Addressing urban outdoor thermal comfort thresholds through public space design

A bottom-up interdisciplinary research approach for thermal sensitive urban design in an era of climate change: The case of Lisbon

Andre Naghi Lopes dos Santos Nouri

Orientadores: Doutor João Pedro Costa e Doutor Andreas Matzarakis

Ramo de Urbanismo

Tese especialmente elaborada para a obtenção do grau de doutor

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Doutor Fernando Manuel Brandão Alves,

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Doctora Maria José Andrade Marqués, Profesor Contratado

Doctor interino da Universidad de Málaga;

Doutor David de Sousa Vale,

Professor Auxiliar da Faculdade de Arquitetura da Universidade de Lisboa;

Doutor João Viljoen Vasconcelos,

Professor Adjunto do Instituto Politécnico de Leiria.

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To my rocks.

Ana Santos & Ahmad Nouri

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Abstract

Within the existing city, factors such as elevated urban temperatures and intensities of urban heat island effects are already revealing prominent thermal discomfort and health concerns during annual periods of more accentuated climatic stimuli. In addition to these exiting risks upon the urban microclimate, climate change projections indicate further exacerbations of such risks factors throughout the course of the twenty-first century.

Although top-down assessments and disseminations have revealed imperative information with regards to such phenomena, the emergence of the climate change adaptation agenda has also arguably propelled the scientific international community to further mature bottom-up approaches to address local risk factors. As such, the perspective of 'locality' has been one which has gained new meaning for disciplines such as urban planning and design when considering the climatic safety, human thermal comfort, and prosperity of the contemporary public realm. Nevertheless, and resultant of its emerging nature, bottom-up approaches are still somewhat limited in terms of its existing breadth between theory and application and practice.

As a response, this thesis undertakes a bottom-up approach and discusses how the union between the individual fields of urban climatology and public space design can be fortified. Such a fortification is directly aimed at investigating how local outdoor human thermal comfort can be improved through an interdisciplinary practice which is backed by scientific know-how and practice. Considering the case of Lisbon, this research deliberates upon how such an approach can overcome issues of climatic and applicative uncertainty, and can: (i) be translated into local design and planning guidelines which can be applied within numerous different urban circumstances; and (ii) aid non-climatological experts to undertake bioclimatic surveys (based both upon site and/or meteorological station data) to determine, and attenuate, local heat and cold stress risk factors within a particular outdoor context. Accordingly, and centred upon a bottom-up approach, which moreover considers important disseminations from top-down assessments, public space design is portrayed as an imperative tool to locally ensure an active, comfortable and safe public realm, both presently, and in an uncertain future.

Key Words:

Public Space Design; Human Thermal Comfort; Microclimates; Climate Change Adaptation; Lisbon, Bottom-up Approaches

Resumo

Na cidade contemporânea, factores como as elevadas temperaturas e a intensidade dos efeitos da ilha de calor em meio urbano, têm vindo a revelar proeminente desconforto térmico e importantes preocupações com a saúde durante os períodos anuais de maior estímulo térmico. Para além destes riscos já existentes e inerentes ao clima urbano, as projecções das alterações climáticas apontam para uma exacerbação destes factores de risco ao longo do Séc. XXI.

Muito embora as avaliações e outputs *top-down* tenham revelado informação de carácter imperativo relativamente a tais fenómenos, a emergência da agenda de adaptação às alterações climáticas veio também incentivar a comunidade científica internacional a maturar e a desenvolver abordagens *bottom-up* mais incisivas, com vista a fazer frente aos factores de risco locais. Assim sendo, a perspectiva de "localidade" tem vindo a ganhar um novo significado para disciplinas como o urbanismo e o *design* urbano, quando confrontados com aspectos como a segurança, o conforto térmico humano e a prosperidade do meio urbano contemporâneo. Todavia e, atendendo ao seu carácter emergente, as abordagens *bottom-up* ainda se encontram numa fase inicial e, consequentemente, relativamente limitadas, tendo em conta a distância existente entre a teoria e a aplicação prática.

Como resposta, esta tese efectua uma abordagem *bottom-up* e uma reflexão acerca do modo como a união entre a climatologia urbana e o *design* do espaço público urbano, enquanto campos distintos, pode ser fortalecida. Tal fortalecimento visa investigar de forma directa sobre a possibilidade de "localmente", o conforto térmico humano em meio urbano exterior, ser melhorado através de práticas interdisciplinares apoiadas no conhecimento científico. Tendo em consideração o caso de Lisboa, esta investigação analisa a forma como esta abordagem pode suplantar questões como a incerteza climática/aplicacional e, consequentemente: (i) traduzir-se em linhas de orientação para o urbanismo e para o *design* urbano local, que poderão ser aplicadas/implementadas em múltiplas circunstâncias e contextos urbanos; visando ainda, (ii) auxiliar especialistas "não-climatólogos" a realizar levantamentos bioclimáticos (baseados em dados locais e/ou na informação obtida a partir da estação meteorológica) com o intuito de determinar/atenuar os factores de risco de stress associados ao calor e ao frio num determinado contexto exterior. Consequentemente e, focado numa abordagem *bottom-up* que para além disso considera outputs relevantes a partir de avaliações *top-down*, o *design* do espaço público é retratado como sendo uma ferramenta indispensável, com vista a assegurar "localmente" um meio urbano activo, confortável e seguro, tanto no presente, quanto num futuro que se afigura incerto.

