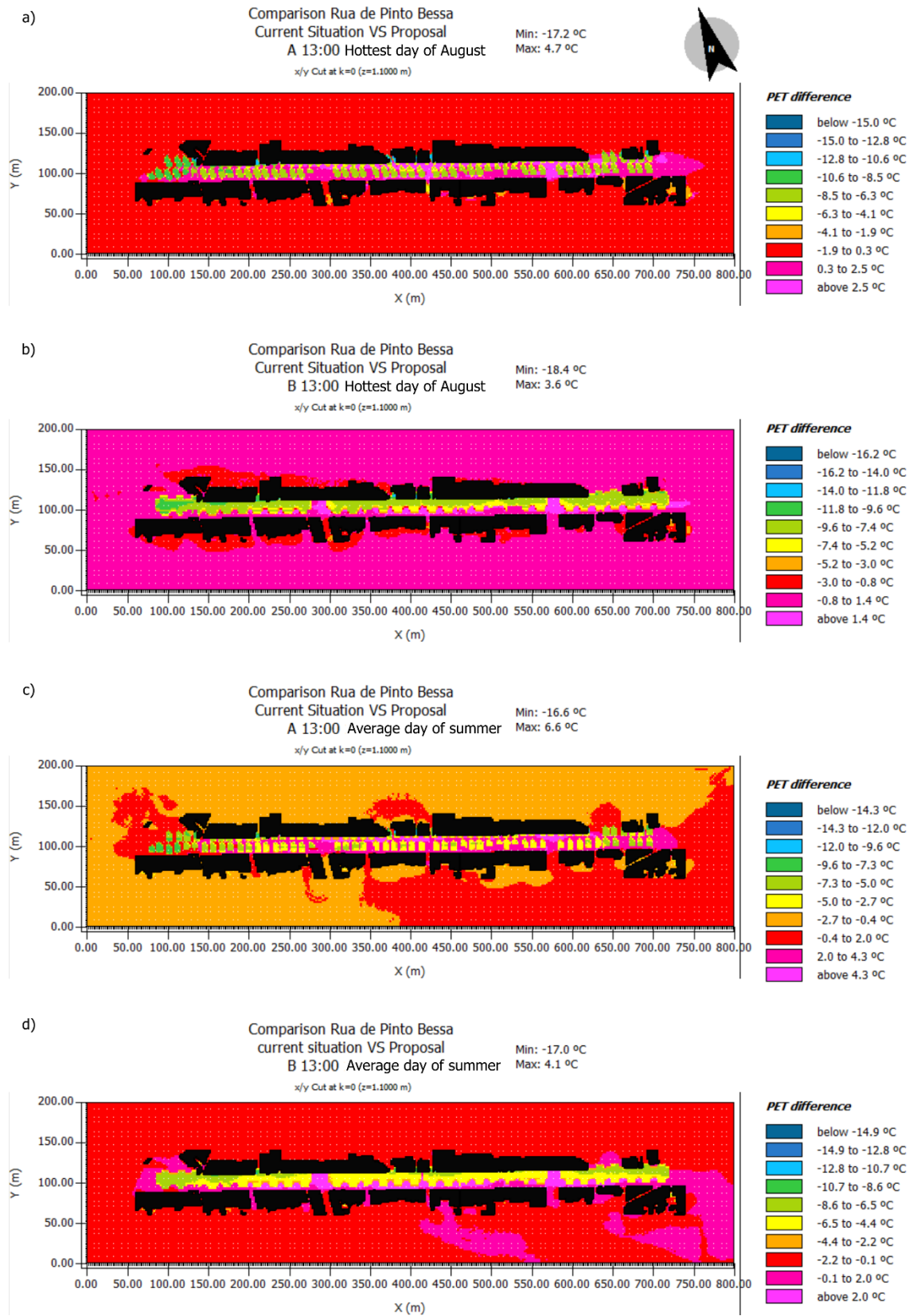


Figure 54. Comparison of PET values of the street canyon, *Rua De Pinto Bessa*, between current situation and proposal A and B for both simulation days.

The PET index values of the parking square, *Largo da Estação*, range from 27.4°C to 54.6°C for the current situation simulation of the hottest day of August, with a total amplitude of 27.2°C and a thermal sensation ranging from slightly warm to very hot. The lowest PET value is obtained under the building shadow with a slightly warm level of thermal sensation, as shown in Figure 55a. While for the proposal simulation of the hottest day of August, the PET index values of the Parking square, *Largo da Estação*, range from 27.2°C to 54.0°C, with a total amplitude of 26.8°C and a thermal sensation ranging from slightly warm to very hot. The lowest PET value is obtained under both tree and building shadow with a warm level of thermal sensation, as shown in Figure 55a-b.

Comparing the current situation and the proposal for the hottest day of August, the PET value difference ranges from -12.6°C and +2.5°C for the proposal (Figure 57a). The influence of trees on PET values varies with spatial distribution: under the shade of trees, PET values are lower than in the current scenario, whereas in the immediate vicinity of trees but outside the shadow, PET values are higher than in the current scenario. Under the tree shadow the PET value difference ranges from -12.6°C to -3.5°C (Figure 57a). While outside the tree shadow, i.e., in the immediate surrounding of the trees, the PET value difference ranges from -3.5°C to +2.5°C (Figure 57a).

The PET index values of the parking square, *Largo da Estação*, range from 21.8°C to 51.4°C for the current situation simulation of the average day of summer, with a total amplitude of 29.6°C and a thermal sensation ranging from neutral to very hot. The lowest PET value is obtained under the building shadow with a slightly warm level of thermal sensation, as shown in Figure 56a. While for the proposal simulation of the average day of summer, the PET index values of the parking square, *Largo da Estação*, range from 21.6°C to 51.2°C for, with a total amplitude of 29.6°C and a thermal sensation ranging from neutral to very hot. The lowest PET value is obtained under both tree and building shadow with a slightly warm level of thermal sensation, as shown in Figure 56b.

Comparing the current situation and the proposal for the average day of summer, the PET value difference ranges from -14.8°C and +5.6°C (Figure 57b). The influence of trees on PET values varies with spatial distribution: under the shade of trees, PET values are lower than in the current scenario, whereas in the immediate vicinity of trees but outside the shadow, PET values are higher than in the current scenario. Under the tree shadow the PET value difference ranges from -10.7°C to -2.5°C (Figure 57b). While outside the tree shadow, i.e., in the immediate surrounding of the trees, the PET value difference ranges from -2.5°C to +5.6°C (Figure 57b).

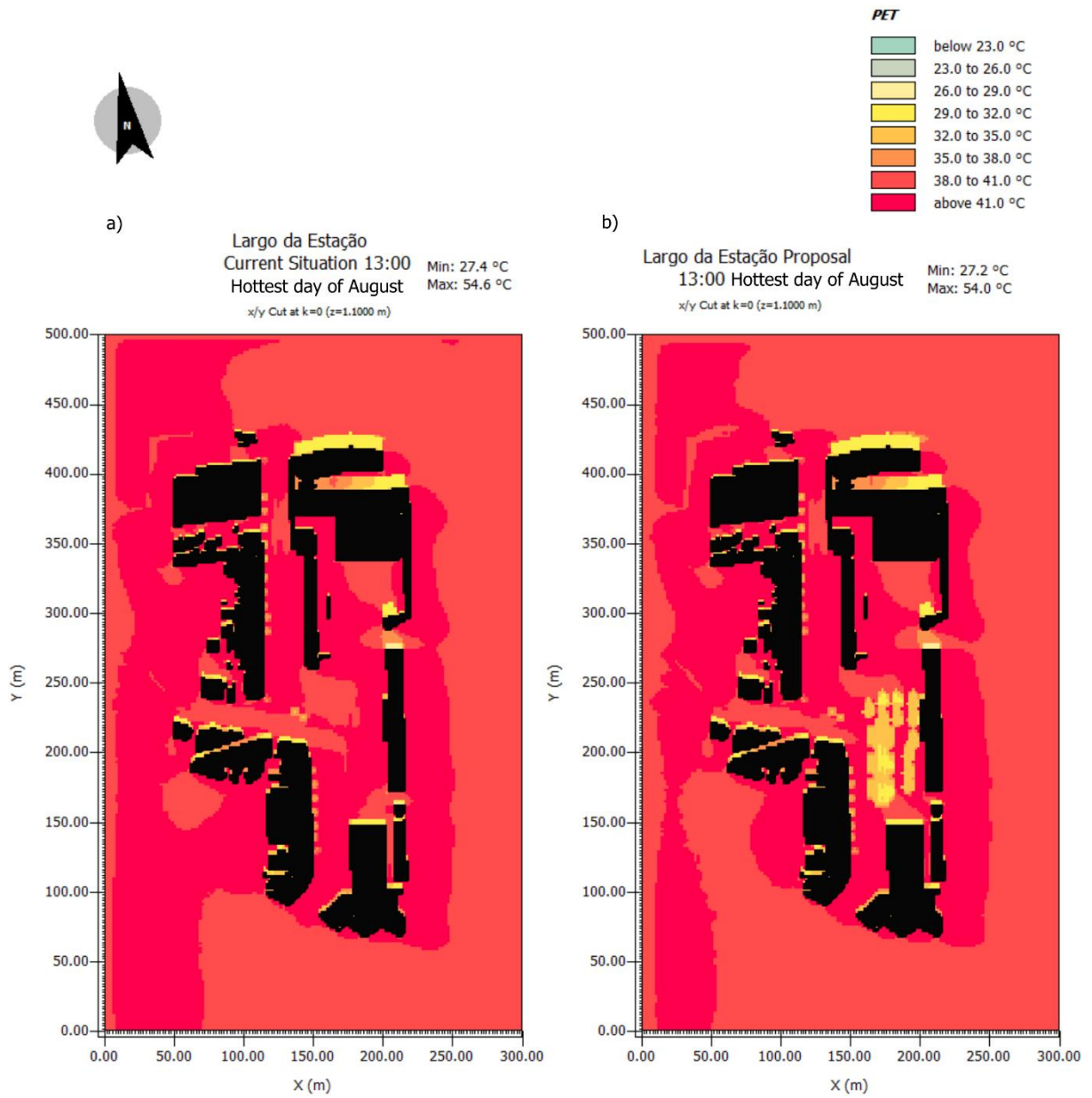


Figure 55. Results of PET values of the parking square, *Largo da Estação*, for hottest simulation day

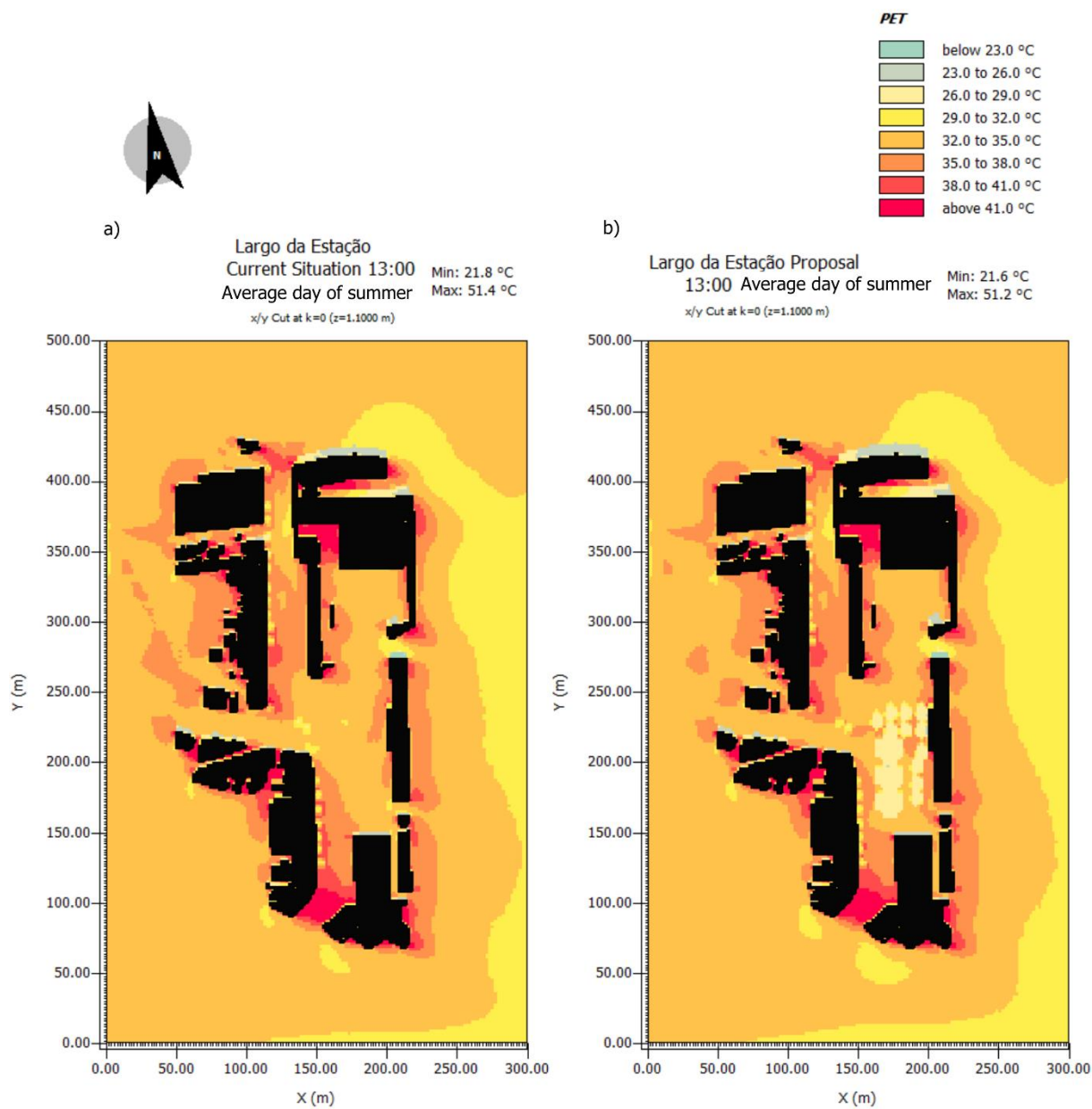


Figure 56. Results of PET values of the parking square, *Largo da Estação*, for average simulation day

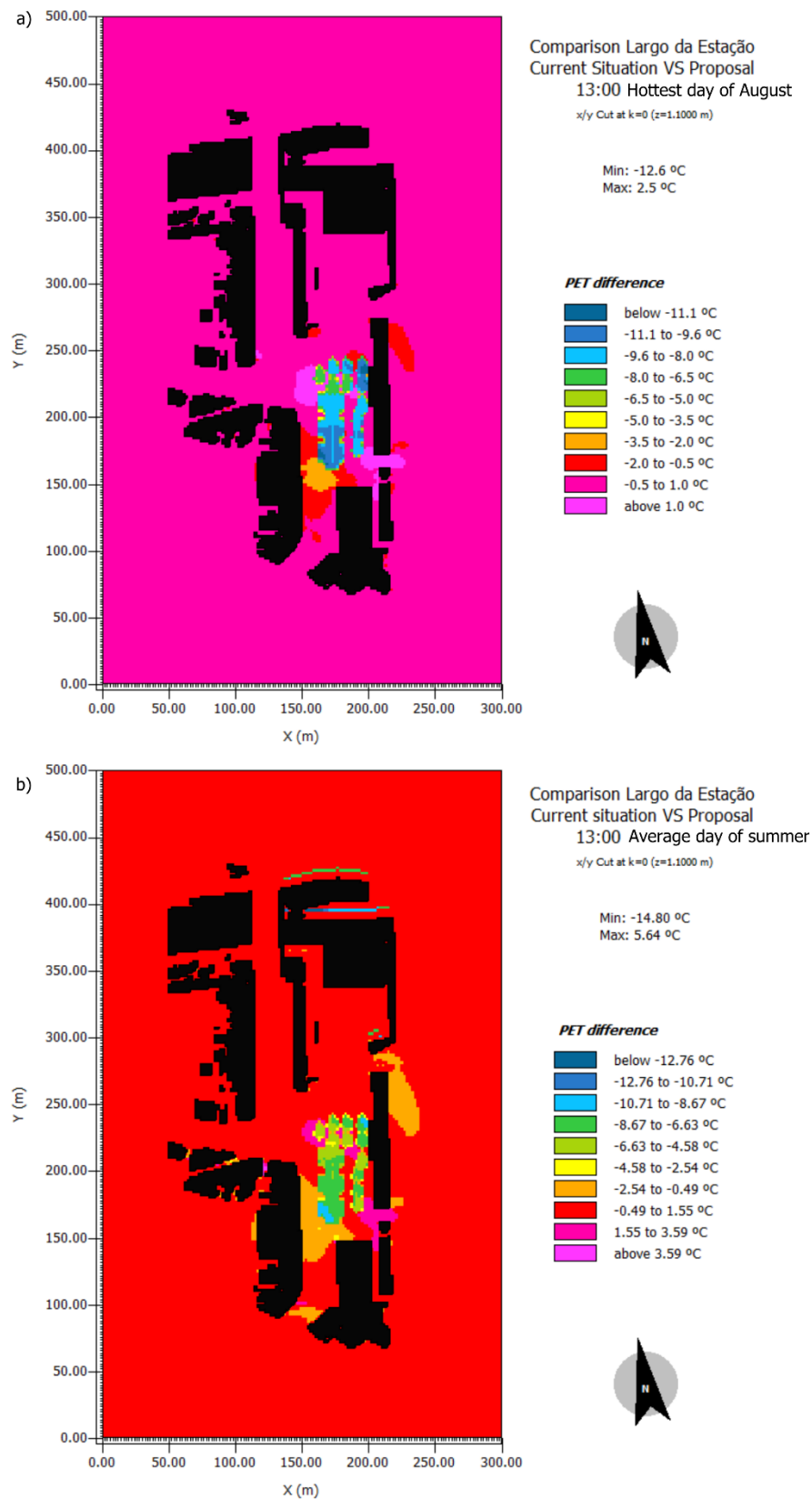


Figure 57. Comparison of PET values of the parking square, *Largo da Estação*, between current situation and proposal A and B for both simulation days

5 DISCUSSION

This study aims to investigate how outdoor thermal comfort conditions are currently for *Alameda de Cláudio Carneiro*, *Rua de Pinto Bessa*, and *Largo da Estação*, as well as how the addition of street greenery—street trees and grass in the tree wells—affects outdoor thermal comfort conditions in *Rua de Pinto Bessa*, and *Largo da Estação*.

For the current conditions, the Porto case study is characterised, during the hottest day of summer, by warm¹ thermal sensation values under building and tree shadow, and hot/very hot thermal sensation values outside tree shadow, and, during the average day of summer, by slightly warm thermal sensation values under building and tree shadow, and hot thermal sensation values outside tree shadow.

For the conditions in the case of street greenery proposals, the Porto case study is characterised by thermal sensation levels as follows.

In general, for *Rua de Pinto Bessa* and *Largo da Estação*, PET values decrease within the tree shadow and increase in the immediate tree surroundings (Table 10). In the limit values, thermal sensation passes from hot to warm level under tree shadow, and from hot to very hot outside tree shadow during the hottest simulation day, while thermal sensation passes from warm to slightly warm level under tree shadow, and from warm to hot outside tree shadow during the hottest simulation day. These variations are the result of changes in the four meteorological elements (relative humidity, air temperature, mean radiant temperature, and wind speed). Annex III contains graphics displaying the results of meteorological values and the differences between the current situations and the proposals, which are summarised in Table 11.

For the street canyon, *Rua de Pinto Bessa*, the two tree designs proposed for the road affect the levels of thermal sensation in a similar way in terms of value (Table 10), but in different ways in terms of spatial distribution along the street canyon, as it is possible to see in Figure 54. Specifically, solution A results in a discontinuous distribution of PET over the northern pathway. It indicates that, in the worst-case scenario, a person walking down the street will experience thermal sensations ranging from warm to very hot on the warmest day of August, and between slightly warm and hot on the typical summer

¹ Recall Matzarakis *et al.* (1999) PET thermal sensation scale shown in Figure 18

day, with a thermal sensation difference of two ranges. On the other side, solution B allows the same person to feel constant thermal perception along all the northern pathway—warm on the hottest day of August and slightly warm on the typical summer day—, as the PET distribution is continuous. The reason for this spatial distribution of PET is that the amount of area covered by the shadow is larger in case B than in case A. Case B, with larger trees and closer spacing between them, has more shadow coverage than Case A.

