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CLIMATE-SENSITIVE URBAN ADAPTATION:

Analysis of Qualitative and Quantitative Data of Outdoor Thermal Comfort in Barranquilla, Colombia

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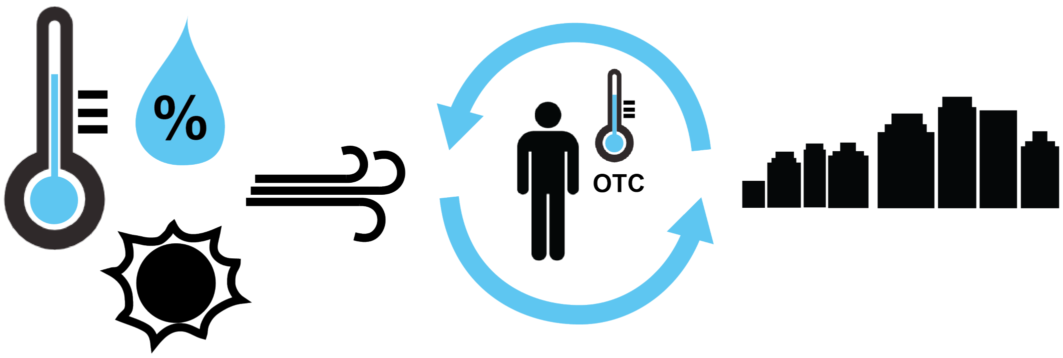

CLIMATE-SENSITIVE URBAN ADAPTATION: Analysis of Qualitative and Quantitative Data of Outdoor Thermal Comfort

Estefania Tapias

The diplomats have done their job: the Paris Agreement points the world in the right direction, and with sophistication and clarity. It does not, however, ensure implementation, which necessarily remains the domain of politicians, businessmen, scientists, engineers, and civil society.

— JEFFREY SACHS
DIRECTOR OF THE EARTH INSTITUTE, COLUMBIA UNIVERSITY

In realm of the 2015 United Nations Climate Change Conference - COP21
Paris, December 2015

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Zurich, 20 October 2016 Estefania Tapias Pedraza

Abstract

Since 2014 more than half of the world population live in cities. As urban population grows, urbanization rates increase. In addition, the world is facing unprecedented speeds in climate change leading to an increase in global average temperatures, commonly referred to as global warming. The simultaneous effects of rapid urbanization and climate change are only beginning to surface, and due to projected trends, they are coming to the forefront on many research agendas. The continuing densification of urban areas contributes to an increase in heat absorption and retention compared with rural areas, leading to the formation of the Urban Heat Islands (UHIs). It is known that this development will have a significant impact on future energy demands as well as the expectation for thermal comfort in outdoor environments. The UHI effect in tropical climates is even more challenging due to the increased baseline of heat levels. As suggested by the United Nations Environment Programme (UNEP), cities need to adapt to the future urban climate as it can directly affect human comfort and ultimately human health. To this end, the understanding and the capability to predict and alter urban microclimates may help to adapt and improve aspects of Outdoor Thermal Comfort (OTC), especially in tropical climates.

Climate-sensitive planning is the connection between urban climate and urban planning. Urban climate refers to the climatic conditions in an urban area, whereas urban planning is the spatial organization of urban functions. Hence, urban climate-sensitive planning addresses the challenges associated with UHIs by considering conditions of microclimates for city planning and design. This thesis proposes to improve climate-sensitive planning by the use of data-driven analysis and simulation models based on the collection of empirical and measurable evidence of OTC. Such data collection methods and prediction tools can provide architects and urban planners with faster and data-driven techniques towards the development of sustainable environments.

The research outlined in this thesis proposes to use the OTC as an indicator to understand how the current urban climate is affecting the thermal comfort of citizens in Barranquilla, Colombia. Initially, the OTC levels are identified in a local-scale area by using two different methods: (i) the evaluation of empirical survey data of the inquired individuals' thermal sensation (qualitative data), and (ii) the computer model-based calculations of the Physiologically Equivalent Temperature (PET), a thermal index which allows the evaluation of the thermal perception of humans (quantitative data). PET is calculated from measurable data of microclimate conditions, such as temperature, humidity, wind and solar radiation. The weather data was collected from a weather station's measurement network installed for a one-year period. Additionally, the PET is calculated from comfort-related factors, such as clothing, and geographical information based on coordinates. After correlation analyses between the outcomes of both methodologies, the matching results validated the data-driven and simulation approach.

The successful scalability of the technique is demonstrated by extending the previously validated survey campaign to a city-scale scenario by the development of a crowdsourcing smartphone application distributed among citizens. The data collection process took place in form of a citizen's marathon during the months of April and May 2016. The marathon collected 1121 responses, from which a sample containing 883 records was selected for data processing.

The city-scale crowdsourcing project, called 'Projecto Confort', resulted in the first evidence-based series of heat maps expressing the OTC of citizens for the city of Barranquilla. As expected, OTC was significantly reduced in densified urban areas. Results showed that the OTC data could indicate the well functioning of an urban area according to human thermal comfort and, ultimately, to microclimate condition. In addition, results outlined the importance of climate-sensitive urban planning to protect human health and comfort. Thus, the crowdsourcing project and the first results illustrated in heat maps can now be used by city planning institutions to understand the OTC of citizens, and for the planning of future climate-sensitive urban strategies around the city of Barranquilla.

Key words: Urban climate, urban planning, climate-sensitive urban planning, data-driven planning, outdoor thermal comfort, tropical climates

Zusammenfassung

Seit dem Jahr 2014 lebt mehr als die Hälfte der Weltbevölkerung in Städten. Mit dem stetigen Bevölkerungswachstum wächst auch die Urbanisierung. Zudem sieht sich die Welt einem rasanten Klimawechsel gegenüber, welcher bekannt als Klimawandel zu einem Anstieg der Temperaturen weltweit führt. Die simultanen Effekte von zunehmender Urbanisierung und Klimawandel sind noch wenig sichtbar, doch aufgrund ihrer vorhergesagten Entwicklung fangen diese Themen an, in diversen Bereichen Forschungsschwerpunkte zu werden. Die anhaltende Verdichtung urbaner Regionen trägt zu einer erhöhten Wärmeabsorption in Städten verglichen mit ländlichen Gegenden bei, was zu einer Bildung von so genannten "Urban Heat Islands" (UHIs) führt. Es ist bekannt, dass diese Entwicklung einen starken Einfluss auf den zukünftigen Energiebedarf sowie die generellen Erwartungen an thermischen Komfort im Außenbereich haben werden. In tropischen Klimazonen ist der UHI-Effekt noch problematischer aufgrund der erhöhten Grundtemperatur. Wie vom Umweltprogramm der Vereinten Nationen (UNEP) vorgeschlagen, müssen sich Städte an das zukünftige urbane Klima anpassen, da es die menschliche Behaglichkeit und letztlich die menschliche Gesundheit direkt beeinflussen kann. Dahingehend können das Verständnis und die Fähigkeit zur Vorhersage und Veränderung von städtischem Mikroklima helfen, Aspekte des thermischen Komforts (OTC) anzupassen und zu verbessern, vor allem in tropischen Klimazonen.

Klimasensible Planung bedeutet die Verbindung zwischen Stadtklima und Stadtplanung. Das städtische Klima bezieht sich auf die klimatischen Bedingungen im Stadtgebiet, während Stadtplanung die räumliche Organisation der städtischen Funktionen beschreibt. Die städtebauliche und klimafreundliche Planung befasst sich daher mit den Herausforderungen im Zusammenhang mit UHIs, indem sie die Bedingungen der Mikroklimata für Stadtplanung und -design berücksichtigt. Der Kern dieser Arbeit befasst sich damit, die Klimasensitivplanung durch die Verwendung von datengetriebenen Analysen und Simulationsmodellen zu verbessern, die auf der Sammlung empirischer und messbarer OTC-Daten basieren. Solche Datenerfassungsverfahren und Vorhersagewerkzeuge können Architekten und Stadtplanern schnellere und datengesteuerte Techniken für die Entwicklung von nachhaltigen Umgebungen bereitstellen.

Die Forschung in dieser Arbeit schlägt vor, den OTC als Indikator zu verwenden, um zu verstehen, wie das aktuelle Stadtklima den thermischen Komfort der Bürger in Barranquilla, Kolumbien beeinflusst. Anfänglich werden die OTC-Werte in einem lokalen Gebiet durch zwei verschiedene Methoden identifiziert: erstens über die Auswertung empirischer Erhebungsdaten der thermischen Empfindung von befragten Personen (qualitative Daten), und zweitens durch computermodellbasierten Berechnungen der Physiologisch Äquivalenten Temperatur (PET), einem thermischen Index, der die Bewertung der thermischen Wahrnehmung von Menschen erlaubt (quantitative Daten). PET wird aus messbaren Daten von Mikroklima-Bedingungen wie Temperatur, Feuchtigkeit, Wind und Sonneneinstrahlung berechnet. Die Wetterdaten wurden von dem Messnetz einer Wetterstation gesammelt, das für einen Zeitraum von einem Jahr installiert wurde. Darüber hinaus wird die PET aus Komfort-Faktoren, wie Kleidung, und geografischen Informationen auf der Grundlage von Koordinaten berechnet. Die Übereinstimmung der Ergebnisse beider Methodiken bestätigte den Erhebungsansatz.

Die erfolgreiche Skalierbarkeit der Methodik wird durch die Erweiterung der zuvor validierten Erhebungsmethode auf ein Großstadt-Szenario durch die Entwicklung einer Crowdsourcing-Smartphone-Anwendung für die Befragung von Bürgern verdeutlicht. Die Datenerfassung fand in Form eines Bürger-Marathons in den Monaten April und Mai 2016 statt. Der Marathon sammelte 1121 Antworten, aus denen eine Auswahl mit 883 Datensätzen für die Datenverarbeitung verwendet wurde.

Das stadtweite Crowdsourcing-Projekt Projecto Confortführte zur ersten evidenzbasierten Reihe von Wärmekarten, die den OTC der Bürger für die Stadt Barranquilla ausdrücken. Wie erwartet, war der thermische Komfort in verdichteten Stadtgebieten deutlich reduziert. Die Ergebnisse zeigen, dass die OTC-Daten das Funktionieren eines städtischen Gebietse nach menschlichem thermischem Komfort und letztlich dem Zustand des Mikroklimas anzeigen konnten. Darüber hinaus skizzierten die Ergebnisse die Bedeutung der klimafreundlichen Stadtplanung zum Schutz der menschlichen Gesundheit und Komfort. So können das Crowdsourcing-Projekt und die ersten Ergebnisse in den Wärmekarten nun von städtebaulichen Institutionen genutzt werden, um den thermischen Komfort der Bürger zu verstehen und die Planung künftiger klimafreundlicher Stadtstrategien rund um Barranquilla zu optimieren.

Stichwörter: Stadtklima, Stadtplanung, Klimafreundliche Stadtplanung, Datengetriebene Planung, Thermischer Komfort, Tropische Klimazonen

Contents

List of Figures

List of Tables

List of abbreviations

BLHI	Boundary Layer Heat Island
CLHI	Canopy Layer Heat Island
ECI	Equatorial Comfort Index
ET	Effective Temperature
ET*	New Effective Temperature
COP	Conference of Parties
IST	Tropical Summer Index
ITS	Index of Thermal Stress
MEMI	Munich Energy-balance Model for Individuals
MRT	Mean Radiant Temperature
OTC	Outdoor Thermal Comfort
OUT-SET	Outdoor Standard Effective Temperature
PET	Physiologically Equivalent Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
SEB	Surface Energy Balance
SET	Standard Effective Temperature
SHI	Surface Heat Island

SVF	Sky View Factor
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UHI	Urban Heat Island
UNEP	United Nations Environmental Program
UTCI	Universal Thermal Comfort Index
WBGT	Wet Bulb Globe temperature
LCZ	Local Climate Zone
ICT	Information and Communications Technology
OI	Open innovation
IoT	The Internet of Things

1 Introduction

The Outdoor Thermal Comfort (OTC) has been used as an indicator to understand urban climate, and to evaluate adaptation measures to climate change. In cities, it is apparent that the effects of climate change are greater than those at a global scale, as cities absorb and retain significantly more heat than rural areas [79]. These are known as Urban Heat Islands (UHI).

The topic of climate change has finally transferred from scientists to policy makers, and the Conference of Parties of 2015 in Paris (COP 21) was essential for the commitment of most countries to transform their national policies to reach their promised targets. The two main aspects frequently addressed on the climate change agenda are mitigation and adaptation. When it comes to cities, these two aspects are best studied and targeted through two fields: energy for mitigation and urban climate for adaptation, both equally important. In order to understand how a city should adapt to the coming changes in climate, we first need to understand the current situation and how it is affecting the city's citizens.

Urban planners intending to create comfortable microclimates can profit from easy methods of assessing the thermal component of climate [44]. In the past decade, several studies on human biometeorology and urban climatology for enhancing urban spaces have focused on modelling and assessment methods from a thermo-physiological perspective [45]. It is necessary to highlight that the degree of impact of the outdoor thermal environment on thermal comfort varies with the thermal requirements of the people in different climatic regions [60].

It is important to first understand that human thermal comfort is both physiological and perceptual [59]. From a physiological perspective, any attempt to understand how human comfort in the urban environment is affected by the microclimate must start with an analysis of the human energy balance. Each person experiences the thermal conditions of a specific place at a certain point in time in a different way [35]. The OTC is studied using (i) **empirical** and (ii) **numerical** methods. Empirical methods are based on the analysis of results from field surveys of pedestrians' environmental comfort. Based on the concepts derived from the outdoor human energy balance, researchers have also attempted to derive numerical methods to understand the thermal conditions people find acceptable. The empirical and numerical methods are typically used in the same research projects in order to validate findings. However, these traditional methods to explore the OTC of humans needs to be transformed into new tools and approaches that fit the new digital era.

Information Architecture and *Information City* explore the main dynamics of *smart cities* in a digital era (digital city). Different fields such as urban economics and urban transportation are currently dealing with understanding and developing these complex systems. Concerning urban climatology, researchers have been using new tools and technologies to harvest data and information, and to use these to arrive at insightful knowledge. However, there are still big steps to be taken.

Information Architecture is defined as the necessary framework to understand architecture, urban systems, and territories in the knowledge society [95]. With respect to urban design, the realm of data is expanding faster than before. Also expanding quickly is the amount of derived information that can be used to build design knowledge. The transformation from **data** to **information** and **knowledge** is one of the most important activities in every society [95], and these three elements form the structure of the *Information Architecture* concept. *Information City* describes the extension of information architecture to the urban scale. In analogy to information architecture, information city has two principal meanings: (1) making the invisible visible on the scale of a city, and thus helping to understand the functions of interactions between components of the city, and aiding the design of new cities; (2) *Information City* might become a metaphor for the structuring and ordering of the increasingly vast amounts of data created by a city's inhabitants and its infrastructure [95].

The elements used in *Information City* for the understanding of city systems are drawn from the new digital era. Sensor technology, the Internet of Things, and rapid data processing and simulation techniques are just a few of these elements. These tools and methods can support decision-making in city planning through data-driven design, big-data informed urban design, cognitive design computing, and citizen-designed science. In urban climatology studies, these methods could be highly beneficial for the exploration and development of adaptation measures in cities, with regards to climate change and urbanization.

Some of these elements are linked to Smart Cities. Smart Cities and Smart Buildings are human-made structures that are monitored, metered, networked, and controlled in order to make systems more smart and efficient. Cities first become smart, and then responsive. Dynamic behaviour is what differentiates the Responsive City from the Smart City. An important aspect of responsive cities is that there is dynamic interaction of smart systems in the city with its citizens. Thus, Citizen-Design Science, a combination of Citizen Science and Urban Design, becomes an important approach for responsive cities [54]. All of this concepts are being further developed and explored by research groups at the Singapore-ETH Centre, Future Cities Laboratory in Singapore (http://www.fcl.ethz.ch/).

1.1 Problem statement

The simultaneous effects of rapid urbanization and climate change are only beginning to surface, and due to projected trends they are coming to the fore on many research agendas. This is particularly important since urban areas absorb and retain significantly more heat than rural areas. This warmth of a city compared to its surrounding area is known as an 'Urban Heat Island' (UHI), and this effect will have a significant impact on future energy demands as well as the expectation for thermal comfort in outdoor environments.

In tropical climates, the situation is even more challenging due to the already warm-humid/dry conditions. As suggested by the United Nations Environment Programme (UNEP), cities need to adapt to the future urban climate, which can directly affect human comfort and ultimately health. Understanding and being able to predict and manipulate urban microclimates may help to adapt and improve aspects of outdoor thermal comfort [92], especially in tropical climates [91, 34].

At the same time, there is an increasing awareness of how to design in accordance with the environment and the climate. Different climatic aspects such as climate conditions, seasonal variations, and climate change place additional demands on the planning and design of urban developments. Urban 'climate-sensitive' design is defined as a process that considers the fundamental elements of microclimates for design purposes. The problem relates to the constant use of this concept to refer to any attempt at environmental design [11]. Thus, this concept requires a more scientific approach, which implies a method of inquiry that must be based on empirical and measurable evidence, and subject to specific principles of reasoning. Using data to improve design, also known as data-driven design, may support architects and urban planners as preconditions for the development of sustainable environments. Additionally, in an internet and big data era, traditional climatologic scientific methods can benefit from the Internet of Things and measurement sensor networks. Using these, massive sets of data can be collected in order to have bigger data samples to be analysed, making it possible to arrive at new findings. These methods are useful, especially in fields like climate change where cities need to understand the effects in order to act quickly and intelligently.

1.2 Hypothesis and research questions

Hypothesis:

Correlating empirical and numerical methods of Outdoor Thermal Comfort (OTC) in a local case study area will allow validation of both methodologies, and will provide a basis to execute a crowdsourcing project to extend the study to a city scale and create knowledge concerning how citizens perceive the thermal condition in outdoor spaces in Barranquilla, Colombia.

Research questions:

What is the correlation between thermal sensation and Physiologically Equivalent Temperature (PET) of a local case study area in Barranquilla?

Is it possible to validate the methodologies of thermal sensation and Physiologically Equivalent Temperature (PET), and their relation to each other?

Would the validation of thermal sensation and Physiologically Equivalent Temperature (PET) methodologies create the basis to extend the OTC research to a city scale?

Is it possible and feasible to use a smartphone application to collect OTC data from citizens, and would these data explain how citizens are feeling in relation to the thermal conditions of the city?

1.3 Research scope

The research outlined in this thesis aims to identify the different degrees of Outdoor Thermal Comfort (OTC) in the city of Barranquilla, by correlating qualitative data of thermal sensation with quantitative data of Physiologically Equivalent Temperature (PET). Further, this research aims to validate both methodologies, and then extend the research to a city scale using the Internet of Things (IoT). Initially, data are collected from surveys and sensor technology in the local case study area. A smartphone application with a survey questionnaire for citizens is used, and the research is extended to a city scale. Finally, it will be possible to use the OTC as an indicator to understand the urban climate conditions around the city, and to explore climate-sensitive urban adaptation measures.

1.4 Thesis organization

This thesis is divided into six chapters including the introduction. The second chapter provides an overview and a description of the state of the art, and the relevant research work. Chapter 3 describes the research methodology and introduces the case study city. Chapters 4 and 5 bring together the research body of the thesis, local scale analysis, and city scale analysis. The last chapter, Chapter 6, presents the final conclusion, discussion, limitations, and necessary future work.

2 Background and related work

This chapter describes the concepts that form the theoretical background of this dissertation. The storyline outlined in this chapter is organised from specific to general, starting from the central topic: **Outdoor Thermal Comfort (OTC)**. The related topics that construct this notion are: people, climate, and city. When linking these topics to each other, three subtopics are created: thermal comfort, urban climate, and citizens. These three subtopics are contextualised in a world stricken by global warming and urbanization, which are seen as external drivers of our central topic. Figure 2.1 explains this interaction, and helps the reader to follow this chapter. By the end of the chapter, the **Information Architecture** concept will be described in terms of the OTC research. Hence, research gaps in related work will be identified and highlighted (with numbers: 1a, 1b, 2, and 3) in order to, by the end, construct the aim of this dissertation.

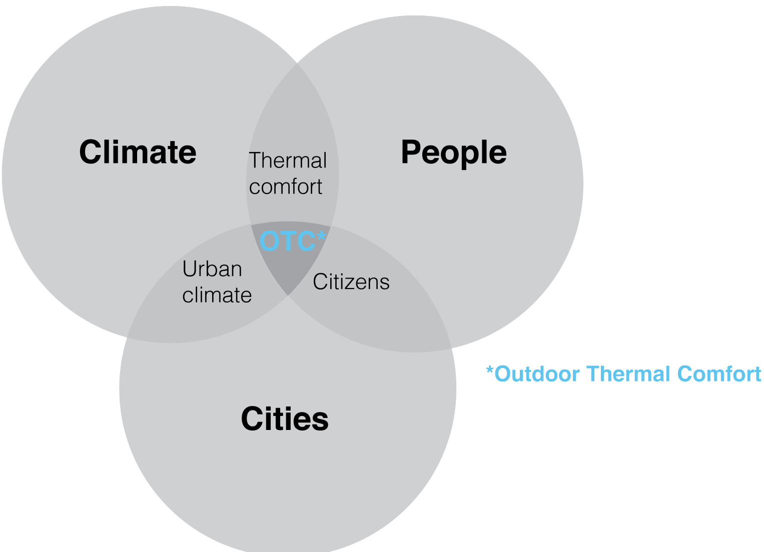


Figure 2.1 – *Research context*

2.1 Outdoor Thermal Comfort (OTC)

Outdoor spaces are important for cities, as they provide routes for daily pedestrian traffic and areas for different outdoor activities, contributing to urban livability and vitality [27]. Promoting the use of streets and outdoor spaces by pedestrians provides benefits to cities with regard to physical, environmental, economical, and social aspects [**?**]. In this way, ensuring that people are comfortable in outdoor spaces is essential for high-quality urban living. Over the past few decades, making outdoor spaces attractive to people, and ultimately used by them, has been increasingly recognized as a goal in urban planning and design [27, 39]. Among many factors that determine the quality of outdoor spaces, the urban microclimate is an important one [35]. Pedestrians are directly exposed to their immediate environment and its variations of air temperature, relative humidity, wind speed, and solar radiation. Therefore, people's sensation of thermal comfort is greatly affected by the local microclimate [27].

The OTC is generally studied in the urban micro-scale, and can be described and linked to microclimatic conditions by steady-state assessment methods. The degree of impact of the outdoor thermal environment on thermal comfort varies with the thermal requirements of people in different climatic regions. From a **quantitative** perspective (numerical methods), a number of bio-meteorological indices have been developed to describe human thermal comfort level by linking local microclimatic conditions and human thermal sensation [27]. One of the most widely used indices is the **Physiologically Equivalent Temperature (PET)** [64]. PET is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed [44]. Complementary to this, from a **qualitative** perspective (empirical methods), survey campaigns are used to capture the **thermal sensation** of people in specific locations in the city [59].

Urban planners intending to create comfortable microclimates can profit from easy methods of assessment of the thermal component of climate [44]. In the past decade, a number of studies on human biometeorology and urban climatology for enhancing urban spaces have been focused on modelling and assessment methods from a thermo-physiological perspective [45]. It is necessary to highlight that the degree of the effect of the outdoor thermal environment on thermal comfort varies with the thermal requirements of people in different climatic regions [**?**].

2.1.1 Energy balance of humans in the urban environment

It is important to first understand that human thermal comfort is both physiological and perceptual [59]. From a physiological perspective, any attempt to understand how human comfort in the urban environment is affected by the microclimate must start with an analysis of the human energy balance. Each person experiences, in a different way, the thermal conditions of a specific place at a give point in time, "but the underlying basis for this thermal sensation is the manner in which that person's body is physically heated, and in turn dissipates heat to the surrounding environment" [35].

Recent studies have revealed a wide variability in the limits of temperature, humidity, and other climatic descriptors that together define the comfort zone, since different populations tend to become acclimatised to different sets of conditions [15] [59, 110]. It is understood that the rapid heating or cooling of the human body causes thermal discomfort. Our physiology includes mechanisms for maintaining thermal equilibrium with the environment, and instinctively and consciously, we tend to avoid the extreme loss or gain of thermal energy. "Therefore, any understanding of how the design of the urban environment may promote thermal comfort will necessarily include a description of the mechanisms through which the body exchanges energy with its surroundings" [35].

As mentioned above, the variability of different microclimatic aspects such as air temperature, relative air velocity, surface temperature, radiant temperature, and relative humidity influence the heat that is transferred between the human body and the ambient environment, which defines the thermal comfort. The heat transfers may vary according to the elements influencing the urban climate. For example, depending upon the time of day or period of the year, the air temperature may vary. Radiant exchanges may also be affected by the influence of shading systems for pedestrians. In the case that this shade is created by vegetation, there may also be an influence on local air temperature due to evapotranspiration, as well as an effect on relative humidity. Additionally, water features may be a source of evaporative cooling.

Before describing how the processes of heat exchange occur between the human body and the environment, we first need to understand the general concept of the urban energy balance between the atmosphere and the urban elements. The Surface Energy Balance (SEB) is understandable in relation to the basic concept of energy balance, which is derived from the First Law of Thermodynamics. This states that energy can neither be created nor destroyed, only converted from one form to another. When applied to a simple system, the energy input is equal to the sum of energy output and the difference in energy stored within it [35]:

Energy input = Energy output + change in stored energy

The urban SEB is observed as a meso-scale phenomenon (see Section 2.2), with the built-up elements represented as a surface that is characterized by its average properties. The energy transfer between the surface and the atmosphere is measured by the fluxes above the urban canopy. The general form of the surface energy balance of an urban area is illustrated in Figure 2.2 and expressed as follows:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \tag{2.1}$$

where Q^* is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the convective sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the net storage heat flux and

ΔQ_A is the net horizontal heat advection [35].

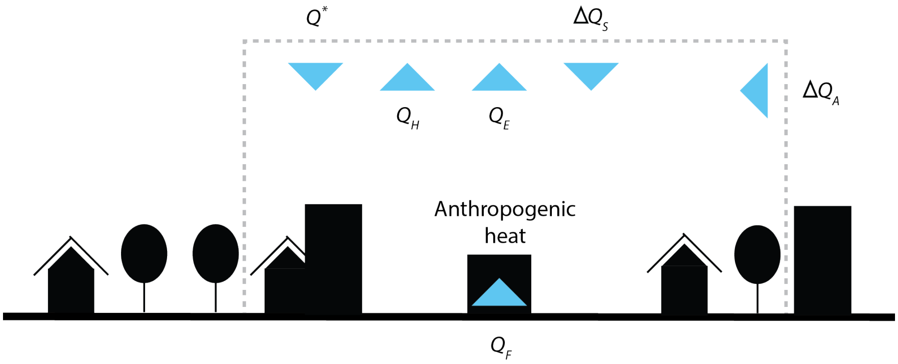


Figure 2.2 – *Urban surface energy balance (SEB) components. Based on [35]*

In a different way, the heat exchanges between the human and the urban environment occur through conduction (9%), convection (23%), radiation (35%), and a combination of evaporation and respiration (33%) [87].

As seen with the SEB, radiation is a predominant variable for the energy balance in urban open spaces. Within the boundaries of a building, a person is likely to be protected from intense solar radiation, and the temperature of room surfaces often remains close to that of the interior air. This allows the indoor thermal environment to be described by a simple temperature, without regard for the radiant field surrounding an occupant.

In an outdoor urban setting, there are two important mechanisms of this sort that are closely dependent on the architectural elements of the space: **radiation** and **convection**. While radiation is the absorption and emission of energy, convection is the absorption/dissipation of heat. Under warm conditions, a body also dissipates heat by **evaporation** (sweating and respiration – thermal stress). To the extent that a body comes in direct contact with other surfaces, it will also gain or lose heat by **conduction** (with respect to clothing effects) [35].

Radiation is a dominant variable of the energy balance in urban open spaces. As opposed to indoor conditions, pedestrians experience wide fluctuations in thermal stimuli due to radiation in two forms: short-wave and long-wave radiation. The former refers to the radiation emitted directly from the sun (sunlight), while the latter refers to the type of radiation emitted by the atmosphere and by lower-temperature terrestrial surfaces that surround people in a built environment [35].

Both forms of radiation can be expressed in terms of the rate at which energy is absorbed (or emitted) by a unit area of a human body's surface (Wm^{-2}). These forms of radiation can be considered together as a total net exchange of radiation (R_n) between a body and the urban environment, expressed as follows:

$$R_n = (K_{dir} + K_{dif} + K_h + K_v)(1 - \alpha_s) + L_d + L_h + L_v - L_s \tag{2.2}$$

The short-wave radiation within the net exchange R_n is subdivided into: K_{dir}, the direct short-wave radiation incident on the body; K_{dif}, the diffuse short-wave radiation incident on the body; K_h, the indirect radiation incident on the body, reflected from horizontal surfaces; and K_v, the indirect radiation incident on the body, reflected from vertical surfaces. The variable α_s represents the albedo of the skin and/or clothing, such that $(1 - \alpha_s)$ is the proportion of all incident short-wave radiation that is absorbed by the body.

The last four terms in the equation represent the long-wave radiation, which is subdivided into: L_d, the long-wave radiation incident on the body, directed downward from the sky, L_h, emitted by horizontal surfaces; L_v, emitted by vertical surfaces; and L_s, the long-wave radiation emitted by the body to the environment. This last term represents cooling and is therefore negative. This absorption and emission of energy through radiation is illustrated in Figure 2.3.

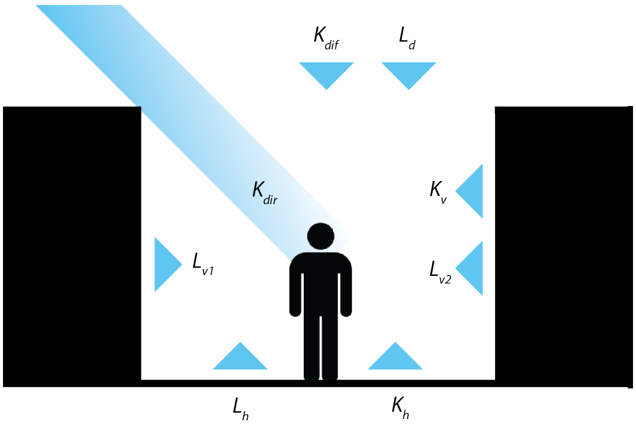


Figure 2.3 – *Radiation exchange between the human and the urban environment. Based on [85]*

Using radiation principles, two coefficients can be used to estimate and predict the energy exchange (heat flows) in a given area: the sol-air temperature ($T_{sol-air}$), and the mean radiant temperature (MRT).

The sol-air temperature is defined as the outdoor air temperature which, in the absence of solar radiation, “would give the same temperature distribution and rate of heat transfer through building elements, due to the combined effects of the actual outdoor temperature distribution plus incident solar radiation” [78]. Given the uncertainties involved in calculating sol-air temperatures accurately from solar radiation and air temperature, “a useful estimation of long-wave radiation may require measuring radiant surface temperatures directly" [35].

The MRT is defined as the uniform temperature of an imaginary enclosure in which radiant energy exchange with the body is equal to the radiant exchange in the actual non-uniform enclosure (IS0 7726). While the MRT concept is straightforward in an indoor and confined area, its estimation outdoors is linked to considerable complexities and uncertainties [35]. One way to calculate the MRT in a complex urban space is by the use of a globe thermometer, which is based on an assumed equilibrium between the radiant balance and convective heat exchange of the globe [111].

Convection is usually the dominant form of heat transfer for a human body. A body exchanges heat with the surrounding air through thermal convection due to local air temperature differences, and through forced convection due to wind [35]. In typical outdoor situations where the wind is dominant, the rate of convective heat transfer (C) per unit area of the body may be given in units of Wm^{-2} as follows:

$$C = h_c \Delta T \tag{2.3}$$

In this equation, h_c is the heat transfer coefficient ($Wm^{-2}K^{-1}$) dependent on wind speed, and ΔT is the mean difference between body surface temperature (T_s) and the surrounding air temperature (T_a). Under most conditions (unless air temperature is above 35°C), the convective exchange represents heat eliminated from the body (e.g. cooling) [35].

Evaporation acts as a human body's cooling mechanism, and is the result of the body's attempt to maintain thermal equilibrium. While radiation and convection explain the energy exchange between a human being and the urban environment, in warm conditions evaporation produces heat loss from the body. One way to deal with evaporative cooling is by means of a model for physiological heat exchange, such as the Index of Thermal Stress (ITS) [41]. This index expresses the overall thermal exchange between the body and its surroundings under warm conditions, with evaporation accounted for in a detailed manner. The ITS is a measure of the rate at which the human body must release moisture to the environment in order to maintain thermal equilibrium [35]. Under warm conditions, the human body attempts to maintain thermal equilibrium through several mechanisms of evaporative cooling, particularly through the production of sweat. The index is based on the assumption that the weight loss of the body, through sweating and evaporation, may serve as an indicator of the overall thermal stress to which the body is exposed [41, 35].

What is clear is that the sense of thermal comfort in any human being at any given moment depends on much more than physiological heat balance alone. Additionally, comfort in the urban environment undoubtedly involves behavioural, psychological and cultural aspects. The next section will consider different OTC indices, which may or may not be validated by these additional variables.

2.1.2 Outdoor thermal comfort indices and models

In the human body, receptors located within the skin record a sensation of relative warmth or cold. To regulate the body's temperature, messages are transmitted to effectors to dilate blood vessels and to initiate sweating. In the inverse case, our effectors may be instructed to constrict the blood vessels, which initiates shivering [35].

"The thermal sensation recorded by our skin receptors and the relative effectiveness of the associated physiological thermoregulatory control mechanisms influences our thermal satisfaction (or comfort)" [87]. However, apart from our thermoregulatory mechanisms, the thermal sensation is not perceived in the same way for all human beings. Actually, we vary depending on our personal expectations, the opportunities available to us to adapt our environment, and age and gender may also have a role [87]. Therefore, both **empirical** and **numerical** methods have been employed in an attempt to characterize thermal comfort aspects as well as to produce predictive models.

Based on the concepts derived from the outdoor human energy balance, researchers have attempted to derive the conditions that people find acceptable. Generally, these models have been designed to predict thermal comfort of people indoors, though these are also applied with little modification for conditions outside buildings. As with indoor thermal comfort literature, the studies concerning outdoor thermal comfort "reflects and embodies a cocktail of contrasting and often competing concepts" [26].

The systematic study of thermal comfort can be traced back to the early 1900s and is therefore one of the oldest areas of building science, specifically in heating and ventilating engineering [35]. The first studies on comfort were developed, based on empirical rules, by researchers Houghton and Yagloglou in the ASHRAE (American Society of Heating and Ventilating Engineers) Pittsburg research laboratories. Initially, these studies typically had a small number of subjects, and involved experiments measuring the energy exchange between human bodies (usually men) and the environment. Where the notion of thermal comfort was proposed, the scientist would obtain a verbal reaction, on a scale consisting of the levels 'hot', 'slightly warm', 'comfortable', 'uncomfortable', or 'cold' [46]. Houghton and Yagloglou defined the Effective Temperature (ET) scale to derive a thermal index using the concept of a standard environment [46]. This research was followed by numerous researchers who tried to vary the 'standard environment'. Victor and Aladar Olgyay introduced the term 'bioclimatic approach' and developed the Olgyay Bioclimatic Chart. "The chart shows how this relatively narrow comfort range may be extended by taking into account the effects of various design options on mean radiant temperature" [35]. It was communicated by the authors that this chart can only be used in the United States and under very specific conditions and limitations [82]. By the 1960s many investigations claimed to demonstrate that the thermal sensation responses concerning the environment showed consistent relationships to a number of measurable physiological mechanisms, excluding other influences such as social habits. Consequently, a number of indices of thermal comfort assessment were developed, such as the New Effective Temperature (ET*) scale and the Standard Effective Temperature (SET) using skin temperatures. A version of the SET adapted for outdoor use has also been developed (OUT-SET*) [102].