Palavras-chave:

Design do Espaço Público; Conforto Térmico Humano; Microclimas; Adaptação as Alterações Climáticas; Lisboa, Abordagens B*ottom-up*

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In my experience, the undertaking of a doctoral thesis is undoubtedly synonymous with years of solitary academic endeavour and exploration. This being said, during such an introverted period, it became evident that I had numerous shadows behind me. Within this page, I would like to take the opportunity to express my everlasting gratitude to numerous shadows which accompanied me in many ways.

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Publication Preamble Symposium

1 – **Journal Review Article** » Publication reviews existing approaches that have addressed local outdoor human thermal comfort levels through public space design. The assessment is divided into two sequential stages, whereby: (1) overall existing approaches to thresholds are reviewed within both quantitative/qualitative spectrums; and, (2) different techniques and measures are reviewed and framed into four Measure Review Frameworks. The results of the publication lead to an encompassing assessment throughout the thesis of the current practices of public space design within three specific subcategories of the Köppen Geiger 'Temperate' classification.

2 – **Book Chapter** » Publication examines the obstacles and developments within the political and scientific arenas with regards to the emergence of the climate change adaptation agenda. Based more predominantly upon an initial top-down approach, the growing recognition for the necessity for action is discussed. Through a structured evaluation, the important contributions from global scientific entities are discussed, and the need for further bottom-up and localised action for urban planning and design is identified.

3 – **Book Chapter** » Publication launches the discussion of how bottom-up orientated planning assessments can approach climatic issues within local scales. In addition, it also synoptically examines how they can moreover contour obstacles such as climatic uncertainty by methodologically approaching local risk factors through numerous identified means and approaches.

4 – **Journal Article** » With the aim of approaching the often lack of bottom-up climatic indicators, tools and practical benchmarks, the publication launches a framework of international built and conceptual projects which address thermal comfort levels within specific climates. Based upon Auckland, such an organisation is cross-referenced with theory supporting its structure and respective division. Such frameworks were subsequently considered in terms of how they could launch new considerations within local policy and design guidelines.

5 – **Journal Article** » Focuses on improving urban design guidelines by reviewing existing theoretical /empirical research of how pedestrian comfort levels can be addressed by public space design. New qualitative and quantitative interrogations were examined against a generic tool which resulted in the introduction of six intangible criteria, and subsequently, six measurable attributes. New generic design tool considerations were established for existing and future public spaces in light of climate change.

6 – **Journal Article** » Orientated at a specific case study, this publication presents results of an empirical analysis undertaken within Rossio. Such an analysis is constructed upon the identification of: (i) ascertaining the principal local risk factors within the square which could influence pedestrian thermal comfort thresholds; and (ii) assessing how the identified risk factors could be translated into creative solutions and opportunities for local public space design.

7 – **Journal Article** » Based upon previously obtained results in Rossio, they are taken a step further in order to consider how a climatic worse-case-scenario by the end of the century could influence the existing conditions within Rossio given incorporation/lack of the proposed public space measures. As a result, a synoptic evaluation of how climate change conditions can aggravate existing thermal comfort conditions around the entire square through different analysed datasets is presented.

8 – **Journal Article** » Lisbon's bioclimatic risk factors are evaluated and then translated into thermal attenuation priorities for public space design during periods of accentuated stimuli. The examination is structured into sequential stages in order to present how lack of meteorological information can be overcome to assess pedestrian comfort thresholds when pondering the application of local measures within different locations of various stipulated default urban canyons.

9 – **Journal Article** » Study examines the 'in-situ' effects of vegetation upon pedestrian thermal comfort levels. Being one of Lisbon's most common shading tree species, the influences of the *Tipuana tipu* is selected in order to evaluate its influences upon thermal stress within different locations within various canyons with dissimilar morphological compositions. Such an examination is conducted both during the winter and summer to present such 'in-situ' influences resultant of the presence/absence of the *Tipuana tipu* tree.

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Introduction

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“ *Many inhabitants of cities throughout the world suffer from health problems and discomfort that are caused by overheating of urban areas, and there is compelling evidence that these problems will be exacerbated by global climate change. Most cities are not designed to ameliorate these effects although it is well-known that this is possible, especially through evidence-based climate-responsive design of urban open spaces.”* (I)

Within the last few decades, several agendas are continually gaining more significance for the interdisciplinary practices of urban planning and design. Interlaced within such agendas, lies the comprehension of how climate change adaptation can address issues of uncertainty and ambiguity when facing possible obstacles and impacts until the end of the century. Nevertheless, and thus far, a considerable amount of research regarding local scales has been carried out through a top-down approach (Wilbanks and Kates 1999). Generally, such methods concentrate upon impact prediction through the utilisation of Global Circulation Models (GCMs) and to some extent, Regional Climate Models (RCMs) as ‘starting points’ to both quantify and estimate climate change scenarios.

For more than a quarter of a century, the need for changing consumption patterns and addressing the risks related to the climate system has expanded exponentially. In 1992, approaches to climate change underwent a significant step forward when the international community established the United Nations Framework Convention on Climate Change (UNFCCC). The catalyst that propagated such an emergence has been a subject of dispute amongst various authors and agencies. Some early theorists have suggested that such multilateral environmental regimes resulted from nations wanting to control resources due to environmental degradation (Homer-Dixon 1994, Gould, Weinberg et al. 1995). On the other hand, alternative approaches indicate that these environmental regimes originated from the changing attitude in global politics/institutions in light of global warming (Giddens 1990, Meyer, Frank et al. 1997, Siebenhüner 2003). Although the former perspective may be valid, it is also important to note that “*the worldwide expansion of scientific discourse and association over* [the twentieth century] *facilitated the rise of world environmental organisation*” (Meyer, Frank et al. 1997, p.631). Such a perspective can be associated to the early disseminations of the Intergovernmental Panel on Climate Change (IPCC) before the turn of the century. With the progression of such scientific collaborations and maturity, it was recognised that the global politics applicable to climate adaptation was inherently different to that of mitigation. Serving as a catalyst to such recognition, was the parallel identification at the time that mitigation efforts alone were no longer sufficient to address the potential changes within the global climate system. Hence, and given ‘risk factors’ associated to such potential aggravations, adaptation became a topic that became more intrinsically allied to the ‘interests’ of individual countries during the enveloping of the 21st century (Costa, Nouri et al. 2013).