For the parking square, *Largo da Estação*, the tree design proposed affects the levels of thermal sensation locally. The decline in PET values is concentrated under the shade of the trees, whereas the values in the surrounding area remain nearly identical compared to the current scenario, with the exception of a few minor locations where they increase, and another where they decrease.

Despite the fact that both alternatives A and B improve the thermal comfort of *Rua de Pinto Bessa*, option A with the trees in two rows next to the walkway will provide a better result in urbanistic terms, taking into mind the balance of the street's composition.

Table 10. List of the PET value differences produced by the addition of trees.

PET value differences on hottest day simulation			
	<i>Rua de Pinto Bessa Current situation VS Proposal A</i>	<i>Rua de Pinto Bessa Current situation VS Proposal B</i>	<i>Largo da Estação Current situation VS Proposal</i>
<i>Under tree shadow (°C)</i>	-10.6 to -1.9	-11.8 to -0.8	-12.2 to -3.5
<i>Tree surroundings (outside tree shadow) (°C)</i>	-1.9 to +4.7	-0.8 to +3.6	-3.5 to +2.5
PET value differences on average day simulation			
	<i>Rua de Pinto Bessa Current situation VS Proposal A</i>	<i>Rua de Pinto Bessa Current situation VS Proposal B</i>	<i>Largo da Estação Current situation VS Proposal</i>
<i>Under tree shadow</i>	-9.6 to -0.4	-8.6 to -2.2	-10.7 to -2.5
<i>Tree surroundings (outside tree shadow)</i>	-0.4 to +6.6	-2.2 to +4.1	-2.5 to +5.6

Table 11. List of the climatic differences produced by the addition of trees.

Hottest day simulation			
	<i>Rua de Pinto Bessa Current situation VS Proposal A</i>	<i>Rua de Pinto Bessa Current situation VS Proposal B</i>	<i>Largo da Estação Current situation VS Proposal</i>
<i>Relative humidity difference (%)</i>	0.0 to +5.8	0.0 to +4.1	-0.1 to +1.7

Air temperature difference (°C)	-0.4 to +0.9	-0.5 to +0.4	-0.3 to +0.1
Mean radiant temperature difference (°C)	-23.1 to +0.4	-22.7 to +0.2	-19.3 to +2.2
Wind speed difference (m/s)	-1.5 to +0.3	-1.0 to +0.3	-0.7 to +0.7
Average day simulation			
	Rua de Pinto Bessa Current situation VS Proposal A	Rua de Pinto Bessa Current situation VS Proposal B	Largo da Estação Current situation VS Proposal
Relative humidity difference (%)	-1.9 to +1.8	-0.7 to +2.3	-0.2 to +1.4
Air temperature difference (°C)	-0.3 to +1.7	-0.5 to +0.9	-0.2 to +0.4
Mean radiant temperature difference (°C)	-19.6 to +1.1	-19.1 to +0.9	-18.2 to +3.0
Wind speed difference (m/s)	-1.4 to +0.3	-1.0 to +0.3	-0.7 to +0.8

The scale developed by Matzarakis *et al.* (1999) is used to locate PET values within thermal sensation ranges since the study by Pantavou *et al.* (2014) found greater agreement than the scale suggested by Cohen *et al.* (2013) for the Mediterranean climate. It should be noted that the Matzarakis *et al.* (1999) PET ranges are calculated for a clothing level of 0.9 clo, i.e., almost winter clothing (Figure 51). This means that PET values may be overestimated, but the level of thermal satisfaction can be adjusted by changing clothes to adapt to summer conditions, i.e., a clothing level of 0.2 up to 0.5 clo (Figure 58) (Andrade & Alcoforado, 2008). In the case of the parking square, *Largo da Estação*, for example, using a clothing level of 0.4 clo, there would be a decrease in PET values under tree shadow of up to -1.2°C and almost a constant value outside tree shadow during the average simulation day (Figure 59).

Given the fact that measurements of the tree canopy are obtained from the ENVI-met database, some branches of the trees in proposal A (two rows) of the street canyon are too close to building facades, according to the general advice mentioned by Cortesão (2013); these issues can be remedied by accurately maintaining the shape of the tree.

Due to some limitations of the ENVI-met programme encountered during the first simulation tests, the inclination of the street canyon was not taken into account in this study, namely, when the topography of the model is taken into account, the calculation of the results is incomplete, some zones of the model have missing values, and the cutting ground option in the LEONARDO sub-model for the visualisation of the results does not work properly. The authors themselves advise against using topography for

simulations, because of these and other drawbacks, and in order to have a simpler and more stable simulation (ENVI-met, 2021a).

The model was not validated because in-situ measurements in the places of interest were not available. Nevertheless, Lee *et al.* (2016) has shown that ENVI-met simulation results highly correlate with experimental data (more than e.g. RayMan - another highly used software suite). Moreover, the case study consisted in the comparison between different configurations to assess their street greenery impact, that is, there is no need for a comparison with a real situation (Jeong *et al.*, 2015; Neves & Bonatto, 2019).

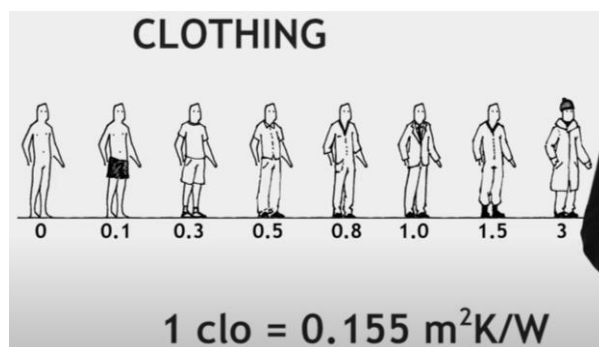


Figure 58. Levels of clothing. Source: (Polimi OpenKnowledge, 2017)

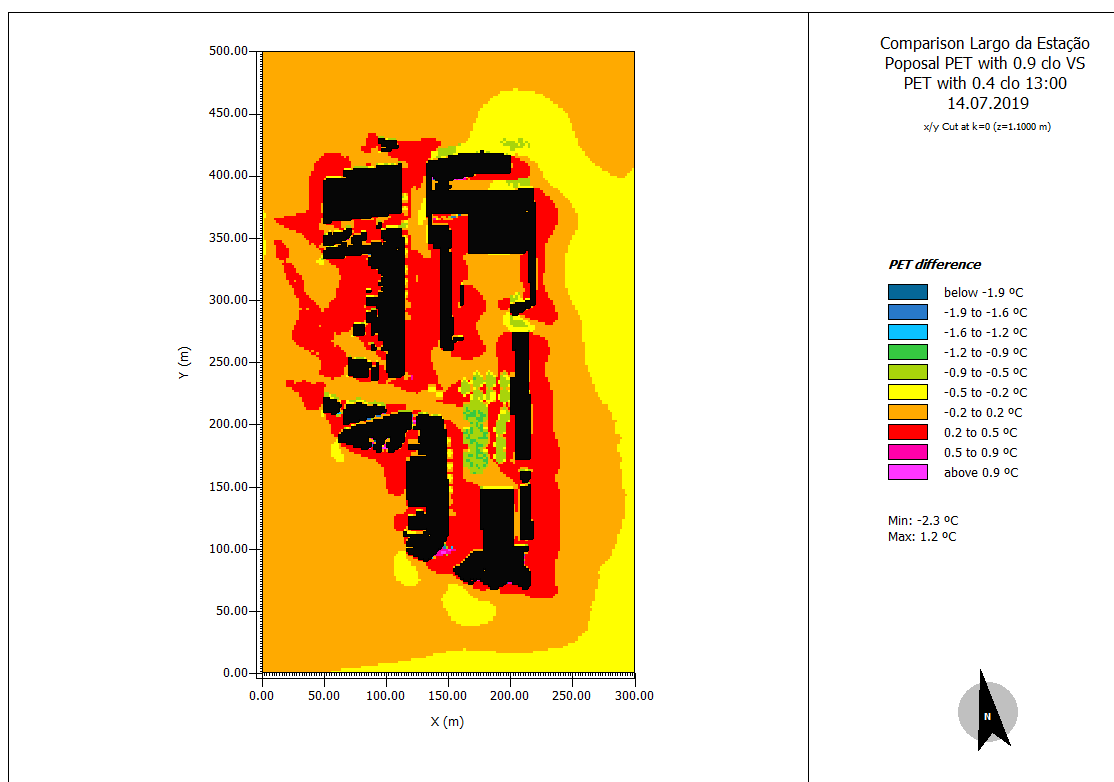


Figure 59. Comparison of PET values of the proposal parking square, *Largo da Estação*, between PET calculated with 0.9 clo and 0.4 clo for average simulation day.

6 CONCLUSION

This research looks at the effect of street greenery on human thermal comfort in a complex of a street canyon and two public squares in Porto, Portugal—*Alameda de Cláudio Carneiro*, *Rua de Pinto Bessa*, and *Largo da Estação*. The Physiologically equivalent temperature (PET) index had been studied through the micro-meteorological software of ENVI-met V4.4.5 Summer 2020.

The current outdoor thermal comfort conditions had been studied for *Alameda de Cláudio Carneiro*, *Rua de Pinto Bessa*, and *Largo da Estação*, as well as how the addition of street greenery—street trees and grass in the tree wells—affects outdoor thermal comfort conditions in *Rua de Pinto Bessa*, and *Largo da Estação*. Six simulations had been run in two summer days of the typical meteorological year of Porto, the hottest day of August and the average day of summer.

For the current conditions, the Porto case study is distinguished by warm thermal sensation values under building and tree shadow, and hot/very hot thermal sensation values outside tree shadow, on the hottest day of summer, and slightly warm thermal sensation values under building and tree shadow, on the average day of summer, and hot thermal sensation values outside tree shadow.

The addition of street greenery in *Rua de Pinto Bessa* and *Largo da Estação* influences the microclimate resulting in a decrease in PET values under tree shadow for all cases in both simulation days (up to 12 °C) and an increase in PET values outside tree shadow (up to 6 °C) in *Rua de Pinto Bessa* and nearly identical PET values in *Largo da Estação*, with the exception of a few minor locations where they increase, and another where they decrease, in both simulation days.

In terms of spatial distribution, the two proposed solutions for the street differ: solution B has a continuous effect along the entire northern pavement, whereas solution A has a discontinuous effect along the entire northern pavement, as it has smaller trees and thus generates smaller and more distant shadows, causing the person walking between one level of thermal perception and another with a difference of two levels—warm-very hot in the hottest day, and slightly warm-hot in the average day.

The thermal sensation case study was carried out around 1 p.m. in the early afternoon. This time of the day was chosen because solar radiation is at its peak in Porto at this time of day, the area is almost completely sunny, and a study conducted in Bilbao, Spain,—which has the same climate classification as Porto—revealed that peak levels of PET are around this time for streets with a NW/SE orientation (Lobaccaro et al., 2019).

Future research could consider 24-hour simulations to study how street greenery affects the trajectory of PET during the day and night in the Porto case study area. Also, other simulations in which tree species and/or spatial configuration are varied may be included in future investigations. It would also be interesting to simulate the Porto case study model using in situ measurements, which can be entered directly into ENVI-met as this latest version allows it, to study effective PET values.

Given that, as a result of climate change, the city of Porto will experience an increase in average temperature, an increase in the number of days with very high temperatures ($\geq 35^{\circ}\text{C}$), and tropical nights with minimum temperatures of $\geq 20^{\circ}\text{C}$, as well as an increase in the frequency and intensity of droughts, it would be interesting to investigate how these changes in factors influence the thermal sensation condition and how effective green heat mitigation can be in the Porto case study area.

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ANNEX I

BUILDING HEIGHTS, MATERIALS AND VEGETATION OF THE PORTO CASE STUDY IN ENVI-MET

BUILDING HEIGHTS



Figure 60. GIS map of building heights of the Porto case study ENVI-met. Source: personal archive and OpenStreetMap.

PAVEMENT MATERIALS

Table 12. ENVI-met details of pavement materials in the Porto case study.

PAVEMENT MATERIALS				
Material	Database-ID	z0 Roughness length (m)	Albedo (frac)	Emissivity (frac)
Asphalt Road	0100ST	0.01000	0.20000	0.90000
Concrete Pavement Gray	0100PG	0.01000	0.50000	0.90000
Concrete Pavement Light	0100PL	0.01000	0.80000	0.90000
Granite Pavement (Single stones)	0100GS	0.01000	0.40000	0.90000
Terre battue (Smashed brick)	0100TB	0.01000	0.80000	0.90000

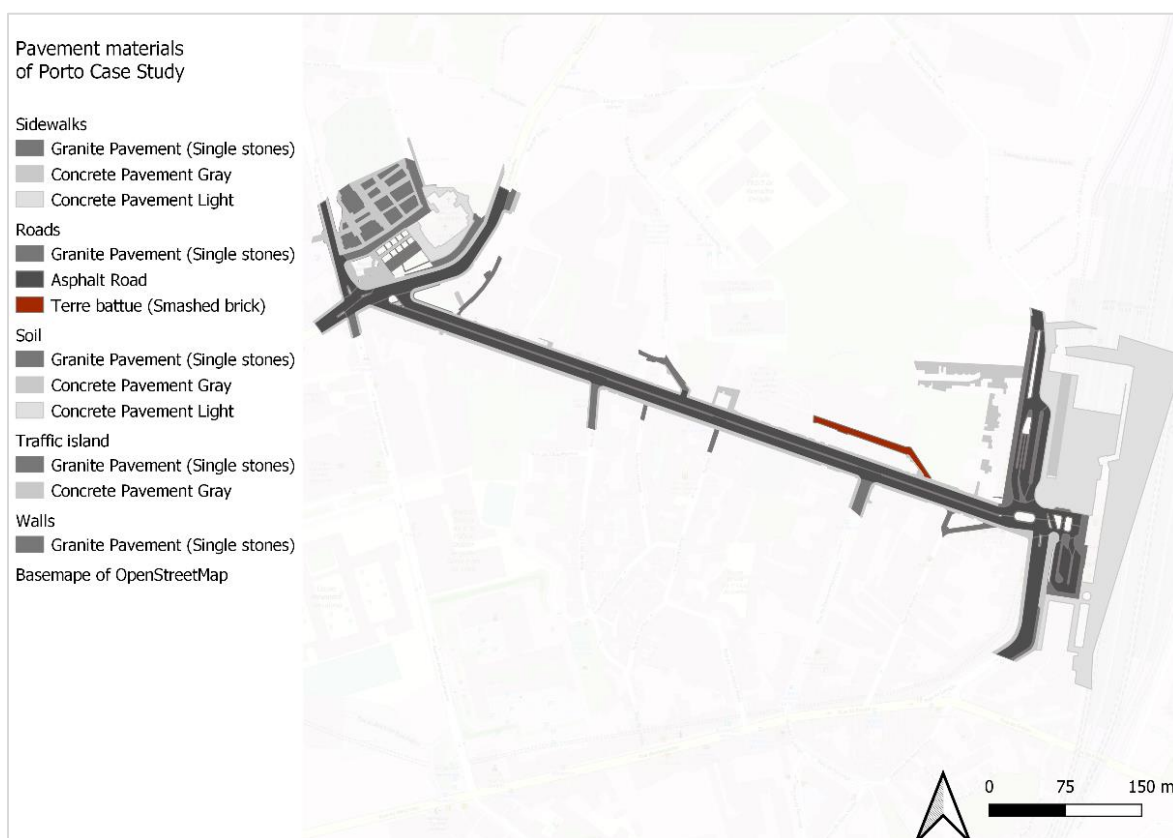


Figure 61. GIS map of pavement materials of the Porto case study in ENVI-met. Source: personal archive and OpenStreetMap.

ROOF MATERIALS

Table 13. ENVI-met details of roof materials in the Porto case study.

ROOF MATERIALS		
Material	Roofing: tile	Roofing: terracotta
Database-ID	0100R1	0100R2
Default Thickness (m)	0.0500	0.0500
Absorption (Frac)	0.50000	0.50000
Transmission (Frac)	0.00000	0.00000
Reflection (Frac)	0.50000	0.50000
Emissivity (Frac)	0.90000	0.90000
Specific Heat (J/(kg*K))	800.00000	840.00000
Thermal Conductivity (W/m*K)	0.84000	0.81000
Density (kg/m ³)	1900.00000	1700.00000



Figure 62. GIS map of roof materials of the Porto case study in ENVI-met. Source: personal archive and OpenStreetMap.

FACADE MATERIALS

- The building facades have been grouped into 12 groups based on the common qualities of the materials that comprise them, as observed with Google Earth.
- Each material used to construct the facades was chosen or generated in the ENVI-met database (Table 14).
- The weights for calculating the equivalent building materials of the building facades were determined using Google Earth images of the facades (Table 15).
- Based on the prior weights, equivalent materials were produced (Table 16)
- The equivalent materials were utilized to build the equivalent walls of the buildings (Figure 63 and Figure 64): for all groups of equivalent wall, except *glass and metal*, and *glass*, a layer of the correspondent equivalent material (3cm) is added to two layers of brick material (15 cm), while for *glass and metal*, and *glass material* three layers (1 cm) of the equivalent materials are combined.

Table 14. Facade materials available and created in ENVI-met database.

FACADE MATERIALS: MY MATERIALS								
Material	Windows	Light azulejos	Dark azulejos	Granite	Plaster	Concrete	Metal	Glass wall
ENVI-met Material Name	<i>clear float glass</i>	-	-	<i>Granite Pavement (single stone)</i>	<i>Default plaster</i>	<i>Ferro-concrete</i>	<i>Steel</i>	<i>heat protection glass</i>
Created Material Name	-	<i>My Light Tile</i>	<i>My Dark Tile</i>	<i>My Granite</i>	<i>My Plaster</i>	-	-	-
Database-ID	0100G4	LIGTIL	DARTIL	GRANIT	MYPLAS	0100FC	0100ST	0100G1
Default Thickness (m)	0.02	0.075	0.075	0.04	0.01	0.1	0.02	0.03
Absorption (Frac)	0.05	0.3	0.7	0.6	0.4	0.5	0.2	0.05
Transmission (Frac)	0.9	0	0	0	0	0	0	0.9
Reflection (Frac)	0.05	0.7	0.3	0.4	0.6	0.5	0.8	0.05
Emissivity (Frac)	0.9	0.9	0.9	0.9	0.9	0.9	0.1	0.9
Specific Heat (J/(kg*K))	750	840	840	780	850	1000	420	750
Thermal Conductivity (W/m*K)	1.05	0.75	0.75	2.8	1.2	2.3	45	1
Density (kg/m ³)	2500	933	933	2750	1500	2520	8000	2500

Table 15. Weights for calculating the equivalent building materials of the building facades based on Google Earth observations.

FACADE MATERIALS: WEIGHTS										
My Material Name	Equivalent material	Windows	Light azulejos	Dark azulejos	Granite	Plaster	Concrete	Metal	Glass wall	Sum
Light azulejos	01	0.4	0.6	0	0	0	0	0	0	1
Light azulejos and granite	02	0.6	0.3	0	0.1	0	0	0	0	1
Dark azulejos and granite	03	0.6	0	0.3	0.1	0	0	0	0	1
Light azulejos and plaster	04	0.4	0.3	0	0	0.3	0	0	0	1
Dark azulejos and plaster	05	0.4	0	0.3	0	0.3	0	0	0	1
Dark azulejos, plaster and granite	06	0.4	0	0.25	0.1	0.25	0	0	0	1
Concrete	07	0	0	0	0	0	1	0	0	1
Granite	08	0	0	0	1	0	0	0	0	1
Plaster	09	0.4	0	0	0	0.6	0	0	0	1
Plaster and Granite	10	0.4	0	0	0.1	0.5	0	0	0	1
Glass and metal	11	0	0	0	0	0	0	0.5	0.5	1
Glass	12	0	0	0	0	0	0	0	1	1

Table 16. Created equivalent materials based on created weights.