Due to non-uniformity of the environmental parameters, dissatisfaction with the microclimate is expressed with other indicators, indices of stress, and indices of local discomfort (consider the Heat Stress Indices (HIS) used in the ITS, described in the previous section). Other thermal comfort studies led to the derivation of other indices, such as the actual temperature (empirically based on an analogy between the real and the standard environment as a result of studies within the US military). The Wet Bulb Globe temperature (WBGT) was developed as an indicator that combines the effect of temperature, relative humidity, heat exchange by radiation, and solar radiation, and was used to determine the extent of exposure to heat conditions [123]. Along the same lines, other temperature indicators were introduced for 'extreme' climatic conditions. These include the Equatorial Comfort Index (ECI) [122], and the Tropical Summer Index (IST).

The work of Fanger [36] and his equation for the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) is perhaps the best-known outcome of laboratory-based comfort research [35]. Fanger demonstrated that a given set of environmental variables (dry bulb temperature, mean radiant temperature, vapour pressure, and relative wind speed) can be used to calculate the PMV of people (assuming a metabolic rate and clothing level), expressed on a seven-point thermal sensation scale ($-3 to +3$) [36]. Because of its significant breakthrough, the PMV formed the basis for the international standard ISO 7730 Moderate Thermal Environments (First published in 1984, revised in 1994 and updated most recently in 2005 with the amended title, ISO 7730:2005 *Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*).

The PMV equation relies on steady-state heat transfer, a condition that rarely occurs in everyday life, particularly in an outdoor environment [35]. A state of dynamic thermal equilibrium would best describe the situation of most people. Therefore, when calculating PMV at a particular time, there may be an error arising from the body's ever-changing thermal state. This error for a sample of individuals is likely to behave in a quasi-random manner, and suggests that the PMV may be of limited value as an index for assessing outdoor environments [35].

In recent years, a new index, the Physiologically Equivalent Temperature (PET) (name adapted from Physiological Equivalent Temperature), first proposed by Höppe [44], has been used extensively. Before describing the PET more in detail though, it is important to first distinguish the (i) **empirical** and (ii) **numerical** methods of OTC mentioned at the beginning of this section.

(i) Empirical methods

Empirical methods are based on the analysis of results from field surveys of pedestrians' environmental comfort. From knowledge gathered by a considerable amount of work on indoor environmental comfort, this method normally involves soliciting candidates to complete a questionnaire while simultaneously recording measurements of the local physical environment. "These surveys may be transverse, in which a broad cross section of respondents are solicited one time only, or longitudinal, in which a smaller set of respondents are requested to participate in the survey at regular intervals for an extended period of time" [87]. Generally, the format of the questionnaire and the physical measurements recorded depend on the field campaign objectives.

Initially, there were a number of systematic attempts to relate wind speed to thermal comfort. This approach stimulated further experimental studies to develop more rigorous wind comfort criteria, based on observation phenomena under different steady wind conditions [68, 86]. In recent years, the use of wind tunnels revealed more practical experimental approaches. However, these isolated mechanical wind comfort criteria are not sufficient to evaluate pedestrians' overall comfort [87].

In a first attempt to quantify relationships between relevant physical variables and their influence on human thermal comfort outdoors, Tacken (1989) conducted a transverse survey involving 210 people of varying age and gender situated in The Netherlands. For each test, participants were seated for 20 minutes before completing a questionnaire. During this time, the coincidental temperature ($t, ^{\circ}C$), wind speed ($v, m/s$), and solar irradiance ($I, W/m^2$) were recorded. These were dominant physical variables influencing human thermal comfort. From these results, the following multiple linear regression equation was derived to predict thermal satisfaction (TS):

$$TS = -0.329 + 0.215t - 0.600v + 0.002I \tag{2.4}$$

In the same case study in The Netherlands, Tacken also recommended that outdoor spaces designed for relaxation should be well oriented to the sun and that the mean wind speed should not exceed 2.5 m/s (though higher wind speeds may be tolerated if compensated for by relatively high solar irradiation, exceeding 700 Wm^{-2} [108]) to provide a comfortable wind climate for outdoor relaxation in urban areas.

Similar procedures were later pursued in different locations [69]. These new studies introduced conclusions such as the idea that thermal sensation is affected by the history of the pedestrians' exposure. This conclusion made researchers include new questionnaire sections in which they asked respondents to report their satisfaction immediately upon interrupting their prior activity [74]. Like previous surveys, coincidental environmental measurements, clothing, and prior activity were also recorded. Recent studies have included the correlation of the thermal sensation information gathered by these surveys with steady-state thermal comfort models (numerical methods). These have not always produced positive correlation, which was attributed to physiological factors that were not taken into account in the models (e.g. PMV) [76].

Regression models of thermal sensation were presented for a variety of European cities, as was a single regression model for the whole of Europe [75]. The use of these regression equations in conjunction with simplified models of short-wave and long-wave irradiance and wind speed made it possible to predict the spatial distribution of pedestrians' sensation [53]. Provided that the models used are valid, this is potentially a powerful tool [87].

In recent years, the use empirical methods to understand the thermal comfort of pedestrians has been extended into various cities in the world. In particular, these studies are essential in cities that already have extreme warm and humid conditions. As described above, these studies are being implemented through the use of thermal sensation surveys, correlated with collected weather data. Taking into consideration that the research outlined in this thesis takes the tropical city of Barranquilla, Colombia as a case study, it is important to describe the scientific research done on thermal sensation for this city. There has been only one attempt so far.

Villadiego, in the thesis *"Une Lecture de la forme urbaine et des microclimats: le cas de Barranquilla"* [119], focused on two fundamental aspects: (i) the relationship between urban form and the microclimate, and (ii) the relationship of these two aspects with the demographic-spatial dynamics of the city (specifically the social stratification). The thesis aimed to understand the thermal comfort of outdoor spaces, proposing the concept of a socio-climatic discrimination [119].

In the first part of the research, Villadiego developed the theoretical basis for the concept of urban form that includes the microclimatic and socio-economic aspects, and contextualised the investigation within the national setting. In the second part, the author analysed the demo-spatial evolution in the city by describing the moments in history that shaped its morphology, and identified elements that could potentially affect microclimatic changes. In the third part, the analysis of urban morphology, microclimate and thermal comfort in outdoor spaces of the city was approached via spatial analysis using the Local Climate Zone (LCZ) methodology [103]. At this stage, Villadiego produced a series of maps that allowed the theoretical analysis of the UHI in the city [119].

Subsequently, the perception of thermal comfort has been studied taking into account local areas and social stratification of the city. A series of surveys accompanied by measurement of microclimatic conditions were performed in five points within the city. The relationship between microclimatic conditions and perception was confirmed. Since the correlation was weak, it was concluded that, in fact, microclimatic data by itself does not demonstrate the thermal perception of pedestrians[119]. Additionally, the trend of socio-climatic discrimination was observed, given the overlap between the LCZ and classification by social stratification of the city.

In the end, the work led to an urban policy analysis, which established critical elements of urban design and planning to adapt the city to its climate. Consequently, this initial investigation of the OTC of Barranquilla opens multiple research opportunities, especially for the study and implementation of thermal comfort indices, such as PET [119].

Based on the findings and conclusion of the aforementioned research work, there is the opportunity to continue the work by including numerical methods for the study of the OTC in this tropical climate.

(ii) Numerical methods

Based on the concepts derived from the outdoor human energy balance, researchers have also attempted to derive numerical methods to understand the thermal conditions people find acceptable. As expressed in previous sections, heat is transferred between humans and their ambient environment principally by convection (C), radiation (R) and evaporation (E). For a given metabolic rate (M) and rate of work (W), the change in energy storage (S), from which we may derive the core temperature, is given as:

$$S = M - W - E - C - R \tag{2.5}$$

From this observation, and using results from "carefully controlled climate chamber experiments", Fanger [36] derived the equation to predict the mean vote of a large population of subjects and thus, the percentage of people that are thermally dissatisfied (PPD). However, it is only appropriate to use this model to predict thermal satisfaction when the human body is expected to be at thermal equilibrium with its environment, such as in indoor environments.

Clearly this is unlikely to be the case in outdoor spaces, in which pedestrians tend to move at a non-constant rate within a microclimate that is highly varied. Additionally, humans respond to the feedback of their perceived comfort, which possibly leads to actions to adapt their activity, walking route, and/or clothing. Given that we are typically outside for relatively short periods of time, a steady-state model would thus give a false result – and typically a pessimistic one [45].

An alternative to the approach adopted by Fanger [36] is to model the dynamic human thermoregulatory responses to environmental stimuli and thus to map, in some way, from sensation to satisfaction. This was the approach adopted by Arens and Bosselmann (1989) [6] in their seminal work on physical modelling techniques with which to adapt hourly rural climate data to the urban context.

The need for dynamic models for pedestrians' thermal comfort evaluation was further emphasized by [45]. This was proposed based on simulation of the time required to reach thermal equilibrium given a range of initial conditions (e.g. prior indoor temperature) and outdoor activities, and used a more sophisticated human thermoregulatory model [87].

A number of bio-meteorological indices have been developed to describe human thermal comfort level by linking local microclimatic conditions and human thermal sensation [27]. These models are based on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium, and they provide numerical solutions to the energy balance equations governing thermoregulation. One of the most widely used indices is the Physiological Equivalent Temperature (PET) [64].

2.1.3 Physiologically Equivalent Temperature (PET)

Like ET*, PET is a temperature dimension index measured in degrees Celsius (°C), making its interpretation comprehensible to people without a great deal of knowledge about meteorology, and giving designers a better feel for the thermal environment than an artificial scale such as the PMV.

PET is based on the Munich Energy-balance Model for Individuals (MEMI). The heat-balance model MEMI is based on the energy balance equation of the human body, and presents a basis for the thermo-physiologically relevant evaluation of the thermal component of climate. Similar in definition to ET* [38], but based on the MEMI, the PET was introduced by Höppe and Mayer [64, 44].

PET is defined as the air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions to be assessed [44]. It assumes that the metabolic rate is relatively low (80 W of light activity added to basic metabolism), and that the heat resistance of clothing is 0.9 clo, based on the typical insulation value of clothing [65].

"In the concrete case of the warm and sunny outdoor conditions, PET value would be 43° C. This means that an occupant of a room with an air temperature of 43° C reaches the same thermal state as in the warm and sunny outdoor conditions. If he were to move out of the direct solar irradiation into the shade this would result in a reduction of PET by 14 K to 29° C"[44]. Based on this explanation, Table 1 shows examples of physiological equivalent temperature (PET) values for different climate scenarios.

The assumption of constant values for clothing and activity in the calculation of PET was made deliberately, in order to define an index independent of individual behaviour. On the other hand, this does not necessarily restrict its applicability, since the variation of clothing and activity does not lead to significantly different PET values [44]. For example, with thicker clothing (higher heat resistance) and for the climate to be assessed, higher skin and core temperatures are calculated than for the reference clothing of 0.9 clo. *"At a constant PET of say*

20° C, a person clad with 0.9 clo (work metabolism 80 W) will reach a mean skin temperature of 33.7° C, a person carrying out the same activity and wearing a coat (2.0 clo), however, will have a skin temperature of 34.7° C." [44]

Although there are other steady state models that serve as analytical tools to assess human thermal responses to the local thermal environment (such as PMV, ITS, fuzzy-PMV, OUT-SET and COMFA), PET is particularly suitable for outdoor thermal comfort analysis [27] [59] and is already included in the VDI (German Association of Engineers) guideline 3787 for human bio-meteorological evaluation of climates in urban and regional planning.

PET can be calculated by several computational tools such as ENVI-met, SOLWEIG, COMFA+, the OTC model, and the RayMan model. The latter of these was developed by Matzarakis et al. [63] and stands for 'radiation on the human body'. It is an urban climate analysis tool that has been used in urban built-up areas with complex shading patterns, and it has generated accurate predictions of thermal environments [59].

"The aim of the RayMan model is to calculate radiation flux densities, sunshine duration, shadow spaces and thermo-physiologically relevant assessment indices using only a limited number of meteorological and other input data. A comparison between measured and simulated values for global radiation and mean radiant temperature shows that the simulated data closely resemble measured data" [63].

The climate data needed as input parameters to calculate PET in the RayMan model are: air temperature (Ta), relative humidity (RH), wind speed (v), human clothing and activity, mean radiant temperature (Tmrt), and either the observed value of global radiation (Gr), or the date, time, location, and cloud cover (Cd). In this way, the evaluation of PET using the RayMan model is very flexible and practical. RayMan has been used extensively to calculate PET in different climatic conditions around the world, including tropical climates [60, 71, 116].

The RayMan model is also a simulation tool that predicts long-term PET for particular outdoor environments. Although people's subjective perceptions and responses to the urban environment are various and not yet well understood, simulation and scenario-testing tools are always of particular importance in an assessment framework because they provide a platform for the integration of knowledge from various perspectives, and allow comparisons of various design scenarios [27]. These prediction tools can support research on how changes in design details influence outdoor thermal comfort, can provide an understanding of climatic conditions, and can provide assessment of human thermal comfort [27].

2.2 Urban climate

Climate is the pattern of variation in precipitation, temperature, humidity, sunshine, wind velocity, and other measures of the weather that occur in a given region over long periods of time. Urban climate refers to climatic conditions in an urban area that differs from the climate of its rural surroundings, and is attributed to urban settlements. Different climatic aspects such as climate conditions, seasonal variations, and climate change bring increasing demands on the planning and design of urban developments.

A city absorbs and retains significantly more heat than rural areas [79], and is thus known as an Urban Heat Island (UHI). The UHI is one of the most important manifestations of the urban climate, and has been the subject of much research since it was first described for the city of London by Luke Howard in 1818. The UHI plays an important role in climate research, as urban heating contributes in some measures to large-scale temperature trends [35]. As suggested by the UNEP, cities need to be able to adapt to the future urban microclimate, which not only implies an increase of energy consumption by buildings, but also a direct effect on human climate comfort in the urban areas. However, to be able to understand the UHI and how the urban elements contribute to the creation of this phenomena, it is important to recognize how the urban climate is studied by researchers.

2.2.1 Elements of urban climate

There is a two-layer classification of thermal modification in an urban context that represent the components of the urban atmosphere. These are the Urban Boundary layer (UBL) and the Urban Canopy Layer (UCL) [79] (Figure 2.4).

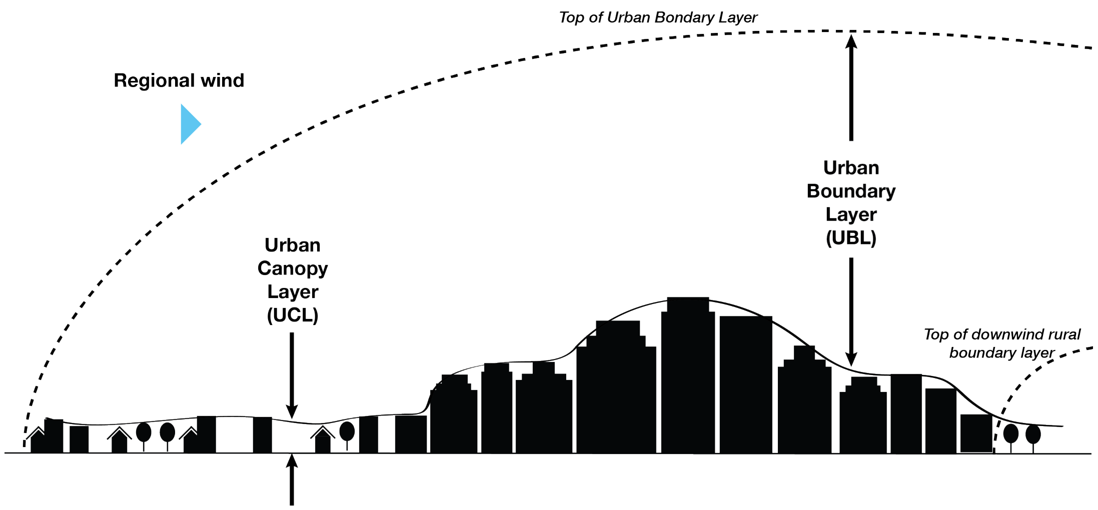


Figure 2.4 – *Schematic section of the urban atmosphere Illustrating the two-layer classification of thermal modification. Based on [79]*

The UBL refers to that portion of the planetary boundary layer whose characteristics are affected by the presence of an urban area at its lower boundary. The UCL is described as the air contained between the urban roughness elements (mainly buildings), where its climate is dominated by the nature of the immediate surroundings (especially site materials and geometry). The UBL may be further divided into a number of sub-layers, with distinctions fundamental to urban climate.

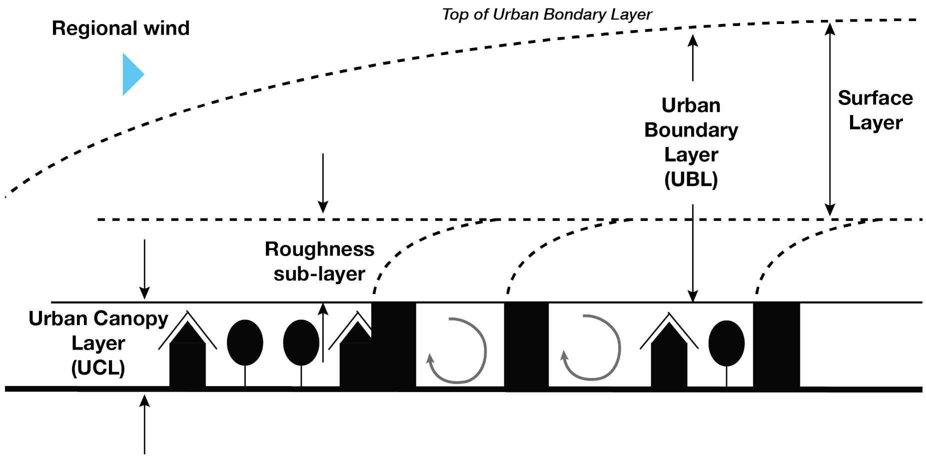


Figure 2.5 – *Schematic section of the urban atmosphere Illustrating the two-layer classification of thermal modification, and the distincyion between the homogeneous surface layer above the city and the hetereogeneous urban canopyThe roughness sub-layer is a transition zone below the surface layer. Based on [35]*

From the upwind (windward) edge of the city, the UBL grows in height as air passes over the built-up territory. The upper part of the UBL is considered to be the 'mixed layer' as shown in Figure 2.5. Within this layer, the atmosphere is influenced by the presence of the urban surface, but is not fully adapted to it. The properties of this layer are not affected by individual urban elements such as single buildings and streets. Rather, they are conditioned by the texture of the urban surface as a whole. This is an extremely important feature, since it is only within this layer that the vertical exchange of energy between the urban surface and the atmosphere is homogeneous, allowing turbulent fluxes of heat (and pollutants) to be measured at any point above the surface [35]. For this reason, the surface layer is also known as a constant flux layer. Moreover, this layer is not positioned immediately above the roofs of buildings. Below this level is a highly variable roughness sub-layer, in which the air flow consists of interacting wakes and plumes produced by individual urban elements. Furthermore, under the roughness sub-layer, and at the very lowest part of the urban atmosphere, is the UCL. This layer extends from ground level to the height of buildings, trees, and other objects as show in Figure 2.5.

Due to the heterogeneous characteristic of the UCL, a unique microclimate is established within any given urban space, with air temperature, wind flow, radiation balance, and other climatic indicators being determined by the physical nature of the immediate surroundings as well as by the urban and regional environments [35].

In addition to the layers, the urban atmosphere can also be represented by three main scales [80] shown in Figure 2.6. The (a) meso-scale is the urban region or the city as a whole, the (b) local scale consists of a single urban terrain zone or land use zone, and the (c) micro-scale is represented mainly as the street canyons. This last scale is where the urban microclimate is located. The microclimate of a city is defined as the climate that prevails at the micro-scale level, and it differs from the surrounding area [35].

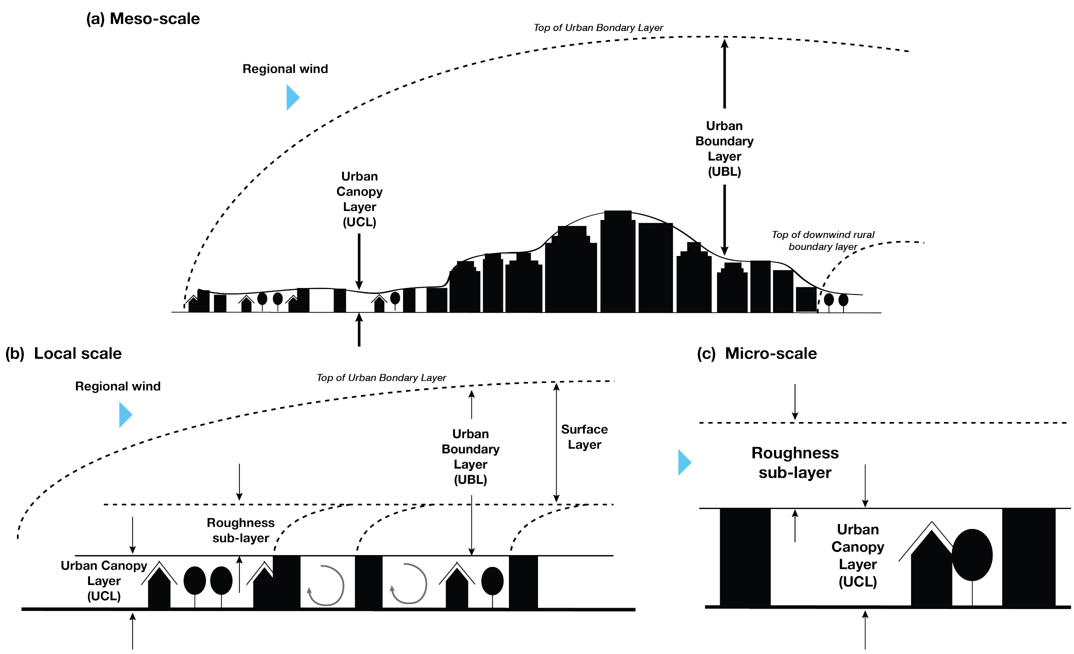


Figure 2.6 – *Scales of urban climate. Based on [80]*

The local scale, also known as the urban scale, is of primary interest in the study of urban climatology. However, the micro-scale refers to the smallest realm for architecture and urban design, where individual structures and trees generate shadows and alter the wind flow, and built elements modify the reflection of sunlight and the radiant temperatures – all the features to which people are most directly exposed.

2.2.2 Urban Heat Island (UHI)

The world is facing the rapid progess of climate change, and cities are seen not only as potential sites of climate vulnerability but also as the main contributor [18]. In cities, reality shows that the impacts of climate change are greater than those at a global scale, since cities absorb and retain significantly more heat than rural areas [105, 79], which is also known as the Urban Heat Island (UHI).

The UHI is one of the most important manifestations of the urban climate, and has been the subject of much research since it was first described. Its intensity varies significantly on a diurnal and seasonal basis (Figure 2.7), and the phenomenon is known to be a complex one [35]. The UHI is defined as the warmth of cities in contrast to their surroundings ($\Delta Tu-r$). Cities clearly have higher temperatures, with maximum values recorded at or near the densest part of urban areas. There are three types of UHI: the Boundary Layer Heat Island (BLHI), the Canopy Layer Heat Island (CLHI), and the Surface Heat Island (SHI) [79, 80, 120]. The first two types are observed at an atmosphere level and the last type at a surface level. There is a clear relationship between the intensity of the UHI and the various factors that contribute to its formation [35]. Two of the major factors of the UHI are: the anthropogenic heat in cities illustrated in Figure 2.2, and the configuration and materials of urban elements such as buildings. The urban elements affecting the UHI are: the building density, impermeable surfaces, vegetation, and urban material. The UHI is not necessarily negative, especially in cold climates. However, for cities in warm climates, there are multiple benefits from a reduction in air temperatures.

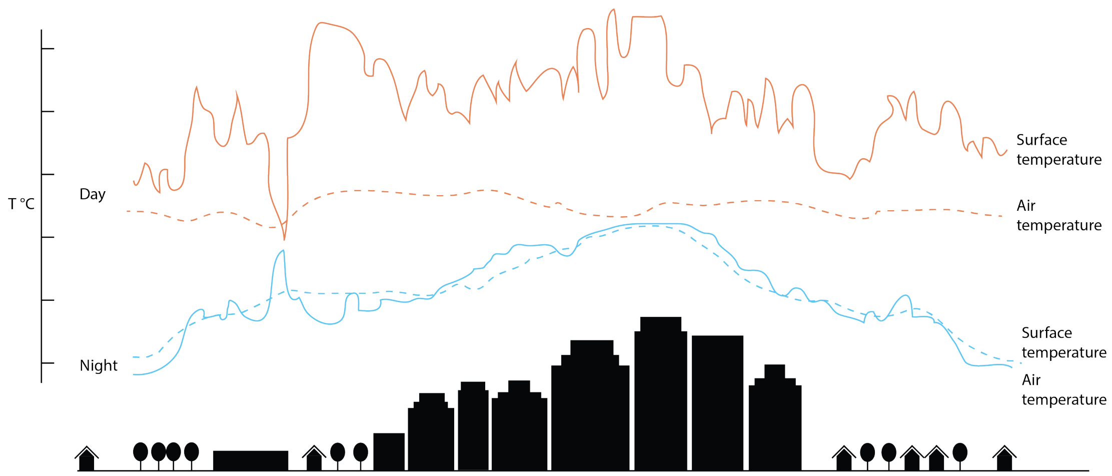


Figure 2.7 – *Example of schematic section of the UHI in Vancouver BC. Based on [79][121]*

In the context of global warming and climate change, UHI plays an important role as urban heating contributes in some measure to large-scale temperature trends [35]. As suggested by the UNEP, in addition to the need to implement mitigation strategies, cities need to be able to adapt to the future urban microclimate, which not only implies an increase of energy consumption by buildings, but also implies a direct effect on human thermal comfort in the urban areas.

The outdoor thermal environment is affected by the urban climate, which is mainly affected by the built environment in terms of: anthropogenic heat [48], ground surface covering [59], evaporation and evapotranspiration of plants [88], and shading by trees and man-made objects. The outdoor thermal comfort is generally studied on the urban micro-scale level, which is affected by the CLHI. As shade can block incident solar radiation, some studies have discussed the shading effect on thermal environments. For example, street orientation and the height/width (H/W) ratio have been measured to assess the shading levels in some studies [34]. In the context of urban planning, how the outdoor thermal environment influences thermal sensations of people and changes their behaviour (use of outdoor spaces) is of great interest for designers of urban spaces.

The proportions of the space, the thermal and optical qualities of its finish materials, and the use of landscape vegetation are all design parameters that modify climate at a UCL and a micro-scale level. Because urban design may have localized impacts such as these on outdoor thermal comfort and building energy loads, the microclimate of urban spaces is rightfully considered an architectural issue [35].

Research gap 1a: *Lack of application of urban climatology research in urban planning.*

2.3 Climate-sensitive design

The aim of *climate-sensitive design* is to consider the fundamental elements of climate (precipitation, sun, wind, darkness, light, cold, and heat) in the design process in order to create environments that mainly enhance human thermal comfort and decrease the energy consumption in cities.

2.3.1 Microclimatic aspects

The knowledge of how the urban microclimate affects the performance of a city is increasing. Accomplishing this is not easy, since trying to respond to different criteria of urban microclimate design might lead to contradictory requirements. However, microclimate has an effect on a very broad range of issues encompassed in the field of urban planning and design, and therefore, these problems need to be explored to benefit from microclimate studies. The different effects of urban microclimate in urban planning and design can be divided into two groups: the effect of microclimate on the performance of buildings, especially in respect to energy conservation; and the effect of microclimate on human activity, especially pedestrian activity, in the spaces between buildings [35].

With understanding of the urban microclimate and its effects on urban planning and design, the application of different strategies to control solar access and airflow in urban areas can be explored to enhance pedestrian thermal comfort. Solar access or solar exposure studies deal with the degree of exposure to solar radiation, which is one of the main controls of microclimate conditions. The strategies derived from the solar access studies are divided into two urban objectives: the solar access for pedestrians (open public spaces), and the solar access for buildings. These days, there are simple methods and tools to measure sun path movements to estimate the solar exposure. The most well known is the stereographic sun-path diagram, which represents annual changes in the path of the sun through the sky in a single 2D diagram. These diagrams provide summaries of solar position that the designer can refer to when considering shading requirements and design options. Based on solar access analysis, researchers and urban planners have arrived at methods to facilitate the design of buildings that respond to solar exposure. One example is the *solar envelope* introduced by Ralph L. Knowles [55] as a framework for architecture and urban design to provide solar access needs according to building geometry, and to support solar energy for future developments. The method is based on the *solar rights*, which is an essential tool for passive solar heating in in buildings [35].

The strategies to control airflow require additional research and computational effort. However, there is existing knowledge on directions of prevailing winds and speeds (documented in wind rose diagrams), and of how wind may react to certain urban obstacles. In this way, it is important to identify the patterns of airflow in build-up areas according to different scales. At each level of scale, physical man-made and natural features have distinct modifying effects on wind speed, direction, and intensity of turbulence. Therefore, there are three scales to study airflow patterns: wind near the ground, wind in the UCL, and wind in the UBL. The first two directly affect the microscale level of the city where thermal comfort is measured. For the wind near the ground, wind flows horizontally (on average). Any changes from level ground (urban elements) will obstruct the flow and modify the pattern. A build-up area with isolated and widely spaced bluff-body structures will be characterized by this type of flow pattern (Obstruction by an isolated obstacle, Bluff-body). Other types of flow in this scale correspond to those affected by building geometries (the windward face of a building or the pressure difference of the face regions of a building – windward and leeward) [35]. Concerning the UCL, wind speed and directions are extremely variable. Observations show a sharp drop of the average wind speed below roof level, but microscale changes in geometry may result in localized areas with high wind speed. In canyon wind flow, three distinct wind regimes can be found according to the spaces between buildings as shown in Figure 2.8 [35]. These different explorations applied to urban spaces are limited to the understanding of how to control airflow, and can be applied only to well-defined linear spaces.

Solar access and air flow are two of the main fields dealing with the understanding of the components for climate-sensitive design. An additional topic of its own is vegetation. Urban vegetation is credited with providing numerous benefits, such as mitigating the UHI, improving air quality, and enhancing human activity. However, there is ongoing discussion regarding the veracity of benefits for different types of vegetation (mainly trees) that actually lower urban climate temperatures, and those which create the opposite effect based on porosity and shading [16]. Sun, wind, and vegetation are the three main aspects taken into consideration when exploring climate-sensitive urban strategies.

2.3.2 Climate-sensitive urban strategies

With the aforementioned knowledge, there is an increasing understanding of how to design in accordance with the environment and the climate. This approach has been addressed as climate-sensitive design, as introduced at the beginning of this section. Climate-sensitive design is applied not only to benefit from the existing urban microclimate, but also to mitigate its already stressed condition, and decrease the negative effects through design and planning options. However, there are vast gaps in our knowledge and understanding of climate-sensitive

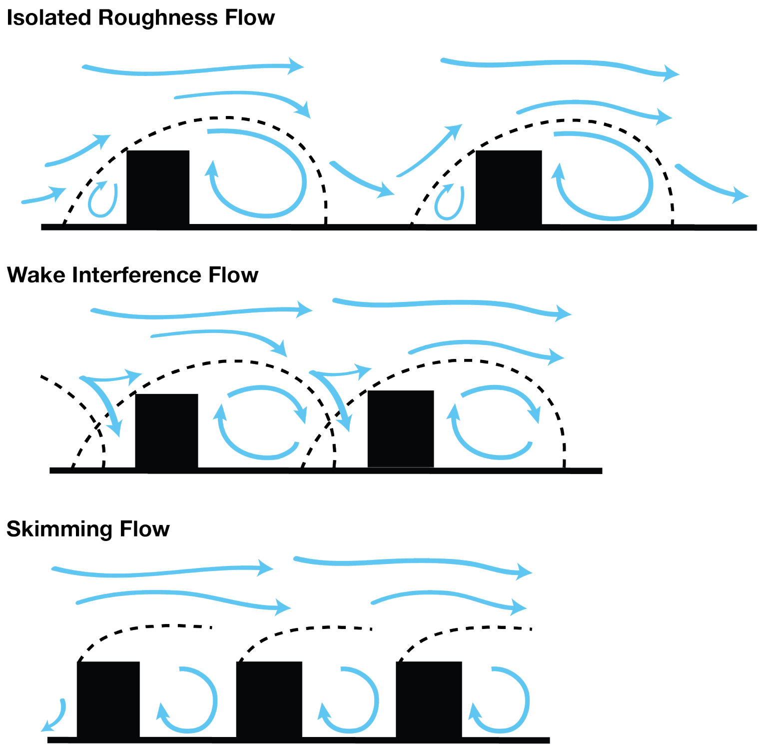


Figure 2.8 – *Flow regimes associated with different geometries. Based on [81]*

urban design, particularly in the tropics [34]. Tropical urbanization is going to take overwhelming attention in the near future due to urban population growth. Increasing land prices, fuelled by very high urban population densities, will continue to exert pressure on the urban ecosystem, and the resulting microclimate changes in tropical areas will be large. In an already stressed climate, the thermal comfort implications of such changes are very serious. At the same time, it is also a challenge to create modern 'indigenous' architecture of the region, using its altered climate as a starting point [34]. A discussion of the thermal comfort requirements in the urban tropics will quickly illuminate the need for solar access control, and the facilitation of air movement outdoors.

Even though we can explore different strategies for urban forms based on microclimate studies, it is not easy to make the appropriate decisions concerning solar exposure and airflow access at each of several levels in the design process. Also, it is important to determine how the different analysis and simulation methods can be combined in a systematic way, and how they can be integrated to generate different solutions according to microclimate criteria, when the potential contradictions between these criteria are considered. Although there are few comprehensive models that can predict pedestrian comfort in public open spaces [35], recent advances in urban microclimatology and biometeorology that combine experimental and computational techniques make the evaluation of these aspects more accessible and realistic.

There are new tools that allow the computational analysis and simulation of different realistic situations based on microclimate conditions.

Strategies that planners and designers can implement range from architectural design to urban settlement planning. On a micro-scale level, previously defined in Section 2.2, these strategies are based on urban microclimatic elements (sun, wind, and vegetation) and vary depending on location. In tropical cities, design guidelines such as building colours (for sun reflection), trees that generate shadows (such as palms), and the control of wind tunnels are fundamental. One example of a method to enhance wind circulation at street level is shown in Figure 2.9.