Given the catalysing proceedings within the global political and scientific arena, and with prominent urban climatology studies dating well before the turn of the century (e.g., Büttner 1938, Olgyay 1963, Höppe 1984, Mayer and Höppe 1987, Oke 1988, Matzarakis and Mayer 1997, Höppe 1999), adjacent research interests and concerns were also raised. Just before the end of the 20th century, it was already recognised that "[up until then], *the bulk of the research relating to local places to global climate change* [had] *been top-down, from global toward local, concentrating on methods of impact analysis that use as a starting point climate change scenarios derived from global model, even though these have little regional or local specificity. There* [was] *a growing interest, however, in considering a bottom-up approach, asking such questions as* (…) *how efforts at mitigation and adaptation* [could] *be locally initiated and adopted.*" (Wilbanks and Kates 1999, p.1). As a response on behalf of the international scientific community, bottom-up approaches and studies that have focused upon the importance of local scales have dramatically increased since the turn of the century.

Accordingly, both the limitations and means to improve local scale analysis tools have been a topic of interest both in the fields of urban climatology and planning/design. Thus far, and in accordance with GCM outputs, it has been suggested that global temperature shall continue to increase throughout the 21st century. Nevertheless, it has been identified that such top-down climatic assessments are often less useful for local scale analysis tools and adaptation. As an example, the within the assessment reports of the IPCC, the effects of weather are often described with a simple index based on amalgamations of air temperature (T_{amb}) and Relative Humidity (RH). Although it is vital to recognise the value of such descriptions within the maturing climate change agenda, when considering bottom-up approaches to climatic vulnerability, the exclusion of vital meteorological factors (i.e., radiation fluxes, wind speed and human thermo-physiological factors) have arguably decreased their significance and utility for local decision making and design (Matzarakis and Amelung 2008, Matzarakis and Endler 2010).

As a result, and arguably catalysed further by the climate change adaptation agenda, local decision makers and designers are continually focussing more upon the implementation of measures to address local 'risk factors'. Such a maturing bottom-up perspective is one that is presented within this thesis as a means to explore how urban planning and design can improve the bioclimatic conditions within local scales. Thus, it discusses how a developing bottom-up perspective can synergise the individual spheres of urban planning and design with that of urban climatology to address meteorological implications through modifications of the urban public realm (Mayer and Höppe 1987, Katzschner 2006, Ali-Toudert and Mayer 2007, Nikolopoulou 2007, Shashua-Bar, Tsiros et al. 2012). Beyond the disseminations derivative of this thesis, utilised as a means to evaluate such modifications, numerous recent studies have incorporated the use of biometeorological studies to examine thermal comfort conditions as part of the public space design process (e.g., Lin, Matzarakis et al. 2010, Vanos, Warland et al. 2010, Krüger, Drach et al. 2013, Abreu-Harbich, Labaki et al. 2015, Algeciras, Consuegra et al. 2016, Charalampopoulos, Tsiros et al. 2016, Matzarakis, Fröhlich et al. 2016, Roshan, Yousefi et al. 2016).

When considering the specific case of Lisbon, it has already been recognised that additional action is required to adapt to future climatic conditions that are already being witnessed/recorded within its urban environment (Alcoforado and Matzarakis 2010, Costa 2013, Alcoforado, Lopes et al. 2014, Matos Silva and Costa 2017). In addition, and as identified by numerous studies (Alcoforado and Vieira 2004, Alcoforado, Andrade et al. 2009), the scientific community has recognised a weakness in studies which focus upon Mediterranean climates with hot-dry summers with regards to local approaches to thermal comfort thresholds. Such an insufficiency frequently relays to a lack of local scale design guidelines and precedents which could otherwise inform practices such as public space design in addressing thermal comfort during the summer period. In accumulation, and commonly within regions such as southern Europe, many cities often present a lapse of climatological data that would otherwise prove useful informing local decision making and design within the public realm. Within this region, such gaps were particularly evident within municipal Masterplans (Alcoforado, Andrade et al. 2009), including with regards to potential climate change impacts (Costa 2013).

As a reaction from the scientific community, there has thus far been an encouraging dissemination of studies that have made very important contributions to comprehending the general bioclimatic conditions within Lisbon's public realm (Andrade 2003, Oliveira and Andrade 2007), causalities of and intensities of Urban Heat Islands (UHI) (Alcoforado and Andrade 2006, Lopes, Alves et al. 2013, Alcoforado, Lopes et al. 2014), wind current studies (Lopes 2003, Alcoforado, Lopes et al. 2006), and, the combination with planning policy (Alcoforado, Lopes et al. 2005, Alcoforado and Matzarakis 2010). In addition, and with regards to the climate change adaptation agenda, studies pertaining to potential impacts upon Lisbon's climate have also been published (Alcoforado, Andrade et al. 2009, Costa 2013, Costa, Sousa et al. 2013, Matos Silva 2016, Matos Silva and Costa 2017). In addition, in recent years, national research groups such as Climate Change Impacts Adaptation and Modelling (CCIAM), and 'ClimAdaPT' have also built upon the incorporation of climate adaptations strategies within municipal documents.