FACADE MATERIALS: MY MATERIALS						
My Material Name	Light azulejos	Light azulejos and granite	Dark azulejos and granite	Light azulejos and plaster	Dark azulejos and plaster	Dark azulejos, plaster and granite
Equivalent Material Name	01	02	03	04	05	06
Database-ID	EQMA01	EQMA02	EQMA03	EQMA04	EQMA05	EQMA06
Default Thickness (m)	0.053	0.0385	0.0385	0.0335	0.0335	0.03325
Absorption (Frac)	0.2	0.18	0.3	0.23	0.35	0.355
Transmission (Frac)	0.36	0.54	0.54	0.36	0.36	0.36
Reflection (Frac)	0.44	0.28	0.16	0.41	0.29	0.285
Emissivity (Frac)	0.9	0.9	0.9	0.9	0.9	0.9
Specific Heat (J/(kg*K))	804	780	780	807	807	800.5
Thermal Conductivity (W/m*K)	0.87	1.135	1.135	1.005	1.005	1.1875
Density (kg/m ³)	1559.8	2054.9	2054.9	1729.9	1729.9	1883.25
FACADE MATERIALS: MY MATERIALS						
My Material Name	Concrete	Granite	Plaster	Plaster and Granite	Glass and metal	Glass
Equivalent Material Name	07	08	09	10	11	12
Database-ID	EQMA07	EQMA08	EQMA09	EQMA10	EQMA11	EQMA12
Default Thickness (m)	0.1	0.04	0.014	0.017	0.025	0.03
Absorption (Frac)	0.5	0.6	0.26	0.28	0.125	0.05
Transmission (Frac)	0	0	0.36	0.36	0.45	0.9
Reflection (Frac)	0.5	0.4	0.38	0.36	0.425	0.05
Emissivity (Frac)	0.9	0.9	0.9	0.9	0.5	0.9
Specific Heat (J/(kg*K))	1000	780	810	803	585	750
Thermal Conductivity (W/m*K)	2.3	2.8	1.14	1.3	23	1
Density (kg/m ³)	2520	2750	1900	2025	5250	2500

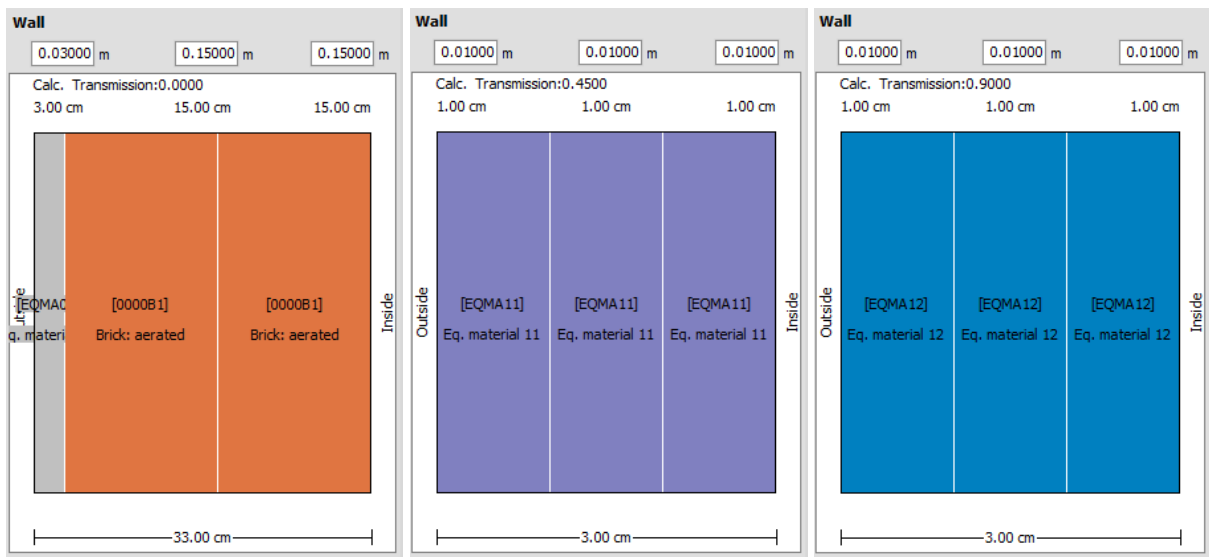


Figure 63. General representation of the layers of the equivalent walls in ENVI-met.



Figure 64. GIS map of equivalent wall materials of facades of the Porto case study in ENVI-met. Source: personal archive and OpenStreetMap.

EXISTING AND PROPOSED 2D VEGETATION

Table 17. ENVI-met details of existing and proposed 2D vegetation in the Porto case study.

2D VEGETATION	
Vegetation type	Grass 25cm aver. Dense
Database-ID	0100XX
CO2 Fixation Type	C3
Leaf Type	Gras
Albedo	0.20000
Transmittance	0.30000
Plant height (m)	0.25000
Root Zone Depth (m)	0.30000 (constant)
Root Area (RAD) Profile	0.10000 (constant)
Season profile	1.00000 (constant)

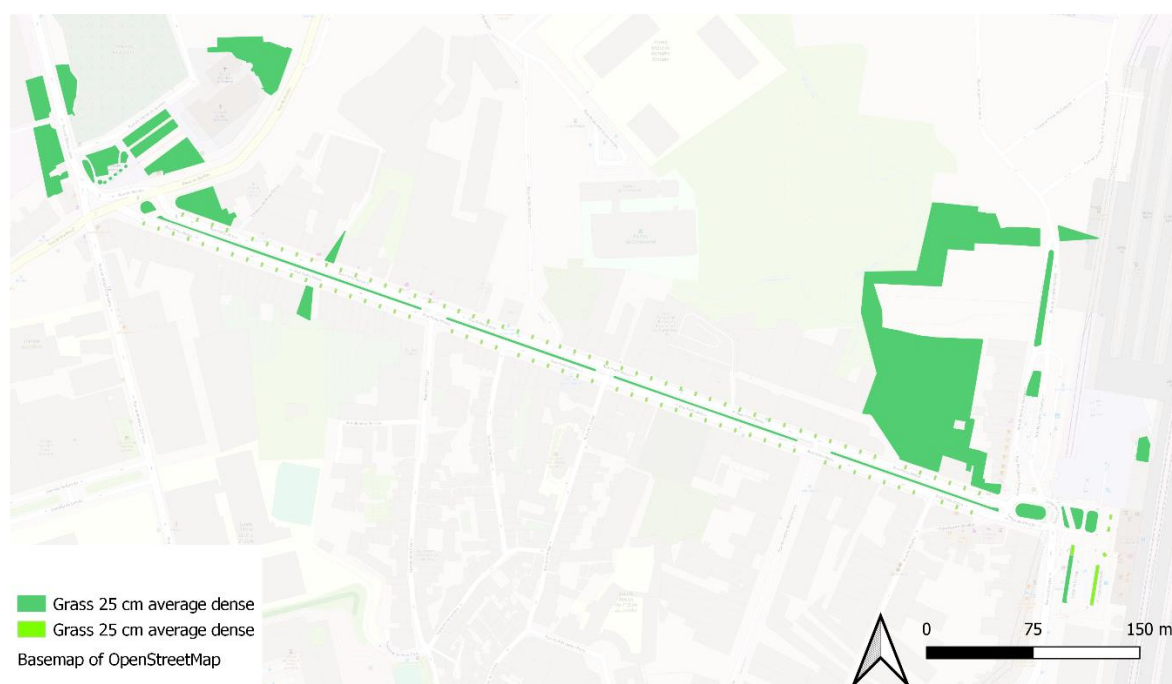


Figure 65. GIS image of the existing and proposed 2D vegetation in the Porto case study. Source: Personal archive and OpenStreetMap

EXISTING 3D VEGETATION

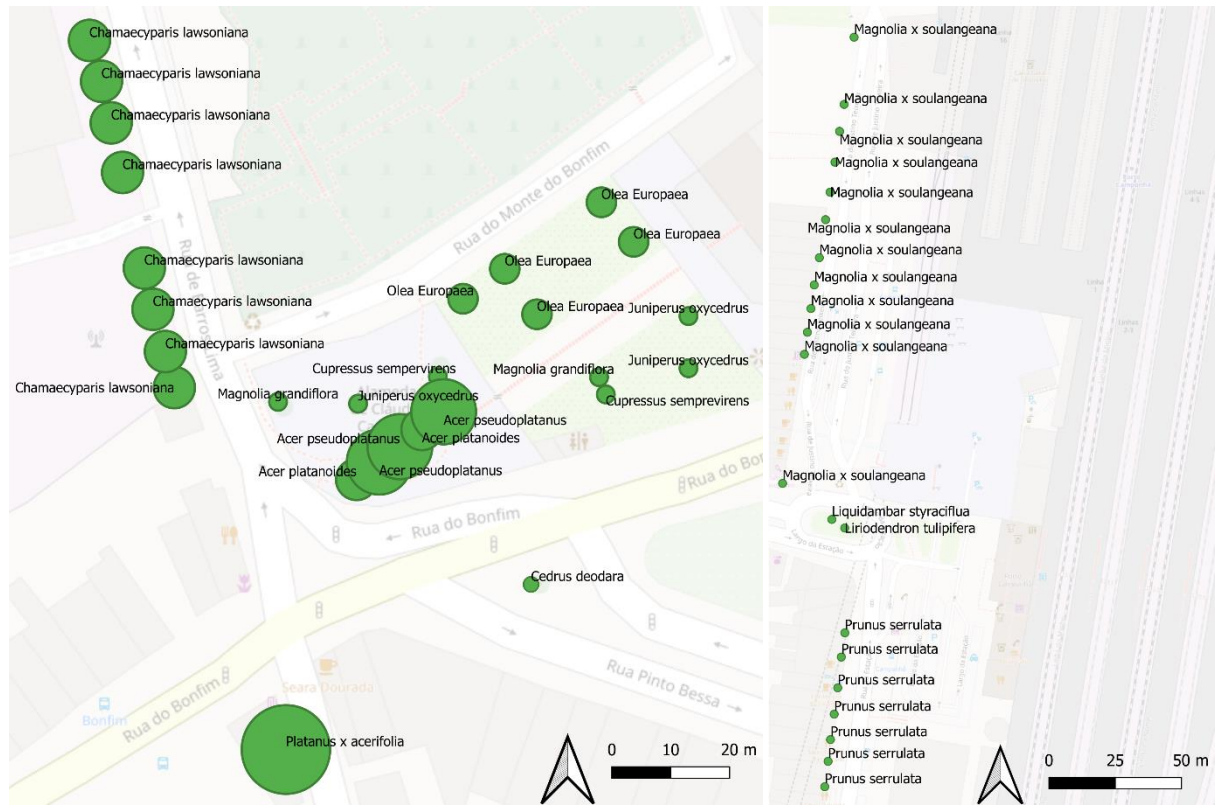


Figure 66. GIS image of the existing trees (scientific name) in the Porto case study. Source: personal archive and OpenStreetMap

Table 18. ENVI-met details of the existing 3D vegetation in the Porto case study.

EXISTING 3D VEGETATION					
Used for the existing tree	<i>Cupressus sempervirens</i>	<i>Acer Platanoides</i>	<i>Acer Pseudoplatanus</i>	<i>Olea Europaea</i>	<i>Platanus x Acerifolia</i>
Scientific Name	<i>Cypress</i>	<i>Acer Platanoides</i>	<i>Acer Pseudoplatanus</i>	<i>Olea Europaea</i>	<i>Platanus x Acerifolia</i>
Common name	Cypress	Norway maple	Maple	Olive Tree	London/Hybrid Plane
Database-ID	0000ZY	000007	0000A8	0000OT	0000B8
Height (m)	7.00	15.00	15.00	4.00	20.00
Width (m)	3.00	7.00	11.00	5.00	15.00
Cells	3 x 3 x 7	7 x 7 x 15	11 x 11 x 15	5 x 5 x 4	15 x 15 x 20
Resolution (m)	1.00	1.00	1.00	1.00	1.00

CO2 fixation type	C3-Plant	C3-Plant	C3-Plant	C3-Plant	C3-Plant
Leaf type	Conifer Leafs	Deciduous Leafs	Deciduous Leafs	Deciduous Leafs	Deciduous Leafs
Foliage Shortwave Albedo	0.30	0.18	0.18	0.50	0.18
Foliage Shortwave transmittance	0.30	0.30	0.30	0.30	0.30
Leaf Weight (g/m2)	100.00	100.00	100.00	100.00	100.00
Isoprene Capacity	12.00	12.00	12.00	12.00	12.00
Depth of roots	2.00	3.45	3.50	2.00	1.50
Diameters of roots (m)	10.00	12.00	12.50	3.00	10.00
Assign LAD	2	2	2	2	2
EXISTING 3D VEGETATION					
Used for the existing tree	<i>Cedrus deodara</i>	<i>Chamaecyparis Lawsoniana</i>	<i>Juniperus Oxicedrus</i>	<i>Magnolia Grandiflora, Magnolia x Soulangeana, Prunus Serrulata</i>	<i>Liquidambar Styraciflua, Liriodendron Tulipifera</i>
Name	Conic, medium trunk, dense, medium (15m)	Conic, small trunk, dense, medium (15m)	Cylindric, large trunk, dense, small (5m)	Heart-shaped, large trunk, dense, small (5m)	Cylindric, medium trunk, dense, small (5m)
Database-ID	01AMDM	01ASDM	01CLDS	01HLDS	01OMDS
Height (m)	15.00	15.00	5.00	5.00	5.00
Width (m)	7.00	7.00	3.00	3.00	3.00
Cells	7 x 7 x 15	7 x 7 x 15	3 x 3 x 5	3 x 3 x 5	3 x 3 x 5
Resolution (m)	1.00	1.00	1.00	1.00	1.00
CO2 fixation type	C3-Plant	C3-Plant	C3-Plant	C3-Plant	C3-Plant
Leaf type	Conifer Leafs	Conifer Leafs	Conifer Leafs	Deciduous Leafs	Deciduous Leafs
Foliage Shortwave Albedo	0.12	0.12	0.12	0.18	0.18
Foliage Shortwave transmittance	0.10	0.10	0.10	0.30	0.30
Leaf Weight (g/m2)	100.00	100.00	100.00	100.00	100.00
Isoprene Capacity	12.00	12.00	12.00	12.00	12.00
Depth of roots	9.00	9.00	3.00	3.00	3.00

Diameters of roots (m)	7.00	7.00	3.00	3.00	3.00
Assign LAD	2	2	2	2	2

PROPOSED 3D VEGETATION

Table 19. ENVI-met details of the proposed 3D vegetation.

PROPOSED 3D VEGETATION			
Scientific Name	<i>Acer Platanoides</i>	<i>Acer Pseudoplatanus</i>	<i>Ulmus minor</i>
Common name	Norway maple	Maple	Field Elm
Database-ID	000007	0000A8	0000E1
Height (m)	15.00	15.00	20.00
Width (m)	7.00	11.00	19.00
Cells	7 x 7 x 15	11 x 11 x 15	19 x 19 x 20
Resolution (m)	1.00	1.00	1.00
CO2 fixation type	C3-Plant	C3-Plant	C3-Plant
Leaf type	Deciduous Leafs	Deciduous Leafs	Deciduous Leafs
Foliage Shortwave Albedo	0.18	0.18	0.18
Foliage Shortwave transmittance	0.30	0.30	0.30
Leaf Weight (g/m2)	100.00	100.00	100.00
Isoprene Capacity	12.00	12.00	12.00
Depth of roots	3.45	3.50	1.60
Diameters of roots (m)	12.00	12.50	12.00
Assign LAD	2	2	2



Figure 67. *Acer Platanoides* and *Acer Pseudoplatanus* in *Alameda de Cláudio Carneiro*, Porto, Portugal. Source: Google Earth



Figure 68. *Acer Platanoides* and *Acer Pseudoplatanus* in *Rua De Ferreira Cardoso, 137*, Porto, Portugal. Source: Google Earth



Figure 69. *Acer Platanoides* Rua das Águas Férreas, 31, Porto, Portugal. Source: Google Earth



Figure 70. *Acer Pseudoplatanus* in Praça da Rainha Dona Amélia, 1, Porto, Portugal. Source: Google Earth



Figure 71. *Acer Pseudoplatanus* in *Rua Firmino Pereira*, 137, Porto, Portugal. Source: Google Earth



Figure 72. *Ulmus Carpinifolia* in *Rua peso da Regua*, 532, Porto, Portugal. Source: Google Earth



Figure 73. *Ulmus Sp* in *Rua Dom Luís de Ataíde*, 137, Porto, Portugal. Source: Google Earth

ANNEX II

GIS MAPS OF THE PORTO CASE STUDY AREA

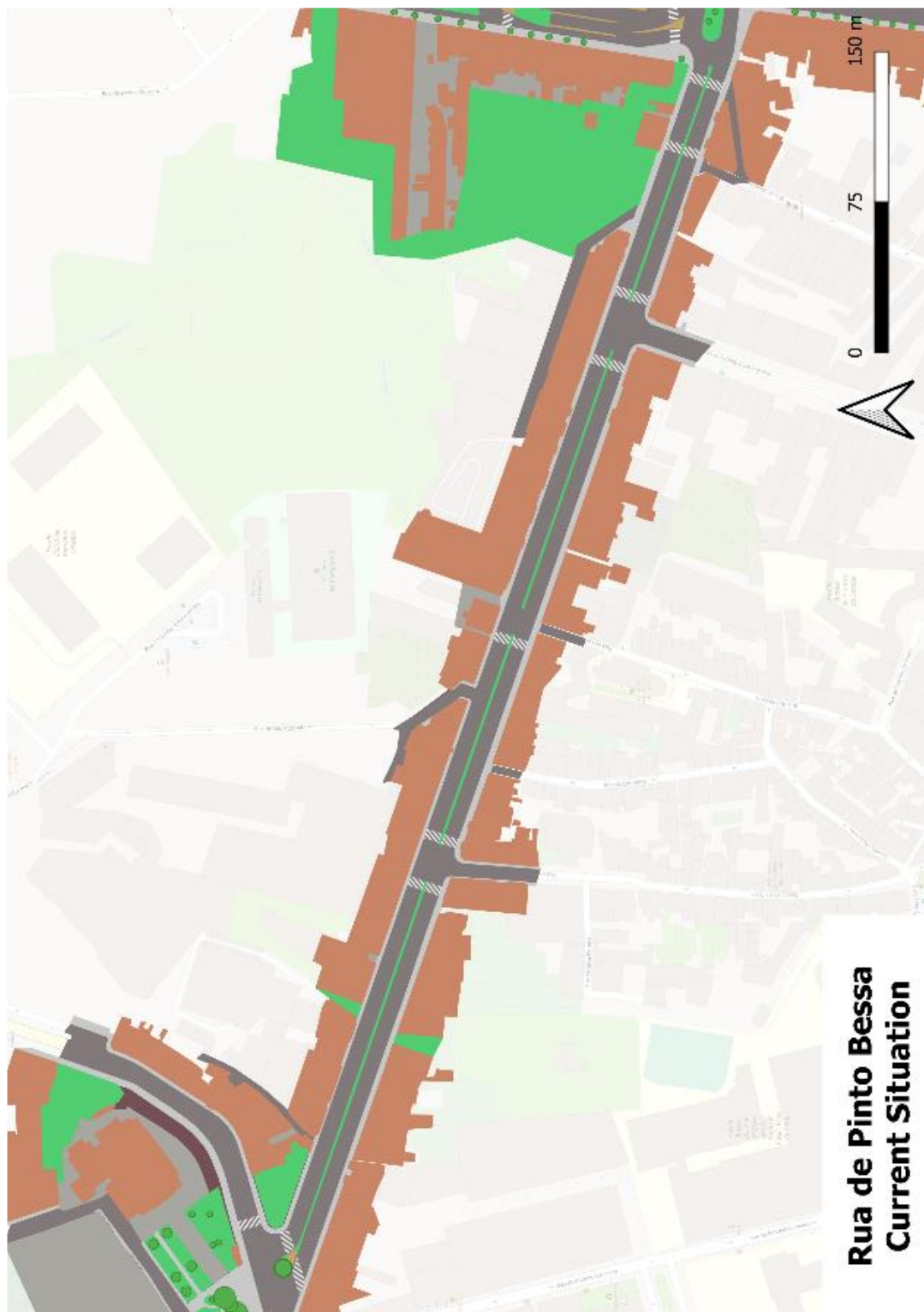


Figure 74. GIS map of the current situation of *Rua de Pinto Bessa* street canyon. Source: personal archive and OpenStreetMap