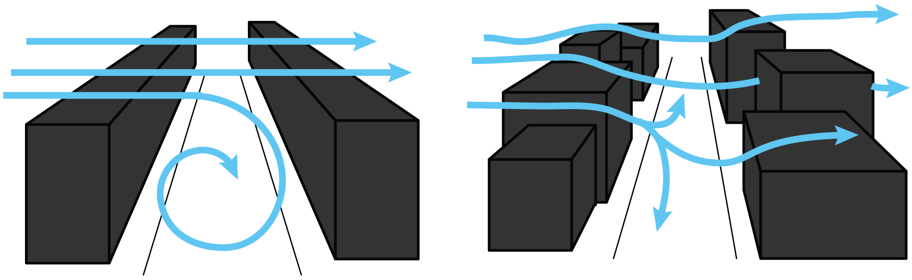


Figure 2.9 – *Wind circulation at street level. Based on [21]*

Although knowledge of how to design with our surrounding climate in mind is improving, the problem still relies on the constant use of this concept to refer to any attempt at environmental design. Therefore, this concept requires a more scientific approach, which implies a method of inquiry that must be based on empirical and measurable evidence subject to specific principles of reasoning. This step can be initiated beginning from the knowledge already gathered by urban climatologists, as discussed in Section 2.2. However, the link between this field of study and urban planners and designers still needs to be enforced. This gap can be seen clearly when planners apply design strategies without any information about the site, which usually ignores the required knowledge of the existing situation, and leads to failed implementations. An example is the construction of shading elements around tropical cities without necessary knowledge of where the critical areas are located. This problem can be addressed with data-driven design, a concept explored later in this chapter, in Section 2.6.

Research gap 1b: *Not using scientific knowledge to derive design strategies.*

2.4 The city and its citizens

A city is a large and permanent human settlement [56]. Cities are generally seen as systems, or in recent years, as complex systems [10] that combine networks, interactions, and physical forms. These days, a city can be extended to suburbs and exurbs, which, as a whole, are described as metropolitan areas and urban areas. This introduces numerous business commuters travelling to urban centres for employment. In 1991, Saskia Sassen [93] coined the term *global city*, as a city of enormous power or influence due to its position as a prominent centre of trade, banking, finance, innovation, and markets. In contrast, a *megacity* refers to any city of enormous size. *Global cities*, according to Sassen, have more in common with each other than with other cities in their host nations.

There is a ongoing debate about whether technology and communications are making cities obsolete, or reinforcing the importance of global cities [22]. Knowledge-based (knowledge-driven) development of cities, innovation network globalization, and broadband technology are the driving forces of a new city planning paradigm. This new paradigm is aimed towards *cities* that use technology and communication to create more efficient settlements in regards to innovation, environment, energy, governance, and delivery of services to the citizen.

Robert G. Hollands, in his article *'Will the real smart city stand up?'* [43] raises the issue of properly defining the concept of *smart cities*, due to the extent of technologies that have been developed and implemented under the *smart city* label. Based on this critique, Deakin and Al Wear defined the *smart cities* concept by the use of four characteristics: (a) the application of a wide range of electronic and digital technologies to communities and cities; (b) The use of Information and Communications Technology (ICT) to transform life and working environments within the region; (c) the embedding of such ICTs in government systems; and (d) the territorialisation of practices that bring ICTs and people together to enhance the innovation and knowledge that they offer [30]. Later on, in the book *'From Intelligent to Smart Cities'* Deakin and Al Wear defined the smart city as one that utilises ICT to meet the demands of the market (the citizens of the city), and that community involvement in the process is necessary for a smart city [31]. A *smart city* would thus be a city that not only possesses ICT technology in particular areas, but has also implemented this technology in a manner that positively affects the local community.

2.4.1 Participatory planning

Urban planning is a technical and political process concerned with the use of land, protection and use of the environment, public welfare, and the design of the urban environment. This includes air, water, and the infrastructure passing into and out of urban areas such as transportation, communications, and distribution networks [109]. Urban planners in the field are concerned with research and analysis, strategic thinking, architecture, urban design, public consultation, policy recommendations, implementation, and management [109]. Urban planning takes many forms, and it can share perspectives and practices with urban design. *Urban design* is the process of designing and shaping cities, towns and villages. In contrast to architecture, which focuses on the design of individual buildings, urban design deals with the larger scale of groups of buildings, streets and public spaces, whole neighbourhoods and districts, and entire cities, with the goal of making urban areas functional, attractive, and sustainable [8].

There are different styles and modes of urban governance, which refers to how cities and stakeholders in a city manage their collective affairs. These can be referred to as different kinds of urban mindsets, or rationalities.

The Market, or *market urbanism*, is one such rationality for governing the city, which might be seen as a dominant one. The value relies on the liberal (or Neo-Liberal) preservation of free choice. The Market is comprised of rational actors who seek to advance their own material or ideal interests. The first reason that regulation in city planning is a poor tool for determining urban form comes from Friedrich Hayek. He identified the calculation problem inherent in central planning: the information necessary to coordinate markets (including land use markets) is held by individuals with particular knowledge of time and place. Even assuming that urban planners are benevolent and seek to provide the best outcomes for their communities, they could never compile the knowledge necessary to determine what those outcomes are. Jane Jacobs [51] identified the same problem in city planning that Hayek found in market planning because cities and markets are both emergent systems that coordinate human activity. She even coined the term locality knowledge, seemingly unaware of his writings on local knowledge. However, the city governance that is given over to rationalities of the market does not always produce good collective outcomes. This can bring uneven development (haves and have nots), shortfalls in collective services (roads, sanitation, etc,), and because of this the State is needed in such a system.

Rational planning and Rational models of urban governance started to emerge beginning in the 1800s. These were inspired by the ideas of the Enlightenment, and its investment in knowledge and order. There was an imperative to intervene in cities to create more rationally ordered spaces – because of bad sanitation and crowding, and poor circulation. The view was that this would contribute to the better social, economic, and political functioning of cities. The rational planning model is used in planning and designing neighbourhoods, cities, and regions. It has been central to the development of modern urban planning and transportation planning. The model has many limitations, particularly the lack of guidance on the involvement of stakeholders and the community affected by planning. For that reason, other models of planning, such as collaborative planning, are now also widely used [109].

These emergent models of rational governance depended upon a new kind of systematic, scientifically acquired knowledge of the city. A good example is the mapping of the social and economic conditions of the residents of London in the late nineteenth century by Charles Booth [12]. Booth was a Social reformer, and his two-volume book gave a detailed account of where the poor and the rich were living, with the Poverty Maps of London. This is often considered to be the first social survey and seeded the Social Survey Movement, which sought to provide social scientific studies in the service of social reform, or as we might call it today, policy development.

It is important to see a difference between this kind of relationship of science and governance to the kind of relationship we might see with earlier examples of the rational city. An example is the urban planning of Haussman with respect to the rational ordering of Paris, between 1853 and 1870. It included the demolition of crowded and unhealthy medieval neighbourhoods, the building of wide avenues, parks, and squares, the annexation of the suburbs surrounding Paris, and the construction of new sewers, fountains, and aqueducts [20].

The 20th Century version of rational urbanism shapes the cities by regulating the excesses of free, market-driven urban development and developing zoning laws for functions (uses, densities) and planning systems such as sanitation, environment, transportation, etc. City planners and city designers are seen as neutral experts presenting and acting on facts for the development and management of the city, facts often reshaped into plans (regulatory principles). Plans operate as a blueprint, or as guidelines to be implemented. "The planner is ideally and appropriately a rational man operating at arm's length from the messy world of politics." [49]

Participatory planning grew out of acknowledgement that using only scientific facts was not enough to create good city development. Many things come into play to allow scientific facts to do their work as components of planning and design. This approach can be seen as the combination of deliberation and participation. *Participatory planning* methods aim to find ways of gathering information about, with, and by local people, and their conditions and livelihoods [66]. In the 1970s and early 1980s these methodologies were concerned primarily with gathering accurate and detailed information efficiently. At that time, the emphasis was on the word 'rapid' for the purposes of 'appraisal' or 'diagnosis' of local problems and priorities, and most of the analyses and actions were controlled by outside researchers and development agents. As experiences and insights grew, it became evident that local people, who had previously been viewed as passive subjects, clients, or beneficiaries, had much to contribute to the research and development process. As these approaches were adapted and modified further, the depth and validity of local people's experiences and knowledge became clear [66].

In recent years, in a digital era, *participatory planning* has taken the next step into information cities. With the use of the Internet of Things (further described in Section 2.6) and smartphone technology, city planners have been able to gather massive amounts of data from citizens more efficiently, and have connected this to spatial information.

2.4.2 Crowdsourcing

Open Innovation (OI) is the flow of ideas into and out of an organization. *Crowdsourcing* is one type of OI [98]. The term was coined by Jeff Howe in a famous Wired story, *'The Rise of*

Crowdsourcing' [47], and is simply defined as "the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call. The crucial prerequisite is the use of the open call format and the large network of potential laborers" [47]. In 2008, Daren C. Brabham used the term crowdsourcing for the first time in a scientific publication [13]. Later in 2013, he wrote the book *'Crowdsourcing'* and defined the concept as an "online, distributed problem-solving and production model." [14].

The term *crowdsourcing* has gained much popularity and is traditionally defined as obtaining data or information by enlisting the services of a large number of people. It now often refers to obtaining information from a range of individual devices, such as smartphones, and this information is typically sent via the internet. Data are often routinely collected, and it can be used simply by harvesting and/or re-purposing it. Many other scientific disciplines are using this information, but less so in atmospheric science dealing with urban climatology studies, described in Section 2.1 and 2.2. Some initial efforts have been applied for the urban climate field, and these examples will be described in Section 2.6.

Crowdsourcing is a powerful resource for innovators [98]. Using citizens as subjects of this data collection process is a powerful approach for supporting decision-making in city planning. Moreover, these technological advances can also bring the next generation of participatory planning: *citizen-design science*.

2.4.3 Citizen science

Citizen science, also known as crowd science or crowdsourced science, is the scientific research conducted, entirely or in part, by non-professional scientists. Citizen science is sometimes described as "public participation in scientific research" [42].

Citizen science recruits members of the public to make and record observations, such as counting, watching, collecting, and recording different natural phenomena. The large numbers of volunteers who participate in such projects collect valuable research data, which results in an enormous body of scientific data on a vast geographic scale. In return, such projects aim to increase participants' connections to science, place, and nature, while supporting science advances and environmental research [32]. In recent years, the use of *crowdsourcing* methods has been implemented in citizen science. Its focus on harnessing the impact of *crowdsourcing* for scientific and educational efforts is applicable to a wide range of fields [32], especially those that touch on the importance of massive collaboration aimed at understanding complex systems such as cities.

One example of citizen science is the Galaxi Zoo. This project was developed by a consortium of different universities around the world and founded by Prof. Kevin Schawinski from ETH Zurich. The project aimed to provide visual morphological classifications for approximately one million galaxies, extracted from the Sloan Digital Sky Survey (SDSS). This was achieved by inviting the general public to visually inspect and classify these galaxies via the internet, making this initiative one of the world's best-known online citizen science project (www.galaxyzoo.org). The success of the project evolved into the creation of The Zooniverse, hosting project using the same technique across many research areas (www.zooniverse.org).

Citizen-design science is the combination of Citizen Science and Design Science. Design science was first introduced in 1963 by R. Buckminster Fuller who defined it as a systematic form of designing [17]. Citizen-design science is the adaptation of both concepts for the design of urban systems (ref).

2.5 The global context and external drivers

There are various global events and conditions that affect the development of cities, especially in respect to the change in urban climate. Two of the main aspects that influence how cities are currently developing and indirectly affect the OTC are global warming, and urban population growth. On one hand, the climate change topic has finally transferred from scientist to policy makers, which has made the Conference of Parties of 2015 (COP 21) essential for the commitment of most countries to transform their national policies to reach promised targets. But these recent events are only the start. Scientists and policy makers (and in this case city planners and designers) still have to understand and develop knowledge, and implement mitigation and adaptation measures. Global population growth adds a layer of complexity, and increases the challenge.

2.5.1 Global warming

Global warming and climate change are similar terms frequently employed to refer to the recent and ongoing increase in the average temperature near Earth's surface. Specifically, global warming is primarily caused by the increase of greenhouse gases concentrations in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change [115]. Climate change refers to any significant change in the measures of climate, such as major changes in temperature, precipitation, or wind patterns, lasting for an extended period of time (decades or longer) [115].

The late 1980s was the first time that the environment became a big story, filling the front pages of newspapers. The greenhouse effect and global warming had emerged from academia and government offices, and moved into the public eye. It was the beginning of international leaders calling for global action, activity that was obscured during the 1980s and before [96]. The global average (land and ocean) surface temperature shows a warming of 0.85 [0.65 to 1.06] °C in the period 1880 to 2012 [83].

According to the United States National and Atmospheric Administration (NOAA), 2015 was not only the warmest year on record, it broke the record by the largest margin by which the record has been broken. From December 2015 to February 2016, the average temperature for the globe was above the 20th century average according to scientists from NOAA [77]. This was the highest temperature for December to February in the 1880–2016 record. The UNFCCC have adopted a range of policies designed to reduce greenhouse gas emissions and to assist in adaptation to global warming [114]. After the COP21, parties to the UNFCCC have agreed that the reduction of emissions is necessary, and that future global warming should be limited to less than 2.0°C relative to the pre-industrial level [114].

The two main items frequently added to the climate change agenda are mitigation and adaptation. When it comes to cities, these two aspects are best explored and addressed by two main fields: energy for mitigation, and urban climate for adaptation, both equally important [107]. Adaptation to climate change may be planned in reaction to anticipated climate change effects [99]. Planned adaptation is already occurring on a limited basis. The barriers, limits, and costs of future adaptation are not fully understood [107].

A concept related to adaptation is adaptive capacity, which is "the ability of a system (human, natural or managed) to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with consequences" [50]. Unmitigated climate change (i.e., future climate change without efforts to limit greenhouse gas emissions) would, in the long term, be likely to exceed the capacity of natural, managed, and human systems to adapt [50]. In order to understand how a city should adapt to the coming climate, we need to understand first the current situation and how it is affecting its citizens.

2.5.2 Urbanization and population growth

From 1800 to 2012, the global population grew from 1 billion to 7 billion, and it is expected to keep growing. Estimates have placed the total population at 8.4 billion by mid-2030, and 9.6 billion by mid-2050 [19]. According to the United Nations population statistics, between 1990 and 2010, the increase of the global population was highest in India (350 million) and China (196 million) [70].

As global population increases, cities have also been growing, leading to an increase in urbanization. People tend to move into cities for various reasons, for instance, economic opportunities. The **urban population** in 2014 accounted for 54% of the total global population, up from 34% in 1960, and it continues to grow [113]. The urban population growth, in absolute numbers, is concentrated in the less developed regions of the world. It is estimated that by 2017 the majority of the global population will be living in urban areas. The global urban population is expected to grow approximately 1.84% per year between 2015 and 2020, 1.63% per year between 2020 and 2025, and 1.44% per year between 2025 and 2030 [113].

Based on these trends, urbanization in tropical cities will be of overwhelming proportions in the near future. In an already stressed climate, thermal comfort implications of such changes are very serious. A discussion of the thermal comfort requirements in the urban tropics will quickly illuminate the need for solar access control, and the facilitation of air movement outdoors [34], as design adaptation measures of climate change.

2.6 Information City and Outdoor Thermal Comfort (OTC)

The concept of *Information Architecture* and *Information City* explores the main dynamics of *cities* in a digital era (digital city), previously described in Section 2.4. Different fields, such as urban economics and urban transportation, are currently dealing with the understanding and development of these complex systems. Concerning urban climatology, researchers have been using new tools and technologies to harvest data and information, and to use these to arrive at insightful knowledge. However, there are still big steps to be taken.

Information Architecture is defined as the necessary framework to understand architecture, urban systems, and territories in the knowledge society [95]. With respect to urban design, the realm of data is expanding quickly, as is the amount of derived information that can be used to build design knowledge. The transformation from **data** to **information** and **knowledge** is one of the most important activities in every society [95], and those three are the elements that structure the *Information Architecture* concept. *Information City* describes the extension of information architecture to the urban scale. In analogy to information architecture, information city has two main meanings: (1) making the invisible visible on the scale of a city, and thus helping to understand the function of interactions between components of the city, and aid the design of new cities; (2) information city might become a metaphor for the structuring and ordering of vast amounts of data, created increasingly by a city's inhabitants and its infrastructure [95].

The elements used in *Information City* for the understanding of city systems derived from the new digital era. Sensor technology, the Internet of Things, data processing, and simulation techniques are a few of these. These tools and methods can support decision-making in city planning through data-driven design, big-data informed urban design, cognitive design computing, and citizen-design science. In urban climatology studies, these methods could be highly beneficial for the exploration and development of adaptation measures in cities with regards to climate change and urbanization, as mentioned in Section 2.5.

2.6.1 *Data* collection

In the context of the city, we refer to data as "the smallest entities of information, as values given to objects, expressions, functions or properties" [95]. In urban climatology, the data collected comes from current or historic environmental conditions derived from weather variables such as temperature, humidity, pressure, etc. The data collected are sets of values of qualitative and quantitative weather variables. The acquisition of these sets of data is an essential aspect of urban climatology. Since the beginning of urban climatology studies, the understanding and prediction of urban climate conditions derived from the collected data. Traditionally, the collection of weather variables have been done with the use of stationary and heavily local weather stations. By definition, a weather station is a facility with instruments and equipment for measuring atmospheric conditions to provide information for weather forecasts, and to study the weather and climate. In cities, these installations are generally located in airports or buildings of governmental institutions, such as research centres.

With the upcoming interest in urban climate research due to global climate change and the effect on the microclimates around the cities, the collection of data has arrived at a new technological era. Advances in technology, communications, and miniaturization of electronics are changing the measurement paradigm. This enables innovation, increased reliability, and lower cost. These days, researchers can benefit from the use of portable mini weather stations to explore weather conditions in different parts of cities. Measurement networks have been installed in major cities and connected to online software for monitoring the collected data. Permanent installations, as opposed to field campaigns, operate over a range of spatial scales in different cities. Examples such as the Oklahoma City Micronet project [9], the Helsinki Testbed [52], or the Basel Urban Boundary Layer Experiment (BUBBLE) [90], have benefited from these measurement networks for massive data collection of weather variables. A properly designed network will allow us to deploy hundreds if not thousands of sensors in the form of weather stations. The advances in weather stations and sensor technologies have enabled a spatial resolution in the coverage area that would be impossible with traditional weather stations. In this context, a new generation of high-resolution urban meteorological networks is emerging [25, 23, 24].

Yet, there are many considerations to take into account when implementing measurement networks at such scales. Some of the issues that this project may encounter relate to cost, battery power, and stability in the system communications (wire connections). Therefore, urban climatology can benefit from the new technological approaches from *smart cities*. In this context, use of the Internet of Things is a game-changing approach. The Internet of Things (IoT) is the network of physical objects, such as devices, embedded with electronics, software, sensors, and network connectivity that enables these objects to collect and exchange data [124].

Crowdsourcing, described in Section 2.4, can be used as an IoT methodology through the use of smartphone devices. Data can be routinely collected with smartphone applications that have a specific purpose. Different fields have used this approach to collect massive data sets from people to understand specific situations, or simply for market research. Urban climatology is not an exception. Projects such as the Smart Citizens (http://www.smartcitizen.me) have developed online platforms connected to small devices equipped with sensors to collect massive amounts of data related to weather conditions around the world. With these types of projects, citizens can place these devices in different locations of the city and, consequently, large amounts of data can be collected. This can save the cost of expensive weather stations, and researchers can involve citizens in day-to-day urban climate science. More importantly, the IoT can be a useful approach in countries where cities cannot afford expensive measurement networks.

At present, the collection of massive data through the IoT is used only for weather variables. A promising further step may be to use this approach to also gather information from citizens regarding how they are feeling, especially in the context of OTC.

Research gap 2: *Measurement networks not applicable for developing countries.*

Research gap 3: *Only collection of weather data.*

2.6.2 *Information* gathering

Data becomes information after interpretation. To better describe objects, expressions, functions, or properties we need data, and the connections or relations between them, to provide information [95]. Information is data that has been given meaning by way of relational connection. “Information sets data in relation to each other, it consists of data and connections.” [95].

In order to give meaning to the collected data, data processing methods, such as data mining, are implemented. In the context of OTC, we can gather information directly from people regarding the sensation they perceive given a specific thermal condition. As described in Section 2.1, the collection of thermal sensation information from people is essential in any OTC validation process.

In climate studies, we can gather information from the different data collected from weather variables. When these data are put together in a meaningful way, climatologists collect the information needed to understand a particular climatic condition. This information can also be illustrated in ways in which people can understand and relate to it in their daily life. The IoT also plays a role when communicating this information to people. Through online platforms, the relation of weather data is illustrated, and people can connect this information to individual devices. This information is also needed in climate studies, for instance, to eventually develop models to predict the climate in the future (weather predictions). In the OTC field, scientists use this information to create simulation models that can be used to derive knowledge on thermal comfort, and to interpret and arrive at solutions.

2.6.3 *Knowledge* creation

Knowledge is the appropriate collection of information, for which the intent is to be useful. “Knowledge is a result of connecting data and information. It is not entirely clear how data and information are combined in the cognitive process into knowledge, but in any case domain knowledge and domain independent knowledge build on data and information." [95]. In urban climatology, knowledge represents a pattern that connects and generally provides a high level of predictability as to what is described, or what will happen next. Usually, the predictions based on data and information are derived from simulation methods.

From a general perspective, simulation is "the act of imitating the behaviour of some situation or some process by means of something suitably analogous". For contemporary life, simulation has been introduced with science and technology and is viewed as synonymous with computation and digital computing. For computer science, simulation is "the technique of representing the real world by a computer program; a simulation should imitate the internal processes and not merely the results of the thing being simulated" [57].

The scientific view of simulation is conceived as an experiment or visualization. Thus, it can be defined as the imitation of a real thing, a process (theory and prediction), or a situation to verify, find, or explain a theory. For decision-making processes, there are two possible directions: the prediction, which is based on assumption; and the simulation, which is the production of probable scenarios that need to be evaluated. On the other hand, the design perspective defines simulation as "the creation of past, present, or future scenarios, representing interaction of crucial parameters and variables" [57]. For this reason, it is presumed that simulation in architecture is taking place in the modelling processes.

For OTC, simulation is essential when the intent is to predict how people feel in certain climatic conditions. The OTC can be used as an indicator of how the urban climate is affecting the urban living conditions of pedestrians, and therefore, makes it possible to arrive at conclusions and solutions that help adapt cities to their current and coming climates. This process will help cities become climate resilient, which is of great interest in the context of global climate change.

An example of a combination of data collection, information gathering, and knowledge creation in the field of urban climatology is the BUCCANEER (Birmingham Urban Climate Adaptation with Neighbourhood Estimates of Environmental Risk) project. This initiative is a Knowledge Transfer Project (KTP) that helps provide the necessary evidence to ensure the effective delivery of the city council's long term vision that the City of Birmingham will be the UK's first sustainable global city with a low-carbon energy infrastructure, and will be well prepared for the effects of climate change [112] [72].

Summary: Other technologies are our best hope of monitoring the urban climate at high resolution. Quality Assurance / Control is the crucial step to make these techniques accepted by the scientific community. Effort needs to be focused on a few key networks to be repurposed as test-beds for modelling campaigns, and on the investigation of the viability of these more sustainable techniques (e.g. *crowsourcing*). These techniques can then be applied rapidly across the world, which will allow us to continue to build our urban climate resilience. The current paradigm of measurements is unsustainable. "Innovation is the true urban climatologist panacea." [25]

2.7 Summary

The Outdoor Thermal Comfort (OTC) is generally studied with the use of index models (qualitative) and validated with survey campaigns (quantitative). Nonetheless, these methods are used together only for specific locations in cities (specific urban canyons). In recent years, urban climatology has benefited from data collection methods using the IoT. These days, we find projects that aim to collect climate data with online software connected to widespread measurement networks, or from citizens using smartphone applications. A promising next step would be to use the same methods not only to collect climate data, but also to collect OTC information from citizens. In this way, it would be possible to engage citizens in scientific projects, moving a step closer to a citizen-design science approach.

In summary, attention on the topic of climate change has increased during the past year, engaging countries to push mitigation and adaptation measures. In cities, urban climatology takes over the studies on how to adapt to the coming climate. The problem relies on the lack of application with urban planning policies. Therefore, it is necessary to create a bridge between urban climatology findings and urban planning adaptation measures. However, research projects intending to collect massive data sets can be expensive, making them difficult to implement outside of countries with significant resources to sponsor such initiatives. Unfortunately, countries in tropical areas, which are more vulnerable to climate change, are those with fewer resources to implement costly measurement networks for weather data collection throughout their cities.

Therefore, we can benefit from the IoT to allow the collection of the necessary sets of data to understand the urban climate conditions throughout cities. In recent years, these approaches have been widely used, though only for weather data collection. The research outlined in this thesis will use the same methods, but will use these methods for the collection of OTC information from its citizens. This approach will involve the citizens in the process of understanding the OTC conditions, moving a step forward into citizen-design science. The understanding of the OTC provides policy-makers with indicators for understanding the effect of the current climate conditions, and determining how their cities should adapt. This method will also allow validation of the existing models that simulate the OTC of people in cities. Figure 2.10 illustrates the research gaps found, and the combined approaches that are proposed in this thesis.

Research aim: The research outline in this thesis aims to identify the different degrees of Outdoor Thermal Comfort (OTC) in the city of Barranquilla, by correlating qualitative data of thermal sensation with quantitative data of Physiologically Equivalent Temperature (PET). Initially, the two sets of data are collected from surveys and sensor technology, respectively, and are based in a specific case study area. To extend the study to the city scale, the Internet of Things (IoT) and simulation techniques will be implemented. Finally, it will be possible to use

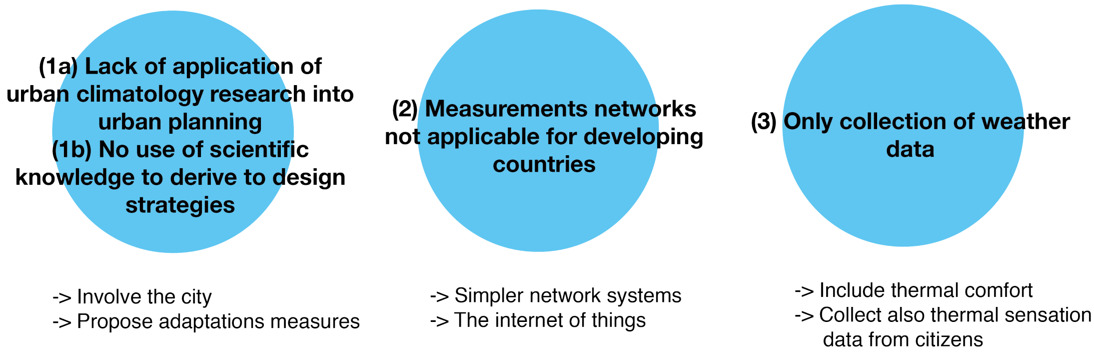


Figure 2.10 – *Summary of research gaps.*

the OTC as an indicator for understanding the urban climate conditions around the city, and to explore climate-sensitive urban adaptation measures.

3 Methodology

This chapter describes the research methodology of the thesis by first introducing the case study, and providing a short historic review of the development of the city. Then, the different parts of the research designed for this thesis are outlined, and finally the two stakeholder workshops that took place at the beginning and at the middle of the research process are described. This final part was important for the overall research because the stakeholder workshops created meaningful insights from feedback sessions, and created a feedback loop to iterate during the implementation of the research framework.

3.1 Case study

The city of Barranquilla is located in the northeast corner of the region called *'Atlantico'*, on the west bank of the Magdalena River, 7.5 km from its mouth in the Caribbean Sea. The city is located at latitude 10°59′16″ North of the equator and longitude 74°47′20″ West of Greenwich, with reference to the Plaza de la Paz, ground zero of the city [1]. Barranquilla has a tropical, arid, and savannah climate, with a mean yearly temperature of 27.4°C [1].

Barranquilla is the largest city in the north Caribbean region of Colombia. Its development over the course of history is attributed to three main factors: (i) its geographical location next to the Magdalena river and the ocean, making Barranquilla the first main seaport of Colombia [73]; (ii) it is the commercial and economical centre of the region due to trade and transport; and (iii) its particular social structure, characterized by the presence of a large group of foreign immigrants and their influence on fundamental economic activities [101]. In the 1930s, the mouth of the Magdalena river was dredged during a period of major infrastructure construction in the country, and with the intention of opening the national economy to the international market. In 1936, the maritime port was built, and was given the name "Golden Gate of Colombia" as the first port in the country [73]. During the first half of the twentieth century, Barranquilla had the largest demographic and urban growth in Colombia, with growth rates higher than all other Colombian cities [33]. From the 1960s until the early 1980s, Barranquilla was plunged into an economic decline largely due to the failure of some

Figure 3.1 – *City of Barranquilla.*

companies engaged in industrial activity which, in turn, failed to consolidate in the city. As a consequence, trade remained as the main economic activity. On August 18, 1993, the Congress of Colombia, through the Legislative Act Number 01 of 1993, gave the city of Barranquilla the distinction of Special District, Industrial and Harbour [100].

3.1.1 Urban development

Toward the end of the 1970s, the national government dictated that all municipalities with more than 20,000 inhabitants must formulate their respective comprehensive development plans based on modern techniques of urban planning and urban-regional coordination [84]. Consequently, the 1990s was an important decade for policies dealing with planning and development, not only in Barranquilla but also throughout the country. In 1997, the national congress issued regulations for the planning of cities, with the aim that each municipality developed a general urban normative (*Plan de Ordenamiento Territorial – POT*). Finally, in 2000, the first POT of Barranquilla was released [33].

The POT is a technical tool that municipalities develop and use to plan and manage their territory with regulations that aim to integrate the physical and socio-economic planning, as well as respect for the environment [33]. It is an instrument that should be part of the state policies in order to foster sustainable development, helping governments guide the regulations and future developments of human settlements. In Barranquilla, the first POT was issued in 2000 and has been revised and transformed through what are called *Planes Parciales* (partial plans). A new POT was issued in 2014, and covers the spatial development of the city for the period of 2012–2035 [2].

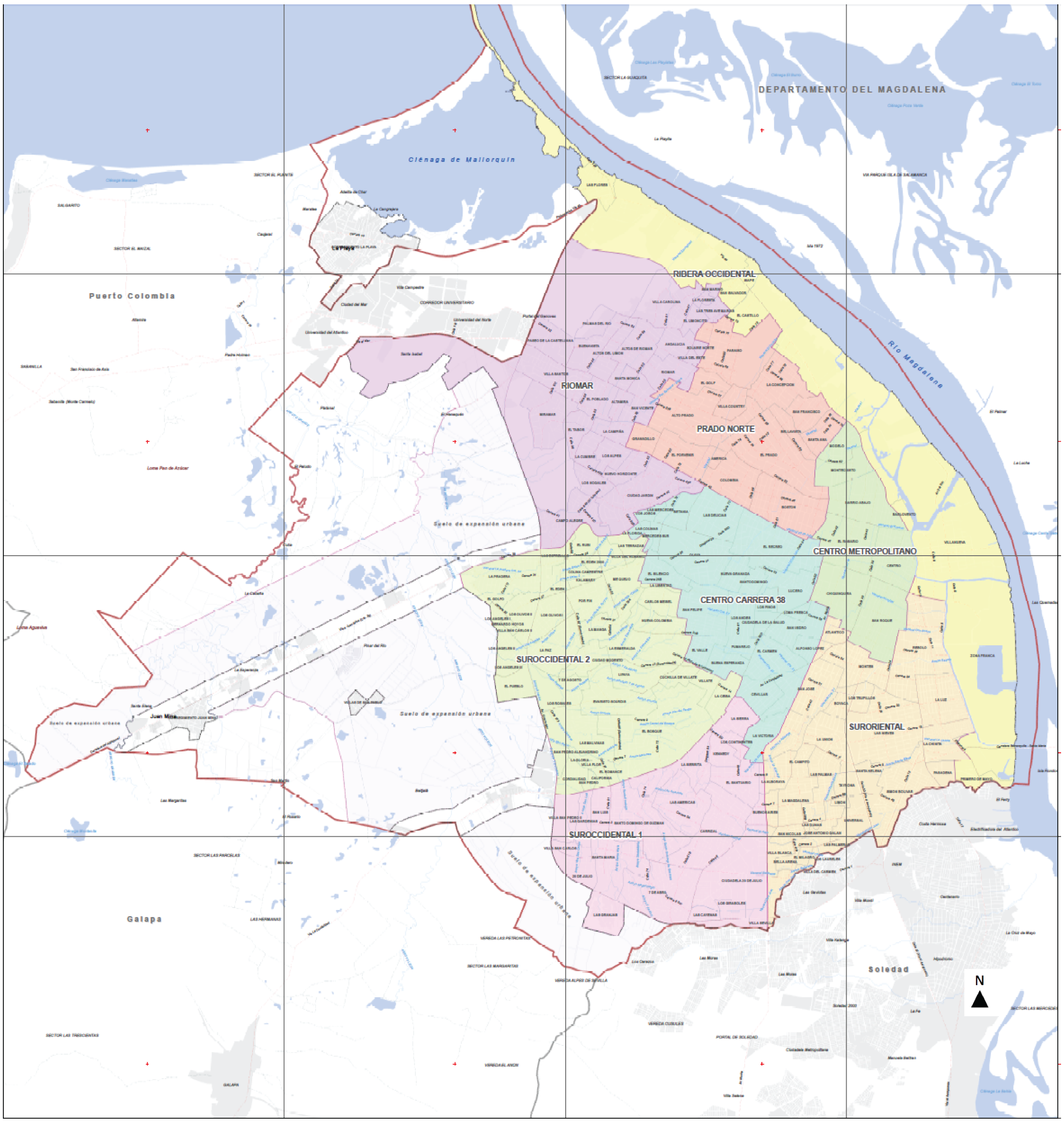


Figure 3.2 – *Administrative division of Barranquilla [97].*

As part of the new POT, the cartography and documentation of the urban strategies are divided into urban sectors where the development targets are represented: *Clasificación del Suelo* (land clasification); *Estructura Urbana* (urban structure); *Usos del Suelo Predializado* (land use); *Sistema y Jerarquización Vial del Distrito* (road system); *Conectividad Vial Metropolitana* (metropolitan road connectivity); *Conectividad Departamental* (departmental road connectivity); *Rutas Alimentadoras de Transmetro* (transmetro system); *Ciclorutas* (bike lanes); *Planes Parciales* (partial plans); *Tratamientos Urbanos* (urban intervention); *Laderas* (terrain); *Zonificacion de Suelos Fuera de lo Urbano* (land use out of the political division);

División Politico Administrativa (administrative and political division); and *Zonificacion Ambiental C.R.A* (environmental zoning) [97]. The latter of these is based on the development target called 'green city and environmental sustainability'. The POT describes this development target as follows: *"an environmentally sustainable green city, and adapted toward a changing climate that values its significant environmental heritage, conservation of natural resources and ecosystems that allow the city of Barranquilla to ensure sustainable development and be in an appropriate position to address the effects of climate change conditions."* [97]. Nonetheless, the strategic plans illustrated in the documented cartography are directed only to the ecological development of the city, meaning that climate change is only being targeted from the perspective of greenery implementation plans.

Thus, if one of the target areas for the future development of the city is to tackle climate change and support policy-making with the development of adaptation measures, it is necessary to understand the current situation of the city based on data, information, and knowledge. In terms of climate change and the city, it is necessary to rely on urban climatology to be able to understand the microclimatic conditions of the city and act based on the knowledge gathered. One example is the Local Climate Zone (LCZ) developed by Stewart and Oke (2012) [104], which aims to operate as a classification scheme, and in particular to help standardize methods of observation and documentation in Urban Heat Island studies.