Importance of Study

Outlining the Lisbon Case

According to Miranda (2006) and Calheiros (2006) within the 'Climate Change in Portugal, Scenarios, Impacts and Adaptation Measures' (SIAM) project (Santos and Miranda 2006), the city of Lisbon currently observes: (i) between 10 and 20 'very hot days', which are those that experience T_{amb} above 35 ºC; (ii) a range between 100-120 'summer days' where maximum T_{amb} surpass that of 25 ºC; and lastly, (iii) frequent occurrences of heat wave events, where T_{amb} sequentially surpass that of 32 ºC during various days. Moreover, and when considering extreme events such as the heatwave of 2003 within Western European countries such as Portugal, required additional measures to warn, cope, and prevent the recurrence of such events were identified (Kovats and Ebi 2006, Matzarakis 2016). More concretely, and within the district of Lisbon, between the 29th of July and the 13th of August, it was identified by Nogueira, Falcão et al. (2005) that: (i) 15 days had a maximum T_{amb} above 32 ºC; (ii) there was a noteworthy consecutive relay of 10 days with maximum T_{amb} surpassing 32 ºC; and finally, (iii) there was a 5 day period which consecutively experienced T_{amb} above 35 ºC. Furthermore, when considering such impacts upon public health, an estimated mortality rate increase of 37.7% (i.e., corresponding to 1316 excess deaths) in comparison to what would be expected under standard conditions. It was noted that such events are representative of current conditions, which have, adjacently, been argued to be already presenting current thermal aggravations associated to climate change (Alcoforado and Matzarakis 2010, Alcoforado, Lopes et al. 2014).

As identified by Peel, Finlayson et al. (2007), Lisbon witnesses a Köppen Geiger (KG) climate classification of '*Csa*' which equates to a Mediterranean climate with hot and dry summers. According to Rubel and Kottek (2010), based upon GCM outputs, it was projected that the entirety of continental Portugal shall witness the same KG classification to what is currently witnessed in Lisbon by 2100. Such a phenomenon implies that northern cities such as Porto shall go from a KG classification of '*Csc*' to '*Csa*', suggesting a considerable change in summer conditions. This being said, such a projection undertaken by Rubel and Kottek (2010), implies that by the end of the century, Lisbon's general climate shall not alter from its present classification.

Nevertheless, the projection that Lisbon shall not change KG classification does not, by any means, imply that climatic conditions shall not potentially modify by the end of the century. To start off with, and as identified by the study undertaken by Matzarakis and Amelung (2008), Western European cities within the Iberian Peninsula could witness changes in thermo-physiological indices by up to 15 ºC based upon worst case emission scenarios, values which sharply differ from the IPCC projections established upon singular climatic variables such as T_{amb} (IPCC 2000).

All the same, before the introduction of Representative Concentration Pathways (RCP) (IPCC 2013) and based upon the Special Report on Emission Scenarios $(SRES)_{A2}$ scenario equating to "*A very heterogeneous world with an emphasis on family values and local traditions*" (IPCC 2000); Miranda (2006) identified, through the use of RCMs, that Lisbon could potentially further witness a: (i) total of 50 days a year with diurnal T_{amb} surpassing that of 35 ºC (i.e. constituting a 'very hot day'); (ii) doubling in duration of days that consecutively surpass 35 ºC (i.e. implying a potential span of 20 uninterrupted days); (iii) radical upsurge of 'Tropical Nights', increasing from 20 up to a potential 80 annual nights where the minimum T_{amb} surpass 20 ºC; and lastly, (iv) potential escalation of 'summer days' (where T_{amb} surpass that 25 ºC) up to 180 days, representing half a calendar year. Notwithstanding, it is important to note that such projections are not based upon the worse-case-scenario of $SRES_{A1FI}$ (corresponding to a $RCP_{8.5}$ according to Rogelj, Meinshausen et al. (2012)), and more accentuated impacts can take place if such a scenario that originates from "*A world of rapid economic growth and rapid introductions of new and more efficient technologies*" (IPCC 2000). In addition to these factors, and within Lisbon, numerous studies have furthermore identified areas which present further susceptibility to local microclimatic risk factors. Due to its morphological composition, areas such as the downtown quarter around 'Baixa Chiado' often witness the highest intensities of UHI (Andrade 2003), and habitually, the highest T_{amb} values during the summer (Alcoforado, Lopes et al. 2005).

Opportunities for Public Space Design

Today, and within what is considered a 'third modernity' where "*the contemporary society witnesses rapid transformations and, resultant of this evolution, the degree and velocity of this transformation is often underestimated* (…) *in the domain of urban planning, such comprehension is even more challenging to appreciate due to the slow evolution of the edified fabric, and because of the comparatively small amount of new annual contributions to the existing fabric…*" (Ascher 2010, p.19, author's translation), the role of public spaces needs to adjust in order to further consider issues related to urban climatology. Referring back to the perspective presented by (Brown, Vanos et al. 2015, p.1) [I] at the beginning of this introduction, urban public spaces can be seen through two respective prisms, as a setting: (1) where urban climatology can lead to thermal discomfort and distress upon pedestrians within the urban fabric; and, (2) where such local risk factors can be improved through evidence based 'climate-responsive design'.