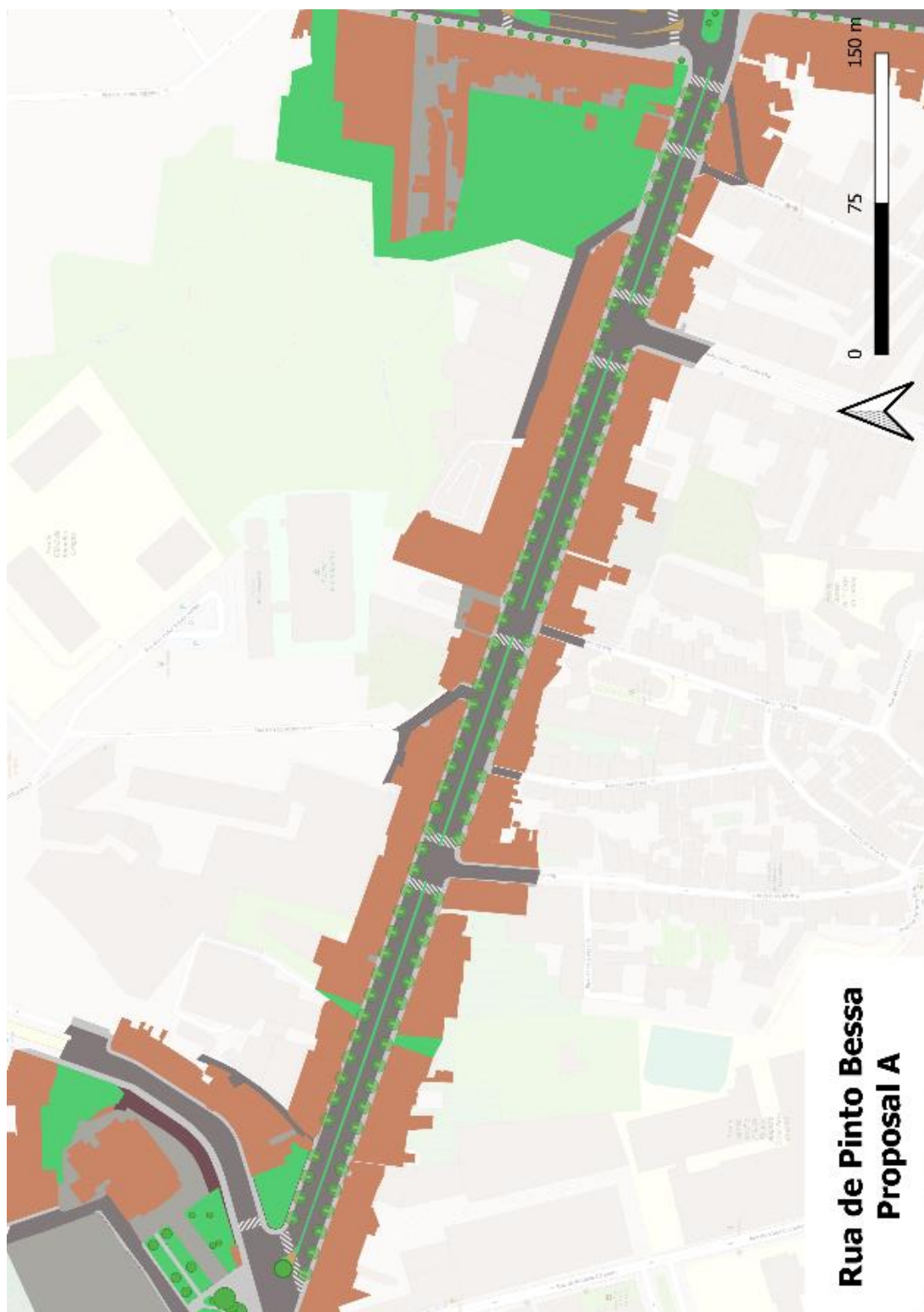


Figure 75. GIS map of proposal A of *Rua de Pinto Bessa* street canyon. Source: personal archive and OpenStreetMap

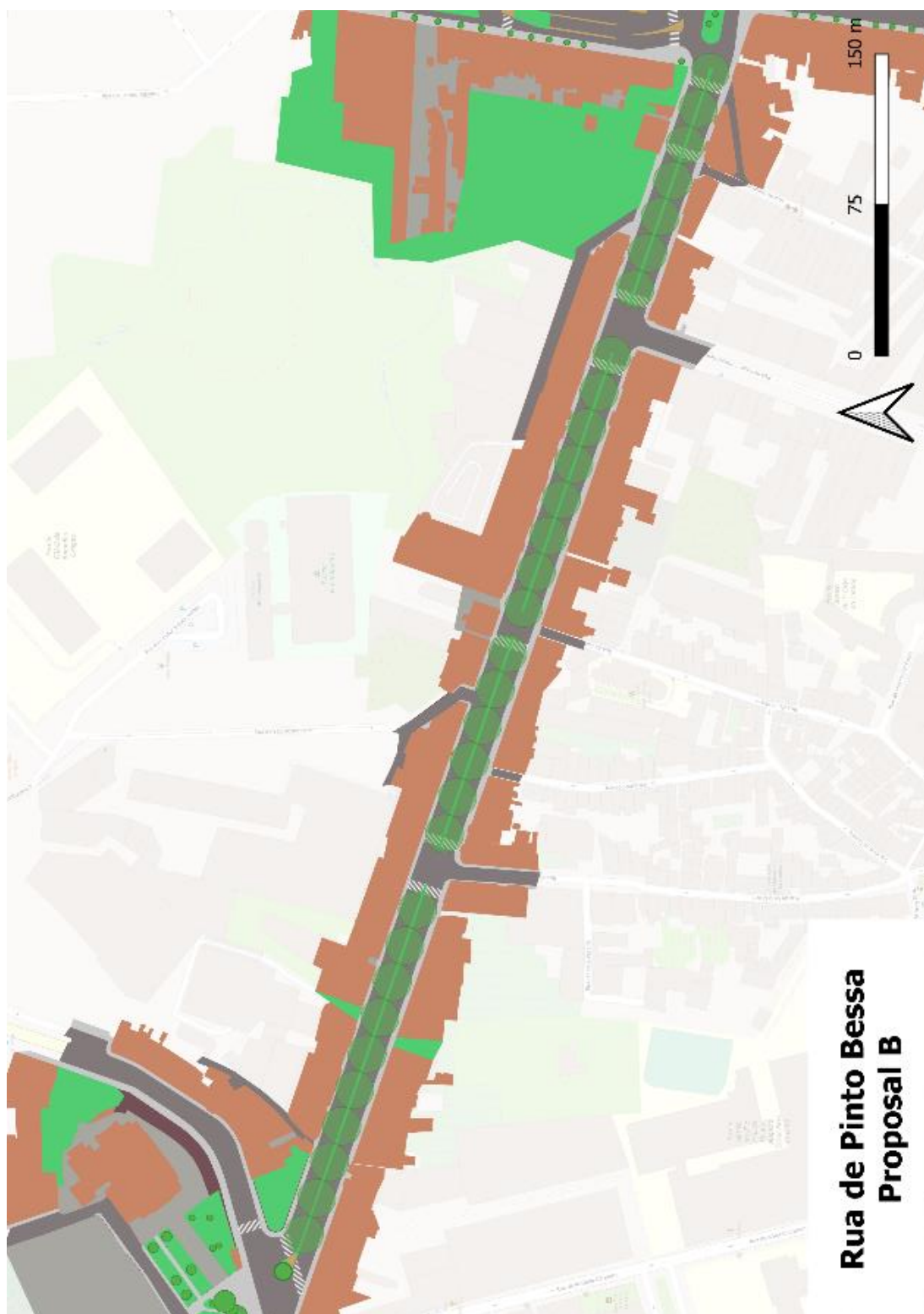


Figure 76. GIS map of proposal B of *Rua de Pinto Bessa* street canyon. Source: personal archive and OpenStreetMap

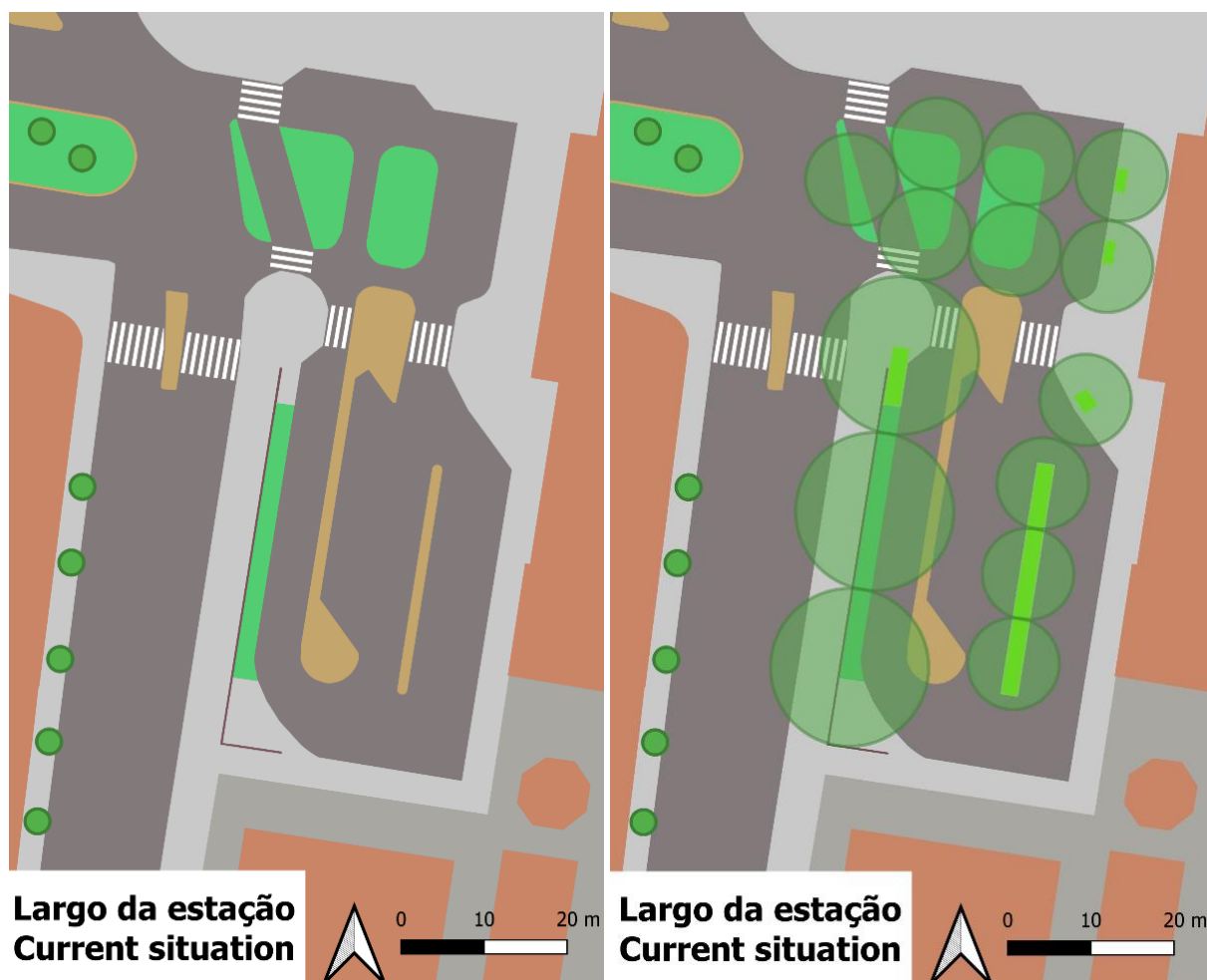


Figure 77. GIS maps of the current situation and proposal of *Largo da Estação*. Source: personal archive and OpenStreetMap

TRANSVERSAL PROFILES OF THE PORTO CASE STUDY AREA

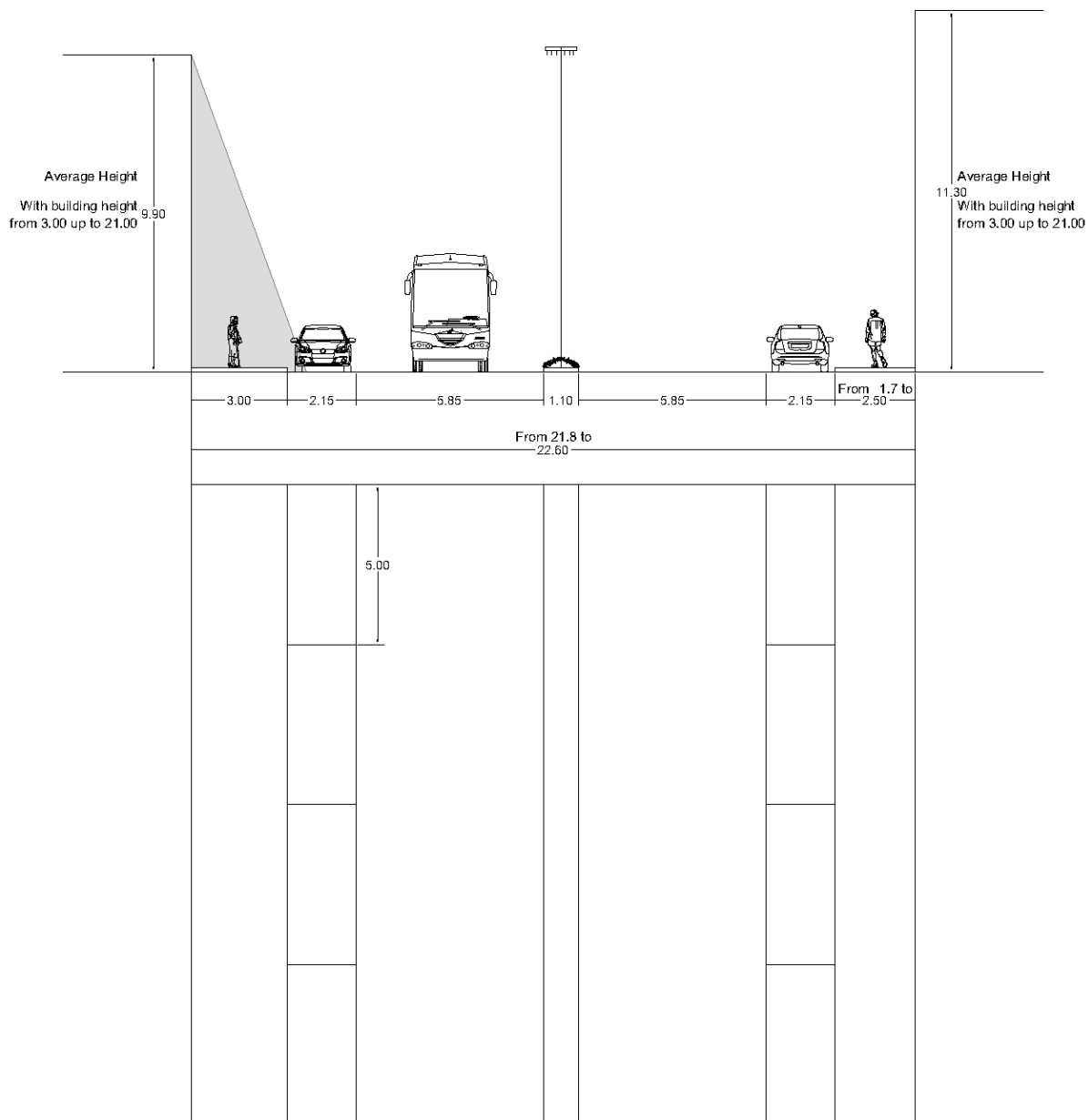


Figure 78. Transversal Profile of the current situation of *Rua de Pinto Bessa* street canyon (dimensions in meters). Shadows at 13:00 during August's hottest day. Source: personal archive

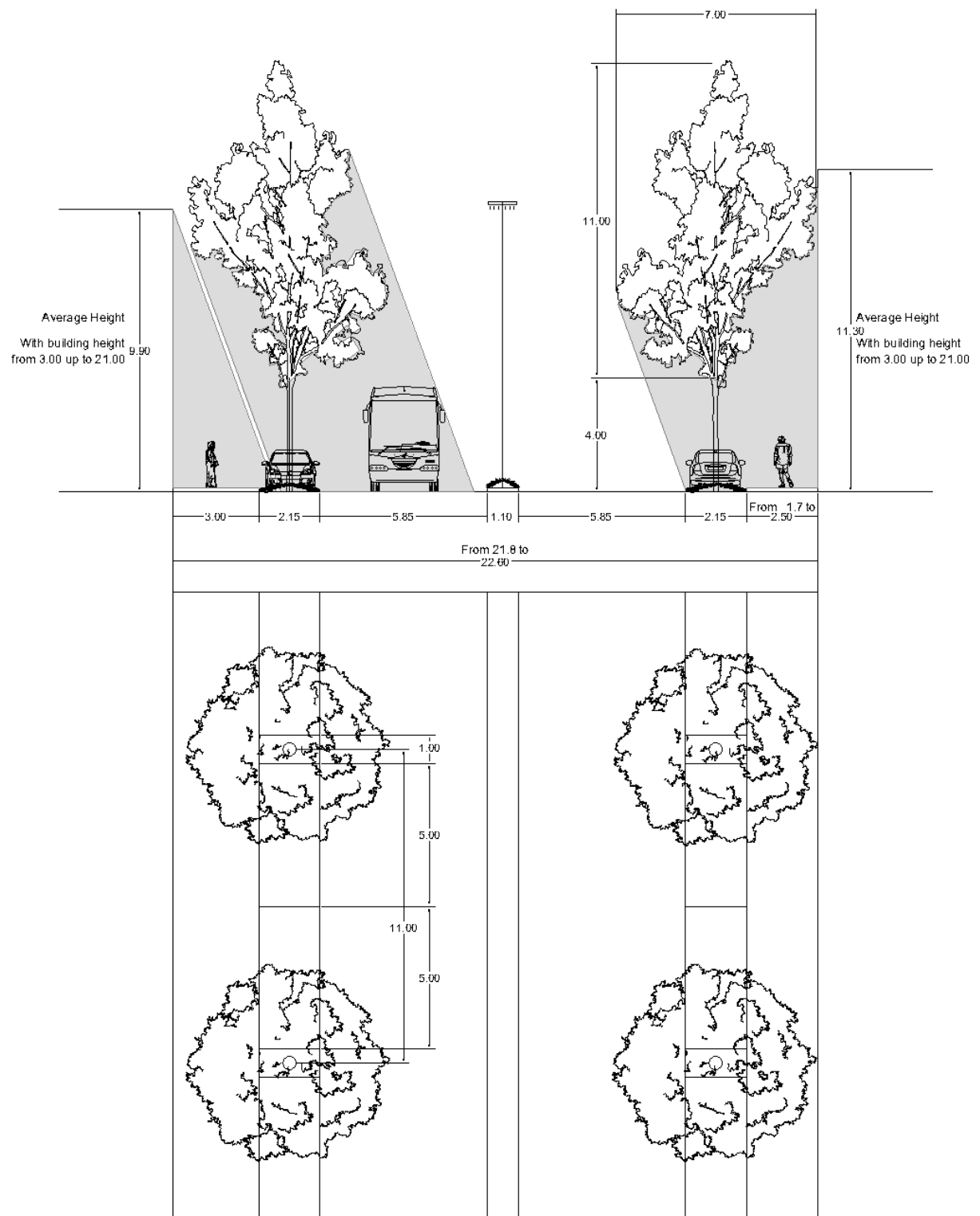


Figure 79. Transversal Profile of the Proposal A of Rua de Pinto Bessa street canyon (dimensions in meters). Shadows at 13:00 during August's hottest day. Source: personal archive