In order to contribute to this approach and adapt the findings to specific cities, it is necessary to collect local data. Hence, documentation on different aspects of the urban climate such as the OTC are necessary. In Barranquilla, the OTC has been studied as recently as 2014 by Villadiego [119], from a qualitative perspective. This study led to a first OTC map of the city of Barranquilla. In order to contribute to this research and validate the findings, it is necessary to investigate the OTC from a quantitative perspective, and use simulation methods to extend the method to a city scale.

The research outlined in this thesis aims to identify the different degrees of Outdoor Thermal Comfort (OTC) in the city of Barranquilla, by correlating qualitative data of thermal sensation with quantitative data of Physiologically Equivalent Temperature (PET). Initially, the two sets of data were collected from surveys and sensor technology, respectively, based on a specific case study area. To extend the study to the city scale, the Internet of Things and simulation techniques were implemented. Finally, it will be possible to use the OTC as an indicator for understanding the urban climate conditions around the city, and explore climate-sensitive urban adaptation measures.

3.2 Research structure

The research methodology of this thesis is divided into two components: qualitative and quantitative. For the qualitative part, a methodology based on the study on Thermal Sensation is implemented. This research method is mainly executed through survey campaigns. Similarly, the qualitative part is designed from a research methodology based on the calculations of the PET from local weather data. Both methodologies are initially implemented in a local pre-selected case study area (local scale) and then translated to a city scale using the Internet of Things and simulation techniques (Figure 3.3). The purpose of this two-part research structure is to analyse the OTC from two sets of results based on two different methodologies in order to validate the findings.

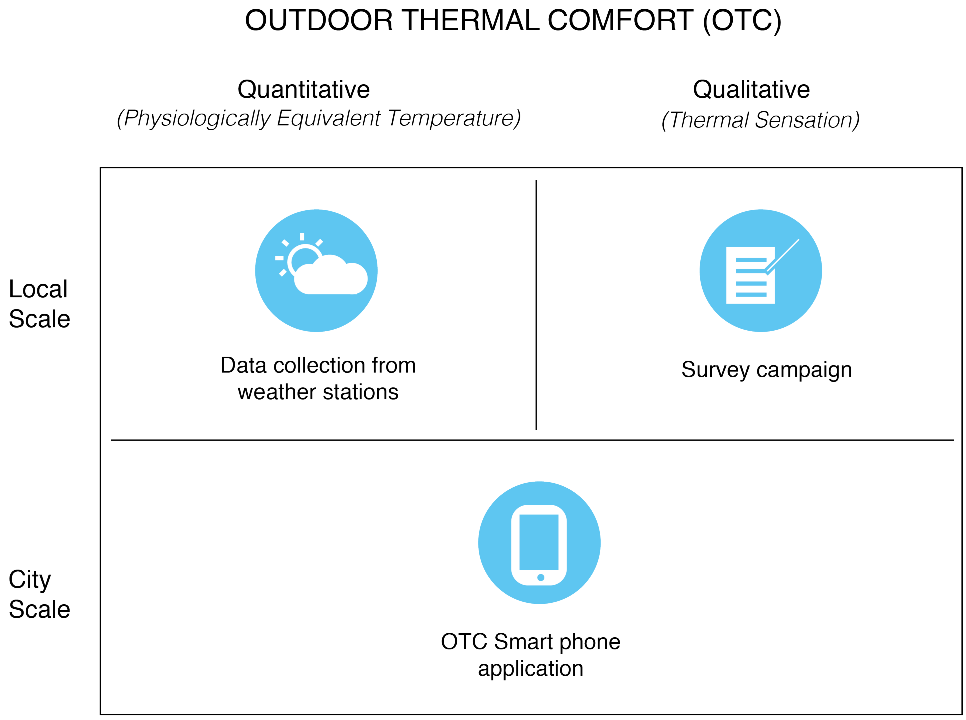


Figure 3.3 – *Research structure.*

On the local scale, the Campus of the *Universidad del Norte* of Barranquilla was selected as the local-scale case study area. The campus is located north of the city and is settled with the same orthogonal urban grid orientation as the city centre. For both research methods (qualitative and quantitative), four locations were selected according to the four different grid orientations of the campus, based on the morphological structure (building footprints). The four points were named from A to B for the qualitative data collection (survey campaign) and 2 to 5 for the quantitative data collection (positioning and installation of mini portable weather stations). The design and execution of the methodologies are described in more detail in Chapter 4.

On the city scale, two different approaches were implemented. First, a project was designed for the data collection of Thermal Sensation (qualitative) around the city of Barranquilla. The project was called '*Proyecto confort*' (thermal comfort project) and was promoted as a survey campaign marathon in three different universities of the city. The idea was to have only students as subjects in order to have the same age range for all participants. The survey was developed into a smartphone application, and downloaded by the participants. Second, the PET (quantitative) calculations around the city were executed using simulation techniques based on the data obtained by the weather stations, and by adapting the simulation according the buildings' heights and footprints. Chapter 5 describes in more detail the implementation of both methodologies on a city scale.

3.3 Stakeholder workshops and feedback

A stakeholder workshop is one way to engage stakeholders, those who are affected by, have a direct interest in, or are somehow involved with the problem identified in a specific situation. During the development of the research methodology, the need was identified to meet with the city authorities and representatives of different institutions in order to collect their feedback on the research undertaken. For this purpose, two workshops were organised: one at the beginning, and a second toward the end.

The first workshop was designed and directed to discuss urban challenges in the city of Barranquilla. It was organised by the Universidad del Norte and the ETH Zurich within the framework of a summer school. The outcome of this workshop helped to identify the scope and needs of the research described in this thesis, and helped gather information to develop the method and application. This congregation took place in August 2014, and brought together representatives of different governmental and non-governmental institutions in the city of Barranquilla. One of the main outcomes of this workshop, specifically for the research in this thesis, was the presentation of a project called '*por la sombrita*' (by the shade) that was launched by a non-profit organization with representatives in attendance. This project aimed to activate social outdoor community integration activities by constructing sun protection urban elements in parts of the city where high temperatures were preventing outdoor activities [7]. One of the biggest challenges was to identify the places to install these structures. For that reason, the OTC is one of the main indicators to identify which parts of the city are more vulnerable regarding thermal comfort. After this workshop, it was clear that the city of Barranquilla is in need of identification and documentation of the different degrees of OTC around the city in order to have a basis for the development of new urban strategies and policies for climate adaptation measures.

The second stakeholder workshop was organised toward the end of the research framework. In contrast to the first workshop, the second was planned specifically to gather feedback on the outlined research. It was used to identify the implementation process into urban policies and create a working group. The meeting took place in February 2016, and gathered representatives from governmental authorities (*Área Metropolitana de Barranquilla, Cámara de Comercio de Barranquilla, DAMAB and Edubar*) and research groups of two different universities in Barranquilla (*Universidad del Norte* and *Universidad de la Costa*). During the meeting, the research work was presented, and was followed by feedback from participants. The main outcome of this workshop was common agreement of the importance of the results, documentation of the OTC, and plans to be implemented in the POT. The other important outcome was the establishment of a working group with the different institutions gathered at the meeting, with the goal of following up on the project. A document with the minutes of these workshops is attached at the end of this thesis, as Appendix A.

Figure 3.4 – *First stakeholder workshop.*

Figure 3.5 – *Second stakeholder workshop.*

4 Local scale analysis

The local-scale analysis constitutes the first part of the overall research structure explained in the previous chapter. This part is divided into two research projects: one for the data collection and analysis of quantitative data of thermal comfort (PET), and the other for the data collection and analysis of qualitative data of thermal comfort (thermal sensation). In this section, each research project is described and the results are analysed. After presenting the results of each project, a correlation between the quantitative and qualitative data is described and analysed, followed by a chapter conclusion.

4.1 PET analysis

PET is a temperature dimension index for OTC, and is measured in degrees Celsius (°C). As previously introduced in Chapter 2, PET is defined as the air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperatures, equal to those under the conditions to be assessed [44]. It assumes that the metabolic rate is fairly low (80 W of light activity are added to basic metabolism) and that the heat resistance of clothing is 0.9 clo, based on the typical insulation value of clothing [65]. Weather data is used as input data for the calculation of the PET. These data need to be collected in specific measurement points with weather stations.

4.1.1 Data collection

The campus of the *Universidad del Norte* was selected as the local-scale case study area in Barranquilla. The campus is located north of the city, and is settled with a similar orthogonal urban grid orientation as the city centre (Figure 4.1). This orthogonal Spanish grid recaptures the colonial period during which Barranquilla was first established. The north-west orientation of one of the orthogonal grid axes increases the amount of prevailing wind that enters the city in this location, affecting the OTC of the city.

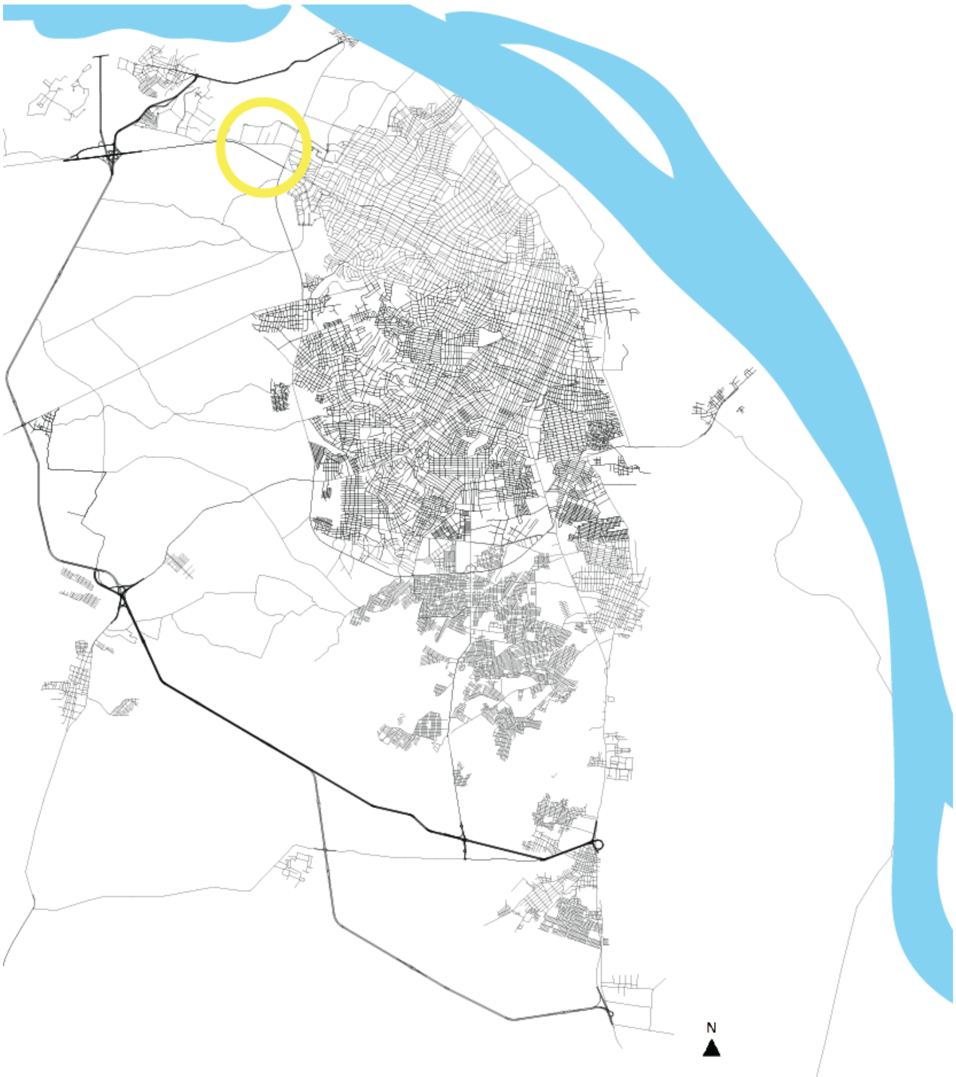


Figure 4.1 – *Street network map of Barranquilla. The yellow circle is the local- sacle case-study area: The university campus of the Universidad del Norte (north-west of the city).*

Measurement network

With this urban area selected as the local-scale case study, four outdoor locations were identified as measurement points for the data collection. The selection was based on four different orientations of the orthogonal grid: north, west, east, and south. The measurement points were also selected to be on pedestrian sidewalks, where there is a continuous use of these streets by people. Additionally, one final location on a rooftop was selected to collect general global weather data from the surrounding.

For the collection of the weather data, five portable weather stations were installed for a year at each of the measurement points (Figure 4.2). For the four pedestrian-scale measurement points, one of these weather stations was mounted at a height of 1.2 metres off the ground. These stations recorded measures of air temperature, humidity, rainfall, wind direction, wind speed (anemometer), and atmospheric pressure (barometer). For the location on the rooftop, an advanced portable weather station was mounted, which measured the same parameters plus solar radiation (pyranometer).

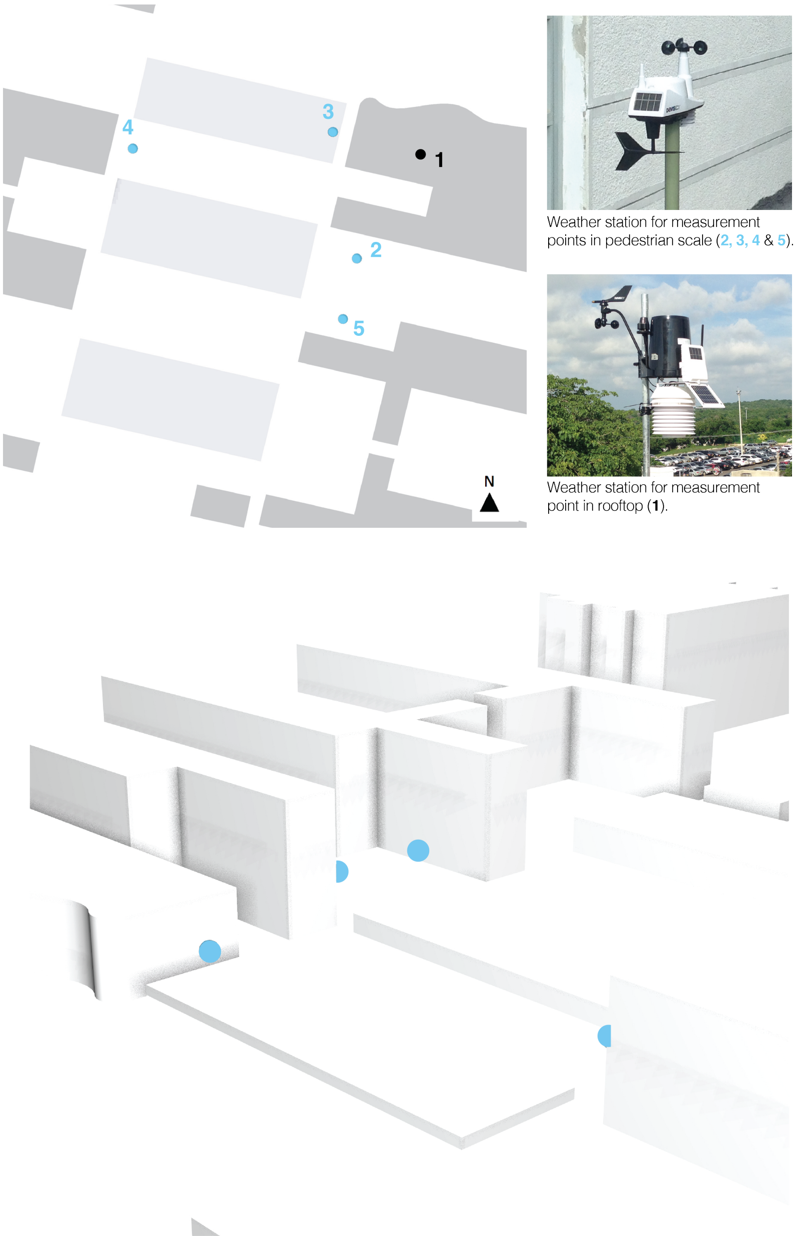


Figure 4.2 – *Measurement points and weather stations used for data collection.*

The weather data at all points were collected for a period of one year. To be able to monitor the data throughout the year, a wireless system was implemented. Each weather station was equipped with a console that showed the weather variables measured by the weather station in real time. The two parts were connected wirelessly to ensure the easy installation of the equipment. The weather station was placed outdoors, and the console was placed indoors, with no more than 3 metres distance from each other. With only these two parts installed, it is not possible to store the weather data. For that reason, a computer had to be constantly connected to the console. For this project, a Raspberry Pi computer was connected to each of the weather station consoles. The biggest advantage of a Raspberry Pi computer is its small size (85 mm × 56 mm), which allowed the console and computer to be placed almost anywhere without disturbing the indoor setting. For each Raspberry Pi computer, a weather-recording software needed to be installed to save the data from the console. For this project, the online web server software called WeeWx (www.weewx.com) was installed on each computer. This software takes the data from the console, sends and saves the database onto an online server, and visualises the data online. Additionally, WeeWx provides statistics on the recorded data, producing graphs, reports, and HTML pages. For this procedure to work, a constant internet connection was necessary. With an internet connection, the computer sends the collected data to the WeeWx software, which then produces a HTML page on a web server (Figure 4.3).

With this installation, it was possible to monitor the weather stations and observe the measurements during the whole year. The weather stations were mounted and recorded data from October 2014 until September 2015. The data were sent and saved every 5 minutes onto the web server. WeeWx visualised the data and updated the measurements every 10 minutes on the websites:

- http://www.barranquilla.arch.ethz.ch/station1,
- http://www.barranquilla.arch.ethz.ch/station2,
- http://www.barranquilla.arch.ethz.ch/station3,
- http://www.barranquilla.arch.ethz.ch/station4,
- and http://www.barranquilla.arch.ethz.ch/station5.

Weather data collected

The weather variables recorded with the four small weather stations were: outside temperature (°C); inside temperature (°C); relative humidity (%); wind direction and wind speed (m/s); atmospheric pressure (hPa); and rain rate (mm/hr). The other weather station installed on the rooftop measured all of these weather variables in addition to solar radiation (W/m^2) and UV radiation. The purpose of the weather station installed on the rooftop was to gather global solar radiation data for use with each of the other measurement points. Other weather variables available from this weather station were not used in this project.

One of the weak points of the measurement network in this project was the wireless internet connection, which led to connection failures and missing data. Another limitation

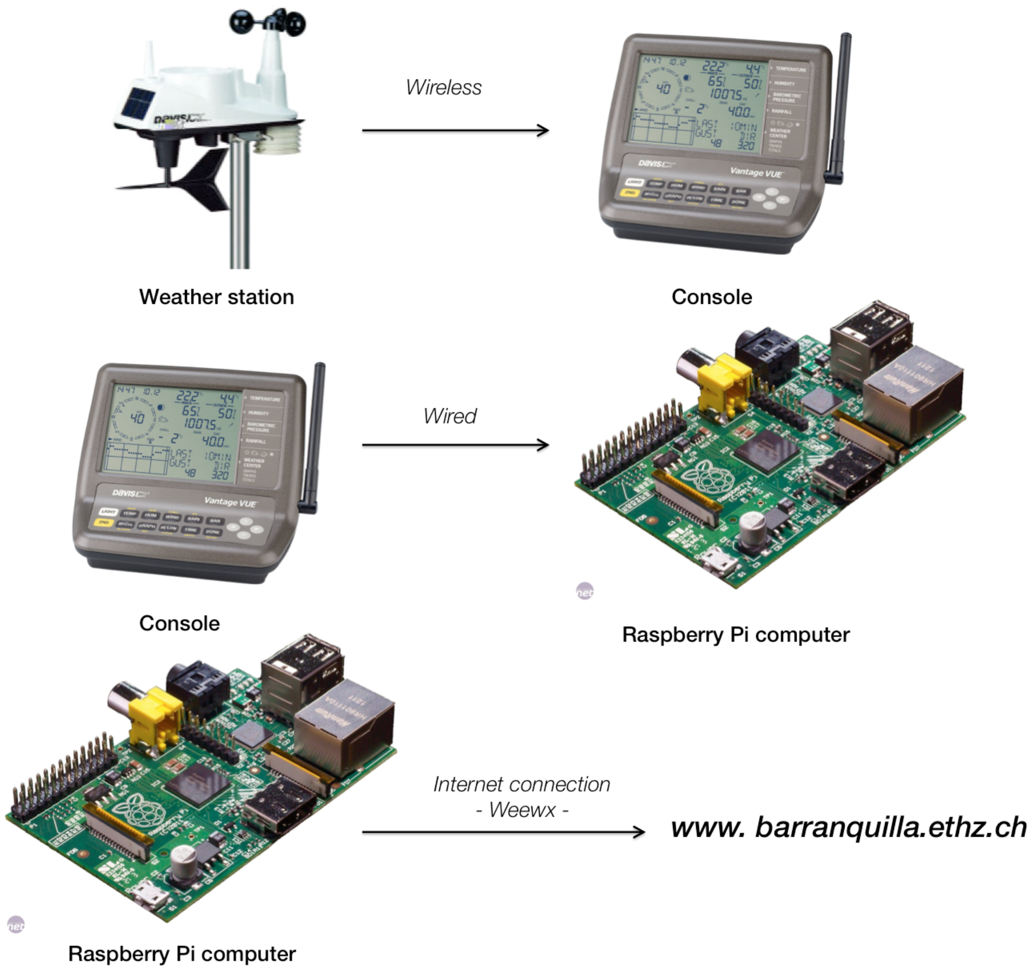


Figure 4.3 – *Measurement network.*

was the electricity outages that are usual in this city, which also led to missing data. For these reasons, each measurement point produced different amounts of recorded data. The number of measurement times for point 1 was 83064, for point 2 was 70255, for point 3 was 64547, for point 4 was 40862 and for point 5 was 80915. For each measurement time of the four small weather stations, data for six different weather variables were recorded. For the single weather station on the rooftop, each measurement time included recorded data for eight weather variables. These measurement times show the stability of the network system for each weather station. The big weather station placed on the rooftop showed the highest stability connection during the course of the year. This was due to the fact that this equipment is more advanced than the other weather stations. Even though the four other weather stations were exactly the same, the weather station at point 4 had the fewest measurement times. This can be explained by local factors such as the electricity stability, or the quality of the wireless internet connection. Because of these local factors, the connection at point 3 and 4 failed more often. This resulted in missing data from point 3 for the month of September 2015 and missing data

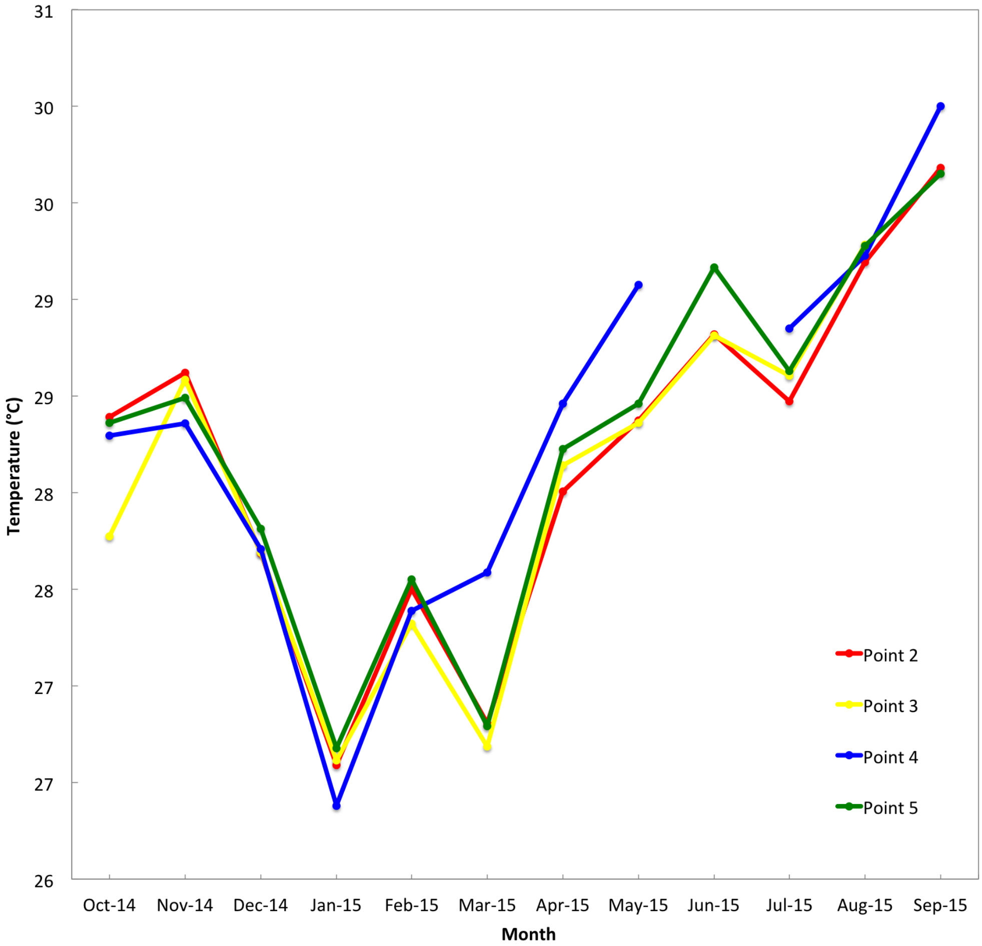


Figure 4.4 – *Average temperature for all four measurement points from October 2014 to September 2015.*

from point 4 for the month of June 2015.

With the weather data collected, it was possible to analyse the trends of each weather variable for the four measurement points at the pedestrian scale, and for the solar radiation at the measurement point on the rooftop.

Figure 4.4 shows the average values of outside temperature (°C) for each month during the whole year. It is clear that all average values for each month are similar at each point. September has the highest temperature average values in all points compared to the rest of the months. In contrast, January has the lowest temperature values for all points.

Figure 4.5 shows the average values of relative humidity (%). This graph illustrates the highest values during the months of December and June, and the lowest values for the months of February and March. From this graph it is also possible to see the individual high peak of point 3 in October and the low peak of point 4 in May, which differ from the other points in these two months.

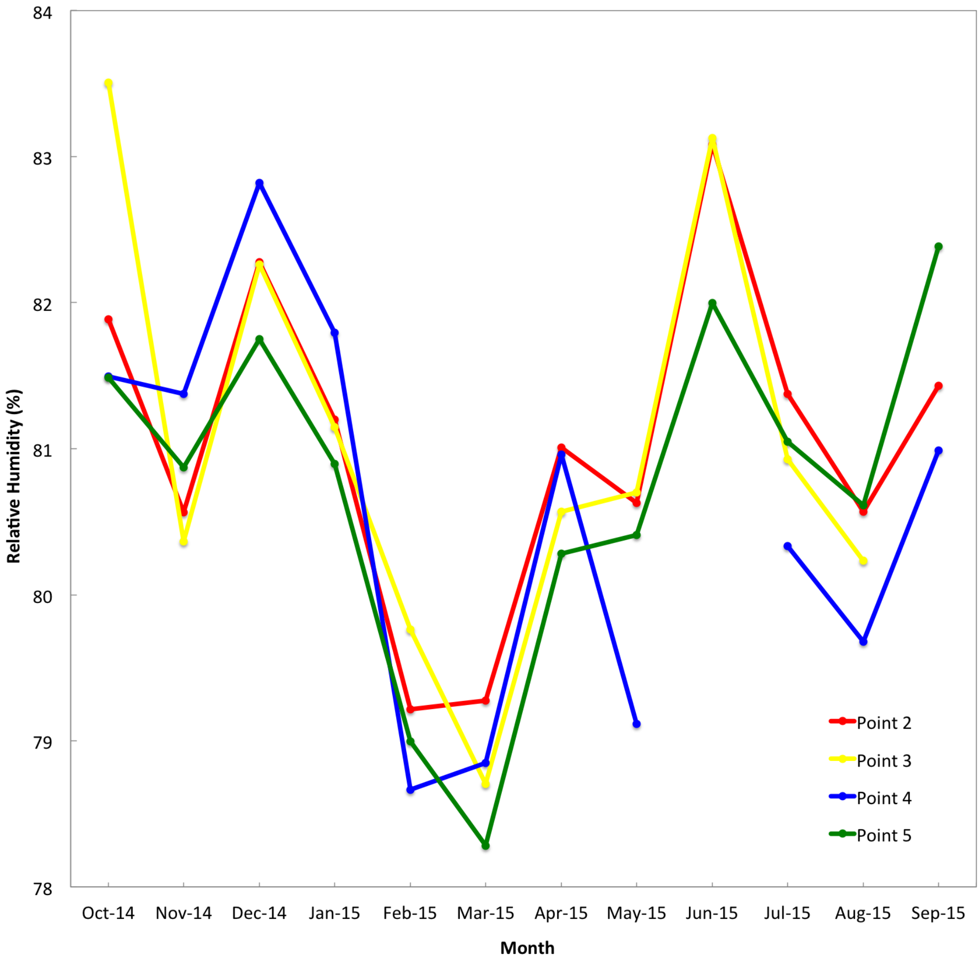


Figure 4.5 – *Relative humidity and wind speed for all four measurement points from October 2014 to September 2015.*

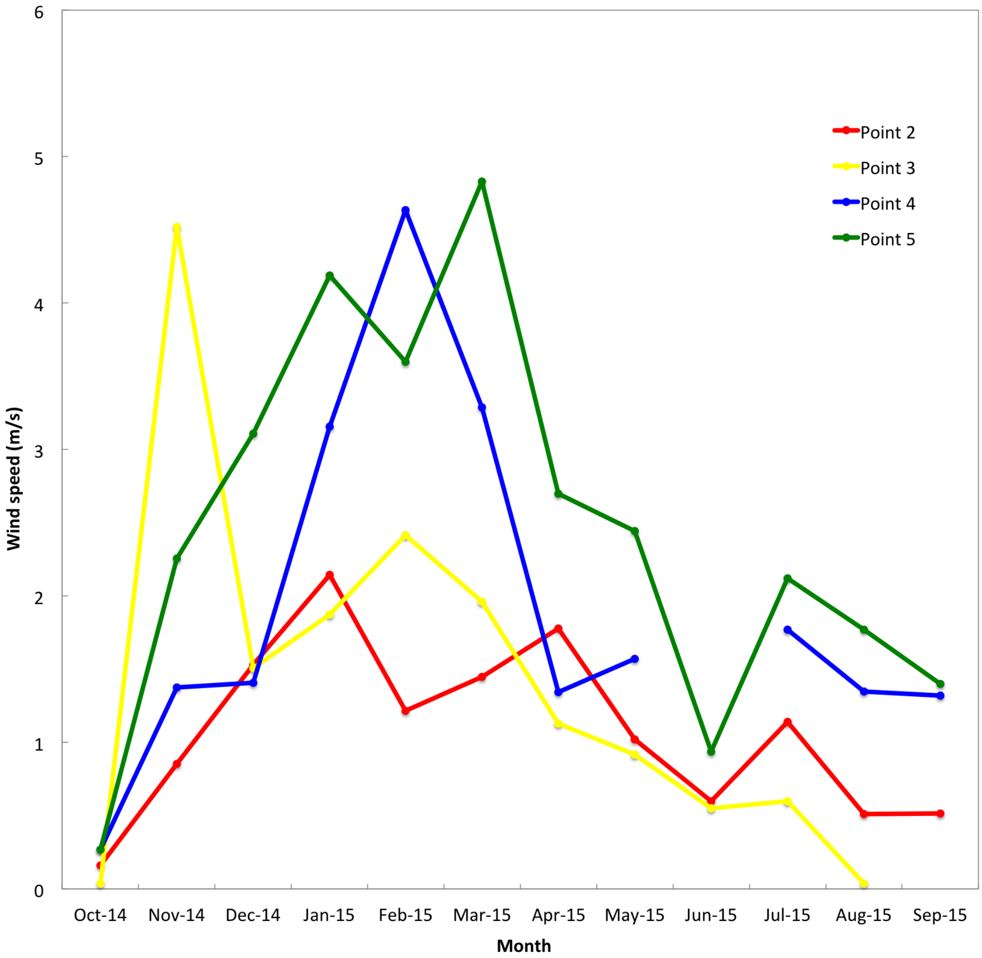


Figure 4.6 – *Wind speed for all four measurement points from October 2014 to September 2015.*

Figure 4.6 shows the average values of wind speed (m/s). In contrast to the previous two graphs, the wind speed average values have no similarity or correspondence between each location for each month. This is due to the different obstacles around the measurement points that affect the wind speed. Each point has a different trend throughout the year. For instance, point 2 and 3 have the lowest wind speed for all months, while point 5 has the highest average values. Additionally, there are two outstanding peaks, one for point 3 during the month of November and the other for point 4 in the month of February. In general, point 5 (facing north and with a street canyon formed from west-east) has the highest values of wind speed throughout the year, a weather variable that has a large effect on the OTC of pedestrians.

4.1.2 PET calculations

After collecting weather data for one year, RayMan [63] was used to calculate the PET for each measurement point. To calculate PET, RayMan requires input data including: outside temperature (°C); relative humidity RH (%); wind speed (m/s); and global radiation G (W/m^2). The data set for solar radiation collected from the rooftop weather station (measurement point 1) is added into the data set of the other four weather stations (measurement points 2–5), and used as the global radiation input for the PET calculations. The RayMan model adapts the global solar radiation accordingly to the orientation and the buildings around each measurement point. For this simulation, a shapefile floor plan is created with the information on building heights, and converted into a .obs file to include it as an input parameter into RayMan. The model was run for each data point collected every 5 minutes, every day for all months (October 2014 – September 2015). Table 4.1 shows the number of data points calculated at all points for each month.

RayMan can also calculate the Sky View Factor (SVF) of each of the measurement points where the weather stations are located (figure 4.7). The SVF measures the ration of free sky spaces affected by geometry [106]. Therefore, this numerical factor shows how much sunlight can be received by the measurement point. Additionally, the sun-path diagram, also generated by RayMan, illustrate the orientation of the building in relation to the measurement point. This information can also show how the measurement points where located in four different orientations in order to collect data from four different positions.

For the analysis of the PET values, the data set is divided into morning and afternoon according to the sunrise and sunset times. The morning period ranges from 6:00 to 12:00 and the afternoon period ranges from 12:00 to 18:00. Table 4.2 shows the average PET morning values and Table 4.3 shows the average PET afternoon values.

By analysing the PET data for the individual measurement points, it is possible to observe the different trends throughout the year. In point 2 (Figure 4.8), the average values of PET have similar tendencies between morning and afternoon, while interchanging the highest values between the two ranges of hours. For instance, the period of April to July has the highest average PET values during the morning period, whereas the period from January to March has the highest PET values during the afternoon period. The highest average PET for the whole year during morning hours is for the month of June, and for afternoon hours it is for the month of August. Meanwhile, the lowest average PET for the whole year during morning hours is for the month of March and for afternoon hours it is for the month of December.