As a result, and considered as an imperative opportunity for public space design in an era of potential climatic aggravations; although their physical attributes may actually not have changed significantly, public spaces must however continue to reflect the values and needs of an ever evolving society. Concerning this evolution, although cities have progressed for centuries around the intuitive feeling for human sense and scale, " *this knowledge was lost somewhere in the process of industrialisation and modernization, which led to dysfunctional city environments for the important and yet ignored segment of city life on foot.*" (Gehl and Svarre 2013, p.3). Extrapolating this perspective a little more in terms identifying tangible (and also intangible) qualities of the 'city life on foot', outdoor spaces can likewise be considered a "*founder of urban form, the space between buildings, that configures the domain of socialisation and 'common' experiences, and likewise of a collective community*" (Brandão 2011, p.34, author's translation). In order to maintain such qualities that have also been identified by many other prominent studies which continue to be cornerstones within contemporary urban planning and design (Lynch 1960, Cullen 1961, Jacobs 1961, Whyte 1980, Gehl 1987, Borja and Muxí 2003, Carmona, Tiesdell et al. 2003, Day and Parnell 2003), there is now the need to further "*recognise the important role that public spaces play in extreme temperatures/combating climate change*" (CABE and Practitioners 2011). It is here where public spaces, a stage of human activity and prosperity within outdoor contexts, can be utilised to improve the safety and comfort of the urban public realm.

Within the early approach conducted by Olgyay (1963), the examination of climatic implications upon the built environment was identified as an imperative starting point for architecture, urban design, and urban planning. More concretely, the sequential interplay of 'climate-comfort' design was based upon: Climate data, biological evaluation, technological solutions, and local application. Founded upon such a rational, one can extract the potentiality of bottom-up perspectives, and that of local urban outdoor spaces. Specifically, the first two steps imply, initially, a careful and wholesome consideration of climatic elements at a given location, and secondly, the impacts of such elements upon human implications. Accordingly, this not only acknowledges the need for microclimatic evaluation, but likewise, the importance of considering thermal comfort implications within the design/maintenance of an urban outdoor space. Taking this line of reasoning a little further for local decision making and design, this raises two predominant considerations: (i) the requirement to improve and/or facilitate the design guidelines within such environmental perspectives for action and adaptation; and, (ii) the growing cogency/necessity for local thermal climate sensitive action. For such motives, the breadth between theory and application/practice needs to continue to be further addressed to inform the better design, and maintenance, of public space design in an era susceptible to potential climatic aggravations.

Hypothesis & Objectives

Hypothesis

The interdisciplinary union between the distinct fields of urban climatology and public space design can be strengthened to improve local pedestrian thermal comfort levels while confronting existing and projected microclimatic aggravations associated to climate change

General Objective

To examine how public space design can improve urban outdoor thermo-physiological factors through a bottom-up approach

Specific Objectives

(1) Inspect implications of the emerging climate change agenda upon the importance of bottom-up approaches to local scale adaptation

(2) Identify existing measures and both quantitative/qualitative approaches to thermal sensitive public space design

(3) Examine how public space design can identify/improve existing/future human thermal comfort risk factors within a specific site

(4) Consider how thermal attenuation priorities can be identified and met through public space design in various urban morphological settings

Thesis Approach and Structure

The approach conducted within this thesis was divided into four sequential sections based upon the stipulated specific objectives. Each section was constructed upon two publications which sought to present scientific outlooks, approaches, and conclusions that ultimately aimed at addressing and testing the original research hypothesis launched by this doctoral thesis by publication.

State-of-the-art:

Publication 1: Approaches to outdoor thermal comfort thresholds through public space design: A Review

Authors: A. Santos Nouri, João Pedro Costa, M. Santamouris, A. Matzarakis

The state-of-the-art of this thesis was structured into a 'Review Article' which was progressively constructed/refined throughout the elaboration of the thesis. As the thesis developed throughout the various sections of the research, the identified existing knowledge was formulated into a structured document which provided a critical outlook upon how outdoor thermal comfort thresholds have thus far been addressed through public space design.

More precisely, and with the aim of discussing and organising the application of scientific knowhow with regards to thermal comfort thresholds through public space design, Publication 1 undertook two sequential approaches to the state-of-the-art. These being upon: (i) ascertaining general approaches to pedestrian thermal comfort thresholds through quantitative perspectives (i.e. considering thermo-physiological indices), and through qualitative perspectives (i.e. considering psychological thermal adaptation dynamics); and subsequently, (ii) the elaboration/organisation of four Measure Review Frameworks (MRFs) which describe the actual application of different typologies of public space design measures within three KG subtypes of the 'Temperate' classification.

Based upon similar distinctions undertaken by (Ahmed 1996, Nikolopoulou 2004, Erell, Pearlmutter et al. 2011), the MRFs were based upon four principal elements, these being: (1) urban vegetation – constituting the Green MRF; (2) shelter canopies – constituting the Sun MRF; (3) urban materials – constituting the Surface MRF; and, (4) water/misting systems – constituting the Blue MRF. Within each measure framework, and identified by the respective studies, the procedures in which microclimatic conditions were assessed and/or modified were reviewed. In addition, and by also referring to thermo-physiological and psychological approaches, it was possible to evaluate how existing measures influenced 'in-situ' conditions, for example: (i) T_{amb}, which generally revealed low reductions, due to encircling atmosphere quickly dissolving such deviations; (ii) Global radiation (G_{rad}), which revealed crucial influences upon thermal comfort levels within studies that considered thermo-physiological indices; and, (iii) Wind speed (*V*), which could be manipulated (e.g., decelerated and/or deflected) through elements such as urban vegetation.