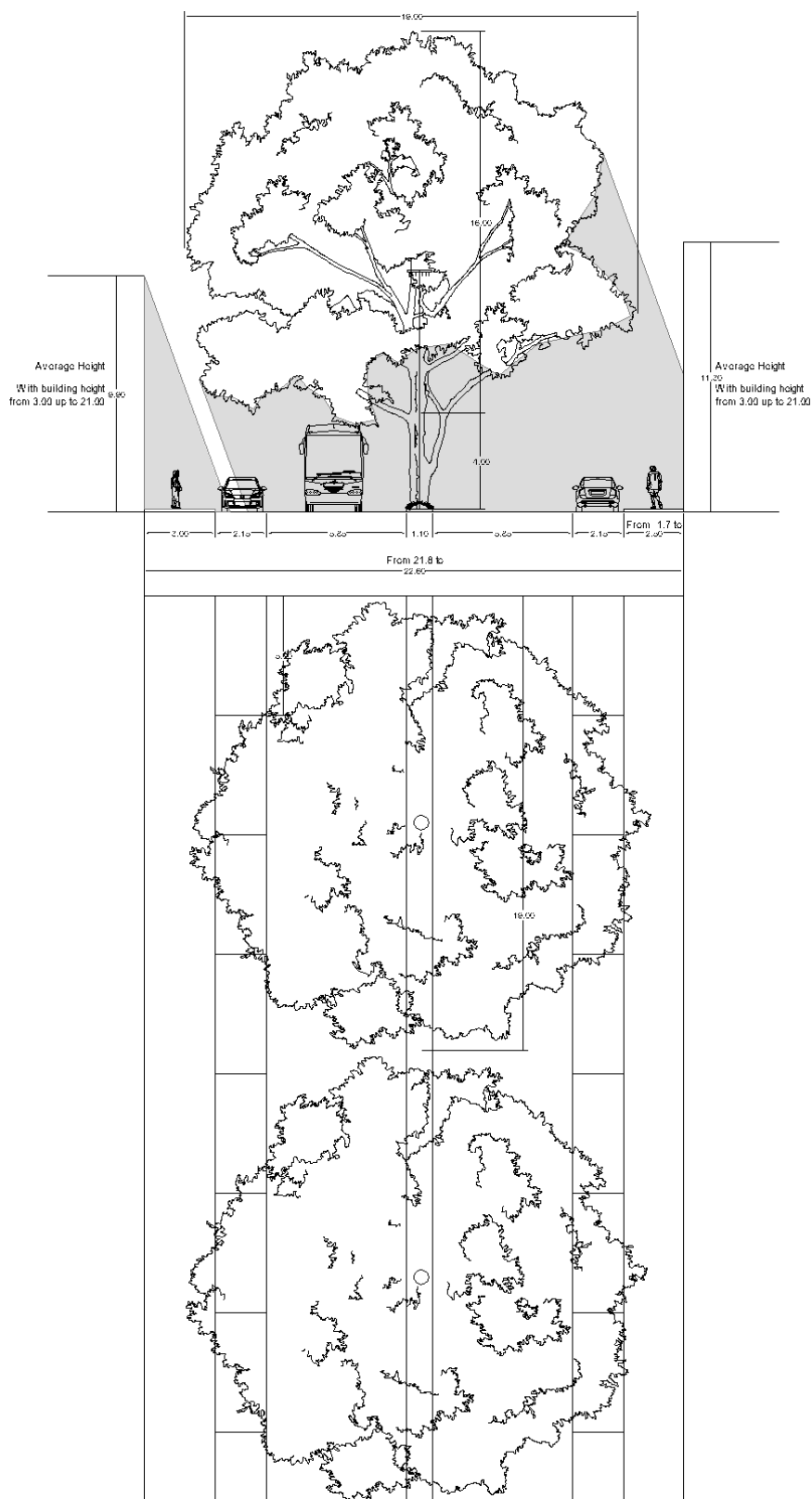


Figure 80. Transversal Profile of the Proposal B of *Rua de Pinto Bessa* street canyon (dimensions in meters).
Shadows at 13:00 during August's hottest day. Source: personal archive

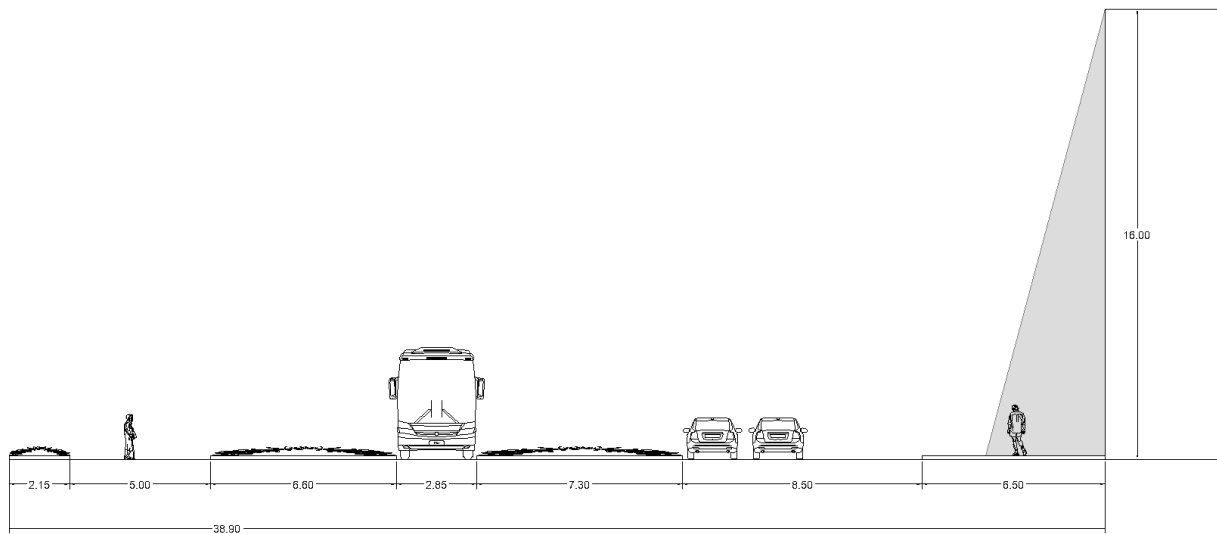


Figure 81. Transversal Profile of the current situation of *Largo da Estação* parking square (dimensions in meters).
Source: personal archive

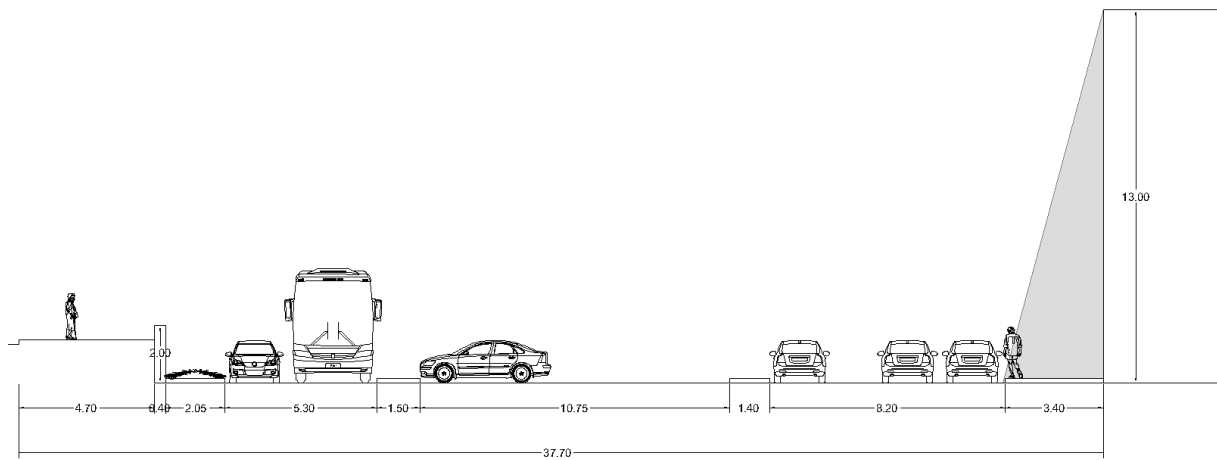


Figure 82. Transversal Profile of the current situation of *Largo da Estação* parking square (dimensions in meters).
Shadows at 13:00 during August's hottest day. Source: personal archive

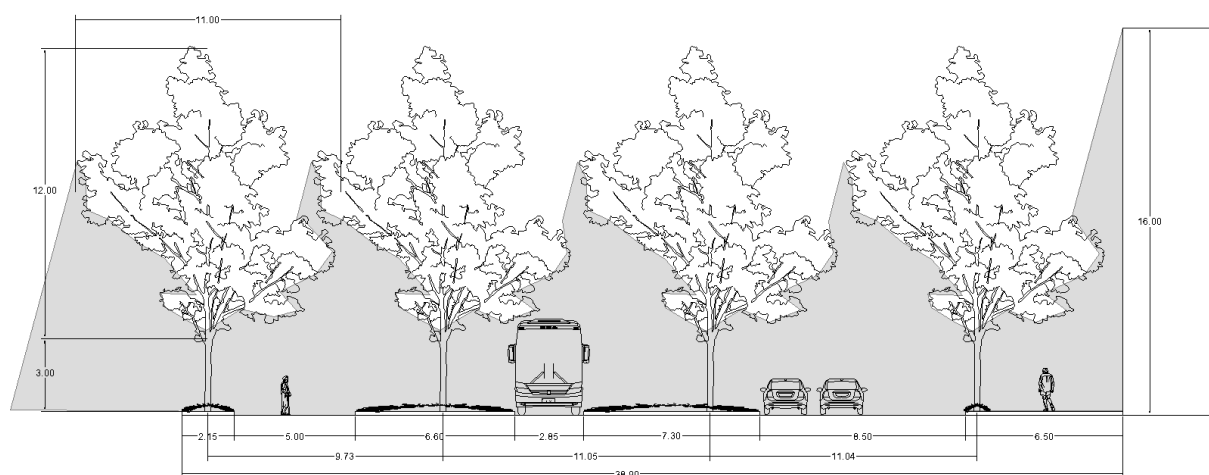


Figure 83. Transversal Profile of the proposal of *Largo da Estação* parking square (dimensions in meters).
Shadows at 13:00 during August's hottest day. Source: personal archive

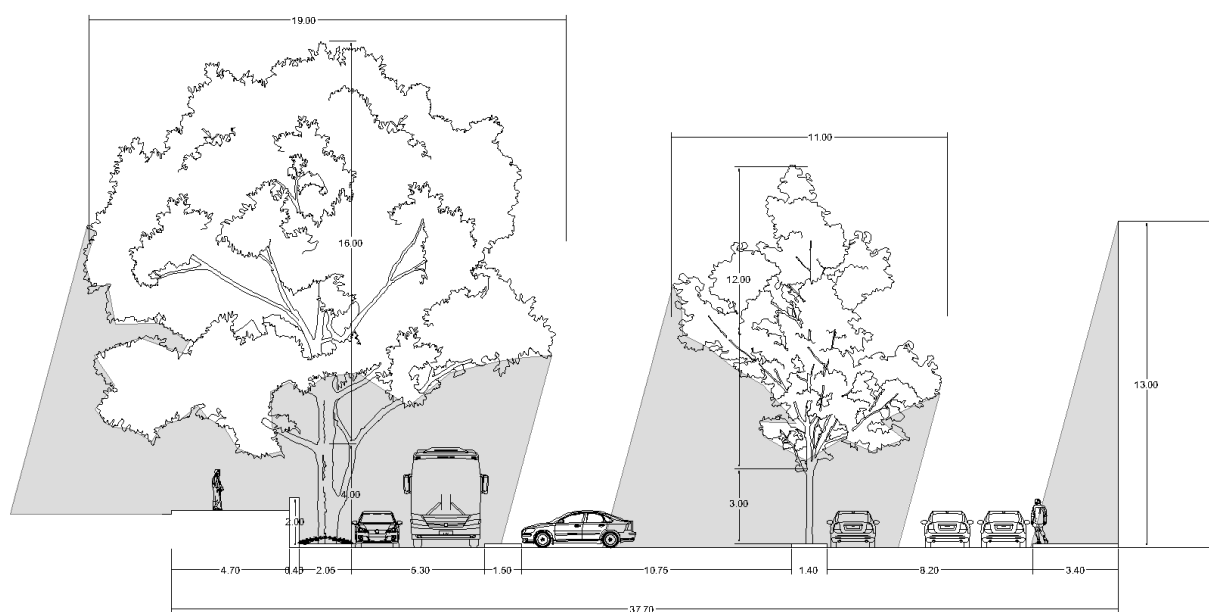


Figure 84. Transversal Profile of the proposal of *Largo da Estação* parking square (dimensions in meters).
Shadows at 13:00 during August's hottest day. Source: personal archive

ANNEX III

METEOROLOGICAL RESULTS OF THE SIX SCENARIO SIMULATIONS

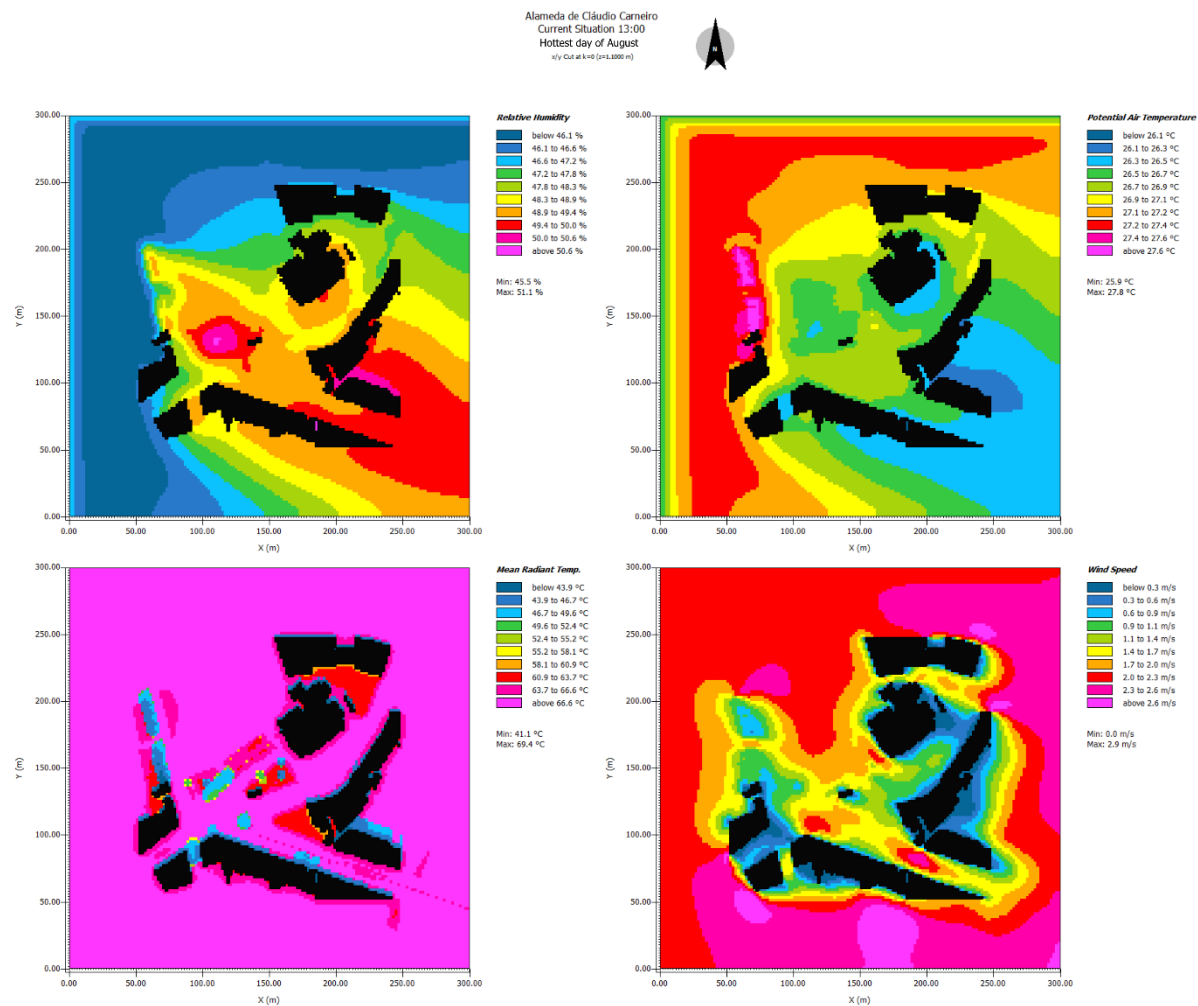


Figure 85. Results of meteorological values of the public square, *Alameda de Cláudio Carneiro*, for hottest simulation day

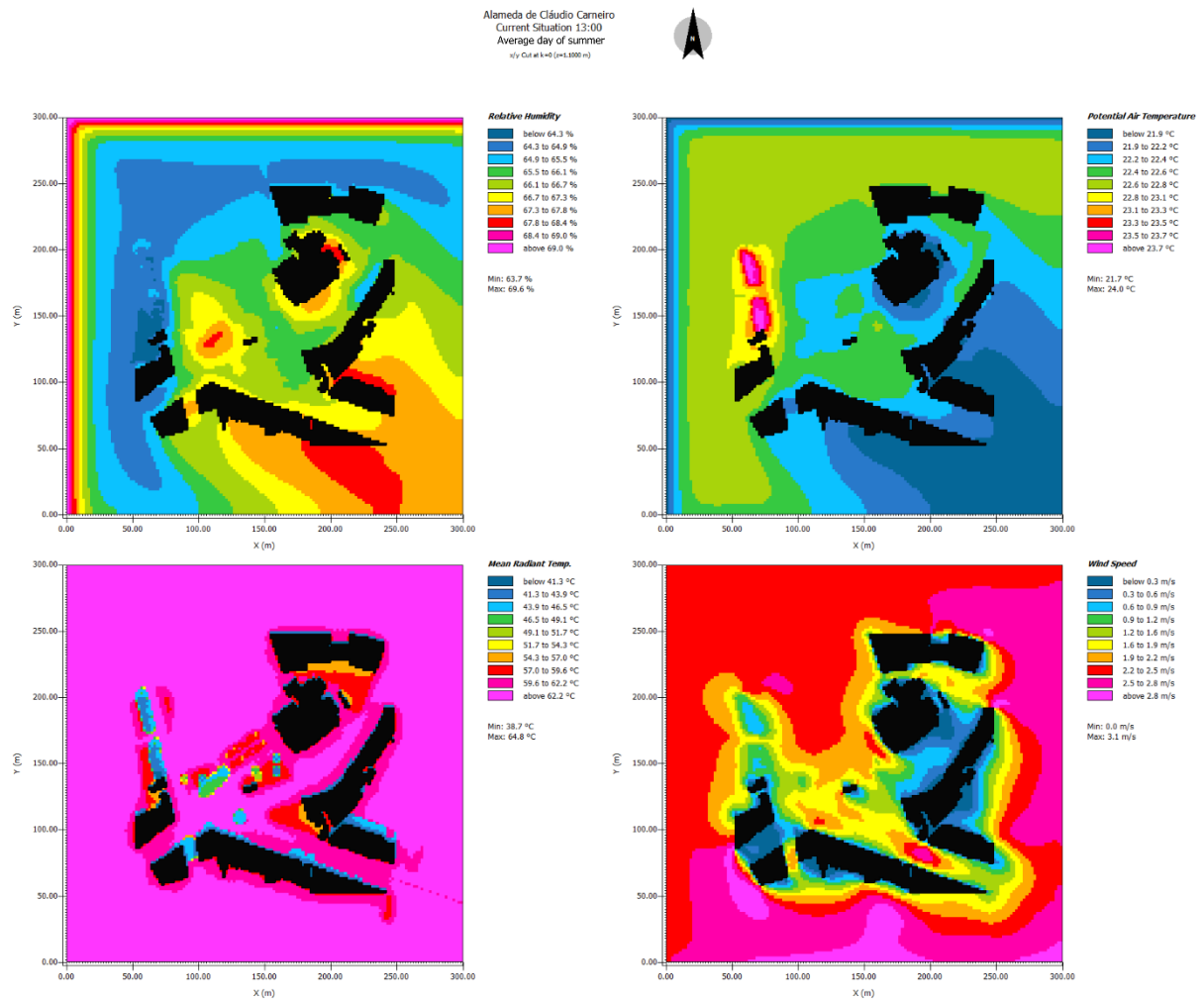


Figure 86. Results of meteorological values of the public square, *Alameda de Cláudio Carneiro*, for average simulation day