Point 3 (Figure 4.9) has similar interchanging tendencies from the highest values in each month between mornings and afternoons. For instance, the period from February to

Table 4.1 – *Number of data points calculated (PET values) for each month for all measurement points.*

Point	Oct14	Nov14	Dec14	Jan15	Feb15	Mar15	Apr15	May15	Jun15	Jul15	Aug15	Sept15
2	3185	3744	6165	8916	8055	6358	8627	8241	4320	4889	3741	4014
3	1858	3728	3728	8914	8055	8909	8640	8928	4309	4886	2592	0
4	3742	3729	5185	7501	2591	1152	5174	1728	0	3165	4015	2880
5	3744	3744	6722	8891	8028	8916	8622	8929	4311	4896	8928	5184

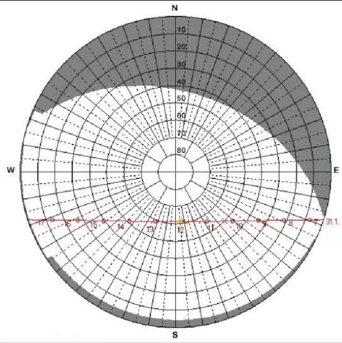
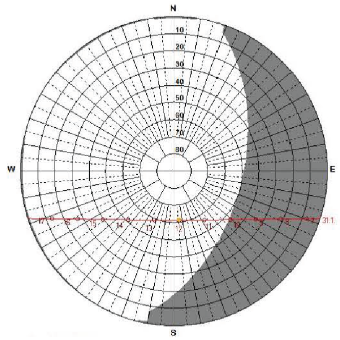
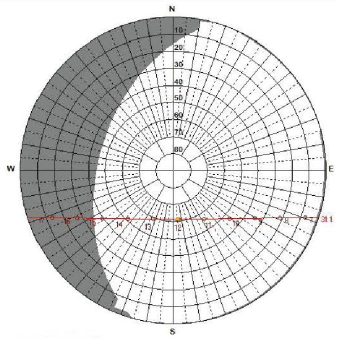
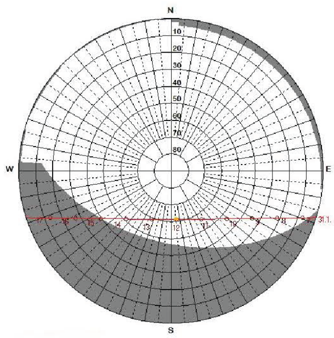
Weather station / Points	Sunpath diagram	SVF
2		0.618
3		0.588
4		0.619
5		0.596

Figure 4.7 – *Sky View Factor (SVF) for all measurement points (weather stations)*

Table 4.2 – *Average PET (°C) values for morning period (6:00–12:00).*

Point	Oct14	Nov14	Dec14	Jan15	Feb15	Mar15	Apr15	May15	Jun15	Jul15	Aug15	Sept15
2	30.6	32.5	29.3	32.0	29.4	28.7	30.6	31.6	32.8	31.5	31.8	32.0
3	31.7	31.7	29.2	29.1	27.7	28.2	31.3	31.9	32.4	31.7	32.7	NA
4	31.6	30.6	28.7	29.6	26.7	25.2	30.1	32.0	NA	31.3	31.2	33.2
5	31.7	30.0	27.9	28.5	27.0	26.3	28.8	30.5	32.3	30.7	32.0	32.4

Table 4.3 – *Average PET (°C) values for afternoon period (12:00–18:00).*

Point	Oct14	Nov14	Dec14	Jan15	Feb15	Mar15	Apr15	May15	Jun15	Jul15	Aug15	Sept15
2	32.5	30.7	28.4	33.0	30.4	29.4	29.3	30.5	31.4	30.6	34.1	33.7
3	30.7	28.4	28.5	33.5	28.1	28.7	31.3	30.4	31.7	32.1	34.2	NA
4	30.7	29.1	28.4	29.3	26.8	28.8	30.6	31.2	NA	30.5	31.6	31.7
5	30.7	29.0	28.2	28.6	27.7	26.0	29.4	29.0	31.6	29.7	31.0	31.2

April has the highest average PET values during afternoon hours, while the period from May to June has the highest average PET values during morning hours. In contrast to point 2, point 3 encounters two months where the average PET values differ considerably between morning and afternoon. In November, the PET average value for morning hours is 31.7 and for the afternoon it is 28.4, and in January the PET average value for morning hours is 29.1 and for the afternoon it is 33.5. The highest average PET for the whole year during the morning and afternoon hours is for the month of August. Meanwhile, the lowest average PET for the whole year during morning and afternoon hours is for the month of February. Both peaks corresponding to the same months.

Similarly to point 2, at point 4 (Figure 4.10) the average values of PET have similar tendencies from morning to afternoon. The graph in Figure 4.10 shows how during the period from October to January, the highest values correspond to morning hours, while in the period from March to April, the afternoon hours correspond to the highest values. Similarly to point 3, point 4 also encounters a peak that creates a large range of values between morning and afternoon. This peak is for the month of March, where the lowest average PET value for morning hours is 25.2 and for the afternoon is 28.8. For the whole year, the highest value during morning hours corresponds to the month of September and the lowest value to March. For the afternoon hours, the highest value is for the month of August and the lowest is for February.

PET average values at point 5 (Figure 4.11) also show a similar tendency between morning and afternoon. Similar to point 2, though different from 3 and 4, point 5 does not have peaks with significant gaps between morning and afternoon values. The highest value for the morning hours is for the months of September and the lowest is for March. For the afternoon hours, the highest value corresponds to the month of June and the lowest to the month of March.

Figure 4.12 shows the graph with the average PET values of all four points during morning hours. By comparing all the points, the values show that the lowest average PET

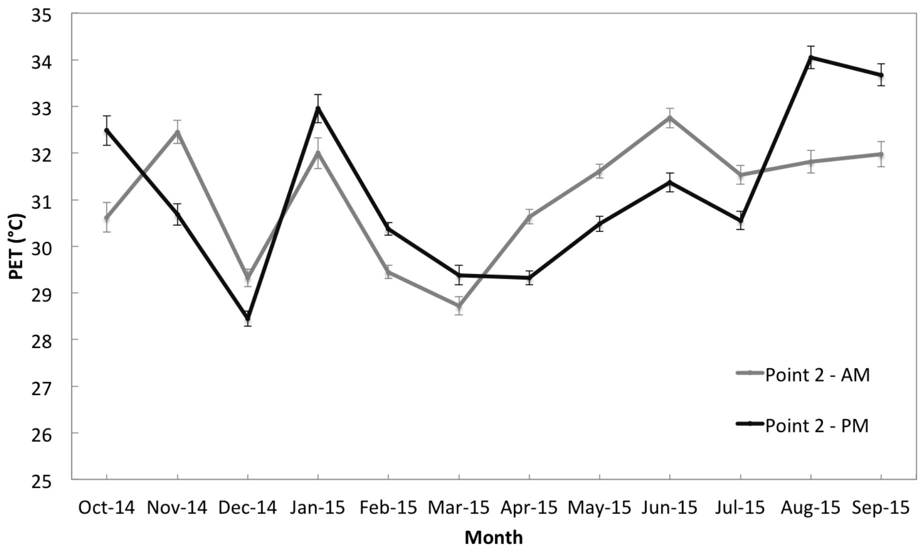


Figure 4.8 – *Average PET (° C) values for morning and afternoon hours in measurement point 1.*

corresponds to the months of February and March, while the highest values correspond to the periods from October to November (2014) and June to September (2015). The graph also shows a considerable constant increase in PET from March to May. Taking the weather data average values from the wind speed from Figure 4.6, it is possible to observe that the highest wind speed values for each of the points correspond to the months of February and March (with the exception of November for point 3), which relate to the lowest average PET values from Figure 4.12.

Figure 4.13 shows the graph with the average PET values of all four points during afternoon hours. As well as the morning hours, during the afternoon the lowest average PET values correspond to the months of February and March, with the exception of December for point 2. In contrast to the morning values, the afternoon values do not have a similar tendency among all of the measurement points. For instance, the highest values for point 2 and 3 correspond to the months of January, August, and September, while the highest values for point 4 and 5 correspond to the months of June, August, and September.

The average PET values for the whole year and for each measurement point show that the height values, both for morning and afternoon, correspond to the measurement point 2 followed by points 3 and 4, and the lowest values correspond to point 5 (Figure 4.14). Measurement point 5 shows a significant gap between the morning and the afternoon hours, while point 3 shows no gap (both values are the same, 30.7). These values are also shown in Table 4.4 and 4.5 with the minimum and maximum PET values per measurement point. These results indicate that the values in point 2 correspond with the location facing south, which means that this point has the longest exposure to sunlight, which explains the high PET values.

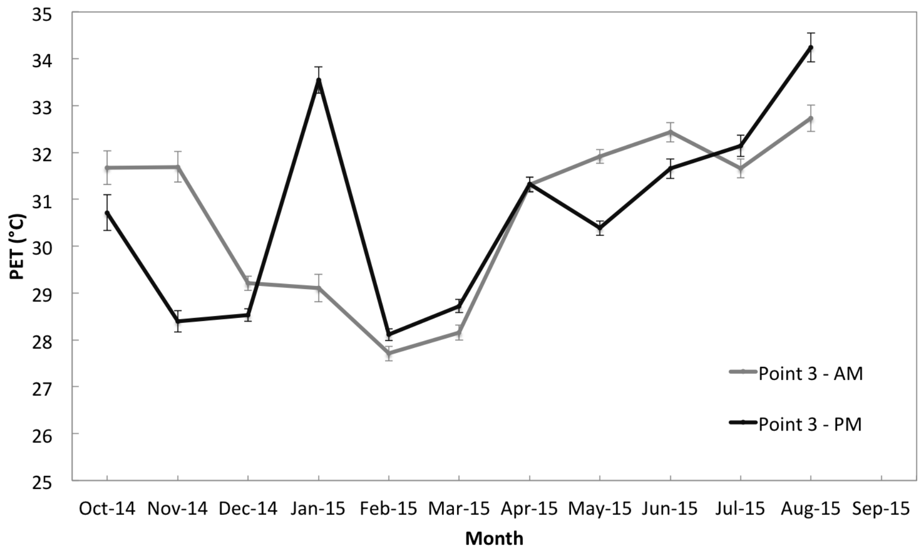


Figure 4.9 – *Average PET (°C) values for morning and afternoon hours in measurement point 3.*

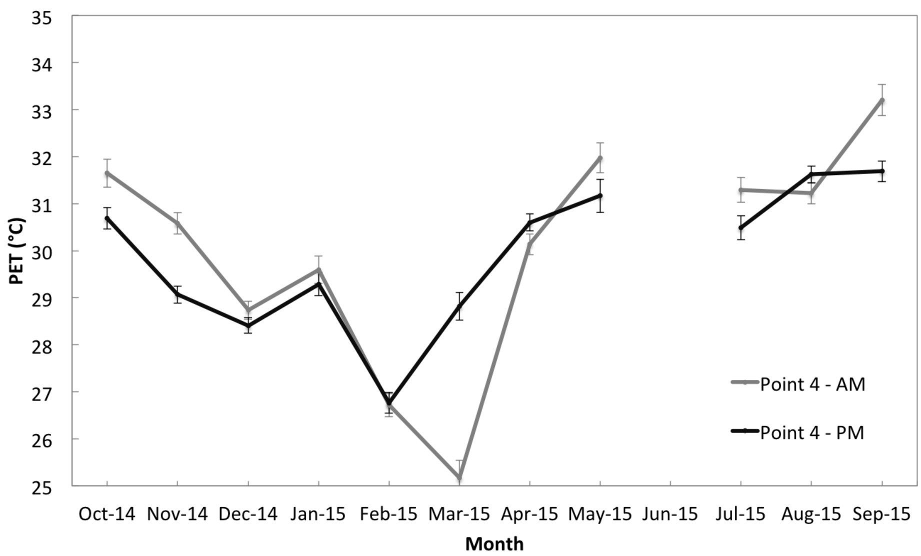


Figure 4.10 – *Average PET (°C) values for morning and afternoon hours in measurement point 4.*

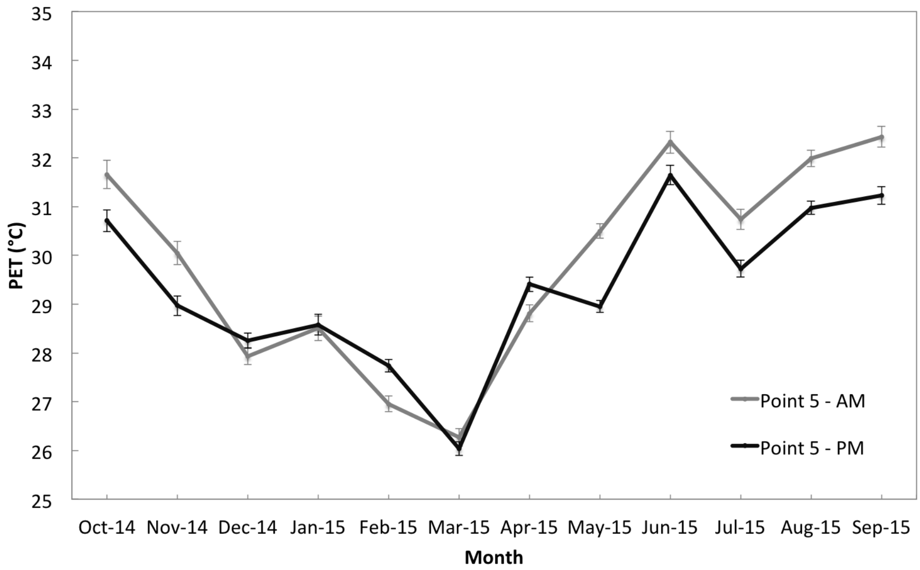


Figure 4.11 – *Average PET (°C) values for morning and afternoon hours in measurement point 5.*

Table 4.4 – *PET (°C) values for morning hours (6:00–12:00) for the whole year.*

Point	Minimum	Maximum	Average
2	28.7	32.8	31.1
3	27.7	32.7	30.7
4	25.2	33.2	30.0
5	26.3	32.4	29.8

4.2 Thermal sensation analysis

The previous PET calculations are quantitative indicators of the OTC of the local-scale case study area. To validate these results, a second research project was designed and executed in the same location. The aim of this project was to gather qualitative information on the OTC by collecting and analysing thermal sensation responses from people.

4.2.1 Data collection

A thermal sensation questionnaire was used to collect information from pedestrians walking around the selected urban area for the local case study, previously described at the beginning of this chapter. The selected points (locations) correspond to similar conditions to the measurement points used for the placement of the weather stations for the previous project. Due to restrictions of the site, the questionnaire locations were placed near the measurement points but not in the exact positions. The selection of the locations was based on preconditions such as orientation, obstacles (e.g. trees) and building heights. Figure 4.15 illustrates the position of each location. The questionnaire locations are named from A to D and correspond

Figure 4.12 – *Average PET (° C) values for morning hours for all four measurement points.*

to the measurement point for the PET calculation as follows: A to 4, B to 3, C to 5, and D to 2.

The questionnaire was designed to be completed in two minutes per person, and was based on Villadiego & Velay-Dabat (2014) [117]. In addition, ISO 7730 norms (2005) and the ASHRAE standard (2004) were taken into account. The structure of the questionnaire consisted of four sections. The first was a control section in which the information was organised to ease the analysis of the results. This section contained the identification number of each folio, the date, time, and the necessary information for the people taking the survey.

The next section was the core questionnaire about thermal perception. For each weather variable, the sensation, satisfaction, and preference was asked (e.g. "How do you feel regarding air temperature at this moment? Which is your satisfaction degree regarding air temperature at this moment? What would you prefer regarding air temperature at this moment?"). In this way, four weather variables were evaluated: air temperature (Thermal Sensation Vote - TSV); relative humidity (Humidity Sensation Vote – HSV); wind speed (Wind speed Sensation Vote –

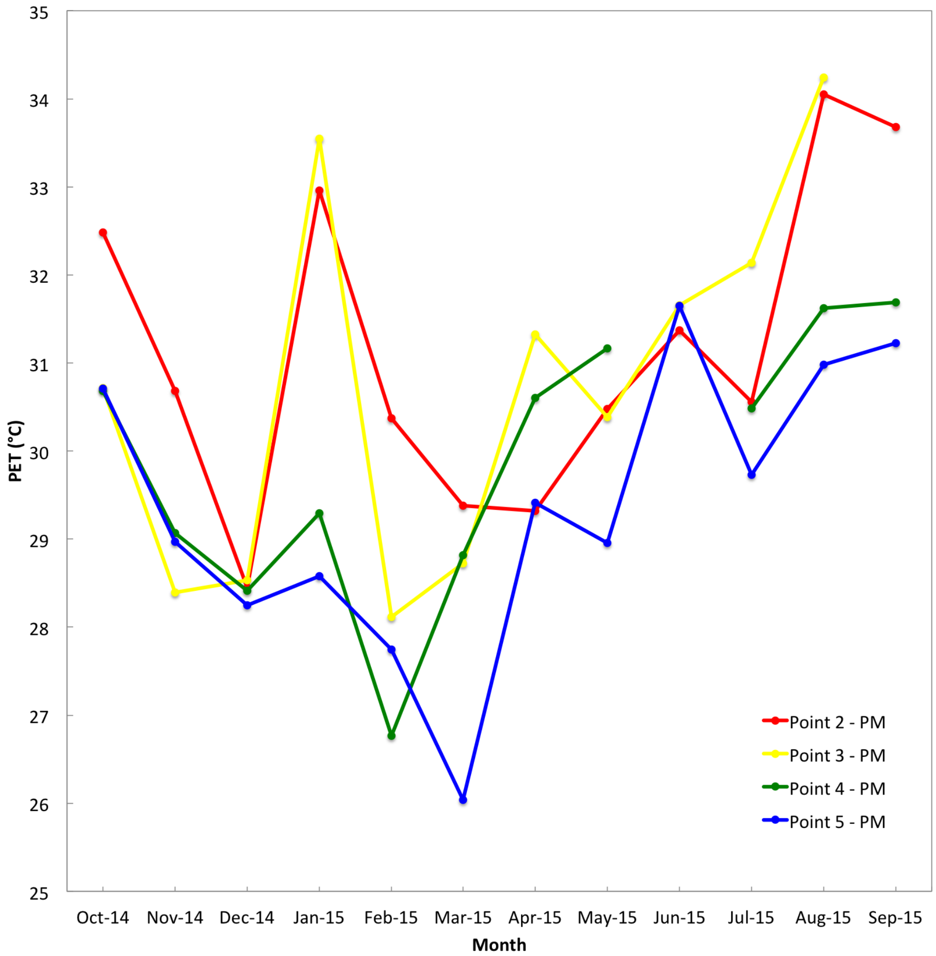


Figure 4.13 – *Average PET (°C) values for afternoon hours for all four measurement points.*

WSV); and solar radiation (Solar radiation Sensation Vote – SSV). A final question regarding thermal comfort was included in order to combine all weather variables to understand and validate the results. Although the questionnaire included all weather variables, for this project the variable evaluated was the air temperature in terms of thermal sensation.

The ASHRAE sensorial scale of seven symmetrical points was used to answer the thermal sensation section. The options provided by the questionnaire to answer the questions regarding thermal sensation were the following: (3) very warm; (2) warm; (1) slightly warm; (0) neutral; (-1) slightly cool; (-2) cool; and (-3) cold.

In addition to this survey campaign, information on physiological characteristics (such as age, gender, height, weight, and origin), type of clothing, and activity of participants was collected.

The survey was carried out from the 27th to the 30th of July 2015, from 9:00 to 12:00 and 14:00 to 17:00. The subjects were selected randomly for all of the locations. In total, the survey

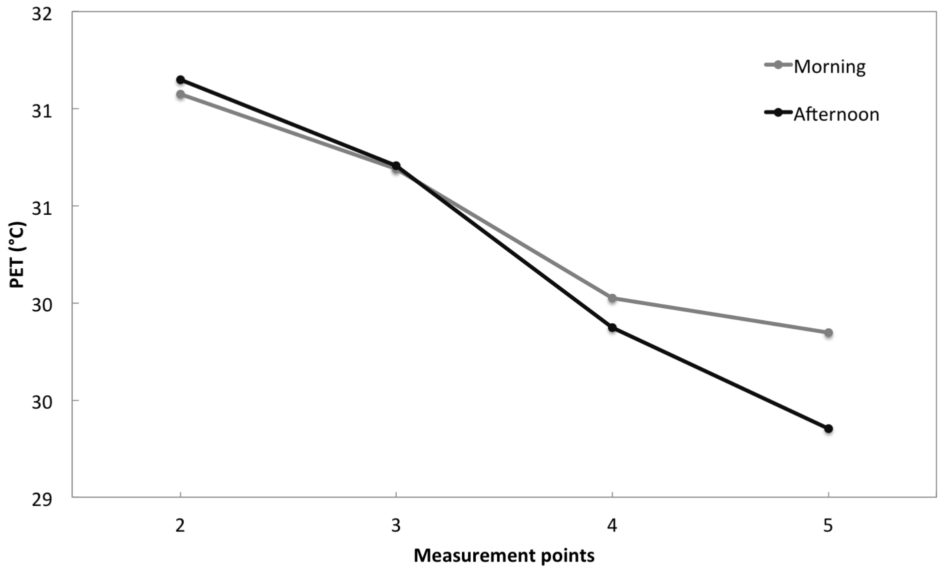


Figure 4.14 – *Average PET (°C) values for the whole year in all four measurement points.*

Table 4.5 – *PET (°C) values for afternoon hours (12:00–18:00) for the whole year.*

Point	Minimum	Maximum	Average
2	28.4	34.1	31.1
3	28.1	34.2	30.7
4	26.8	31.7	29.9
5	26.0	31.6	29.4

obtained a sample of 577 interviews, 352 in the mornings and 225 in the afternoons, with an average of 144 people per day. The frequency in the morning was higher than in the afternoon (the average in the morning was 88 people per day, versus 56 in the afternoon).

The survey campaign interviewed only students, whose average age was 20 years old, with 62% males and 38% females. In order to include the potential health risks of participants, the average Body Mass Index (BMI) was determined for each person. A BMI under 16 indicates low weight, and a BMI over 30 indicates an overweight person. It was important to collect this information because the thermal sensation could be affected by metabolism. For this study, the BMI of participants interviewed ranged from 14 to 36, but outliers represent only 3.5% of the sample. Additionally, the questionnaire results showed that 60% of the people have always lived in Barranquilla, which implies that this percentage of people interviewed are thermally adapted to the local climate.

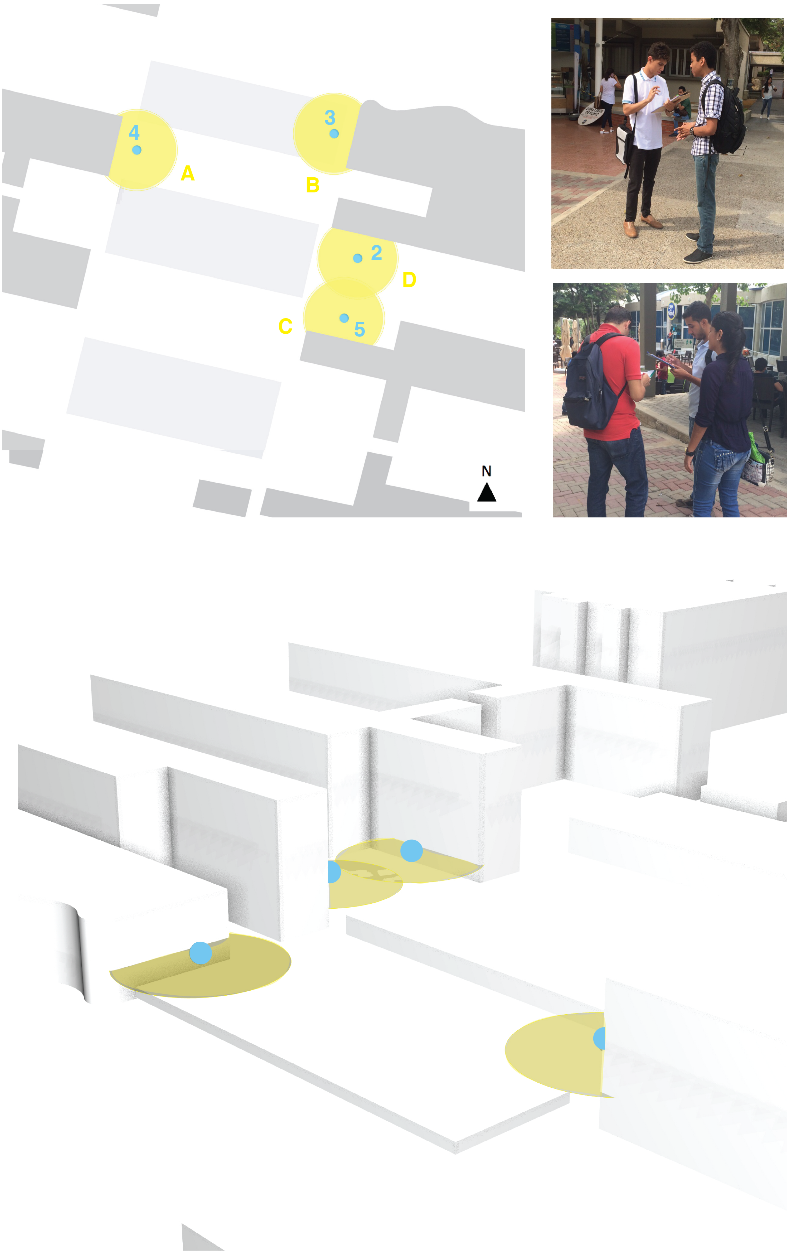


Figure 4.15 – *Survey campaign locations with corresponding weather stations.*

4.2.2 Thermal sensation results compilation

The results of the thermal sensation questionnaire were first documented in absolute values of people that participated and answered the questionnaire. During the survey campaign, the number of people who answered the survey was higher during the morning session. This was observed every day, at each location. Therefore, it was necessary to consider the results in relative values (%).

Figure 4.16 shows the results of the thermal sensation at point A in relative values. The results of point A show that the highest percentage thermal sensation, for both morning and afternoon, was 'slightly hot – 1' (29.9% and 29.4%, respectively). This graph also shows a tendency toward the thermal sensation 'hot – 2' during the morning, where people were exposed to the sun. During the afternoon, the percentage of people who said 'not cold or hot – 0' is 11 percentage points higher compared to the morning period. This can be explained as a result of the solar exposure. Similarly, the neutral thermal sensation is the second most selected option during the afternoon. The shadow exposure might explain this result.

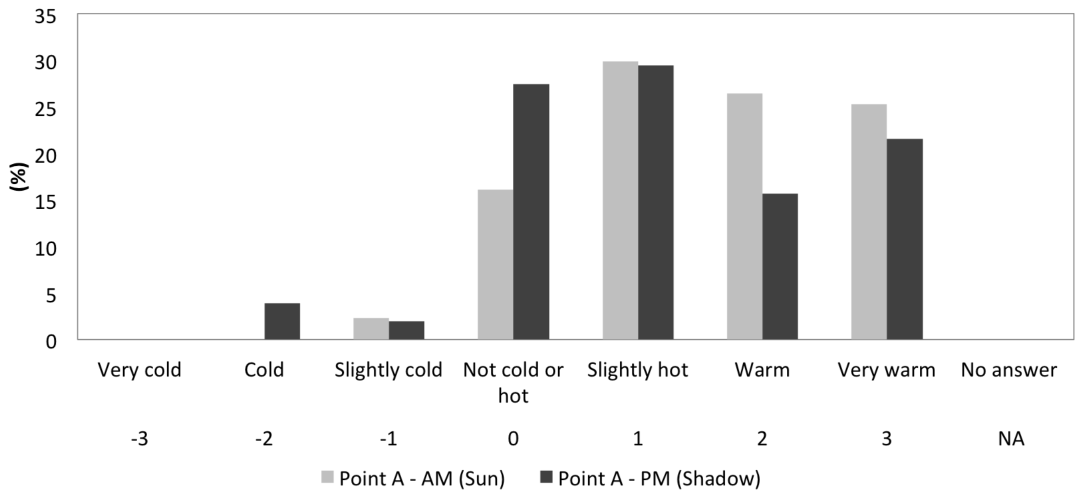


Figure 4.16 – *Thermal sensation survey result in point A.*

At point B (Figure 4.17), for both morning and afternoon, the percentage of thermal sensation responses of 'heat – 2' are greater than at any of the other positions. This response is persistent throughout every day of the survey campaign period. In this case, people had less perception of the effect of shade or sun exposure.

Differing from the previous two locations, at location C (Figure 4.18) the difference between the number of participants is not much higher, at only 8% (11 people). At location C, the predominant thermal sensation during the morning was 'warm – 2', while in the afternoon the predominant feeling was 'not cold nor hot – 0' (neutral). This result could be attributed to the conditions of this site, where the shadow of the afternoon came mainly from trees and not buildings. Taking into consideration the surroundings of this location, external elements

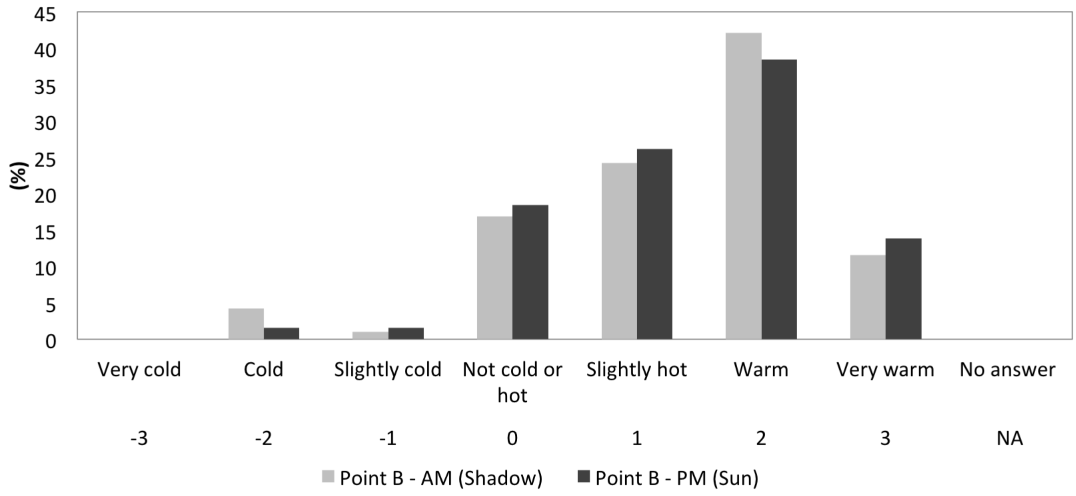


Figure 4.17 – *Thermal sensation survey result in point B.*

could have affected the results. In this location, the control of the constant variables was more challenging due to trees and cars.

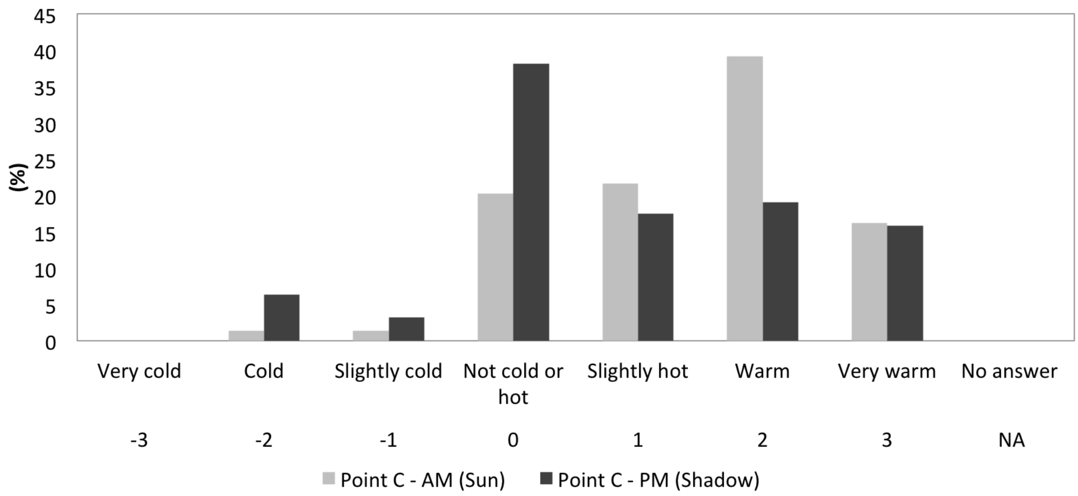


Figure 4.18 – *Thermal sensation survey result in point C.*

At location D (Figure 4.19), the tendency toward warm thermal sensation was higher than at the other locations. However, there is a difference between the morning and afternoon thermal sensation. While in the morning the 'warm – 2' thermal sensation is predominant, in the afternoon people felt 'very warm – 3'. It is important to highlight that during the afternoon people were exposed to sunlight, which is the likely cause of the difference in thermal sensations, even though the tendency remains warm.

To analyse and compare the survey results between all locations, it was important to divide the information into morning and afternoon categories, the same division for the PET

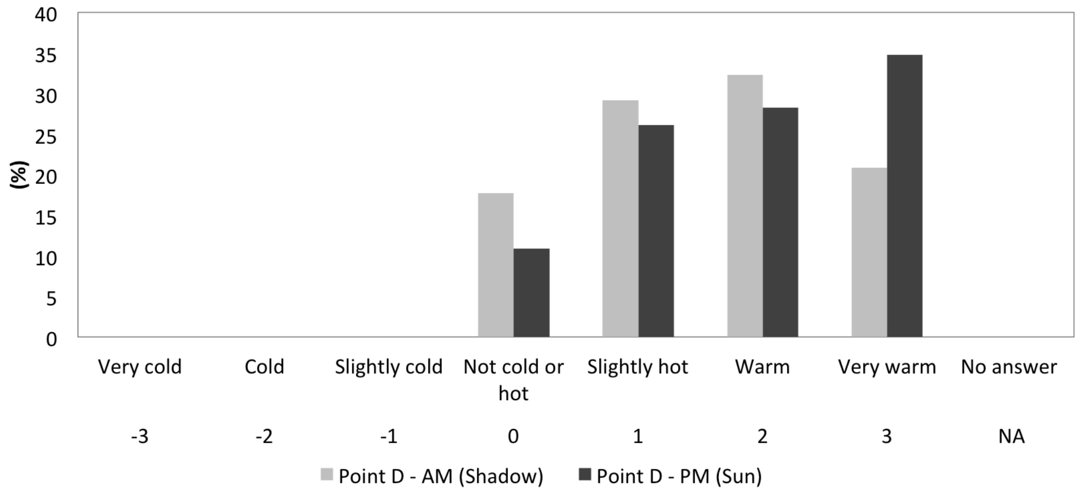


Figure 4.19 – *Thermal sensation survey result in point D.*

calculations described in Section 4.1. Table 4.6 shows the percentages of responses for each ranked position on thermal sensation (very warm, warm, slightly warm, neutral, slightly cold, cold, very cold) for each location during the morning period, and Table 4.7 for the afternoon period.

Table 4.6 – *Survey responses for morning hours (9:00–12:00) in relative values (%).*

Location	Very warm (3)	Warm (2)	Slightly warm (1)	Neutral (0)	Slightly cold (-1)	Cold (-2)	Very cold (-3)
A	25.3	26.4	29.9	16.1	2.2	0	0
B	11.6	42.1	24.2	16.8	1.1	4.2	0
C	16.2	39.2	21.6	20.3	1.4	1.4	0
D	20.8	32.3	29.2	17.7	0	0	0

Table 4.7 – *Survey responses for morning hours (14:00–17:00) in relative values (%).*

Location	Very warm (3)	Warm (2)	Slightly warm (1)	Neutral (0)	Slightly cold (-1)	Cold (-2)	Very cold (-3)
A	21.6	15.7	29.4	27.5	2.0	3.9	0
B	13.8	38.5	26.2	18.5	1.5	1.5	0
C	15.9	19.0	17.5	38.1	3.2	6.3	0
D	34.8	28.3	25.5	10.9	0	0	0

Looking, for instance, at the responses in Table 4.6, the numbers show that participants feel significantly more warm in location A, which represents measurement point 4. In Table 4.7, the higher percentage for the same response (very warm) shifts to location D, corresponding to measurement point 2. Looking at this single correlation, the locations with warmest thermal sensation, according to the survey, are related to the locations with more sun exposure (south and east orientation) (Figure 4.15).