Given the very 'review' nature of Publication 1, and as identified by the constant dissemination of new scientific studies and results, it was considered essential that the state-of-the-art would accompany the progression of this research document until its very final stages. Within such stages of the research, where appropriate, the outcomes of the publications conducted in this thesis were also introduced to consider: (i) how such outcomes built upon various aspects within existing approaches and attitudes; (ii) the comparative opportunities for further work and development with regards to the outcomes presented by the thesis; and, (iii) the future prospectus for thermal comfort factors and public space design, and which areas have still to be explored to their full potential in an era that shall likely witness the continuous maturing and dissemination of new approaches/methods in an era of potential climate change.

Section 1: The emergence of the climate change adaptation agenda and the growing role of bottom-up approaches to local scales

Section 1 had the objective of approaching two predominant components: (1) the emergence of the climate adaptation agenda, its intrinsic constitution within international scientific arena, and resulting implications for urban planning and design; and, (2) how methods of impact prediction could correspondingly be undertaken through bottom-up urban planning and design approaches at local scales. Such an attitude enabled an initial appraisal into the climate adaptation agenda, both through a top-down perspective and a bottom-up perspective, each with their own strengths and shortcomings.

Yet, and within Section 1, the ultimate goal was to sequentially downscale the analytical scale in to identify the vital role of local scales in addressing how existing/future climatic aggravations can be approached through the interdisciplinary practice of public space design.

Publication 2: Climate change adaptation in urbanised estuaries contributes to the Lisbon case

Author/s: João Pedro Costa, A. Santos Nouri, A. Fernandes

Publication 2 launched an encompassing global view of the emergence of what was previously a commonly overlooked and disregarded issue, especially for urban planning and design. Such a chapter was launched as part of the integration within the research project "Urbanised Estuaries and Deltas. In search for a comprehensive planning and governance. The Lisbon case" (PTDC/AUR/2008/100309). Within this chapter, and based more upon an initial top-down approach to climate change, the growing recognition for the importance and necessity for action was discussed. Such an importance was also enforced by identifying 'frontrunners' (both in terms of countries and organisations) that were presenting significant scientific breakthroughs with regards to approaching national adaptation strategies; and in some cases, in measure application. These disseminations were approached as scientific insights to an emerging problem/urgency which could serve as information for other national adaptation efforts around the world. As a result this permitted the perspective that the comprehension of local and dynamic risk factors was indirectly or directly (based upon a case-by-case perspective), backed by scientific knowhow. In this way, such a two-way-synergy permitted 'frontrunners' to rely on scientific knowledge, yet moreover address their own national processes of adaptation. In both perspectives, one of the most significant breakthroughs was application and teaching of approaches of 'down-scaling' climatic adaptation. For this reason and through a structured evaluation, both the invaluable contributions from global scientific entities (such as the UNFCCC, and the IPCC) were established, but moreover, the need, and scientific thirst, for bottom-up and localised action for urban planning and design was also indubitably identified.

Publication 3: A bottom-up perspective upon climate change – approaches towards the local scale and microclimatic assessment

Author/s: A. Santos Nouri

Instigated by the work undertaken within the "Urbanised Estuaries and Deltas" project, which although focused more upon risks/opportunities presented by urban flooding, especially in terms of local adaptation measures as identified within Publication 2; the project also identified the importance of addressing other climatic aggravations such as increases in T_{amb} and occurrences of heat waves in Lisbon. Similarly and as already described, there was also the essential opportunity to consider such issues at a local scale through a bottom-up approach. Within Publication 3, such a perspective was framed into establishing an early overview of how local scales could present a means to both recognise, and evaluate, such local microclimatic 'risk factors'.

More concretely, and with regards to recognition, still acknowledging the paramount contributions of top-down approaches, particularly regarding extreme climate events with an estimated 'return period'; the significant responsibility for local scales to also address "*the high-frequency and microscale climatic phenomena created within the anthropogenic environment of the city*" (Hebbert and Webb 2007, p.126) was presented. In addition, the attributes of the urban environment such as street orientations and Aspect Ratios (AR) were approached as means to bridge how practices of urban climatology with urban planning and design could tackle microclimatic risk factors. Subsequently, numerous existing approaches that already presented valuable means to evaluate microclimatic 'risk factors' were overviewed, namely: (i) the an interpretation of Olgyay (1963) regarding moderate European climates with regards to determining 'thermal comfort zones' within outdoor environments; (ii) the use of the Physiologically Equivalent Temperature (PET) index (Mayer and Höppe 1987), based upon the Munich Energy-balance Model for Individuals (MEMI) (Höppe 1984, Höppe 1993) - that is defined as the T_{amb} at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and perspiration rate are equivalent to those under the conditions to be assessed (Höppe 1999); (iii) the ranges of PET for different grades of Thermal Perception (TP) and Physiological Stress (PS) upon the human body as discussed in (Matzarakis 1997, Matzarakis, Mayer et al. 1999); and, (iv) the human-biometeorological RayMan model (Matzarakis and Rutz 2006, Matzarakis, Rutz et al. 2007, Matzarakis, Rutz et al. 2010) which incorporates calculations of non-temperature microclimatic variables such as radiation fluxes upon the human body within complex urban environments.

Finally, within Publication 3, the strategic approach of '*What if?*' discussed by (Costa 2011, Coelho, Costa et al. 2012) was also discussed as a means to confronting climatic uncertainty through a flexible exploratory approach by estimating/projecting certain scenarios within a given specific urban outdoor location/setting. Such a method was based upon the tentative approach of "*…by asking the right questions in sun and wind studies, by experimentation,* [one] *can find better ways to board the sun, to* *double its light, or to obscure it, or to cut down breezes in winter and induce them in summer* […and] *learn lessons in semi open niches and crannies that people often seek.*" (Whyte 1980, p.45).