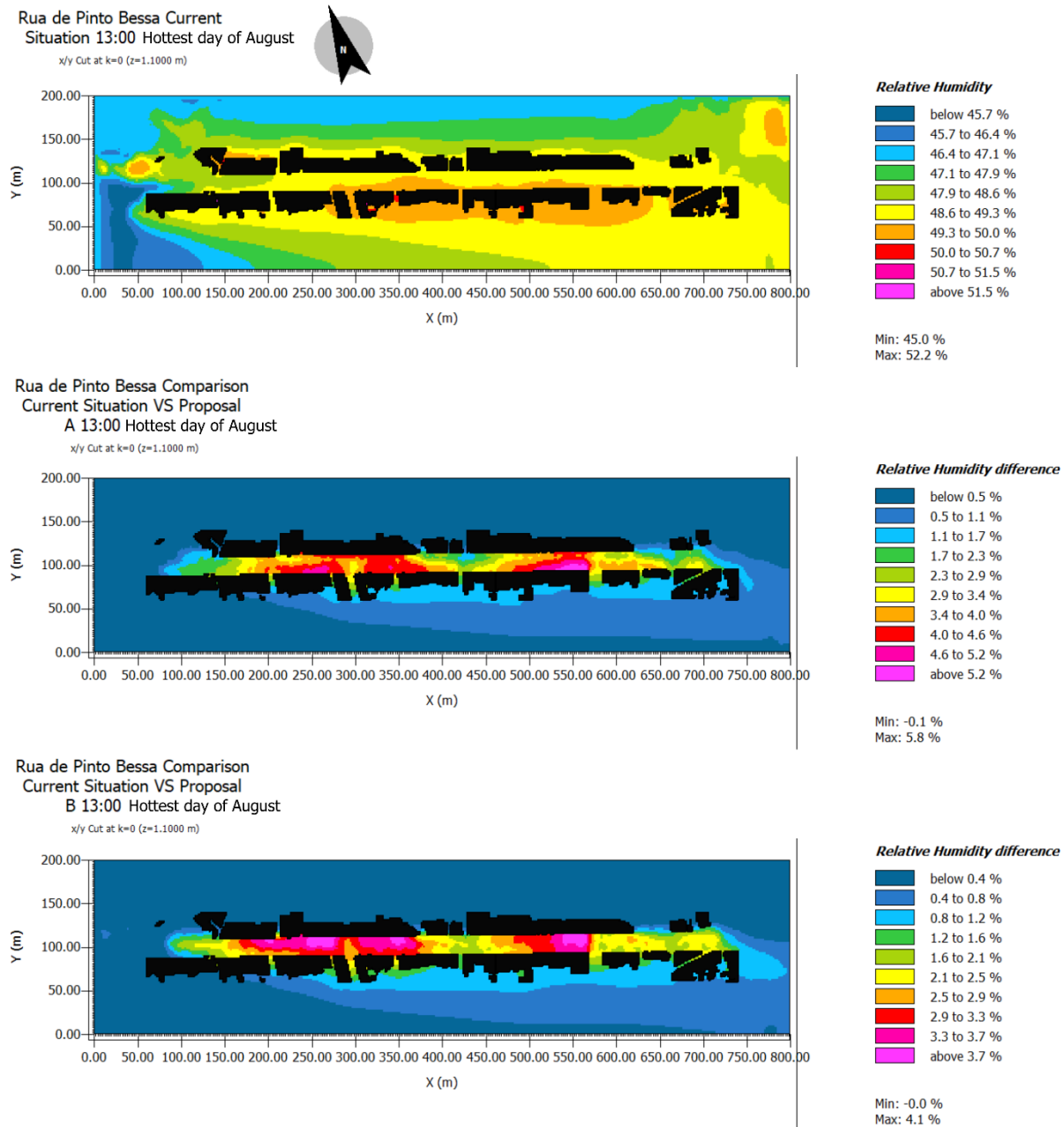
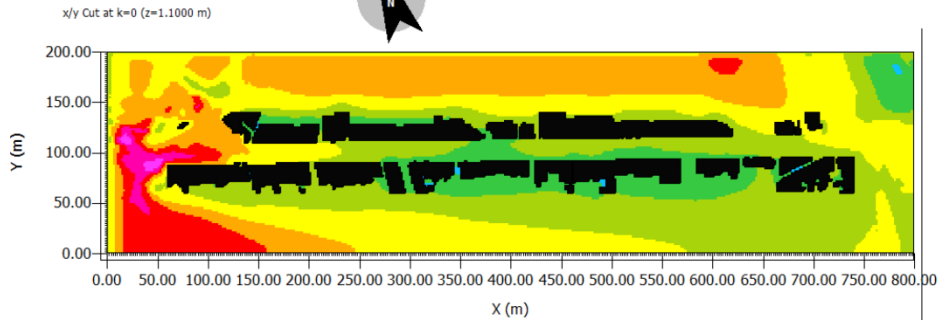
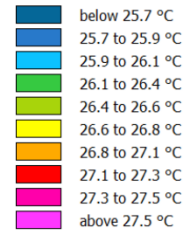


Figure 87. Results of relative humidity and difference values of the street canyon, *Rua de Pinto Bessa*, for hottest simulation day

Rua de Pinto Bessa Current
Situation 13:00 Hottest day of August

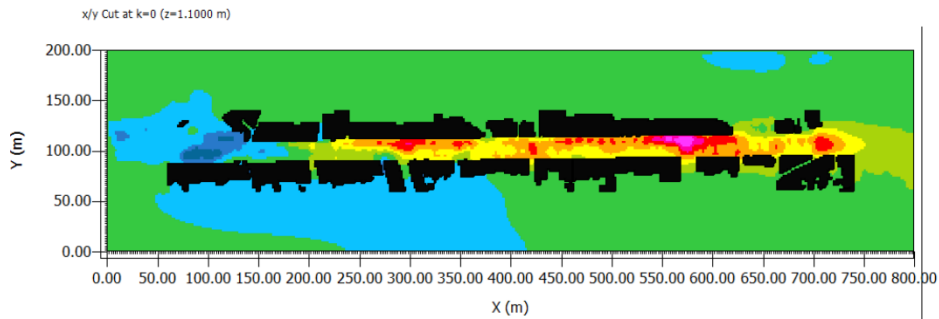


Potential Air Temperature

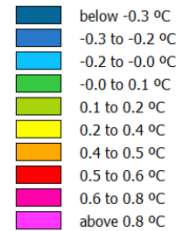


Min: 25.5 °C
Max: 27.8 °C

Rua de Pinto Bessa Comparison
Current Situation VS Proposal
A 13:00 Hottest day of August

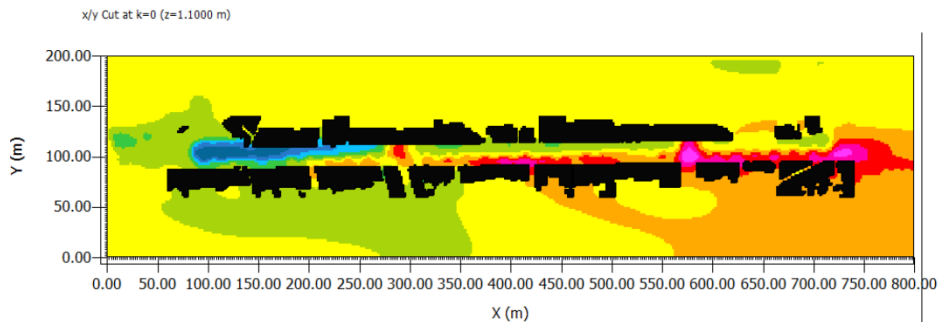


Potential Air Temperature
difference

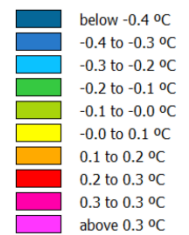


Min: -0.4 °C
Max: 0.9 °C

Rua de Pinto Bessa Comparison
Current Situation VS Proposal
B 13:00 Hottest day of August



Potential Air Temperature
difference



Min: -0.5 °C
Max: 0.4 °C

Figure 88. Results of air temperature and difference values of the street canyon, *Rua de Pinto Bessa*, for hottest simulation day

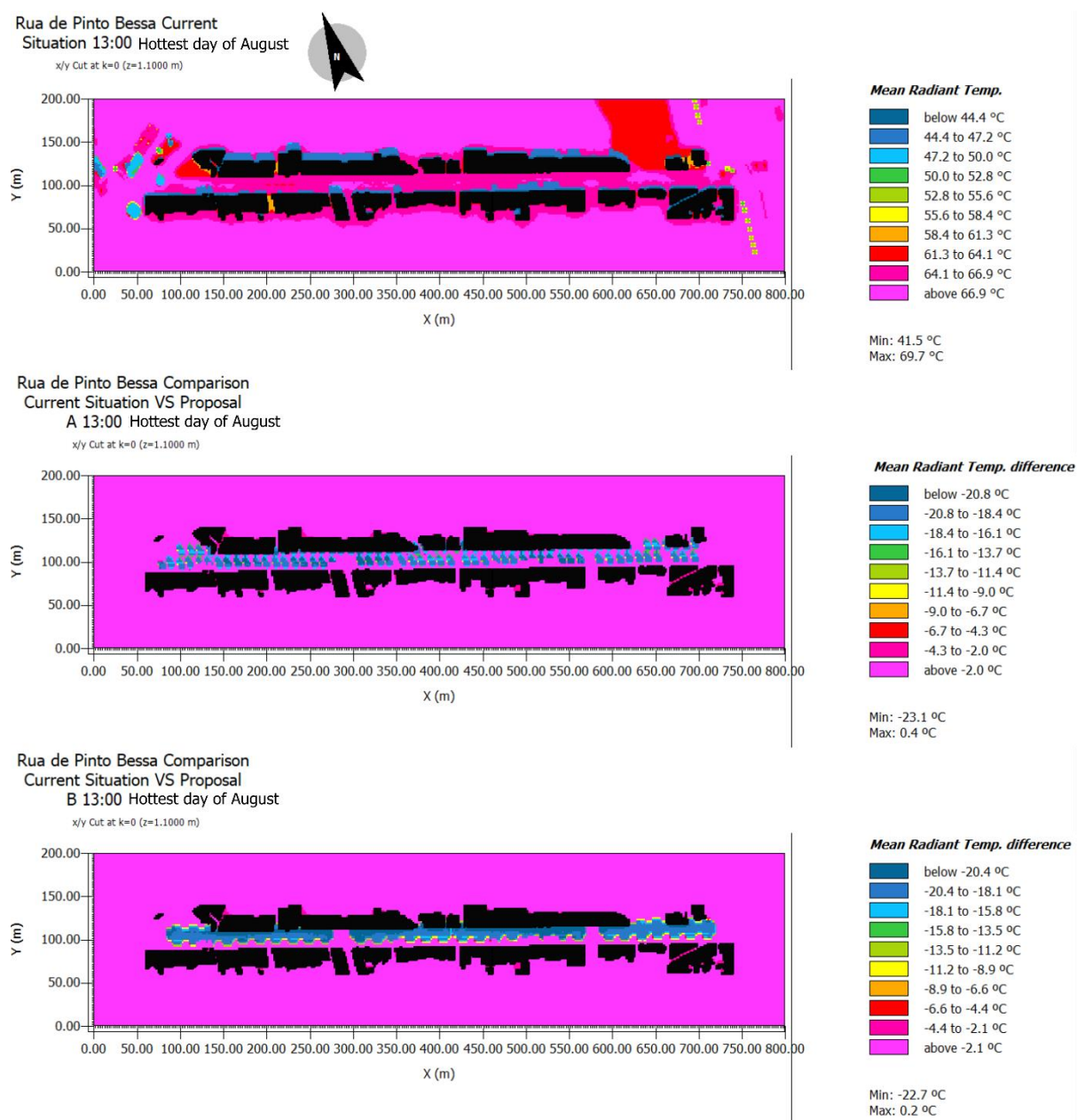


Figure 89. Results of mean radiant temperature and difference values of the street canyon, *Rua de Pinto Bessa*, for hottest simulation day

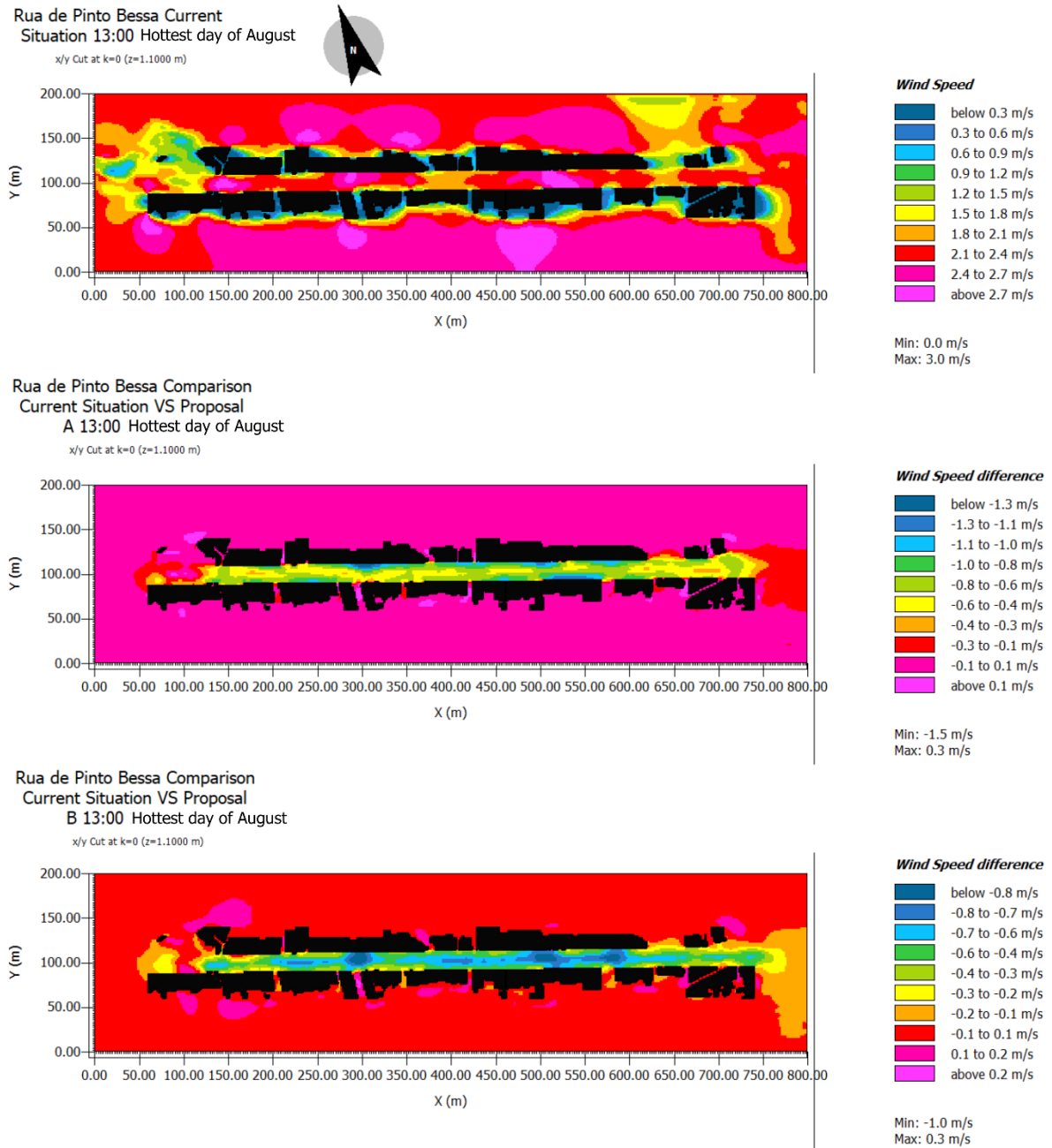


Figure 90. Results of wind speed and difference values of the street canyon, *Rua de Pinto Bessa*, for hottest simulation day

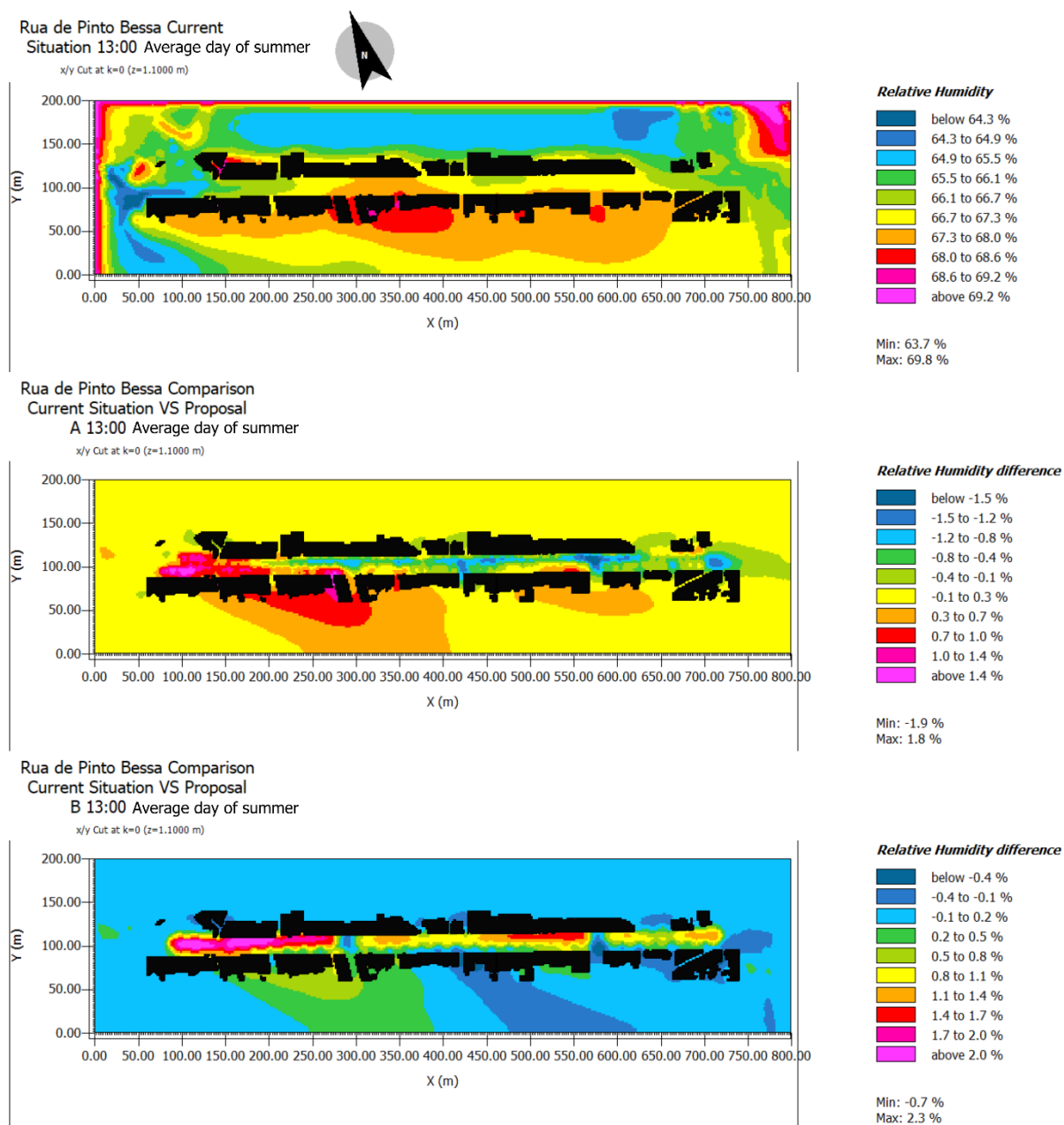


Figure 91. Results of relative humidity and difference values of the street canyon, *Rua de Pinto Bessa*, for average simulation day

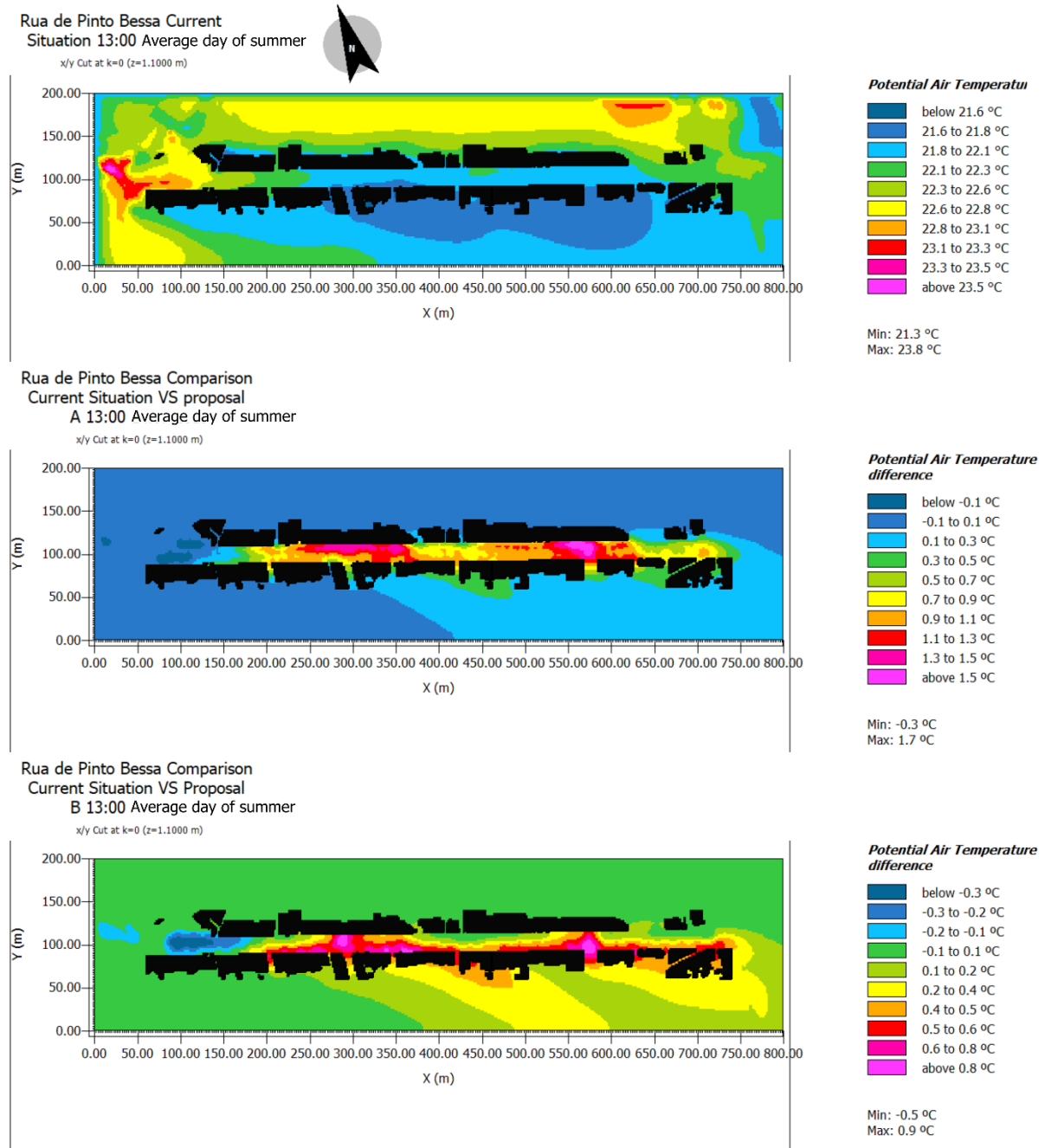


Figure 92. Results of air temperature and difference values of the street canyon, *Rua de Pinto Bessa*, for average simulation day