Taking relative values (%) of the responses during the morning period for each location, Figure 4.20 shows that the majority of people responded ‘very warm’ in location A (oriented

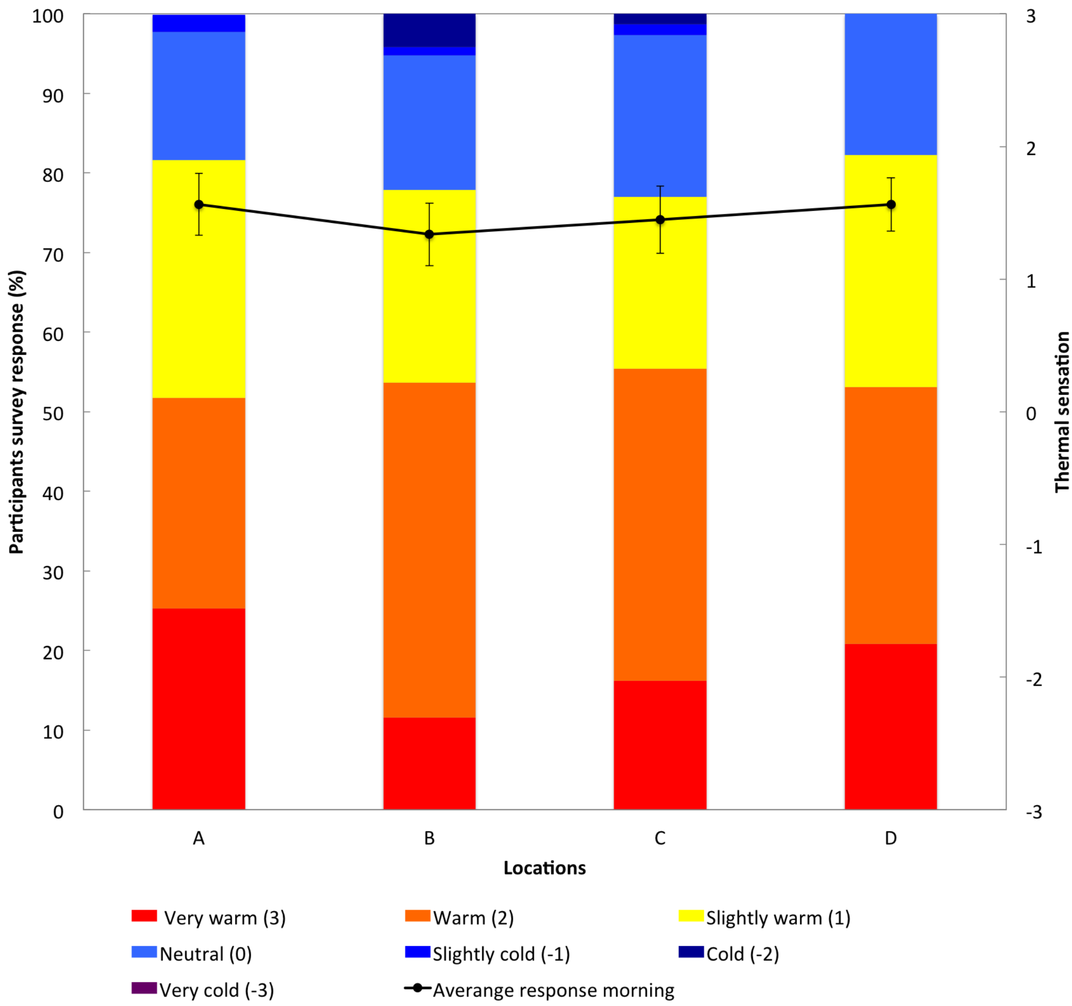


Figure 4.20 – *Survey responses on thermal sensation with percentages (%) of responses for each location, and the average values during morning hours.*

east), 'warm' in location B (oriented west), 'slightly warm' in location A, and 'neutral' in location C (oriented north). The responses of 'slightly cold' and 'cold' are pronounced in location B. Location D had the most homogeneous responses for the first four options (3 to 0). Figure 4.20 also illustrates the average responses for each location, where it is shown that location B has the lowest average because of the high percentage in responses of 'neutral', 'slightly cold', and 'cold'. On the other hand, location A and D have the highest average correlated to the highest number of 'very warm' responses for A and the homogeneous responses of location D from 'very warm' to 'neutral' (3 to 0).

Similarly to Figure 4.20, Figure 4.21 illustrates the percentages of the responses for each location for the afternoon hours. The graph in Figure 4.21 shows that the majority of people responded 'very warm' in location D (oriented south), 'warm' in location B (oriented west), the 'slightly warm' response is homogeneously distributed in all locations, and 'neutral' in location

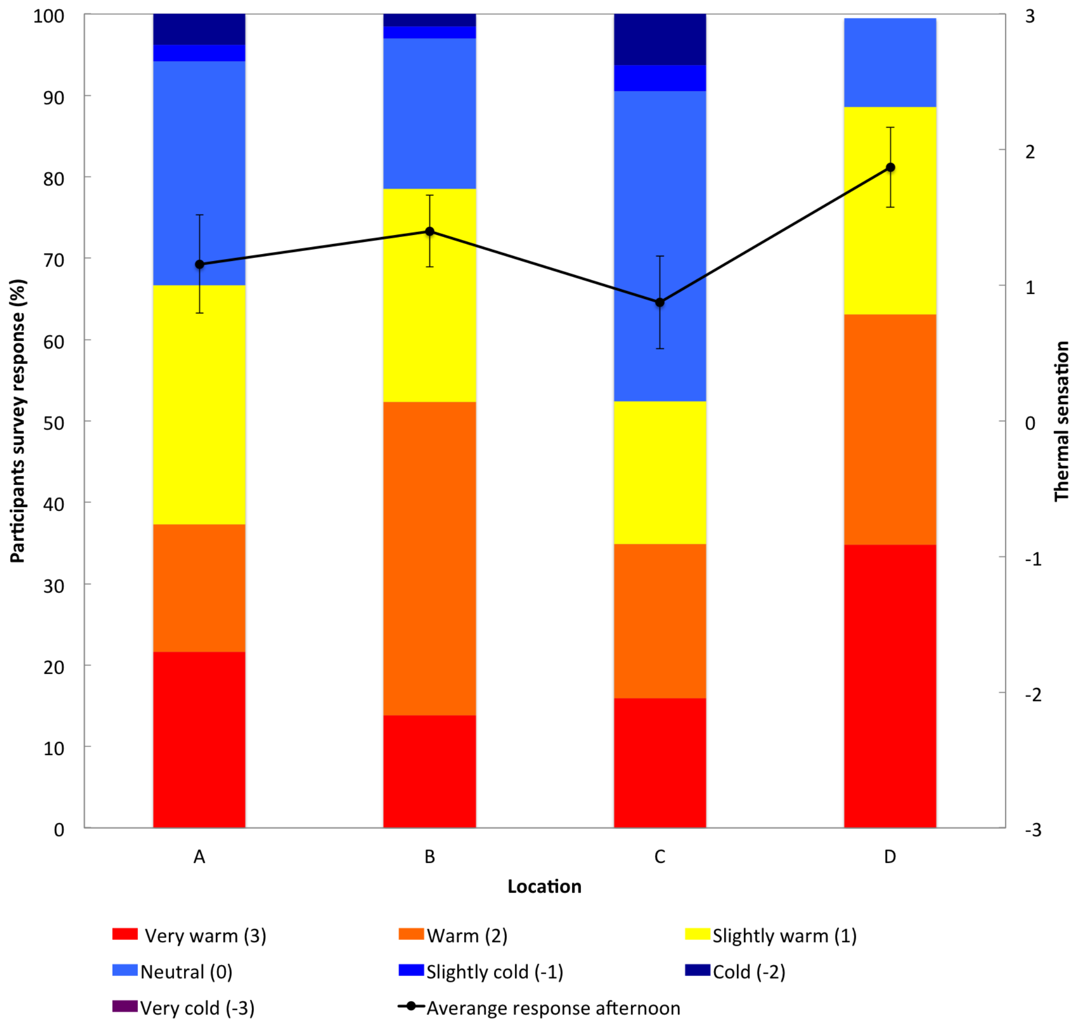


Figure 4.21 – *Survey responses on thermal sensation with percentages (%) of responses for each location, and the average values during afternoon hours.*

C (oriented north). The responses of 'slightly cold' and 'cold' are pronounced in location C. Location D again had the more homogeneous responses throughout the first three options (3 to 1). This graph also illustrates the average responses for each location, showing how location C has the lowest average because of the high percentage in responses of 'neutral'. On the other hand, location D has the highest average due to the highest number of 'very warm', 'warm', and 'slightly warm' responses.

Between the graphs in Figure 4.20 and Figure 4.21, the tendency of the responses for locations B, C and D are the same, while location A decreases in percentage for responses of 'very warm and 'warm'. Another significant change is the increase in percentage of the 'neutral' response for location C. By comparing the average values for each location, an inverse situation is created due to the positioning of the sun and the creation of opposite shadows between the morning and afternoon, as seen in Figure 4.15.

4.3 Correlations between PET and thermal sensation

For the correlation between the PET and the thermal sensation results, the PET values from the period in which the survey campaign was executed are selected. This period ranges from the 27th until the 30th of July 2015. The data selected per day is the same as the two time periods from the survey campaign (morning from 9:00 to 12:00, and afternoon from 14:00 to 17:00).

Taking both sets of results, Table 4.8 compiles the averages for each location and measurement point for the morning hours, and Table 4.9 for the afternoon hours. These values show that during the morning, the highest average of responses (thermal sensation) corresponds with the highest PET number for location 2/D. This means that people felt warmer in the same location where the model calculated the highest temperature feeling. However, the lowest values between the two variables are not equivalent. The lowest average PET value is also one of the highest thermal sensation average values. For the case of the afternoon hours, the lowest value for PET corresponds to the lowest values of thermal sensation in location 5/C. The highest value of PET corresponds to the second highest value of thermal sensation in location 3/B. Taking the average values of the whole day for both, PET and Thermal sensation, it is shown that the highest values are for 2/D and 3/B. However, by taking the average value of PET for the whole year, it is shown that point 2/D has the highest values for both, PET and Thermal sensation. Table 4.10 illustrates this correlation.

Table 4.8 – *Average values of thermal sensation and PET (°C) during morning time (9:00–12:00).*

Point	Location	Average responses on thermal sensation (-3 to 3)	Average PET (°C)
2	D	1.6	33.6
3	B	1.3	33.6
4	A	1.6	33.0
5	C	1.4	33.1

Table 4.9 – *Average values of thermal sensation and PET (°C) during afternoon time (14:00–17:00).*

Point	Location	Average responses on thermal sensation (-3 to 3)	Average PET (°C)
2	D	1.9	30.9
3	B	1.4	33.0
4	A	1.2	29.6
5	C	0.9	29.1

Table 4.10 – *All day average values of thermal sensation and PET (°C), and average PET (°C) for all year.*

Point	Location	Average responses on thermal sensation (-3 to 3)	Average PET (°C)	Average PET (°C) all year
2	D	1.8	32.3	31.1
3	B	1.4	33.3	30.7
4	A	1.4	31.3	30.0
5	C	1.2	31.1	29.8

The graphs in Figure 4.22 and Figure 4.23 show the percentages of responses for each location by ranking (3 to -3) with the average PET values for the morning and for the afternoon.

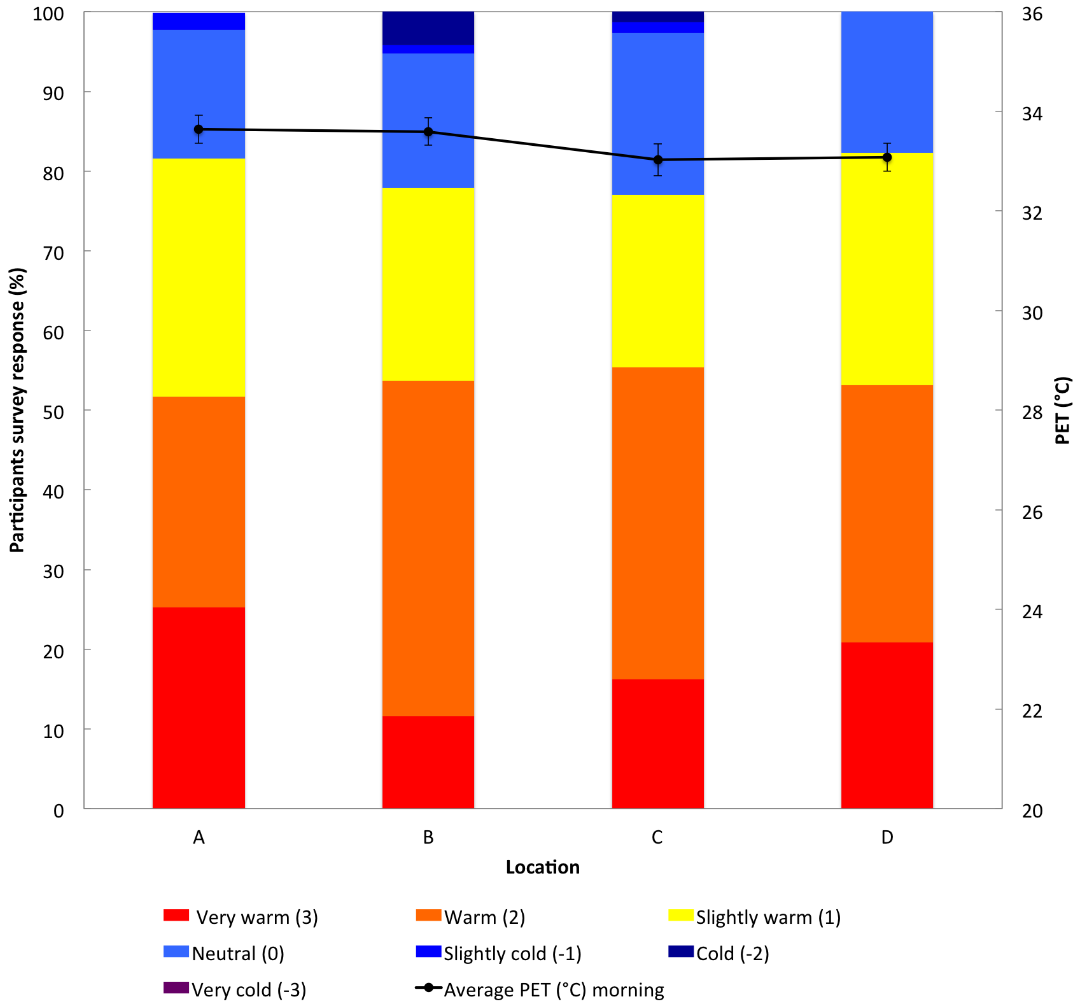


Figure 4.22 – *Survey responses on thermal sensation and PET average values for each location, and the average values during afternoon hours.*

In Figure 4.22, the lowest average PET in location 5/C corresponds with the large percentage of 'cold' responses. On the other hand, Figure 4.23 shows the two highest PET averages in location B and D, which can be related to the height percentages of the 'warm' and 'very warm' responses.

The day of the 30th of July is selected to have a detailed sample to calculate the correlation factor between the thermal sensation and the PET values. The values are graphed, and a linear regression is calculated for each of the locations as shown in Figure 4.24 for morning hours, and in Figure 4.25 for afternoon hours. One limitation is that the answers of the questionnaire and the PET values are chronologically ordered, but do not correspond to exact times. Additionally, the number of answers and the number of PET data points is not the same, and therefore, the data needed to be distributed equally to maintain the chronological order. The correlation factor for both morning and afternoon is not higher than 0.1, which

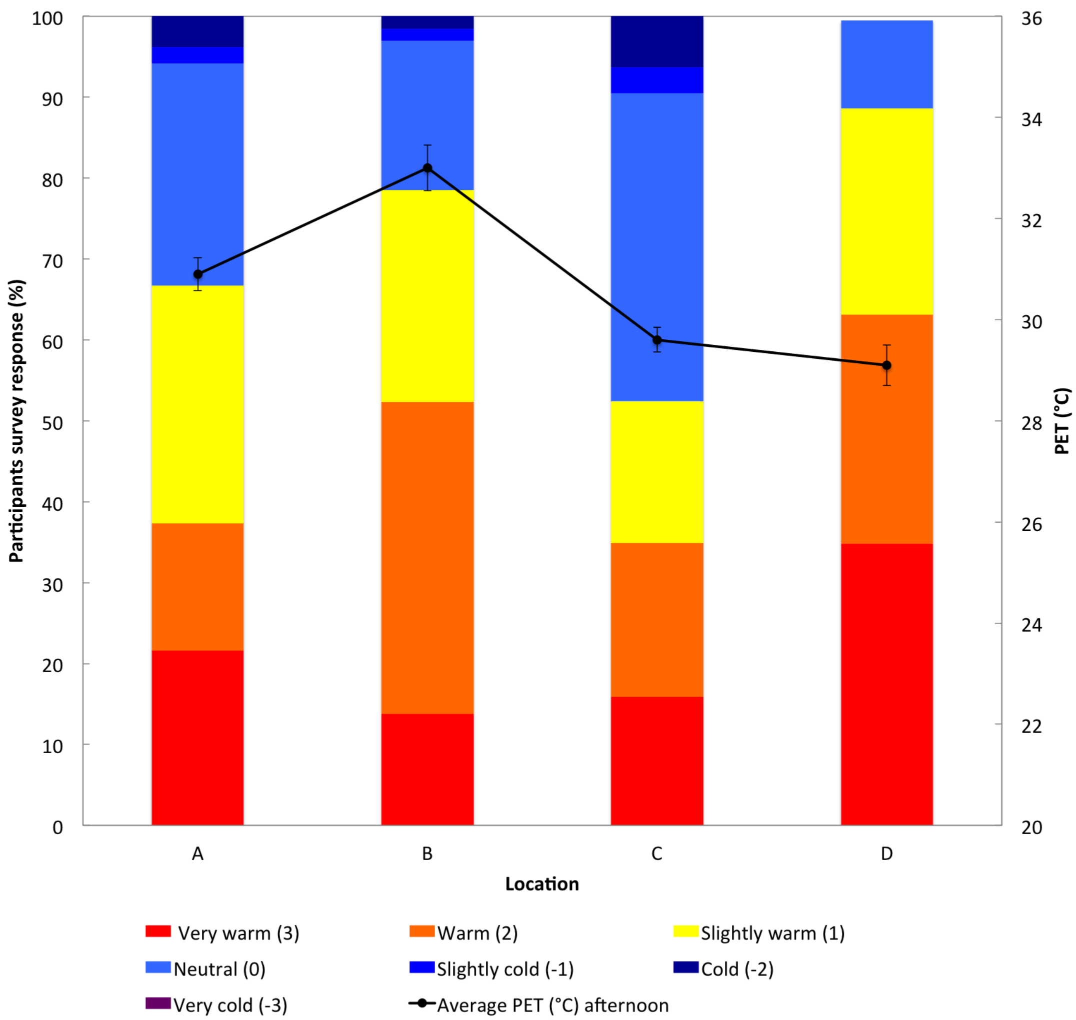


Figure 4.23 – *Survey responses on thermal sensation and PET average values for each location, and the average values during afternoon hours.*

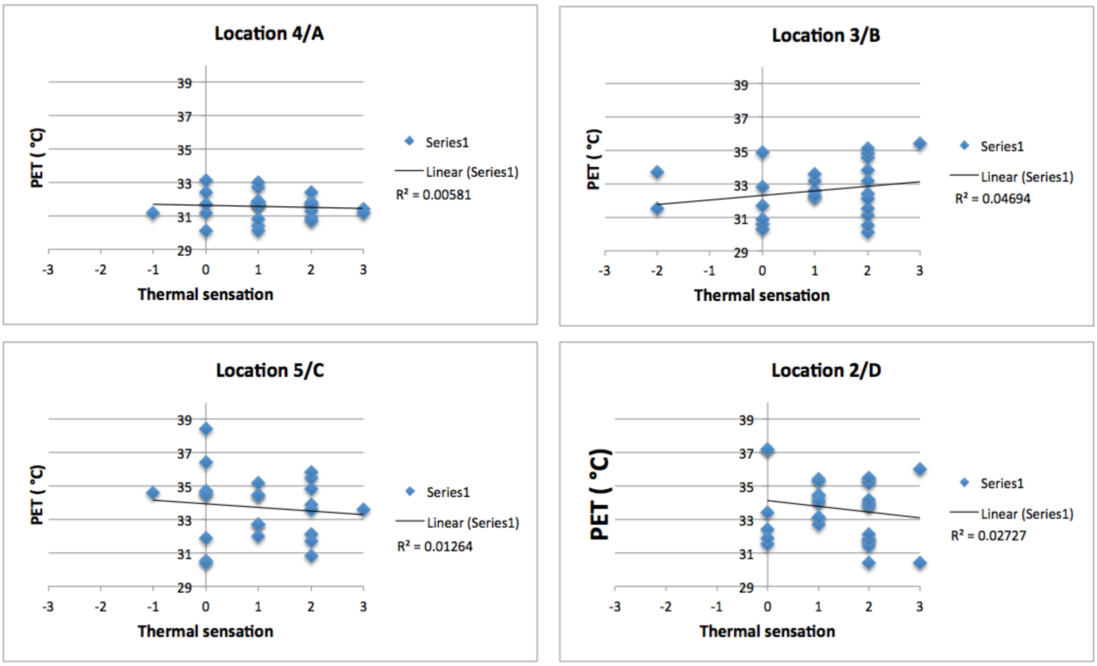


Figure 4.24 – *Linear regression for thermal sensation and PET correlation during morning hours.*

means that the correlation is bad, in a range from 0 (bad) to 1 (good).

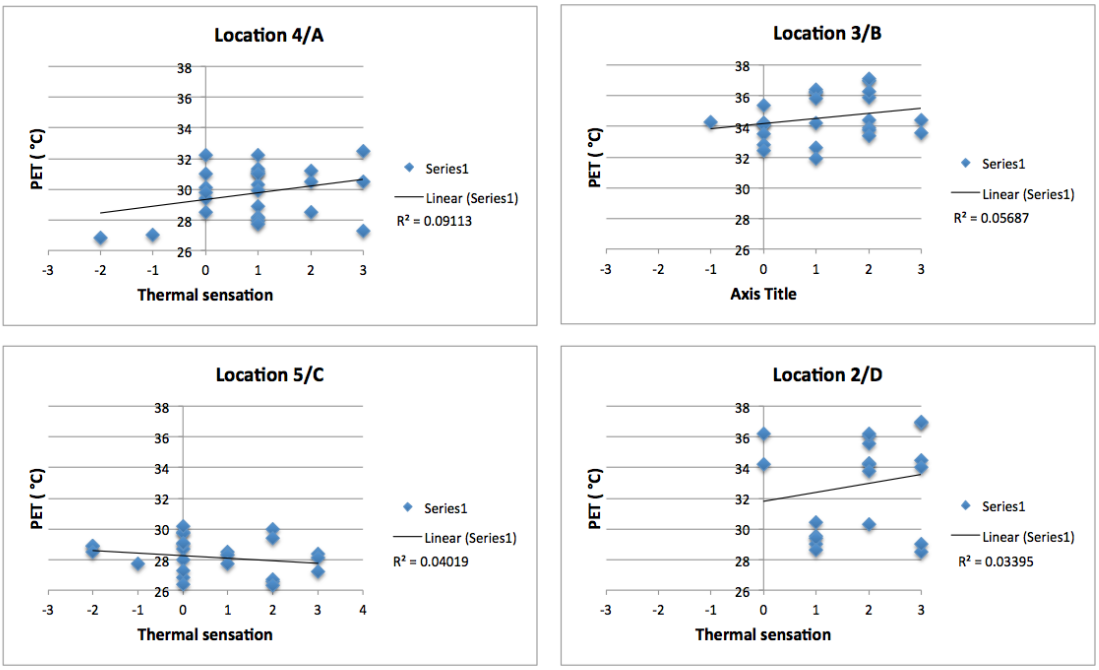


Figure 4.25 – *Linear regression for thermal sensation and PET correlation during afternoon hours.*

4.4 Conclusions

Chapter 4 was divided into three main parts: the PET analysis, the thermal sensation analysis, and the correlation between PET and thermal sensation. The PET analysis gathered the calculations of the PET in four different measurement points of the local case study area for a period of a year, from October 2014 to September 2015. The final results showed that the highest average PET values for the whole year, for both for morning and afternoon, correspond to the measurement point 2. This relation resulted from the position of point 2 facing south, thus obtaining the highest exposure to sunlight during the day.

The result of the thermal sensation analysis showed that location D, which is the same as measurement point 2, obtained the highest percentage of responses toward ‘warm’ and ‘very warm’ for both morning and afternoon. This result can also be explained with the orientation of this location facing south, thus receiving the highest exposure to sunlight during the day.

The finding from the correlations between PET and thermal sensation show some similarities. During the morning hours, the highest average of responses (thermal sensation) corresponds with the highest PET number for location 2/D. This means that people felt warmer in the same location where the model calculated the highest temperature feeling. This result shows again that the location 2/D has the highest value of PET and thermal sensation. However, the lowest values between the two variables are not equivalent. The lowest average PET value is also one of the highest thermal sensation average values. For the case of the afternoon hours, the lowest value for PET corresponds to the lowest values of thermal sensation in location

5/C. The highest value of PET corresponds to the second highest value of thermal sensation in location 3/B, meanwhile the highest values of thermal sensation correspond to point 2/D.

Even though the average values of both PET and thermal sensation show similarities between each other, a detailed analysis of one day in the year showed that this correlation is bad, with a correlation factor no more than 0.1.

Recent research on PET in tropical climates [60, 29, 28, 89], show that the climatic conditions affect, in different ways, the thermal comfort of people depending on the geographical location. For instance, these studies present that in some cities people have more tolerance to wind speed and in other cities people tolerate more humidity and air temperature [60]. As a result, studies show that it is important to take into consideration the thermal adaptation of humans according to their environmental. Thermal adaptation in different geographical locations reveal that local climate conditions must be considered when dealing with thermal comfort.

With the results from the local-sacle analysis of Barranquilla presented in this chpates, it is possible to analyse the human thermal adaptation, based on climate conditions, by selecting the measurement point/location that had the highr responses closer to neutral (0) during the time of the day without shadows (total sun exposure). In this case, the location with comfortable thermal condition (neutral) is point/location A. With the location A identified, the weather data for this point for the month of July shows that location A, which corresponds to measurement point 4 (table 4.8 and 4.9), has the lowest relative humidity values, the highest temperature values and the second highest wind speed value (figures 4.4, 4.5 and 4.6). Therefore, this values show that people in Barranquilla are adapted to humidity and air temperature, and wind is a very important factor that greatly affects the thermal sensation of people. This results show the same conclusion for the city of Taichung, Taiwan in a previous study [58]. Taichung is locate 24 °09'N and Barranquilla is located 10 °57'50"N, and both in the global tropical zone. The research study for the city of Taichungfrom [60] analysed also the thermal sensation of Lisbon and shows that the city, which is not located in the global tropical zone, people tolerate more the wind conditions rather than humidity and hight temperatures.

A part form the effect of weather conditions on the thermal adaptation of people, the results obtained in the local-scale analysis can also be use to stablish a first approximation of the PET ranges for Barranquilla, Colombia based on thermal sensation. The average responses for all locations (measurement points) were 1 (slightly warm). At the same time, the average PET values calculated ranged from 31 – 33 (°C). Therefore, table 4.11 shows the PET values in responses 1 (slightly warm), and minus 4 degrees for 0 (neutral / comfortable) and plus 4 degress for 2 (warm), assuming that 4 degree less/more is the range for 0 and 2. Figure 4.11 also shows the PET ranges of other geographical locations in the world based on previous similar studies [62, 61, 67]. Comparing the different values in this table, it is shown that the values more similar to Barranquilla are those for Taiwan. This can be explained by the geographical location of both near the equator line and in the tropical zone, condition that also explains the thermal adaptation factors explained in the previous paragraph. This results still need further statistical analysis but can be use as a first approximation.

Table 4.11 – *Thermal sensation and PET ranges for Western/Middle Europe [62], Taiwan [61], Sao Paulo [67] and Barranquilla*

Thermal Sensation	PET Western-Middle Europe	PET Taiwan	PET Sao Paulo	PET Barranquilla
Very cold	-	-	-	-
cold	<13	<22	<12	-
Slightly cold	13 - 18	22 - 26	12 - 18	< 25
Comfortable	18 - 23	26 - 30	18 - 26	27 - 31
Slightly warm	23 - 29	30 - 34	26 - 31	31 - 33
Warm	29 - 35	34 - 38	31 - 43	33 - 37
Very warm	>35	>38	>43	>37

In tropical climates, the effect of the “shadow umbrella” can be applied to improve thermal comfort in outdoor environments. Previous studies confirm the effect of the “shadow umbrella” to improve thermal comfort in outdoor environments in tropical climates [34, 29, 28]. The case of the local-scale analysis in Barranquilla was designed specially to study the effect of showing based on orientation (north, sought, east and west), and the effect of the wind direction formed by street canyons. Results showed and confirm the importance of shadowing and wind in tropical climates.

5 City scale analysis

The city scale analysis aims to extend the OTC research to the city of Barranquilla, from a local scale to a city scale. This second part of the overall research is based on the validation process from the local-scale analysis (previous chapter), and is designed to collect OTC data from citizens around the city. For this purpose, a crowdsourcing project was developed. This chapter describes in two parts the city scale approach. The fist part describes the OTC crowdsourcing project and presents the results and analysis of this initiative for the city of Barranquilla. The second part is the conclusion from the previous analysis, and an outlook for the crowdsourcing project.

5.1 OTC crowdsourcing project

As described in Chapter 2, the term *crowdsourcing* is traditionally defined as obtaining data or information from a large number of people. These days, the term often refers to obtaining information from a range of individual devices, such as smartphones, and typically sent via the internet. *Crowdsourcing* is a powerful resource for innovators [98], as it uses citizens as subjects of this data collection process for supporting decision-making in city planning. Moreover, these technological advances can bring about the next generation of participatory planning: *citizen-design science* (c.f. Section 2.4).

The previous chapter describes the two methods for studying the OTC on a local scale. The aim was to validate and compare the results of these two methods, which are based on different data sources: qualitative data (thermal sensation surveys), and quantitative data (PET calculations from weather data). In this case, both methods are feasible due to the local-scale conditions, especially the low number of measurement points. For such a project, the fact that only five weather stations were needed made the monitoring and maintaining of the equipment possible. Likewise, the survey campaign was also possible considering that the project aimed to study only four locations. By the end, the results of the OTC from the two methods were compared and the results showed that both methods arrived at similar results.

However, this type of OTC research becomes more complex when considering a larger case study area such as a whole city. For that reason, a crowdsourcing project was developed based on the thermal sensation data collection process from the previous local-scale project.

5.1.1 *Proyecto confort* (comfort project)

The need to understand the OTC in the city of Barranquilla is based on the latest rises temperature that are affecting the citizens and their daily outdoor activities. According to the IDEAM (Institute of hydrology, meteorology and environmental studies of Colombia) the average temperature in Barranquilla for the month of May is normally 33.5°C. However, this year (2016), the average temperature increased to 34.6°C. The city faced a heat wave in which temperatures reached 37°C, with a thermal sensation of 48°C. This situation has been predicted, raising discussions to introduce new tools and research projects that will support the understanding of this phenomenon.

Regarding the research outlined in this thesis, a workshop was organized in February 2016 aimed to provide discussions with different stakeholders within the city of Barranquilla on how to extend the local-scale OTC project into the city (see more about this workshop in Chapter). As a result of the discussions, a crowdsourcing project was proposed and supported by a working group made up of the stakeholders participating in the workshop and representing different city institutions and universities. The project was developed and named *Proyecto confort*, 'comfort project' in English, and aimed to develop a smartphone application to collect thermal comfort data from citizens.

In order to have the same age group of participants, the project was promoted only in universities. The promotion campaign was designed as a marathon with a winning prize as an incentive for participants. Students first had to register by providing personal information such as age, weight, and gender. After the registration, each participant was assigned a user ID.

The questionnaire used in this project was based on the questionnaire used in the local-scale OTC analysis described in Chapter 4. This questionnaire was adapted and shortened in order to create a user-friendly smartphone application (Figure 5.1). Additionally, the application records: the geo-referenced location, the date, and the time.

Apart from the smartphone application, a website platform (http://www.proyectoconfort.co/) was developed to describe the project to the participants, provide video tutorials on how to use the application, and visualised the project in a map, showing where participants are responding to the questionnaire (Figure 5.3). The functions of the smart phone application can be found on a video under the following link https://www.youtube.com/watch?v=pK7_eDsai-A.

Based on the agreements during the stakeholder workshop, this first attempt to gather OTC data from citizens was defined as a pilot project, and will be adopted and developed

Termal comfort perception						
-3	-2	-1	0	1	2	3
2.1 Thermal sensation		***How do you feel at this moment in respect to temperature?***				
☐ Very cold	☐ Cold	☐ Slightly cold	☐ Neutral	☐ Slightly warm	☐ Warm	☐ Very warm
2.2 Satisfaction		***What is your satisfaction at this moment in respect to temperature?***				
☐ Satisfied		☐ Neutral		☐ Dissatisfied		
2.3 Thermal preference		***How would you like to feel at this moment in respect to temperature?***				
☐ More cold		☐ The same, no change			☐ More warm	
2.4 Humidity perception		***How do you feel st this moment con respect to humidity?***				
☐ Very humid	☐ Humid	☐ Slightly humid	☐ Neutral	☐ Slightly dry	☐ Dry	☐ Very dry
2.5 Satisfaction		***What is your satisfaction at this moment in respect to humidity?***				
☐ Satisfied		☐ Neutral		☐ Dissatisfied		
2.6 Humidity preference		***How would you like to feel at this moment in respect to humidity?***				
☐ More humid		☐ The same, no change			☐ More dry	
2.7 Wind perception		***How do you feel st this moment con respect to wind?***				
☐ No wind	☐ Slight wind	☐ Moderate wind		☐ Strong wind		
2.8 Satisfaction		***What is your satisfaction at this moment in respect to wind?***				
☐ Satisfied		☐ Neutral		☐ Dissatisfied		
2.9 Wind preference		***How would you like to feel at this moment in respect to wind?***				
☐ More wind		☐ The same, no change		☐ Less wind		
2.10 Solar exposure perception		***How do you feel st this moment con respect to the sun?***				
☐ No sun	☐ Sun	☐ Moderate sun		☐ Too much sun		
2.11 Satisfaction		***What is your satisfaction at this moment in respect to the sun?***				
☐ Satisfecho		☐ Neutro		☐ Insatisfecho		
2.12 Sun preference		***How would you like to feel at this moment in respect to the sun***				
☐ More sun		☐ The same, no change		☐ Less sun		
2.13 Thermal comfort perception			***In general, how do you feel in respect to the climate:***			
☐ Comfortable				☐ Uncomfortable		

Figure 5.1 – *Smartphone application questionnaire (translated into English).*

further by the Urban Observatory of the Chamber of Commerce of Barranquilla.

5.1.2 Data collection

The *Proyecto confort* marathon ran during two months (April and May 2016), collecting 1121 data points from all participants. The participants were all students from three different universities and range in age from 17–26 years old. As well as the local-scale projects, the city-scale data collected were also divided into morning and afternoon time periods. The morning hours ranged from 6:00 to 12:00, and the afternoon ranged from 12:00 to 18:00. After excluding the data collected out of these hour ranges, the final sample size was 883, with 403 data points for morning and 478 for afternoon (Table 5.1).