Section 2: Examining existing measures and approaches to thermal sensitive public space design

Within Section 2 of the thesis, two distinct stages were established. The first was aimed at exploring initial means in which public space design measures could address thermal comfort at local scales based upon a specific climate. This section of the research was conducted through the attributed AUSMIP+ Program Doctoral Mobility Scholarship (X50-0-25-0012-Y80) to Auckland, New Zealand. Publication 4 revealed some of the results obtained during this segment of the research. The reason for choosing Auckland for this segment of the research was twofold:

- Firstly, and unlike Lisbon, Auckland witnesses a KG classification of '*Cfb*' which according to Peel, Finlayson et al. (2007) relays to lower temperature extremes during the summer. Nevertheless, before reaching the mid-21st century, it is expected that population, urban density and CO_2 emissions shall significantly increase. Accordingly, and in amalgamation with the council's aim to make Auckland the world's most 'Liveable City' by 2040 (Auckland-Council 2013), the proposed 'Auckland Unitary Plan' recognised the need to address local 'risk factors' through urban planning and design; both as a result of future urban densification, but moreover, to address climatic projections. According to MfE (2008) and Gluckman (2013), with regards to thermal conditions, the following 'very confident' projections were established: (i) a T_{amb} increase up to 2.0 ºC by 2040, and 5.1 ºC 2090; (ii) an increased frequency of high temperatures; and, (iii) an increase of at least 40 additional 'hot days' where maximum T_{amb} exceed that of 25 ºC (implying an increase of 200% comparative to existing levels) by the 2100. For these reasons, and in line with the Unitary Plan (UP) recognising the need to "*increase the resilience of Auckland's communities and natural and physical resources to the anticipated effects of climate change such as* (…) *more frequent and extreme weather events*" (Auckland-Council 2013, p.178) such circumstances provided an excellent scope in which to examine a set of initial thermal sensitive urban benchmarks within a city aiming at soon becoming the world's most 'Liveable City'.

- Secondly, and again referring to Peel, Finlayson et al. (2007), Auckland's '*Cfb*' classification also implied increased humidity levels in comparison to those encountered in Lisbon. Such a difference was considered to be an opportunity to examine how factors such as increased RH levels (due to a lack of annual dry seasons) could be overcome when considering the application of certain types of public space design measures during the summer. This exercise proved to be very beneficial later in the research when considering such applications within Lisbon's hot-dry summers as the evaporative cooling of water particles could be exploited further without exacerbating stipulated acceptable RH levels.

Within the first segment of this section, public space design approaches that could potentially be considered within a concrete climate classification/city were explored. However, in order to approach a 'specific outdoor setting', the second segment undertook an analysis into how existing approaches to public space design could be further developed with regards to addressing: (i) existing thermal comfort thresholds; and, (ii) how current thresholds could potentially become further aggravated at local scales as a result of potential climate change. Such an examination was undertaken through both quantitative and qualitative aspects within Publication 5.

Publication 4: A framework of thermal sensitive urban design benchmarks: Potentiating the longevity of Auckland's Public Realm

Author/s: A. Santos Nouri

With Auckland as the case study for the Publication 4, a framework of international precedents of built and conceptual projects that addressed similar microclimatic stimuli were organised into an open ended framework. This examination was undertaken while hosted within the University of Auckland and with the very much esteemed support from the 'Transforming Cities: Innovations for Sustainable Futures' research group. Although two locations were exemplified within Auckland's Central Business District (CBD) (i.e. Queen Elizabeth Square and Queen Street), the objective of the paper was not to assess a specific public space. Instead, two principal objectives established, namely: (1) to categorise different types of public space design measures which could potentially reduce existing/future thermal stress within Auckland's public realm; and, (2) to explore how identified measures and benchmarks could be incorporated within regulatory UP, and non-regulatory Auckland's

Design Manual (ADM) to possibly introduce more concrete guidelines to improve thermal comfort levels within the city's public realm. More precisely, and bearing in mind the ADM's 'Section4 – Design for Comfort and Safety', the presented framework of measures explored how an online extension of Section 4, explicitly orientated towards 'Dealing with Thermal Comfort and Climate Change' could be launched. Before the termination of this segment of the research in New Zealand, the much esteemed invitation was made on behalf of 'Built Environment Team' within the Auckland council to present the results obtained within the publication. Such an experience also enabled an opportunity to discuss, with a regulatory entity, how scientific approaches could potentially be translated into local thermal sensitive urban design guidelines in a city which aimed at becoming the world's most 'Liveable City' by 2040.

Publication 5: Placemaking and climate change adaptation: new qualitative and quantitative considerations for the "Place Diagram"

Author/s: A. Santos Nouri & João Pedro Costa

Within the previous article, potential public space measures were explored for a specific city and climate. Nevertheless a concrete outdoor space was not evaluated in terms of 'in-situ' thermal risk factors; or how such measures could potentially address such identified risk factors. In order to undertake such an approach later in the study, Publication 5 sought to further explore existing public space design approaches to address qualitative and quantitative elements of the interdisciplinary concept of 'Placemaking' in an era potential of climate change.