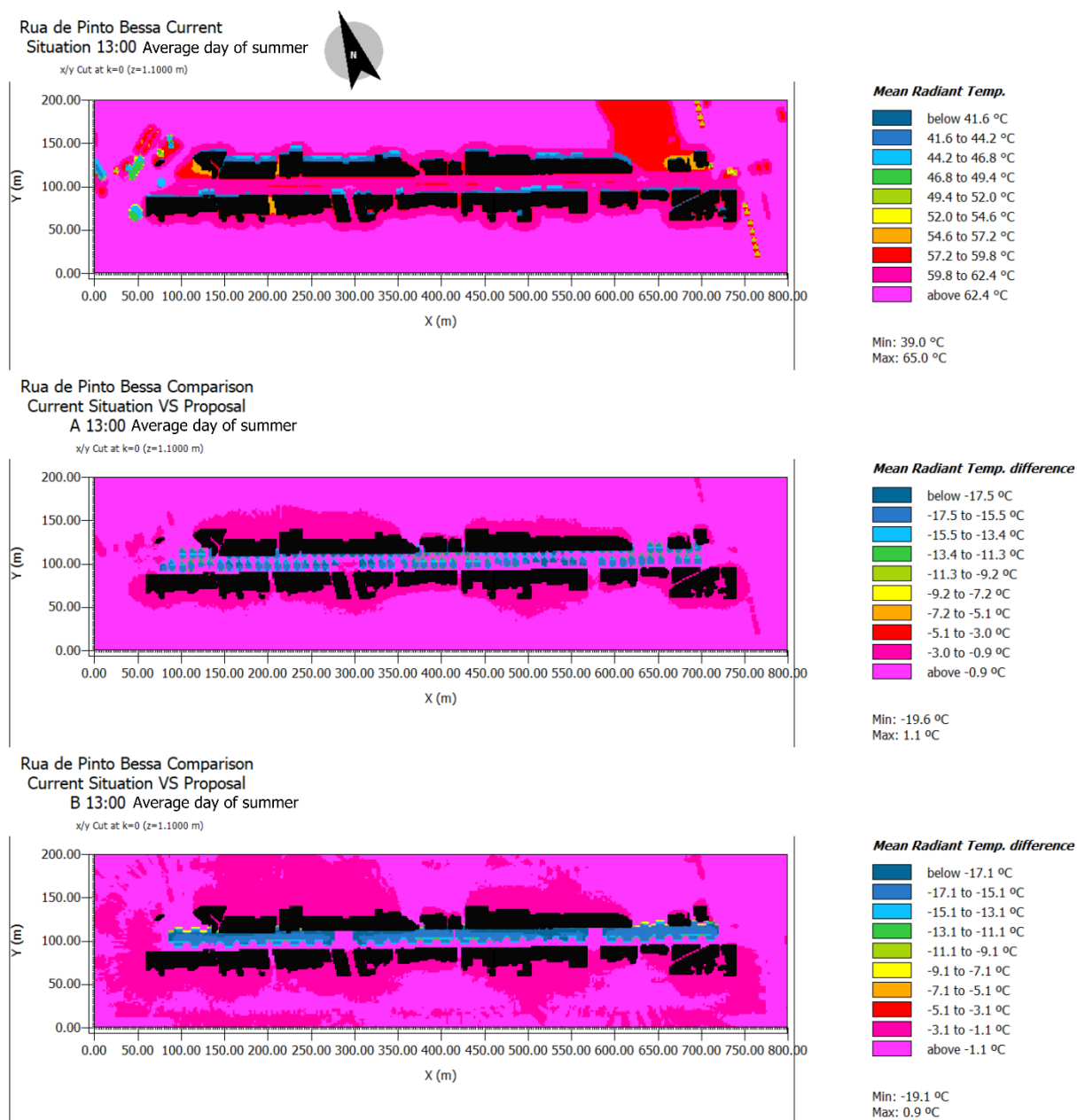


Figure 93. Results of mean radiant temperature and difference values of the street canyon, *Rua de Pinto Bessa*, for average simulation day

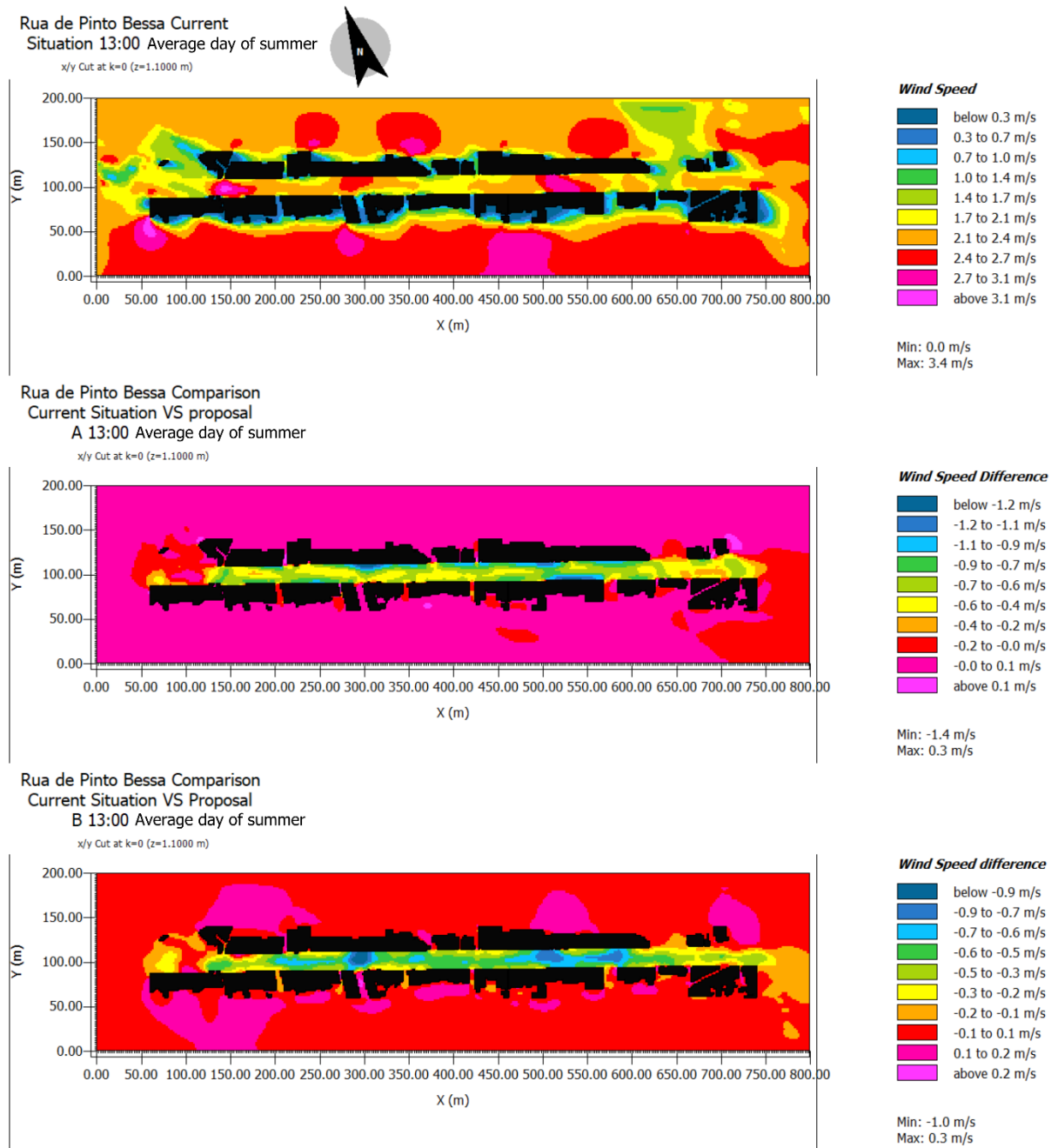


Figure 94. Results of wind speed and difference values of the street canyon, *Rua de Pinto Bessa*, for average simulation day

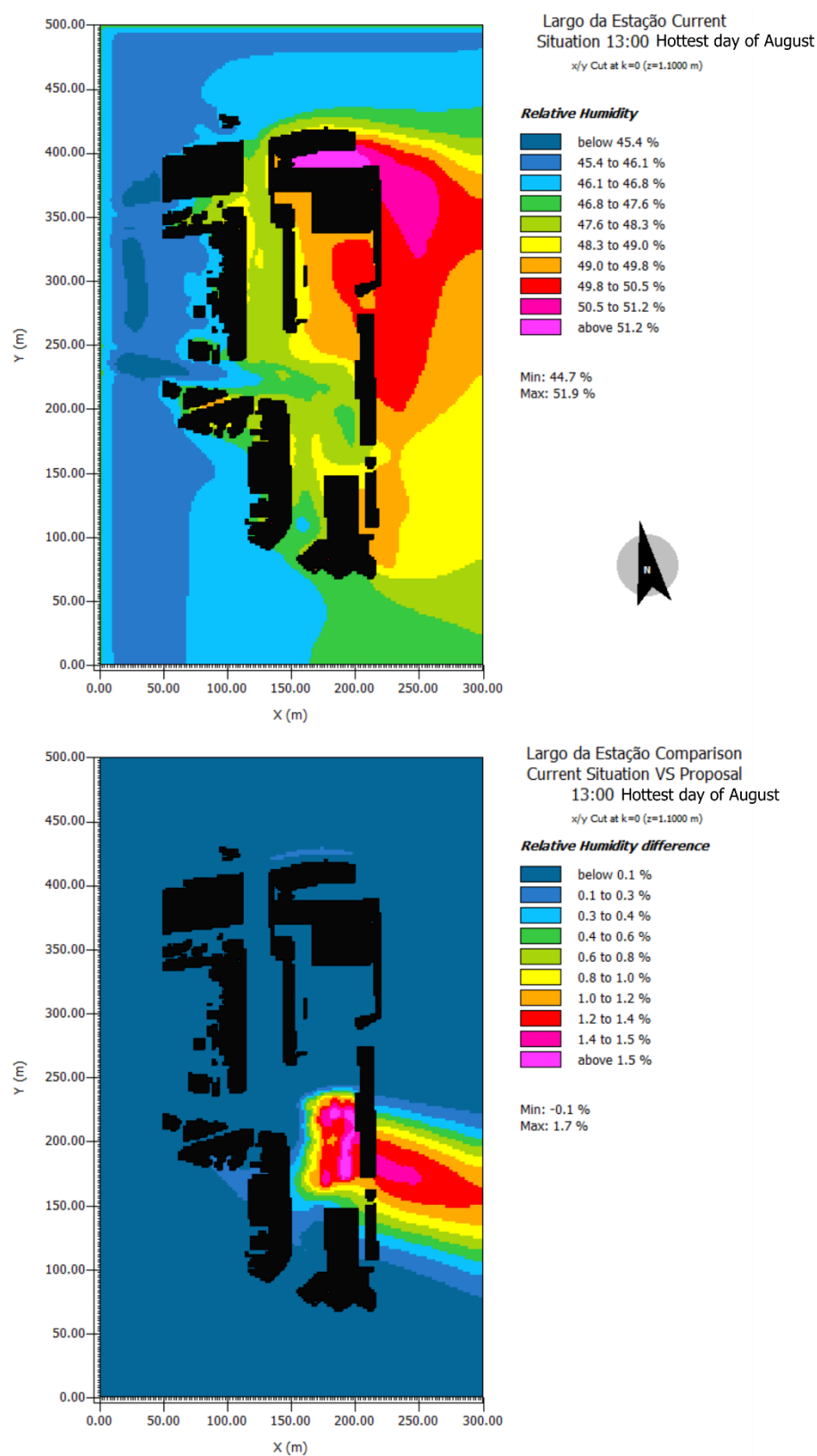


Figure 95. Results of relative humidity and difference values of the parking square, *Largo da Estação*, for hottest simulation day

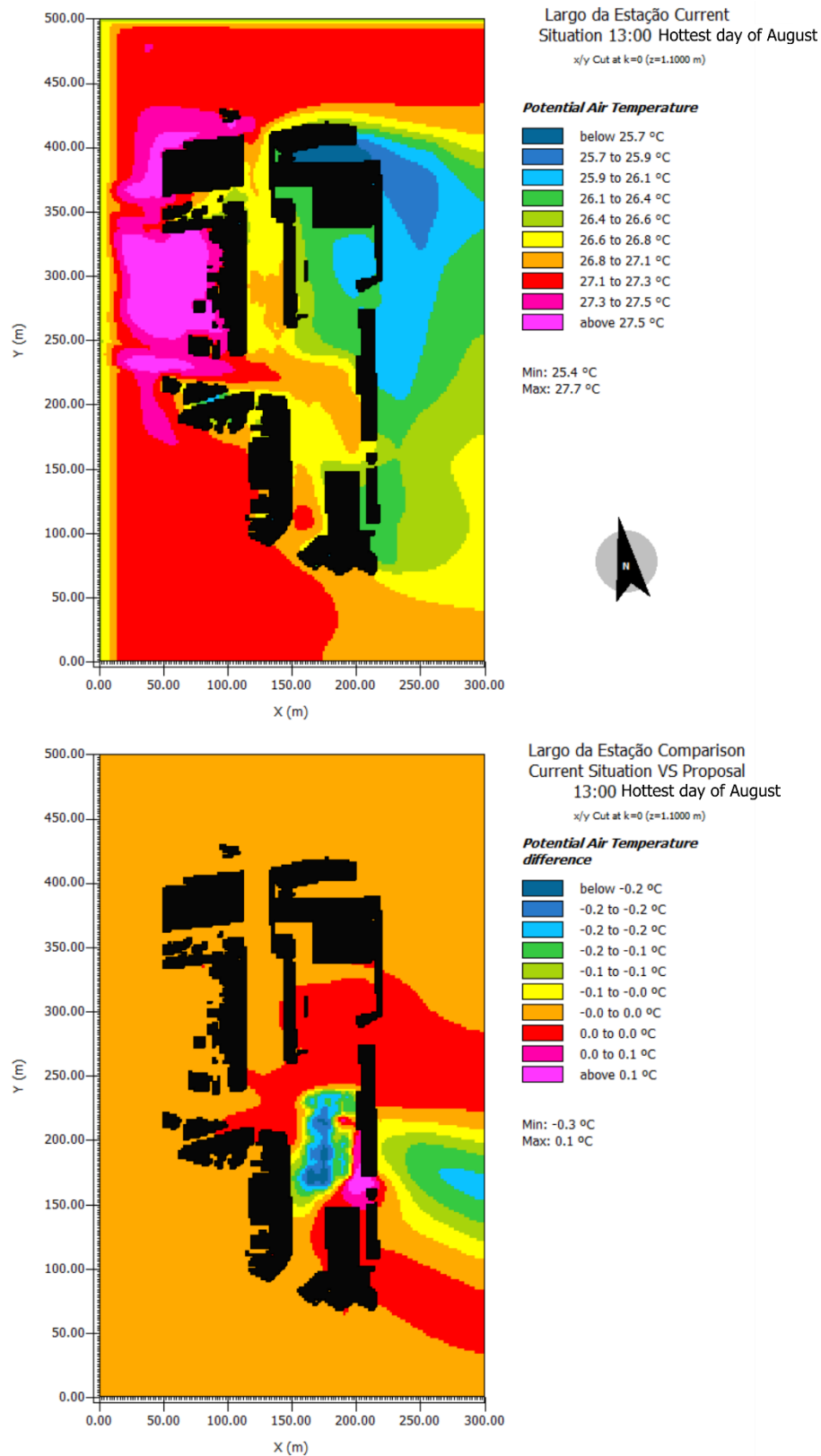


Figure 96. Results of air temperature and difference values of the parking square, *Largo da Estação*, for hottest simulation day

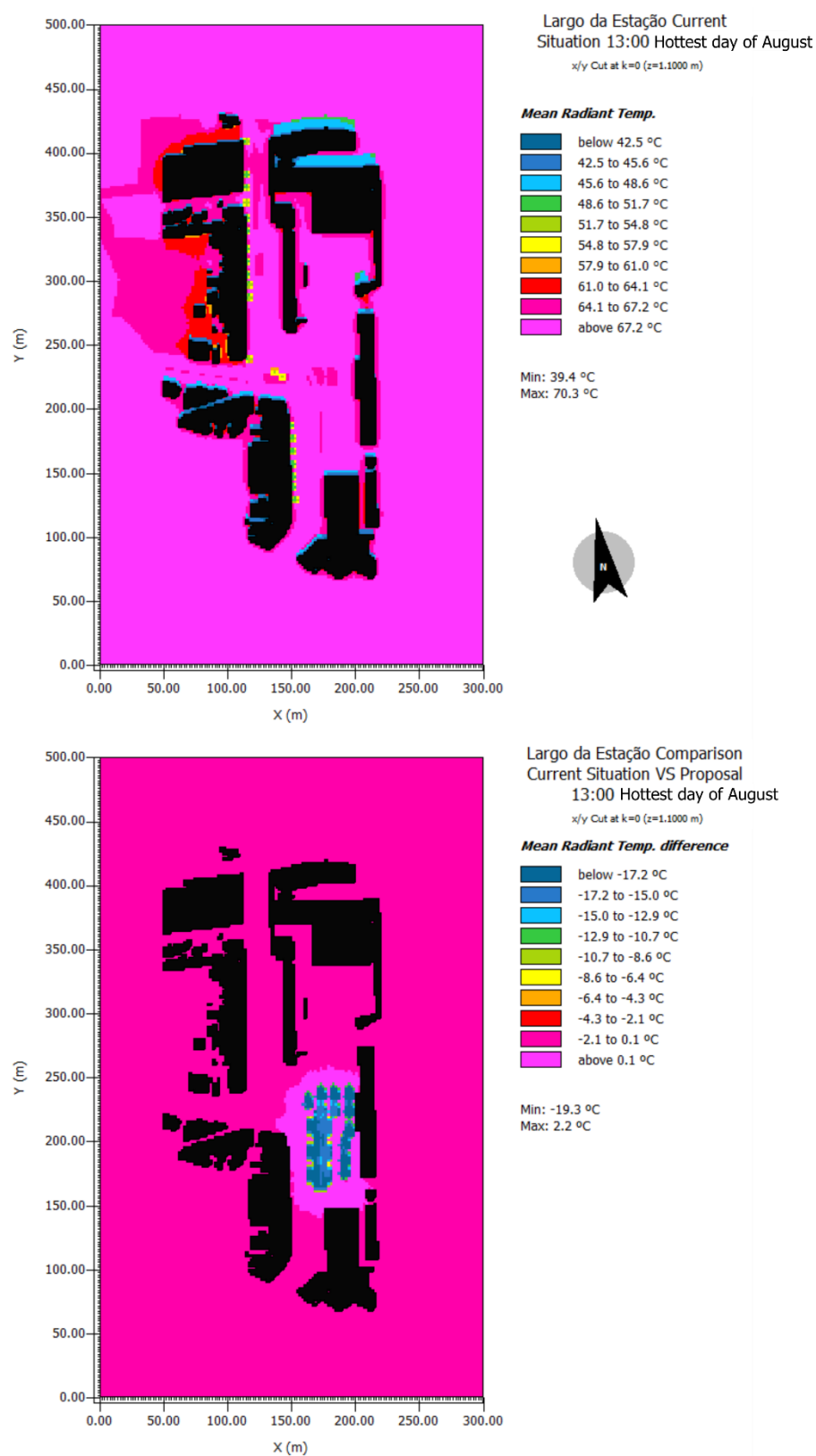


Figure 97. Results of mean radiant temperature and difference values of the parking square, *Largo da Estação*, for hottest simulation day