The questionnaire used for the smartphone application was divided into five sections: temperature, humidity, wind, solar exposure, and general thermal comfort (Figure 5.1). For

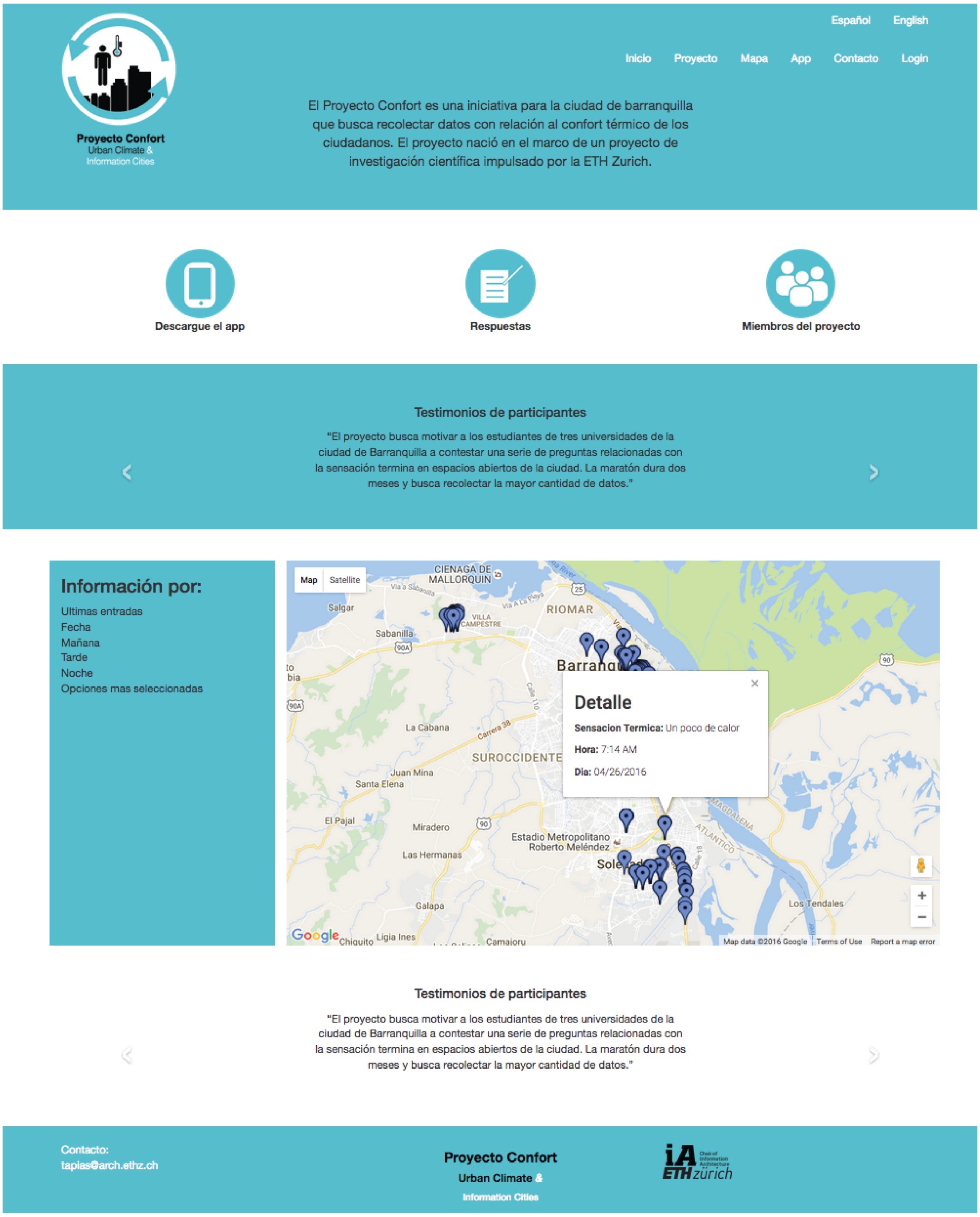


Figure 5.2 – *Website Proyecto confort (http://www.proyectoconfort.co/).*

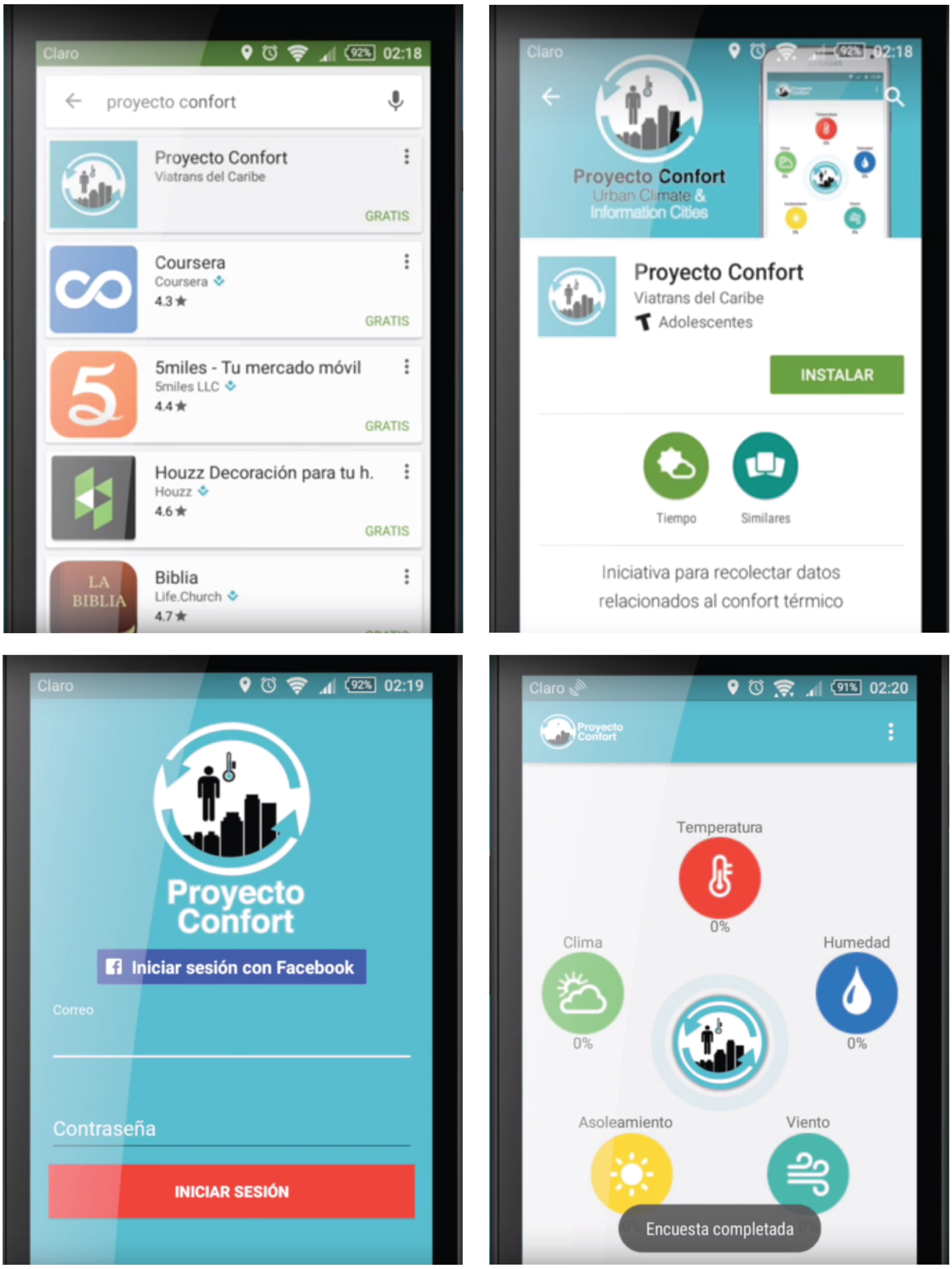


Figure 5.3 – *Screenshots of the smart phone application*

Table 5.1 – *Data points collected during marathon.*

Total data points	Data inside hour ranges	Morning hour range	Afternoon hour range
1121	883	406	478

the research outlined in this thesis, the first and the last were analysed (thermal sensation and thermal comfort perception). The thermal sensation questions used the same numeric codes for the thermal sensation responses as were used in the local-scale survey questionnaire: (3) very warm; (2) warm; (1) slightly warm; (0) neutral; (-1) slightly cool; (-2) cool; and (-3) cold. The highest relative value (%) of responses during both morning and afternoon hours was (0) neutral, followed by (1) slightly warm (Table 5.2). The last question of the questionnaire, regarding general thermal comfort, has two response options: (-3) comfortable and (1) uncomfortable. According to the responses, the thermal comfort for morning versus afternoon is reversed. During the morning hours, the higher relative value (%) of responses corresponded to (1) uncomfortable, while for the afternoon corresponded to (-3) comfortable (Table 5.3).

Table 5.2 – *Distribution of responses in relative values (%) – thermal sensation.*

Hour range	Very warm (3)	Warm (2)	Slightly warm (1)	Neutral (0)	Slightly cold (-1)	Cold (-2)	Very cold (-3)
Morning	2.4	8.5	23.2	26.8	18.3	20.7	0
Afternoon	15.3	14.3	19.4	32.7	11.2	2.0	0

Table 5.3 – *Distribution of responses in relative values (%) – general thermal comfort.*

Hour range	Comfortable (-3)	Uncomfortable (1)
Morning	27.3	33.5
Afternoon	53.8	38.4

The website platform visualises the responses of people according to their location. By clicking on a certain response, a window opens showing the thermal sensation (Figure 5.4).

5.1.3 Data analysis

A series of heat maps of the data collected from the smartphone application were created in order to graphically represent the data of the individual values. These maps are separated into morning and afternoon time periods, and are also divided according to the responses.

The first series of maps corresponds to the data collected from the thermal sensation responses. The data points are first visualised and distributed on the map according to the geo-location to provide an initial understanding of where the data was collected during the morning and afternoon. Based on this map, the heat maps illustrate the clustering of the responses. The minus values, (-1) slightly cool; (-2) cool, and (-3) cold, are gathered in one map due to the low number of data points. The other vales, (3) very warm, (2) warm, (1) slightly

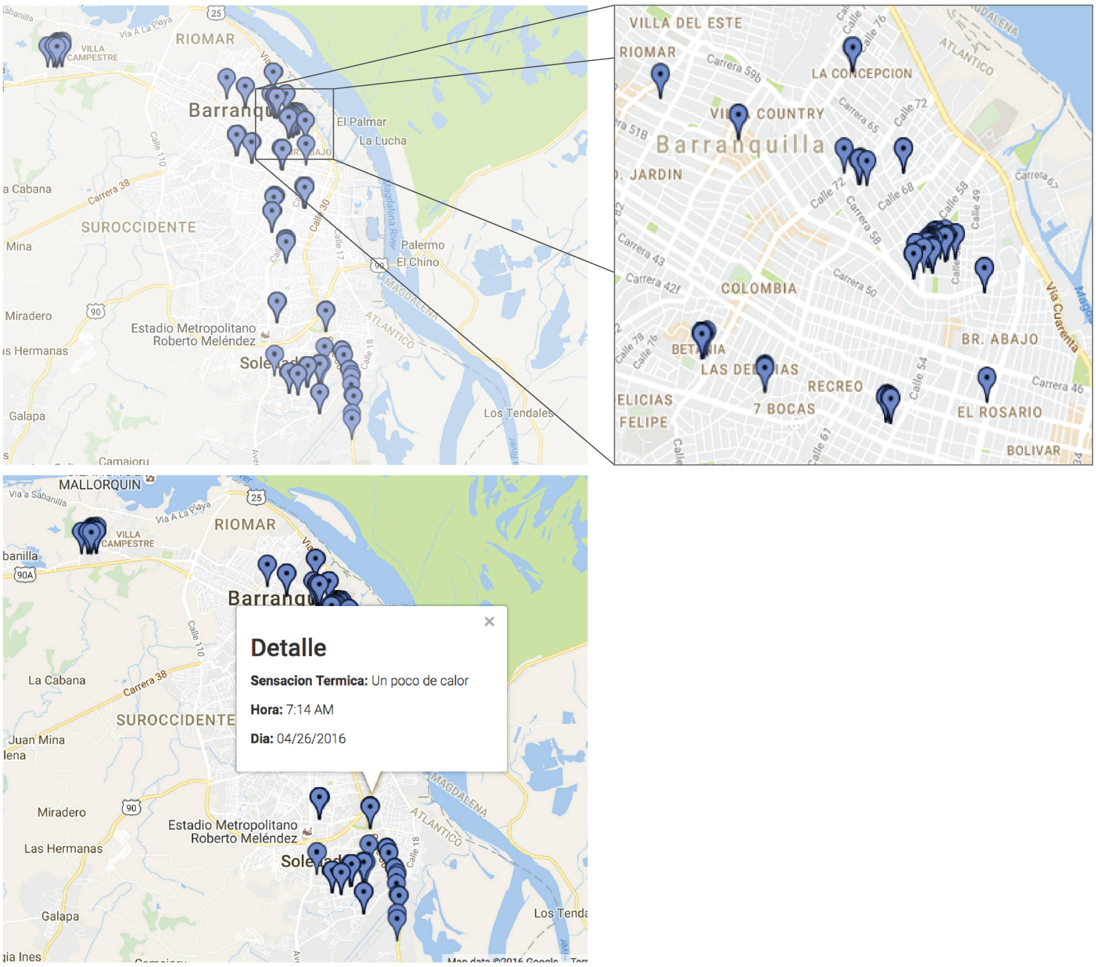
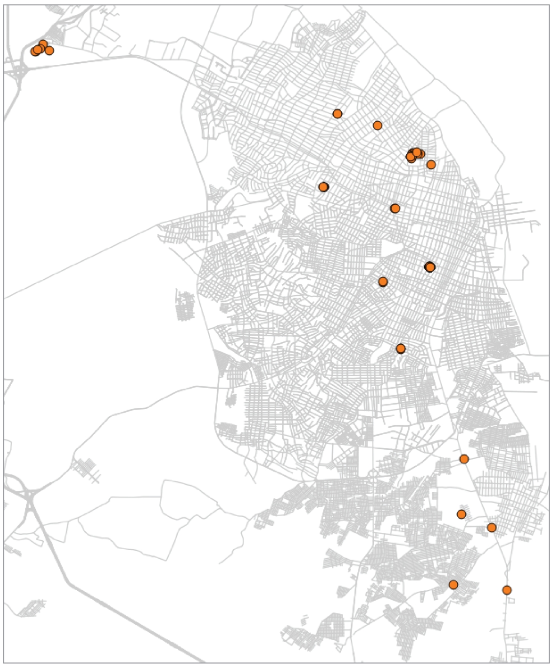


Figure 5.4 – *Website Proyecto confort (http://www.proyectoconfort.co/), map with responses.*

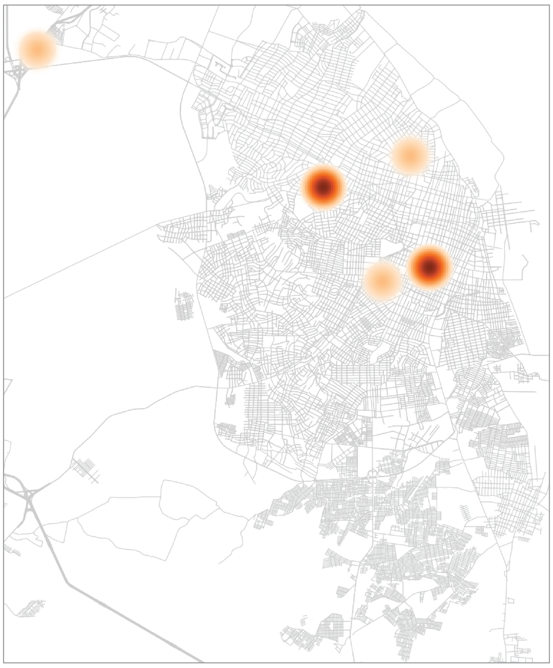
warm, and (0) neutral, are divided into individual maps.

In respect to the morning data, a common result from all heat maps is the high numbers of data collected at the same geo-location. This location corresponds to the city centre of Barranquilla. Away from this location, the concentration of responses varies. For instance, the minus values and the (0) neutral response are concentrated in the centre and north part of the city, while the (2) warm and (1) slightly warm are more equally distributed around the city, obtaining responses in the south part. The (3) very warm responses are located mainly in the centre of the city (Figure 5.5 and Figure 5.6).

Regarding the afternoon data, and in contrast to the morning data, the city centre is only the highest location of data points for the responses (3) very warm, (2) warm, and (1) slightly warm. For the (0) neutral response, the higher concentration of responses is in the northeast, while for the minus values the highest concentration is in the northwest. Another difference is that the responses of (0) neutral are more evenly distributed than the other responses. This



Responses during morning period (6:00 - 12:00)



Response -3, -2 & -1 (very cold, slightly cold & cold)

Figure 5.5 – *Geo-location of responses during morning time and heat map of -3, -2 and -1 morning responses.*

Response 0 (neutral)

Response 1 (slightly warm)

Response 2 (warm)

Response 3 (very warm)

Figure 5.6 – *Heat map of 0, 1, 2 and 3 morning responses.*

means that people feel more thermally neutral around the city and feel warmer near the city centre (Figure 5.7 and Figure 5.8).

The second series of maps corresponds to the last question of the survey: general thermal comfort perception. These data were also divided into morning and afternoon time periods, as well as by the responses (1) uncomfortable and (-3) comfortable.

For the morning hours, both maps resemble each other in regards to the magnitude of the concentration of responses in the city centre. Additionally, the two maps show very similar distributions for comfortable and uncomfortable responses, with a slightly higher distribution for the comfortable response in other parts of the city, away from the city centre (Figure 5.9).

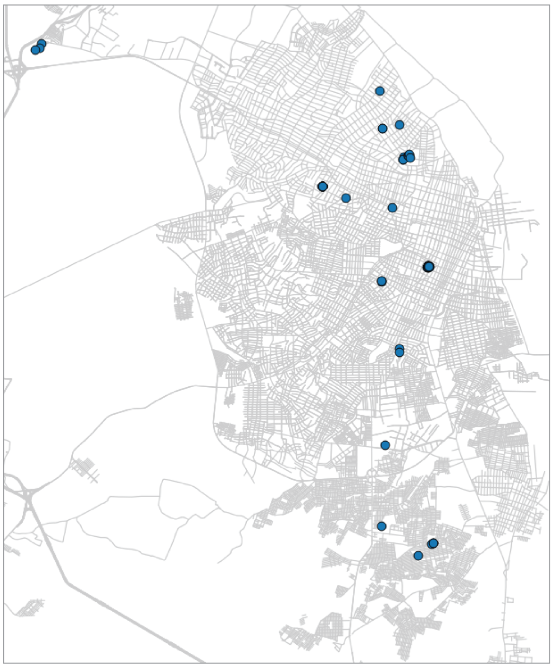
Regarding the afternoon hours, both maps also have a high concentration of responses in the city centre. The distribution of data around the city is higher for the comfortable responses with respect to the morning hours. On the other hand, the uncomfortable responses are concentrated more in the centre, in a similar way to the morning hours (Figure 5.10).

5.2 Conclusions

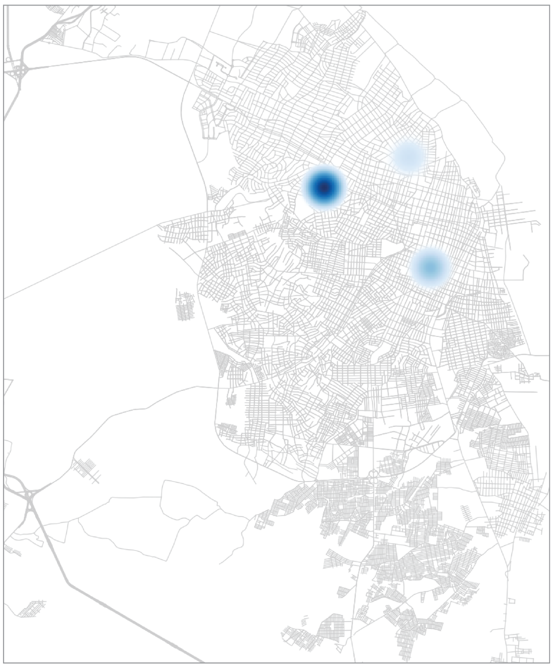
The crowdsourcing project was developed based on the local-scale projects described in Chapter 4, and was based on the discussions and the input of the working group created in one of the stakeholder workshops. The project aimed to collect OTC data of Barranquilla from the citizens in order to understand how people relate to the outdoor thermal conditions. Additionally, the data collected shows in which part of the city the people feel warmer or colder, and thermally comfortable or uncomfortable.

Results show that citizens feel warmer in the city centre. This can be explained by the higher traffic, human activity, and the lack of green vegetation (Figure 5.11). Looking at the data collected, this result can also be explained by the higher number of data points concentrated in this part of the city, which means that this location will always have a high concentration of responses. On the other hand, the differences can be identified by looking at the other responses, where the distributions change from one response category to the other. For instance, when observing the negative-sign responses, or 0 to 1, a more distributed heat map can be observed. The location with the highest concentration of minus responses (very cold to cold) is an area with a low density of buildings and with more green areas and vegetation (Figure 5.12).

Despite the consistency of the responses with some of the characteristics of the urban environment, there are a few limitations to take into account when analysing the results. During the marathon and collection of data, there were no entries in some areas of the city, for instance the centre-west part of Barranquilla. This means that there is no information about the thermal comfort of citizens in this area. Another limitation is the age group. People in different ages have a different feeling of their thermal sensation due to different physical



Responses during afternoon period (12:00 - 18:00)



Response -3, -2 & -1 (very cold, slightly cold & cold)

Figure 5.7 – *Geo-location of responses during the afternoon, and heat map of -3, -2, and -1 afternoon responses.*

Figure 5.8 – *Heat map of 0, 1, 2 and 3 afternoon responses.*

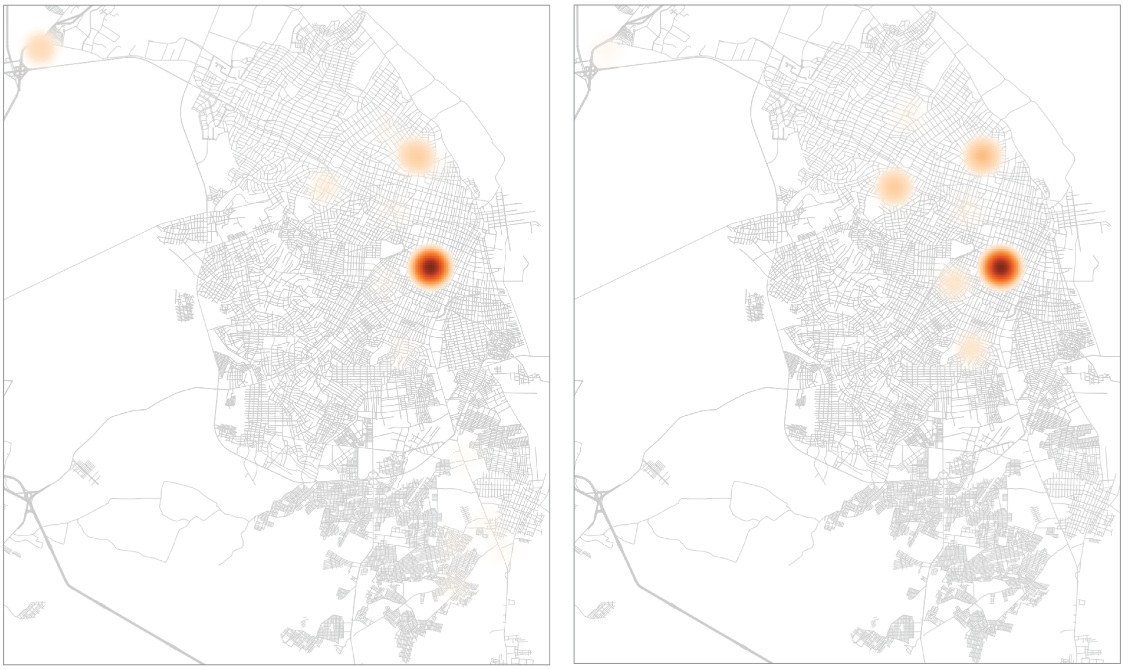


Figure 5.9 – *Heat map of thermal comfort responses during morning hours.*

characteristics such as body mass. Therefore, the results only reflect the perception of one population group in Barranquilla.

An important aspect that has to be taken into consideration is the thermal adaptation of people. The citizens of Barranquilla had always been used to the warm and humid conditions of the city, and therefore the results show that the tendency of thermal comfort is towards being comfortable and that (0) neutral responses have the most even distribution around the city. An interesting observation could occur if this survey campaign were executed during an unexpected heat wave like the one that occurred one month after (June 2016) the marathon. In this situation, the responses could change significantly, not only because of the higher temperatures, but also because of the short time that citizens would have to thermally adapt to the unexpected climate. This marathon was the fist attempt to understand the thermal perception of people in Barranquilla. A further development of this initiative to collect more data needs to be taken into consideration in order to gain improved knowledge of the situation.

The relevance of this research project relies on the understanding of the thermal comfort of citizens in a city where the temperatures are increasing. Cities need to adapt to the coming climate, and one of the first steps is to understand how the current situation is affecting the people and where in the city it is more critical. After gaining this knowledge, cities can then implement adaptation measures for future climate resilience.

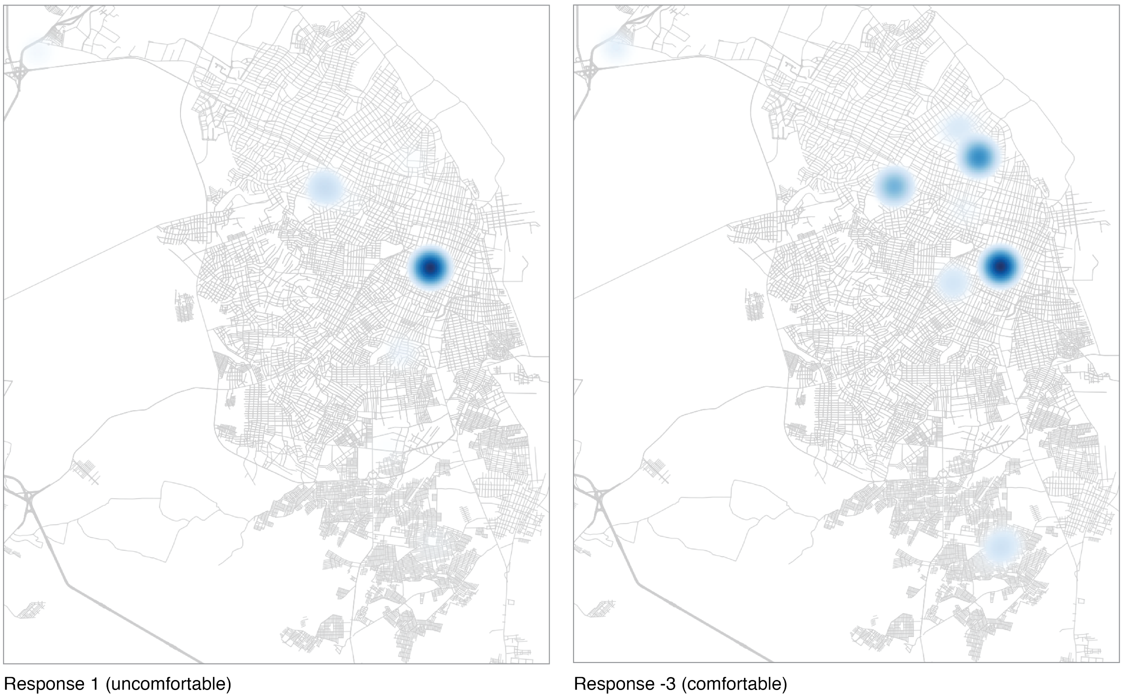


Figure 5.10 – *Heat map of thermal comfort responses during afternoon hours.*

The results and the heat maps of the thermal sensation in Barranquilla can be compared with a previous study executed by Kattia Villadiego [118]. The author developed the Local Climate Zones (LCZ) for Barranquilla (figure 5.13), based on the system proposed by Stewart & Oke [103] to classify urban forms and to describe site measurements.

One of the conclusions from the study conducted by Villadiego is the important role of temperature, solar radiation and wind speed on thermal sensation. A correlation between thermal preferences for this specific study showed a link between wind speed and solar radiation preferences and relative humidity appears as a less significant factor. The fact that relative humidity is significantly less relevant for human thermal sensation in Barranquilla, is also a main conclusion from the local case study analysis in Chapter 4. People in Barranquilla tolerate more the humidity conditions in the city due to adaptation, therefore, this condition has a low effect in the human thermal sensation.

Villadiego conducted thermal sensation survey campaigns in the numbers shown in figure 5.13 [118]. This study concluded that the zones where people felt colder are 1 and 4, neutral are 3 and 4 , slightly warm is 2, and warm are 2 and 5. By comparing these results with the heat maps created from the crowdsourcing project, it is possible to see some correlations. For instance, the responses (morning and afternoon) corresponding to cold match to zone 1, neutral to zone 3, and slight warm and warm to zone 2. Despite this similar results, there are still some areas in the city of Barranquilla that have not been yet explored and that need to be

Figure 5.11 – *City center of Barranquilla.*

Figure 5.12 – *Northwest part of Barranquilla.*

included for a more detailed thermal sensation study. Therefore, the crowdsourcing project should be developed further and apply in a second citizens marathon.

Villadiego also concluded that in order to establish comfort zones or comfort indices for tropical regions, it is necessary to enlarge the surveys about subjective thermal perception including thermal preferences [118]. Following this remark, the crowdsourcing project described in this chapter intended to develop a tool that allowed collection of massive data around the city and contribute to the study of thermal sensation and OTC in Barranquilla.

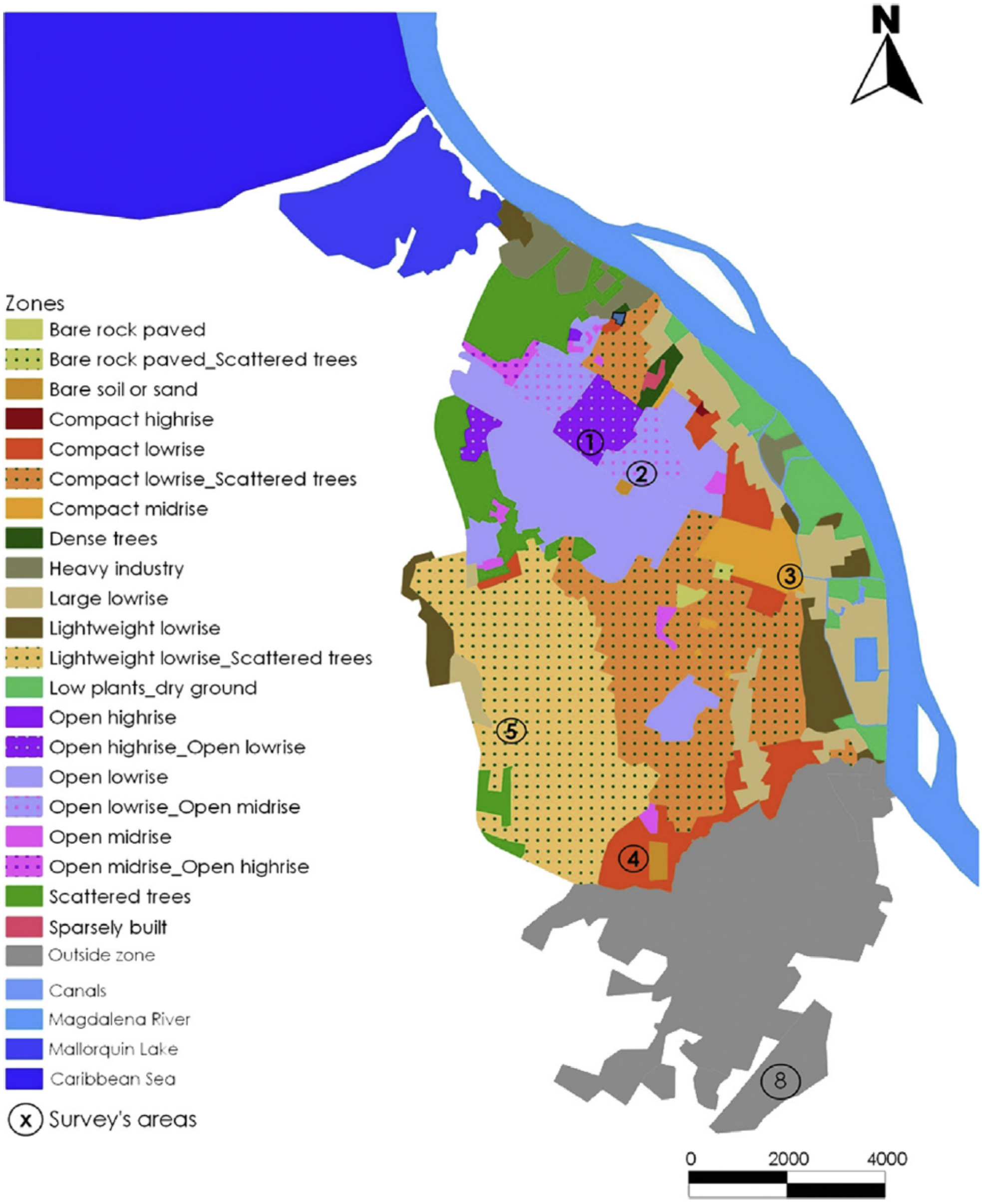


Figure 5.13 – *Local Climate Zones (LCZ) of Barranquilla with selected locations in numbers for survey campaigns.*

6 Conclusions and outlook

The climate change topic has received increased attention since the Paris agreement during COP21, and governments have been engaged to push mitigation and adaptation measures. In cities, urban climatology informs the studies of how to adapt to the coming climate. The problem arises from the lack of application within urban planning policies. Thus, it is necessary to create a bridge between urban climatology findings and urban planning adaptation measures. On the other hand, research projects intending to collect massive amounts of data can be expensive, which makes them difficult to perform outside of countries with enough resources to sponsor such initiatives. Unfortunately, countries in tropical areas, which are more vulnerable to climate change, are those with fewer resources to implement costly measurement networks for weather data collection throughout the city.

The research outlined in this thesis identified the different degrees of Outdoor Thermal Comfort (OTC) in a local-scale area by correlating qualitative data of thermal sensation with quantitative data of Physiologically Equivalent Temperature (PET). The results of this correlation allowed validation of both methodologies and served as a base to extend the OTC research to the city of Barranquilla through a crowdsourcing project called *Proyecto Confort*. Initially, data were collected from surveys and sensor technology in the local area, and using a smartphone application with a survey questionnaire for citizens, the research was extended to the city scale.

Thus, this thesis used the Internet of Things to collect the necessary sets of data to understand the Outdoor Thermal Comfort of people around the city. In recent years, these approaches have been widely used, however, only for weather data collection. Proposing a next step, the *Proyecto Confort* was designed and executed to collect data of OTC from its citizens. This crowdsourcing project interacted with the citizens by asking them how they perceive the environment in terms of thermal sensation. The results helped understand and document the OTC conditions around the city. Additionally, the project was a step forward into citizen-design science. Understanding the OTC provides policy makers with indicators for understanding the effect of the current climate conditions, and supports the development of new strategies to guide climate adaptation in cities.

Chapter 4 described the method and results of the local scale analysis, which was divided into three main parts: the PET analysis, the thermal sensation analysis, and the correlation between PET and thermal sensation. The PET analysis gathered the calculations of the PET in four different measurement points of the local case-study area for a the period of a year, from October 2014 to September 2015. The final results showed that the highest average PET values for the whole year, both for morning and afternoon, correspond to measurement point 2. This relation resulted from the position of point 2 facing south, and it obtaining the highest exposure to sunlight during the day.

The result of the thermal sensation analysis showed that location D, which is the same measurement as point 2, obtained the highest percentage of responses toward 'warm' and 'very warm' for both morning and afternoon. This result can also be explained based on the orientation of this location facing south, and receiving the highest exposure to sunlight during the day.

The findings from the correlations between PET and thermal sensation show some similarities. During the morning hours, the highest average of responses (thermal sensation) corresponds with the highest number of PET for location 2/D. This means that people felt warmer in the same location where the model calculated the highest temperature feeling. This result shows again that the location 2/D has the highest value of PET and thermal sensation. However, the lowest values of the two variables are not equivalent. The lowest average PET value is also one of the highest thermal sensation average values. For the case of the afternoon hours, the lowest value for PET corresponds to the lowest values of thermal sensation in location 5/C. The highest value of PET corresponds to the second highest value of thermal sensation in location 3/B, meanwhile the highest values of thermal sensation correspond to point 2/D.

The results and correlations of the local-scale analysis allowed validation of the two methodologies, empirical and numerical, and created a basis for the extension of the research to the city scale

Chapter 5 described and documented the results of the crowdsourcing project called *Proyecto confort*. This project was developed based on the local scale methodologies and findings described in Chapter 4. Additionally, the initial proposal of the project went through a series of iterations based on the discussions and the input of the working group created in the second stakeholders' workshops.

The aim of *Proyecto confort* was to collect OTC data for Barranquilla from the citizens to understand how people relate to the outdoor thermal conditions. Additionally, the data collected identifies in which parts of the city people feel warmer or colder, and thermally comfortable or uncomfortable.

Results showed that citizens feel warmer in the city centre. This can be explained by the higher traffic, human activity, and the lack of green vegetation around this area. Looking at the data collected, this result can also be explained by the higher number of data points concentrated in this part of the city, which means that this location will always have a high concentration of responses.

An important aspect that has to be taken into consideration for the whole research work, local-scale and city-scale, is the thermal adaptation of people. The citizens of Barranquilla had always been used to the warm and humid conditions of the city, and therefore the results show that the tendency of thermal comfort is towards being comfortable and that (0) neutral responses have the higher equal distribution around the city. An interesting observation could occur by executing this survey campaign during an unexpected heat wave like the one that occurred one month after (June 2016) the marathon. In this situation, the responses could change significantly, not only because of the higher temperatures, but also because of the short time in which citizens had to thermally adapt to the unexpected climate. This marathon wan the first attempt to understand the thermal perception of people in Barranquilla. A further development of this initiative to collect more data needs to be taken into consideration in order to gain an improved knowledge of the situation.

This thesis has proven the hypothesis stated in the Introduction chapter: correlating empirical and numerical methods of Outdoor Thermal Comfort (OTC) in a local case study area allowed validation of both methodologies, and will provided a basis to execute a crowdsourcing project to extend the study to a city scale and create knowledge concerning how citizens perceive the thermal condition in outdoor spaces in Barranquilla, Colombia.

The relevance of this research project relies on the knowledge acquired on the thermal comfort of citizens, in a city where the temperatures are increasing. Cities need to adapt to the coming climate and one of the first steps is to gather knowledge of the current situation and understand how it is affecting the people. In this way, city planners will identify the critical parts of the city that need climate adaptation strategies and develop more climate resilience urban environments.

Additionally, the studies on OTC characteristics also indirectly affect the energy performance of buildings due to the adaptation and alteration of microclimates in the city. The building energy performance topic has to be included in microclimatic studies such as the effect of urban climate on the OTC of citizens. This aspects have approached by research groups at ETH including the group of Prof. Jan Carmeliet [5, 3, 4] and Prof Arno Schlüter [37, 94, 40].

6.1 Discussion

The Outdoor Thermal Comfort (OTC) has been explored as a potential indicator to understand the urban climate, and to evaluate adaptation measures for climate change in cities.

Each person experiences the thermal conditions of a specific place at a given point in time in a different way [35]. The OTC is a study from (i) **empirical** and (ii) **numerical** methods. Empirical methods are based on the analysis of results from field surveys of pedestrians' environmental comfort. Based on the concepts derived from the outdoor human energy balance, researchers have also attempted to derive numerical methods to understand the thermal conditions people find acceptable. The empirical and numerical methods are typically used in the same research projects in order to validate the findings.

In Chapter 2, three main research gaps were identified (Figure A.1).

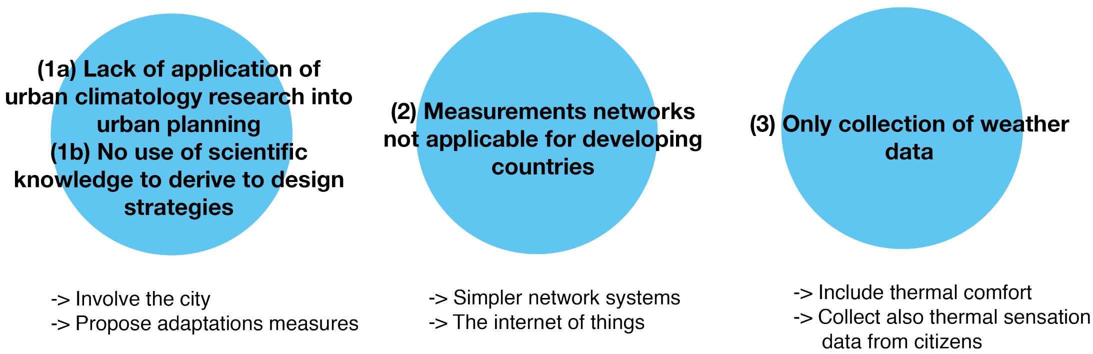


Figure 6.1 – *Summary of research gaps.*

The first research gap is the lack of application of urban climatology research in urban planning. In urban climatology, the OCT is a central topic to understand how the change in urban climate is affecting the humans living in cities. Nonetheless, the connection between the findings and the application to city planning and urban policy-making is an open question on the research agenda. Therefore, the research designed for this thesis aimed to involve different stakeholders dealing with urban development and policy-making in the city of Barranquilla. Representatives of different local government institutions were gathered in workshops to discuss and agree on the design and prototype of the methodology used in the local-scale analysis and, later on, for the crowdsourcing project. At the end, the OTC maps created by the crowdsourcing project will be used as evidence to take the *Proyecto Confort* to the next level of development. The *Proyecto Confort* is the bridge that connected the scientific knowledge with the future urban development and design strategies.

The second research gap identified in Chapter 2 was the fact that measurement networks around the world are not applicable for developing countries because of the costs of the equipment, maintenance, and data storage. Therefore, this thesis developed a project that could extend the exploration of OTC from a local scale to a city scale. The local-scale analysis aimed to correlate empirical and numerical methods for the analysis of OTC and the findings were used as the scientific basis for a crowdsourcing project. Therefore, the local-scale analysis and the crowdsourcing project (city scale) allowed the collection of large amounts of data with the use of simpler and smaller network systems supported by the Internet of Things.

The last research gap highlighted in Chapter 2 was that the use of new digital tools are only concentrated in the collection of weather data. The collection of microclimate data is important to understand how the climate is changing in different parts of cities, however, information on how this change in climate is affecting the citizens is also important. This thesis aimed to involve the citizens to improve the understanding of how the change in climate is affecting thermal comfort. The crowdsourcing project called *Proyecto Confort* is one of the first initiatives of collective massive data regarding the thermal sensation of people in cities. This project is also the first step into the citizen-design science approach that plays an essential role for new generations of cities. Cities become first smart, and then responsive. Dynamic behaviour differentiates the Responsive City from the Smart City. An important aspect of responsive cities is the dynamic interaction of smart systems in the city with its citizens. Therefore, Citizen-Design Science, a combination of Citizen Science and Urban Design, becomes and important approach for Responsive Cities [95].

6.2 Limitations

Despite the reliability of the findings, there are a few limitations to take into account when analysing the result.

One of the main limitations during the local-scale analysis was the positioning of the weather stations. Even though the selected location was a closed University campus, there was the risk of the outdoor equipment getting damaged or stolen. Therefore, it was necessary to place the weather stations at points where they were not overly visible. Therefore, the location of the weather stations was not always ideal. Additionally, the points needed to be free from trees and other elements that may have disrupted the readings. Avoiding these elements added another level of difficulty to finding the locations for the weather stations.

Another limitation for the local-scale analysis was the maintenance of the network system between the console of the weather stations, the Raspberry Pi computers and the Wi-Fi connection, which allowed sending the data to the server. A break in this system led to the loss of data during the month of June 2015 for the weather station at point 4, and during the month of September 2015 for the weather station at point 3.

For the city-scale analysis, the main limitation was during the marathon and collection of data of the *Proyecto Confort*. The lack of entries in some areas of the city, for instance the centre-west part of Barranquilla, resulted in missing information of thermal comfort in these areas of the city. Another limitation is the age group of respondents. People in different age groups have different feelings of thermal sensation due to different physical characteristics, such as body mass. Thus, the results only reflect the perception of one population group in Barranquilla.

The main limitation for both the local- and city-scale analysis was the thermal adaptation of people that are living for extended periods in a particular place. Owing to this, it is important to take into consideration where people are coming from, and how long they have been in outdoor environments before taking the survey. Additionally, the thermal comfort information needs to be collected when there is a significant change of climate in the city. In that situation, people would have to react to a new environmental change, and there would be less time for them to adapt to a new climatic condition.

6.3 Future work

The research developed in this thesis created the basis for two new projects. The first of these is a second version of the *Proyecto Confort*. From what was learned from this crowdsourcing initiative, the working group (formed from the members of different institutions of the city of Barranquilla) will develop the second version the crowdsourcing tool and will conduct a similar data collection marathon.

The second project that extends the work in this thesis is related to the limitations of the city-scale analysis. On the local scale, the validation of the two methodologies was possible due to the small and easy-to-install measurement network (data collection with portable weather stations). Because this measurement network cannot be implemented and spread around the city due to costs, the city-scale analysis could only replicate the validated survey campaign. Therefore, a new project called 'CLOUDia' has been created to explore and develop small and low-cost weather stations that can be used by citizens, and can be placed around the city. These portable mini weather stations will be connected to an online platform where all of the data collected can be stored and visualized. In this way, it will be possible to collect a big data set of weather variables in the city, and run the measurement campaign in parallel to the survey campaign from the *Proyecto Confort*. The innovation of this new weather station is the technology behind the measurement of the solar radiation, which will replace the pyranometer (usually the most expensive part of a weather station).

Additionally, the research methodology will be introduce in other research projects in other cities that intend to explore the OTC of citizens. One of this projects is the Cooler Calmer Singapore develop by the Future Cities Laboratory in Singapore (http://www.fcl.ethz.ch/).

7 Nomenclature

t	Temperature
v	Wind speed
I	Solar irradiance
R	Radiation
E	Evaporation
M	Metabolic rate
W	Rate of work
S	Energy storage
Q*	Net all-wave radiation
Q_F	Anthropogenic heat flux
Q_H	Convective sensible heat flux
Q_E	Latent heat flux
Q_S	Net storage heat flux
Q_A	Net horizontal heat advection
R_n	Net exchange of radiation
K_{dir}	Direct short-wave radiation incident on the body
K_{dif}	Diffuse short-wave radiation incident on the body
K_h	Indirect radiation incident on the body. Horizontal

L_d	Long-wave radiation incident emitted downwards by the sky
L_h	Long-wave radiation incident emitted by horizontal surfaces
L_v	Long-wave radiation incident emitted by vertical surfaces
L_s	Long-wave radiation incident emitted by the body
C	Convection
$T_{sol-air}$	Sol-air temperature
h_c	Heat transfer coefficient
T_s	Body surface temperature
T_a	Surrounding air temperature
K_v	Indirect radiation incident on the body. Vertical
α_s	Albedo of the skin and/or clothing

Units

Wm^{-2}	Watts per meter square
$°C$	Degree Celsius
m/s	meters per second
clo.	Reference clothing

A Appendix

A.1 Appendix A. Stakeholder workshop minutes - original

Primera mesa de trabajo – Proyecto Confort

FEB 11, 2016 AT 8:30 AM

REUNIÓN ORGANIZADA POR	Líderes de proyecto: Kattia Villadiego y Estefania Tapias
TIPO DE REUNIÓN	Mesa de trabajo - Workshop
FACILITATOR	Líderes de proyecto: Kattia Villadiego y Estefania Tapias
MINUTAS	Estefania Tapias

Participantes

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Temas de Agenda

TIEMPO	TEMA	PONENTE
8:30 - 9:00	Llegada de los participantes y café de bienvenida	
9:00 - 9:15	Bienvenida por parte de los líderes del proyecto	Líderes de proyecto
9:15 - 9:30	Contexto de proyecto (primera parte)	Kattia Villadiego
9:30 – 9:45	Contexto de proyecto (segunda parte)	Estefania Tapias
9:45 – 10:00	Presentación del proyecto confort	Estefania Tapias
10:00 - 10:30	Discusión: retroalimentación por parte de los participantes	Participantes
10:30 - 11:00	Coffee break	
11:00 - 11:30	Discusión: perspectivas del proyecto confort	Participantes
11:30 - 12:00	Conclusiones y puntos de acción	Líderes de proyecto

Discusión

Los participantes coincidieron y resaltaron la importancia del Proyecto Confort para el desarrollo urbano de Barranquilla.
Importancia de colaboración inter-institucional. Potencial del Proyecto Confort para lograr este objetivo.
El Observatorio Urbano que agrupa varias universidades y entidades va a ser el facilitador del proyecto para que todos los actores institucionales participen.
La primera etapa del Proyecto Confort es la aplicación (app) para Smartphone.
Para lograr que los estudiantes de las diferentes universidades participen en el proyecto descargando el app es necesario desarrollar una campaña de divulgación.
El app va a circular durante dos meses (Abril y Mayo) y se va a desarrollar en forma de Maratón generando incentivos.
El proyecto confort puede tener como producto el inicio de un código verde urbano que puede nacer del Observatorio.
Para poder mostrar el alcance del Proyecto Confort se va a desarrollar un proyecto urbano que demuestre su potencial. Este se va a desarrollar después de obtener los resultados del app y del *'PET tool'*.

Conclusiones

El Observatorio será el facilitador del proyecto y velará por su ejecución. El liderazgo del proyecto seguirá en manos de Kattia Villadiego y Estefania Tapias.
La primera etapa del Proyecto Confort es la promoción y el uso de app por parte de estudiantes de diferentes universidades de Barranquilla.
La segunda etapa es la validación de la PET Tool - desarrollada en el marco del doctorado de Estefania Tapias - con los datos obtenidos con la app.
La tercera etapa es la definición de un proyecto urbano piloto como prototipo para demostrar el alcance del Proyecto Confort en el desarrollo de políticas verdes en la ciudad de Barranquilla.
La cuarta etapa será impulsar una iniciativa de código verde urbano para la ciudad de Barranquilla.
Reuniones periódicas del grupo de trabajo. Las fechas serán coordinadas por las líderes del proyecto.

Plan de acción

ACTIVIDAD	PERSONA RESPONSABLE	FECHA LIMITE
Creación de grupo de trabajo – Miembros del grupo son los participantes de esta primera mesa de trabajo	Líderes de proyecto	11.02.2016
Desarrollo profesional del app	Líderes de proyecto	30.03.2016
Campaña de divulgación del app en las diferentes universidades	Representantes de las universidades y Evelyn Castellón	22.02.2016 – 31.05.2016
Material para campaña	Líderes de proyecto	22.02.2016

OBSERVACIONES	Las acciones futuras serán decididas durante la segunda reunión del grupo de trabajo.

A.2 Appendix B. Stakeholder workshop minutes - translated into English

First working group meeting – '*Proyecto Confort*'

FEB 11, 2016 AT 8:30 AM

ORGANIZATION TEAM	Project leaders: Kattia Villadiego y Estefania Tapias
TYPE OF MEETING	Working group meeting - Workshop
MODERATOR	Project leaders: Kattia Villadiego y Estefania Tapias
MINUTES	Estefania Tapias

Participants

NAME	AFILIATION	EMAIL ADDRESS
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Evelyn Castellón	Alumnus from the architecture department, *UNINORTE*	mguerramulford@gmail.com
Marlon Guerra	Architecture student, *CUC*	evelyncastellon1@gmail.com

Agenda

TIME	TOPIC	RESPONSIBLE
8:30 - 9:00	Arrival of participants	
9:00 - 9:15	Welcome and introduction	Project leaders
9:15 - 9:30	Background and context of the project (part 1)	Kattia Villadiego
9:30 – 9:45	Background and context of the project (part 2)	Estefania Tapias
9:45 – 10:00	Presentation of the project	Estefania Tapias
10:00 - 10:30	Discussion: feedback from participants	Participants
10:30 - 11:00	Coffee break	
11:00 - 11:30	Discussion: project outlook and future work	Participants
11:30 - 12:00	Conclusion and action points	Project leaders

Discussion

Participants agreed on the importance of the project for urban development in Barranquilla.
Participants agreed to keep the inter-institutional collaboration and the project is the first step to achieve this.
The Urban Observatory, which brings together several universities and institutions, will be the facilitator of the project for all institutional actors involved.
The first stage of project is the development and disemination of the smartphone application (app).
The project leaders need to develop an outreach campaign to get students from different universities involved in the project and downloading the app.
The app will run for two months (April and May) and will be develop in form of a Marathon with incentives.
As a result, the project may bring kwodlege for the creation of an urban green code that can be developed by the Urban Observatory.
With the results of the project, other urban planning projects can derived from the knowledge acquire and can be initiated and developed by the Urban Observatory.

Conclusions

The Urban Observatory will be the facilitator of the project and will ensure its implementation. Kattia Villadiego and Estefania Tapias will continue as project leaders.
The first stage of the project is the promotion of the marathon in the different universities in Barranquilla.
The second stage is the data processing and statistics from thedata collected from the app, which will be part of the doctoral thesis of Estefania Tapias.
The third stage is the definition of a second prototype of the project to demonstrate acquire more information for the development of green policies in the city of Barranquilla.
The fourth stage is thel promotion of the initiative for a urban green code for the city of Barranquilla.
Regular meetings of the working group. The dates will be coordinated by the project leaders.

Action points

ACTIVITY	RESPONSIBLE	DATE
Creation of the working group - Group members are participants of this first workshop.	Project leaders	11.02.2016
Development of the smart phone application.	Project leaders	30.03.2016
Promotion and outreach campaign in different universities.	University representatives	22.02.2016 – 31.05.2016
Material for promotion campaign.	Project leaders	22.02.2016

OBSERVATIONS	Next actions points will be decided at the second meeting of the working group.

A.3 Appendix C. Weather data statistics from weather station in the rooftop

The following figures show the weather data collected by the weather station in the roof top of the building (measurement point 1). This weather station was intended to collect weather data that was not affected by any urban obstacle Figure A.1, A.2 and A.3 show the average values of the weather data collected by each measurement point (2-5) plus the data collected by the roof top weather station (point 1). Additionally, this weather station measured the global solar radiation used by the PET calculations of each of the measurement points (the four principal weather stations). Figure A.4 shows the average values of the global solar radiation per month.

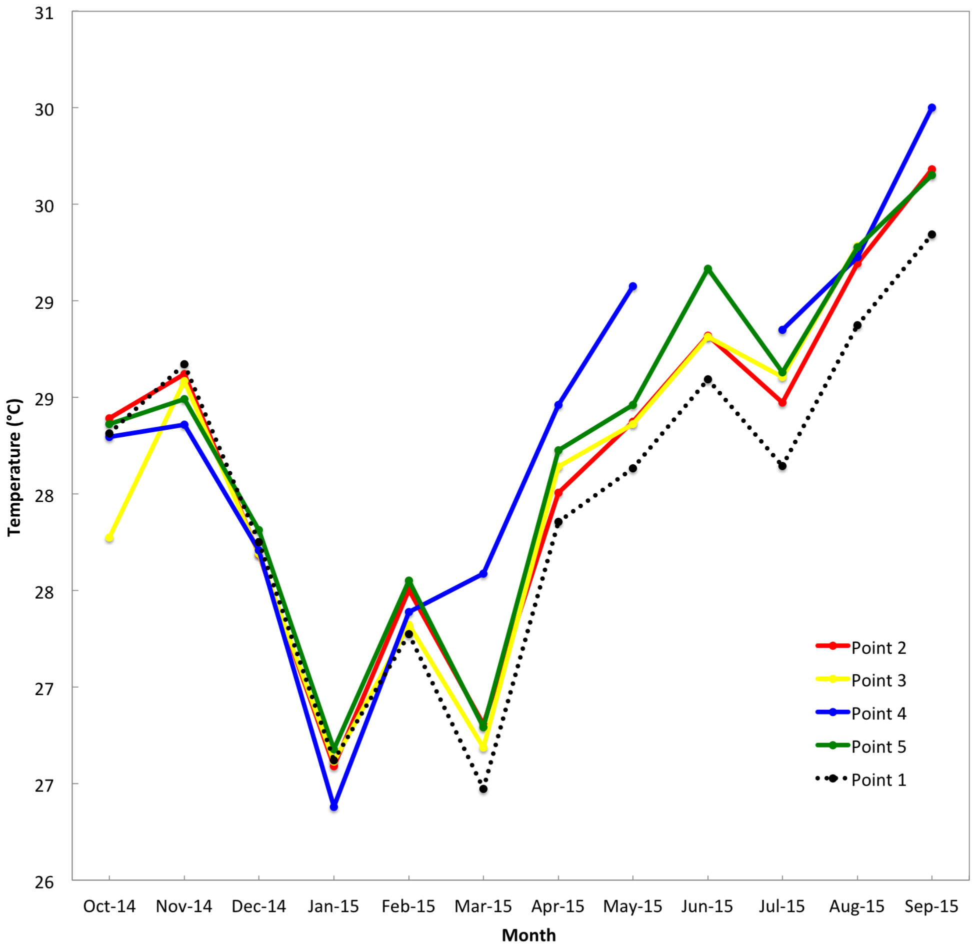

Figure A.1 – *Average temperature for all four measurement points with the roof top data (point 1) from October 2014 to September 2015.*

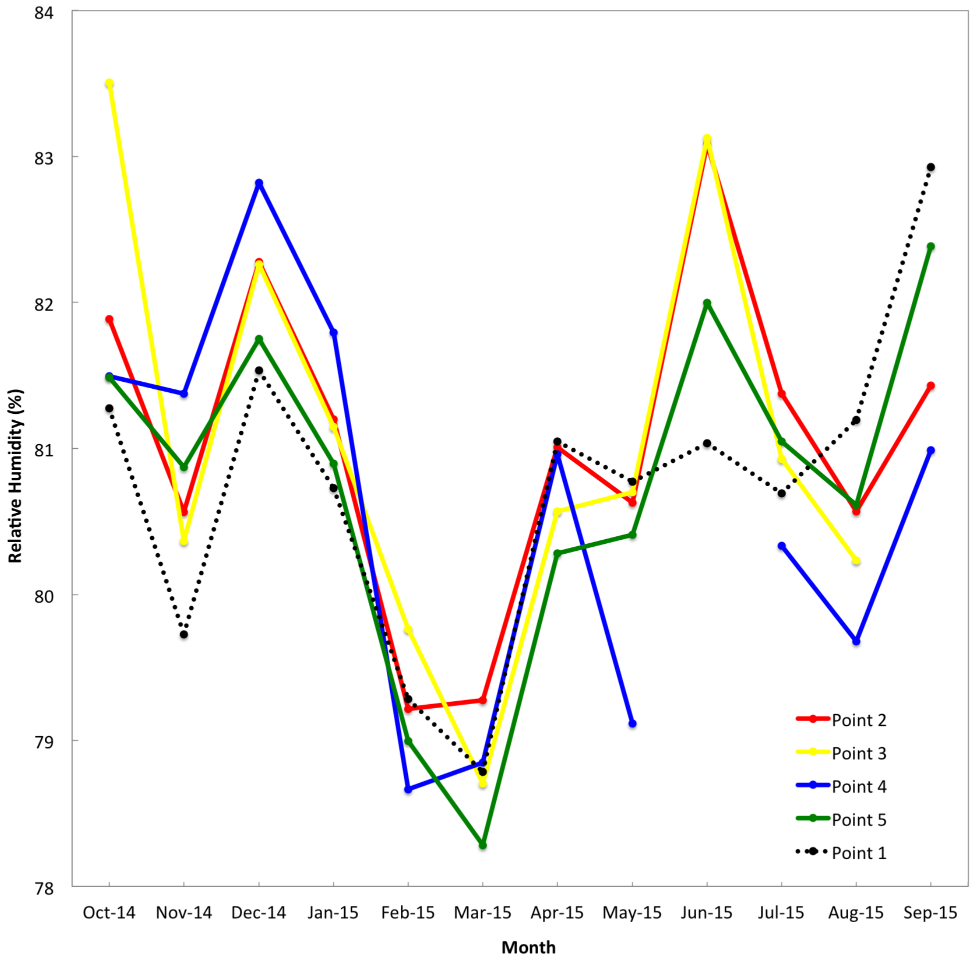

Figure A.2 – *Average humidity for all four measurement points with the roof top data (point 1) from October 2014 to September 2015.*

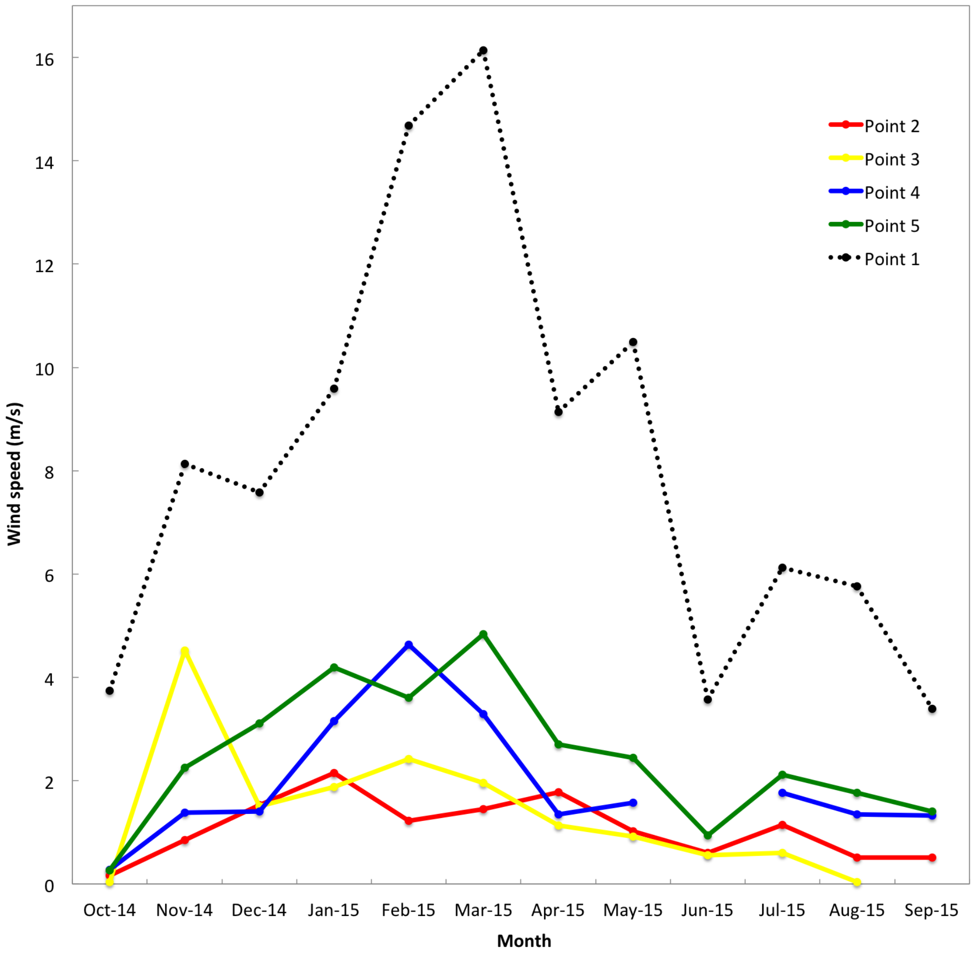

Figure A.3 – *Average wind speed for all four measurement points with the roof top data (point 1) from October 2014 to September 2015.*

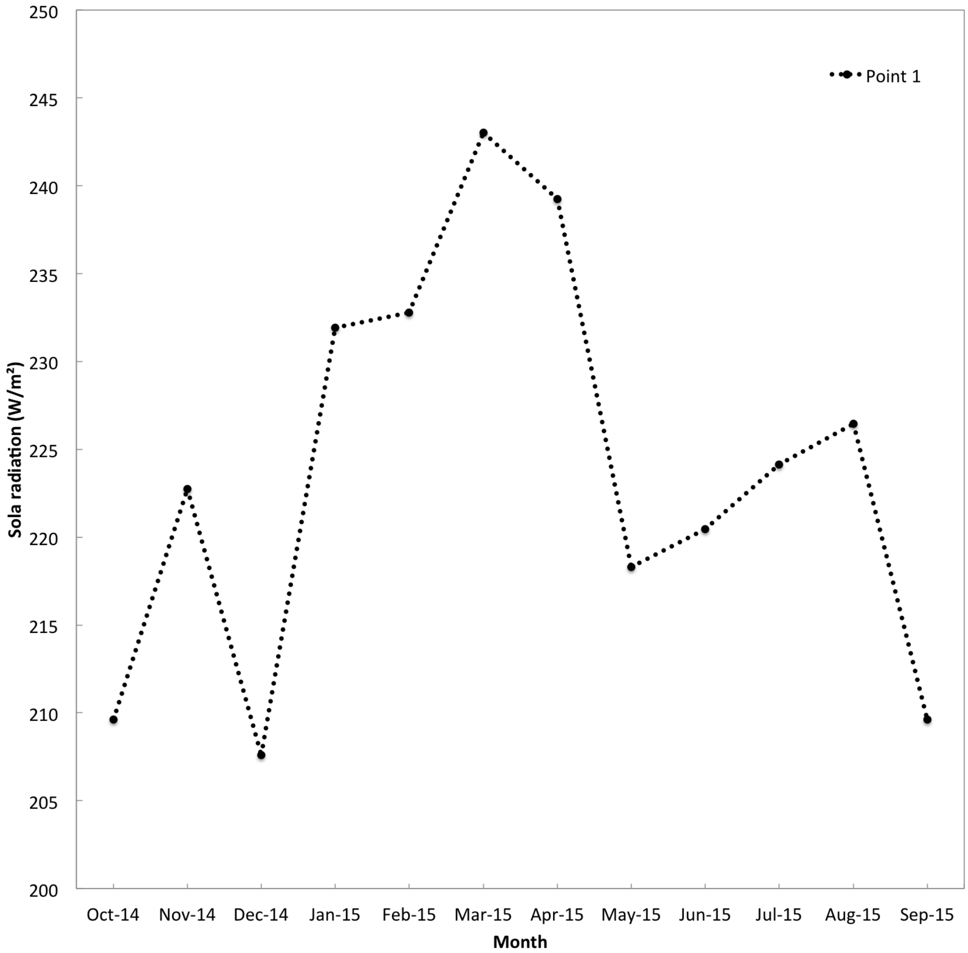

Figure A.4 – *Average global radiation taken from the roof top weather station (point 1) from October 2014 to September 2015.*

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Postdoctoral fellow & Lecturer, ETH Zurich

Summary

Postdoctoral fellow:
As a urban scientist, I focus on the development of research projects for the search of solutions towards climate-friendly urban environments.

Urban MOOCs:
Additionally to my research work, I am part of the development team of the urban MOOC's (Massive Open Online Courses) at ETH. As the 'content responsible', I work together with a team from the ETH Zurich and the Future Cities Laboratory in Singapore for the development of the 'Future Cities' MOOC series offer by ETH Zurich in the Edx platform.

Professional Experience

2017.01 - present	**ETH Zürich** **Chair of Information Architecture, Dept. of Architecture** *Zurich, Switzerland* Postdoctoral Fellow & Lecturer
2014.04 - present	**ETH Zürich & Edx onlie** Lecturer and content responsible Future Cities MOOC (Massive Open Online Course) series
2016.04 - present	**EIT Alumni** **European community** President 2016 - 2017
2012.11 - 2016.12	**ETH Zürich** **Chair of Information Architecture, Dept. of Architecture** *Zurich, Switzerland* Research Assistant & Lecturer
2015.01 - 2016.12	**Climate-KIC Alumni Association** **European community** President 2015 & 2016
2012.03 - 2012.11	**ETH Zürich** **Chair of Information Architecture, Dept. of Architecture** *Zurich, Switzerland* Internship NRP65 project - Sustainable Urban Patterns

Education

2013.02 - 2016.12	**ETH Zürich & EIT Climate-KIC** **Chair of Information Architecture, Dept. of Architecture** *Zurich, Switzerland* PhD degree - Information Cities and Urban Climate
2010.09 - 2012.09	**Politecnico di Torino** **Dept. of Architecture** *Turin, Italy* Master of Science (MSc) Sustainable Architecture
2006.07 - 2010.07	**Pontificia Universidad Javeriana** **Dept. of Architecture** *Bogotá, Colombia* *Architecture degree (Arch)*

Areas of Expertise

Climate change
Urban science
Urban climatology
Urban planning
Research & Development

Languages

Spanish (Native proficiency)
English (Bilingual proficiency)
Italian (Professional working proficiency)
German (Elementary proficiency)

Awards / Certificates

ETH Zurich delegate:
The Chicago Forum on Global Cities 2015
Chicago, U.S.
&
Global Youth Scientist Summit 2016
Singapore

Climate-KIC:
PhD label

Politecnico di Torino:
Master thesis publication
- *'Meritorious theses'* -

Speaker

EIT Innovation Forum - INNOVEIT
Budapest, Hungary, 2016

Sustainable Innovation Forum - Young Entrepreneurs for Low Carbon Innovation
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Publications

Conference papers:

TAPIAS, E., 2012. Un Metodo per la Costruzione di Tipolgie Urbane Sostenibile con Analisi Microclimatiche: Il Caso Studio di Altstetten, Zurigo. Meritorious Master thesis, Politecnico di Torino, online publication <http://www.architesi.polito.it/dettaglio_tesi.asp?id_tesi=14391>

TAPIAS, E., KUNZE, A., ROCCASALVA, G., SCHMITT, G., 2013. A decision-making support process using microclimate analysis methods and parametric models for optimizing urban climate comfort. eCAADe, Proceedings of the 31st Education and research in Computer Aided Architectural Design in Europe; Faculty of Architecture, Delft University of Technology. 1: 41-50.

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Teaching publications:

KOENIG, R., TAPIAS, E., SCHMITT, G., Digital Urban Simulation: Documentation of the teaching results from the spring semester 2015. ETH Zurich. <https://www.researchgate.net/publication/282607718_New_Methods_in_Urban_Analysis_and_Simulation >

KOENIG, R., TAPIAS, E., SCHMITT, G., Digital Urban Simulation: Documentation of the teaching results from the fall semester 2014. ETH Zurich. <https://www.researchgate.net/publication/277309068_Digital_Urban_Simulation_Documentation_of_the_teaching_results_from_the_fall_semester_2014>

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