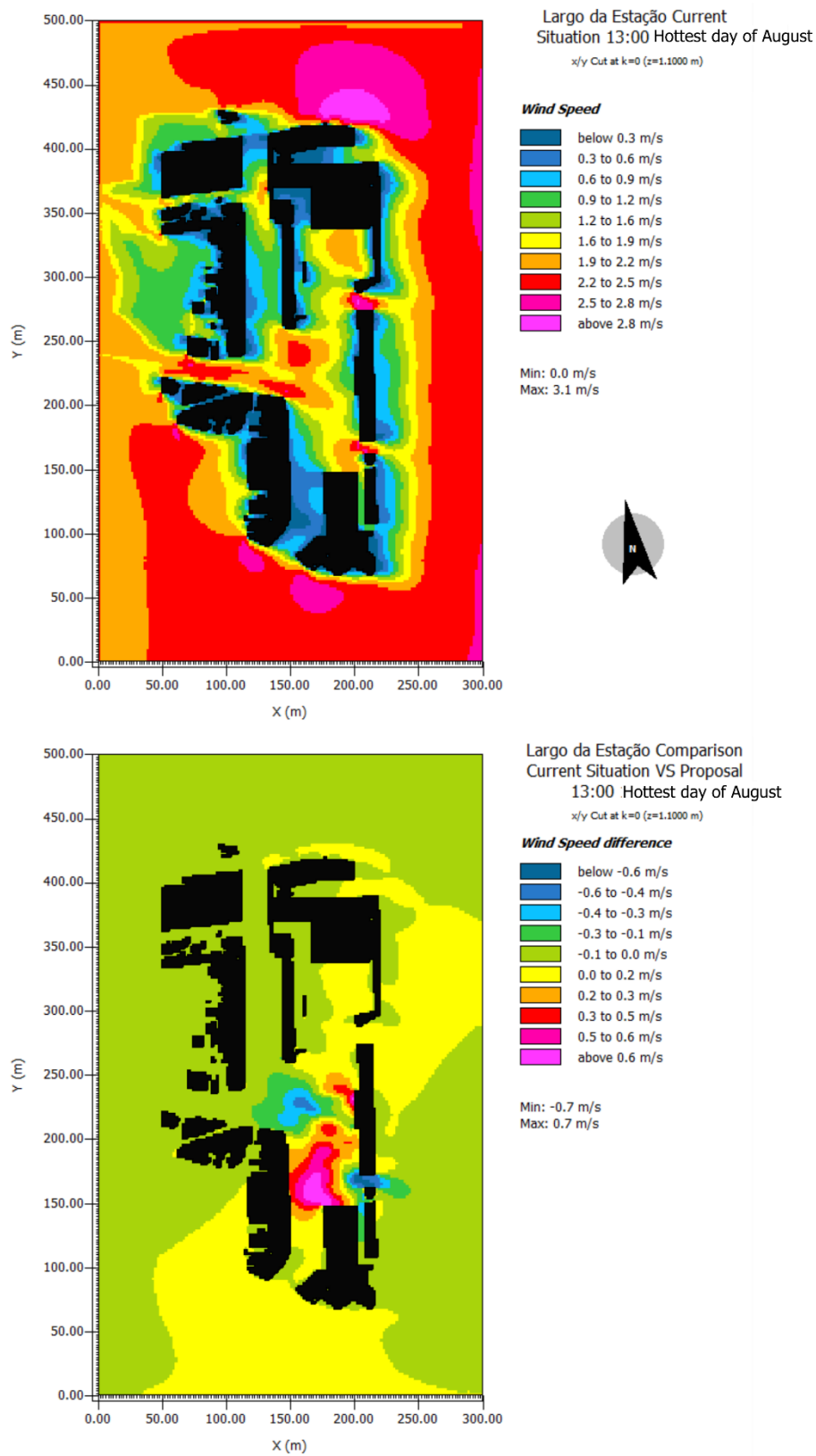


Figure 98. Results of wind speed and difference values of the parking square, *Largo da Estação*, for hottest simulation day

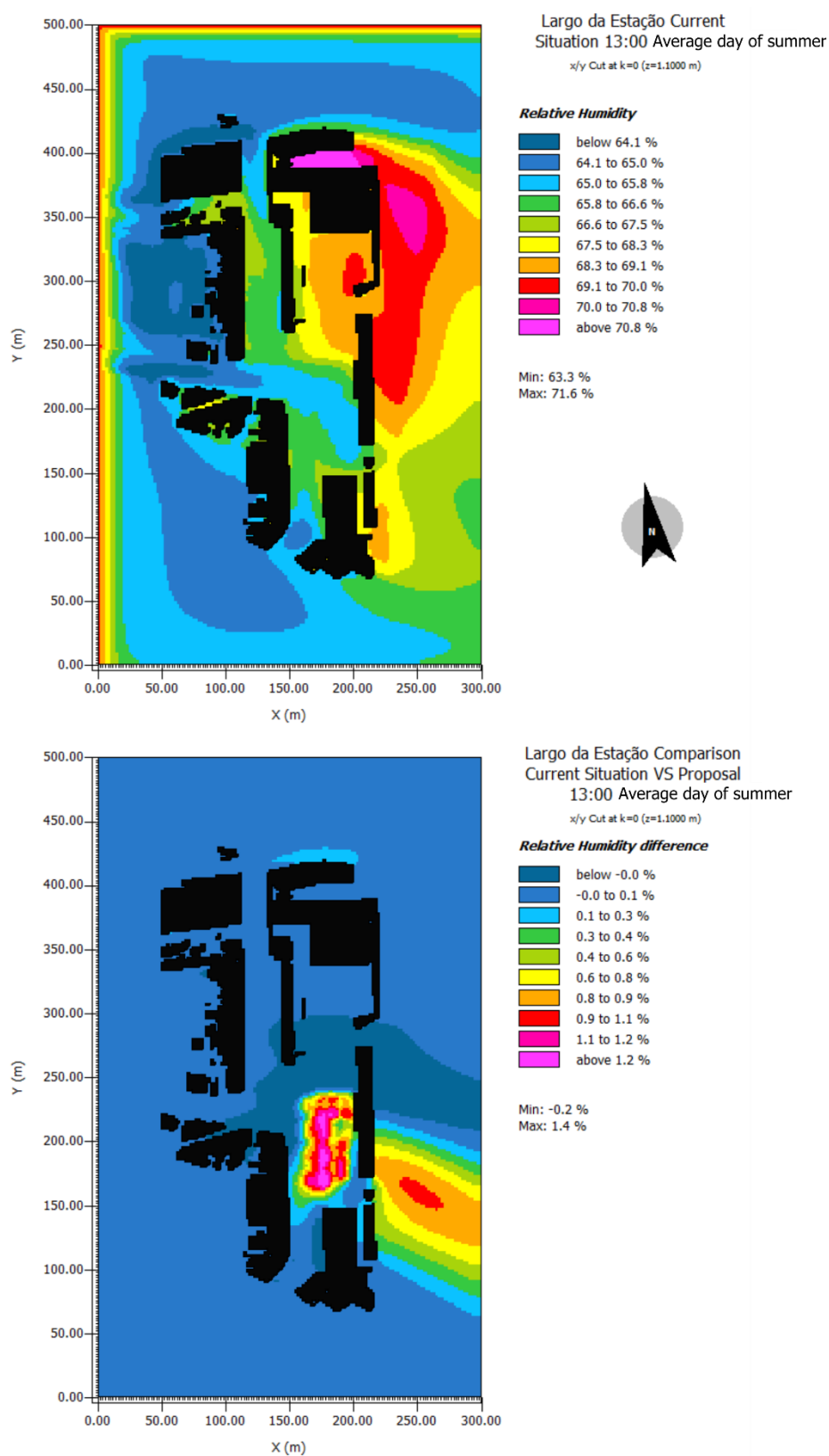


Figure 99. Results of relative humidity and difference values of the parking square, *Largo da Estação*, for average simulation day

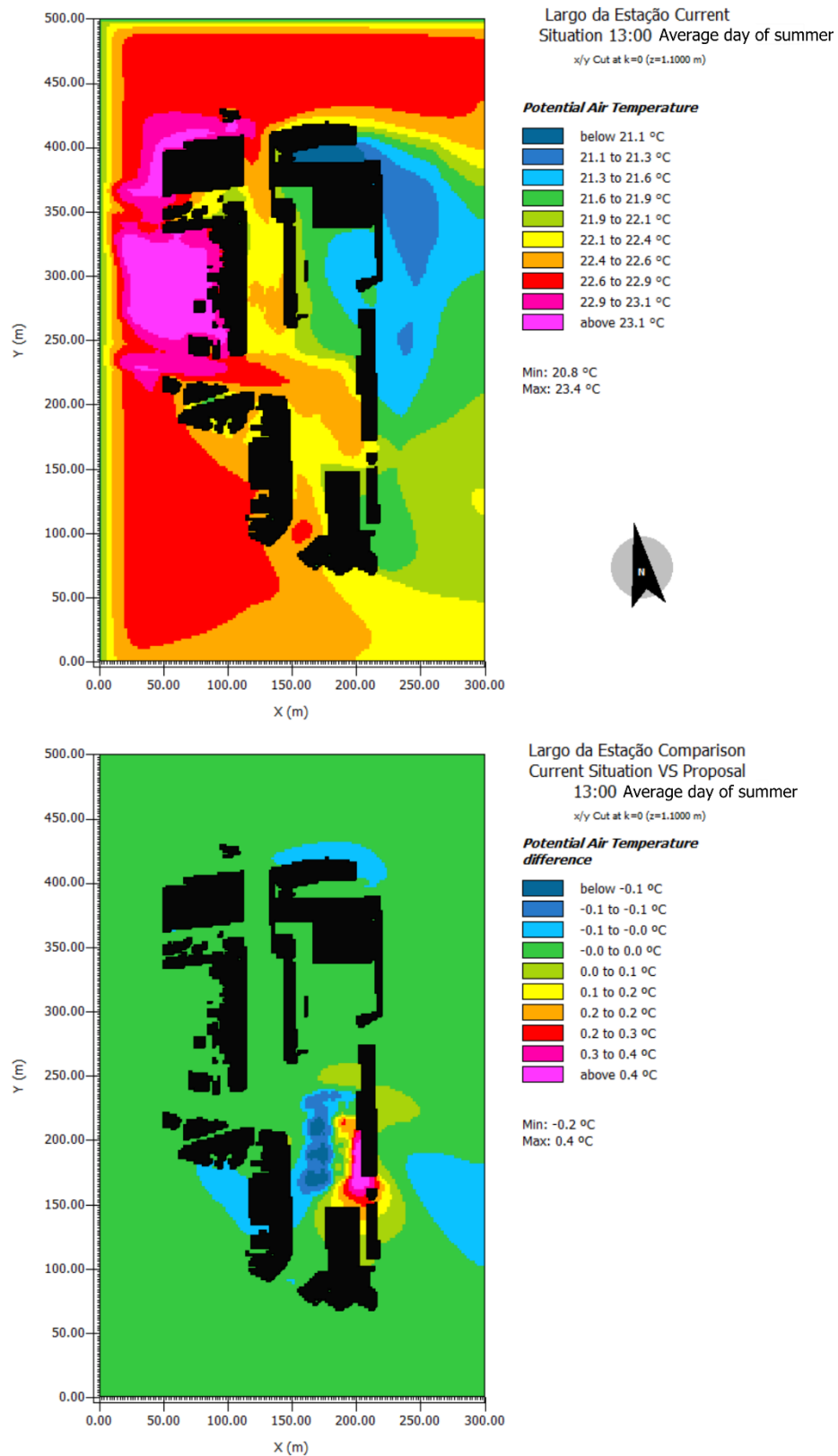


Figure 100. Results of air temperature and difference values of the parking square, *Largo da Estação*, for average simulation day

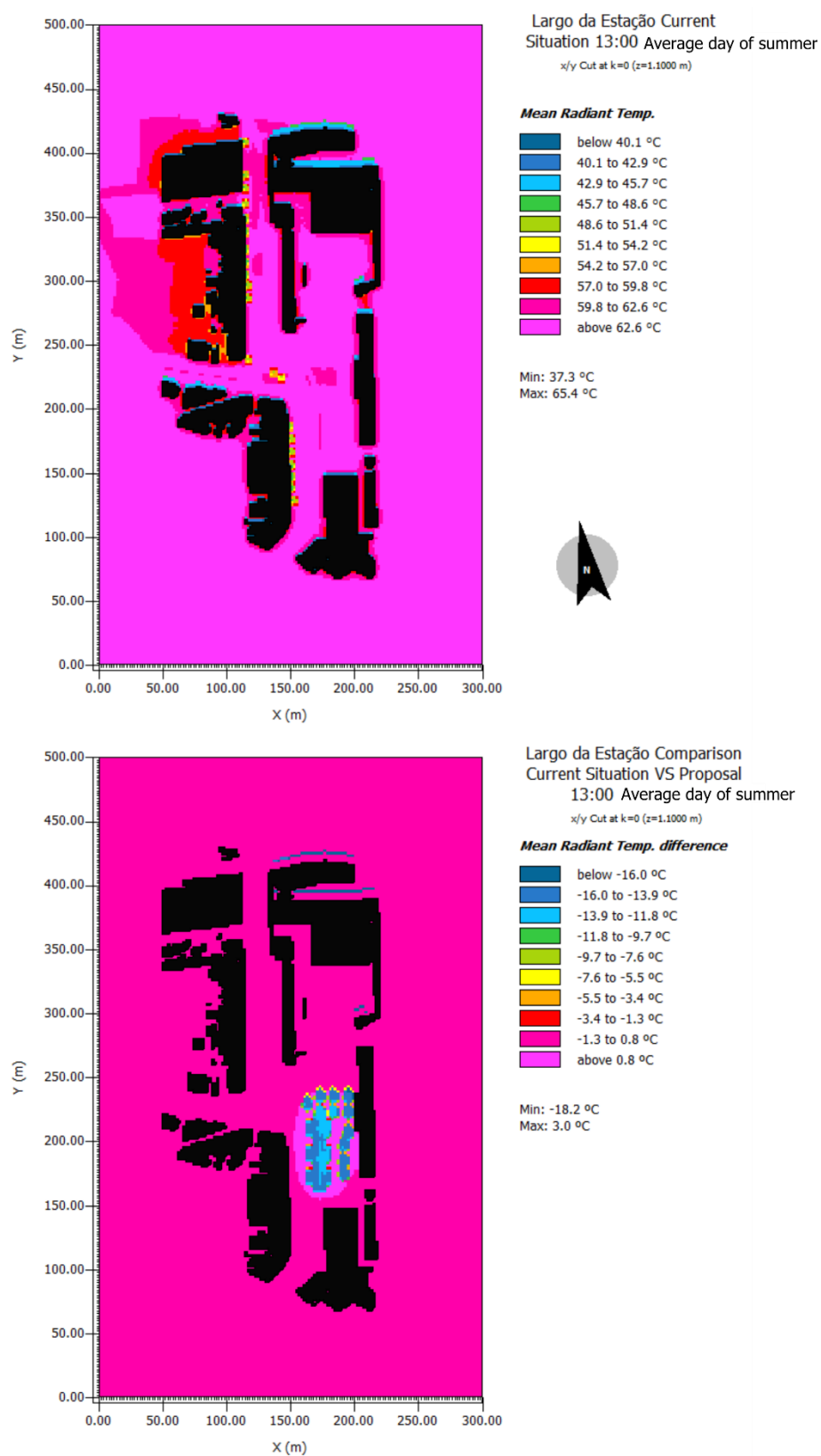


Figure 101. Results of mean radiant temperature and difference values of the parking square, *Largo da Estação*, for average simulation day

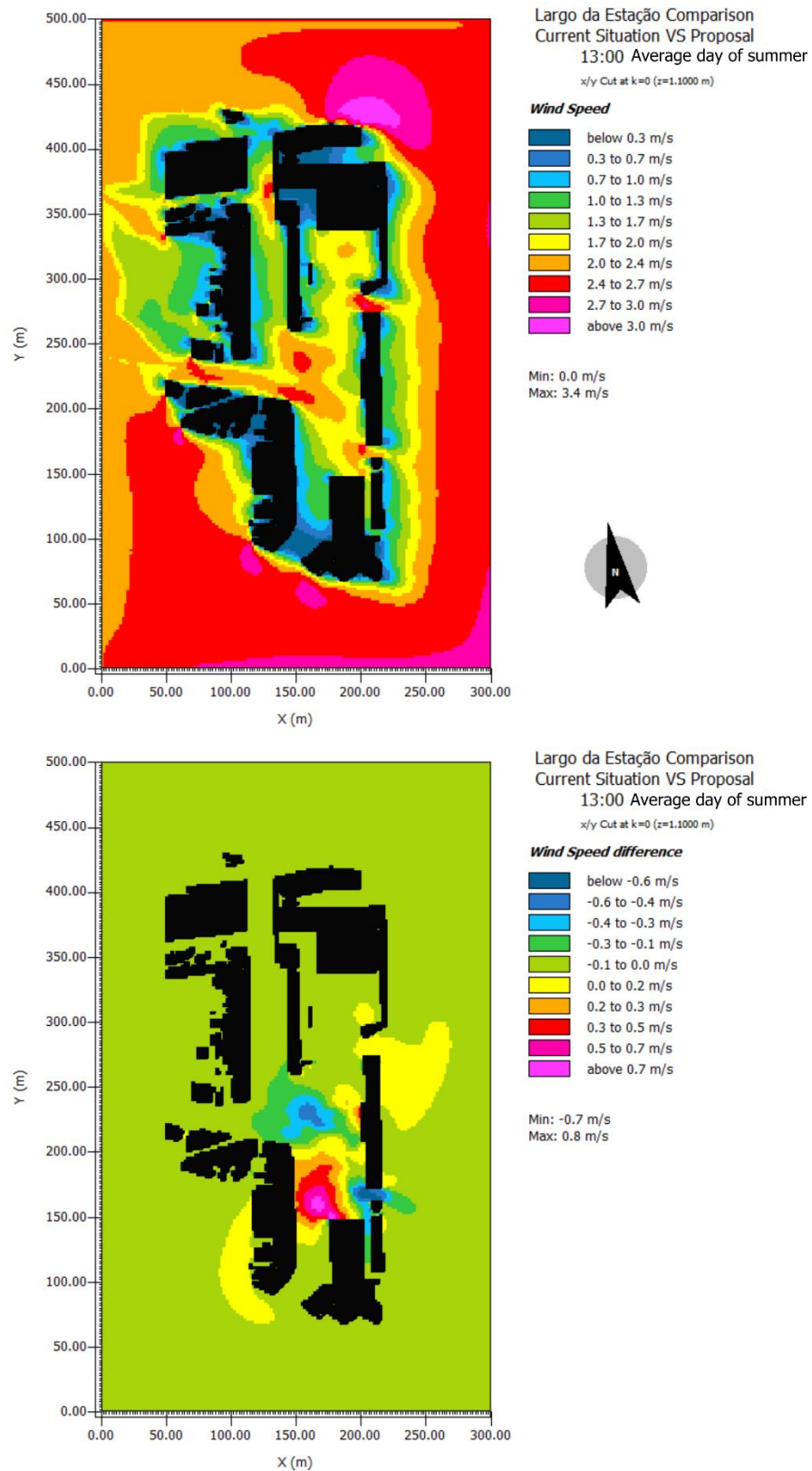


Figure 102. Results of wind speed temperature and difference values of the parking square, *Largo da Estação*, for average simulation day