As a result, and with the interest of also expanding upon current influential interrogations (almost slogans) such as 'What makes a great place?' (PPS 2003); the aspect of 'comfort' within the 'Place Diagram' was extended to more effectively consider pedestrian thermal comfort aspects, especially in light of climate change. Such an exercise consisted upon a 'new approach' which looked into the future functioning/roles of public spaces, and also, beyond that of past and current functionality. As a result, the publication was divided into two predominant sections: (i) the identification of new qualitative criteria (or intangibles) which considered the processes which pedestrians go through to improve the fit between the environment and their thermal requirements; and, (ii) the assessment of quantitative criteria (or measurable data) which raised reflections into local characteristics that require consideration/modification to address pedestrian comfort. Although still at a 'generic' level, the publication presented concrete qualitative/quantities criteria, enabling a new perspective upon the aspect of 'comfort' within the PPS's traditional generic tool to evaluate the long-term 'success' of a public space. Accordingly, and by also referring to the '*What if?*' approach, the concept of 'success' was also revised to go beyond past and existing evaluation perspectives within an era of potential climate intensifications. Such results enabled a more concrete understanding to be consolidated towards local intangible and measurable data which both have a key influence upon thermal comfort thresholds.

Section 3: Addressing existing and future thermal comfort thresholds within the square of Rossio, Lisbon

Within Section 3, and focusing upon the case of Lisbon, a specific outdoor space was selected to undertake a two-step examination upon how local thermal comfort thresholds could be addressed through public space design. Focused upon one of Lisbon's most iconic historical public spaces, Rossio, this section of the research was based entirely upon site visits and measurements. Within Publication 6, the study was constructed upon two principal objectives: (1) to identify the predominant microclimatic risk factors within the square that could jeopardise pedestrian thermal comfort thresholds; and, (2) examine how identified risk factors could be attenuated through public space design. Subsequently, and within Publication 7, such results were taken a step further by considering how worst-case-scenarios of climate change ($SRES_{A1FI}/RCP_{8.5}$) could potentially influence the existing thermal conditions within the square by the end of the century. In addition, such influences were also considered given the presence of the investigated measures. The reason for selecting Rossio for this section of the study was twofold: (i) due being located in the district which often witnesses the highest effects of UHI and T_{amb} values during the summer; and, (ii) due to its lower AR (≈0.21) in comparison to most surrounding canyons, increasing its susceptibility to microclimatic stimuli such as solar radiation.

Publication 6: Addressing thermophysiological thresholds and psychological aspects during hot and dry Mediterranean summers through public space design: The case of Rossio

Author/s: A. Santos Nouri & João Pedro Costa

With the aim of approaching both the quantitative and qualitative measurements/intangibles as identified in Publication 5, and incorporating lessons learnt from some of the public space measures initially approached in Publication 4; Publication 6 presented the first 'site specific' bioclimatic study within the thesis. As a result, it was important to concretely specify the step by step methods (from initial computer simulations to result analysis) in order to: (i) justify the decisions, techniques and results obtained by the study; and just as importantly, (ii) enable such techniques to be replicated in future bioclimatic studies/projects when approaching local thermal comfort thresholds.

Based upon pre-site measurements, initial and indicative studies were undertaken to both identify areas that were more prone to microclimatic risk factors, and subsequently validate initial simulations (i.e., Computational Fluid Dynamic (CFD) and Shadow Behaviour Simulation (SBS) assessments). Once established, between 10:00 and 17:00, and through the use of meteorological equipment, six Points of Interest (POI) around the square were distributed to obtain hourly climatic measurements of: V, T_{amb}, RH, G_{rad}, and surface temperature (T_{surf}). In addition, two further recordings were obtained, namely: (i) fish-eye-lens photographs within the centre of each POI to later process the single-point Sky View Factor (SVF) values; and, (ii) the amount of footfall within each POI during lunch time to ascertain a general indication of pedestrian numbers distributed around the square.

Such an exercise was conducted during July 2015, which accommodated 8 site visits evenly distributed throughout the entire month (i.e., with a 2.5 day average interval between visits). In addition, and based upon the results obtained from Publication 5, Pedestrian Based Responses (PBR) interviews were also undertaken to approach psychological (or qualitative/intangible) comfort aspects. The interviews were divided into two distinctive stages, in order to: (1) obtain a sample of responses to evaluate perception of 'in-situ' microclimatic variables; and, (2) examine the cognitive microclimatic variables around the entire square.

Subsequently, the climatic measurements were translated into PET values through the use of RayMan. As identified within Publication 3, the calculation of PET is based upon the MEMI model (Höppe 1984, Höppe 1993), which is constituted by the energy balance as shown in **Eq.1**. Once obtained, the PET values were compared against Physiological Stress (PS) grades upon the human body according to Matzarakis (1997) and Matzarakis, Mayer et al. (1999).

Equation:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \qquad \textbf{Eq.1}$$

Whereby: M → metabolic rate (internal energy production); W → the physical work output; R → net of radiation of the human body; C → convective heat flow; E_D → latent heat flow to evaporate water diffusing through the skin (imperceptible perspiration); E_{Re} → sum of heat flows for heating and humidifying the inspired air; E_{Sw} → heat flow due to evaporation of sweat; S → storage heat flow for heating or cooling the body mass

Note: All units for energy fluxes are in Watts. In addition, the following individual heat flows shown within **Eq.1** are regulated by the following meteorological parameters as identified by (VDI 1998, Höppe 1999):

→ Air temperature: C, E_{Re}
→ Air humidity: E_D, E_{Re}, E_{Sw}
→ Wind Velocity: C, E_{Sw}
→ Mean radiant temperature: R

In addition, the following parameters are required (and included within the RayMan):

→ Heat resistance of clothing (clo)
→ Activity of humans (Watts)

In addition, and as output of the RayMan model, the mean radiant temperature (T_{mrt}) (or R within **Eq.1**) was also obtained and discussed. Although some studies have explored means to obtain it through local variables such as globe temperature (T_{globe}) and V oscillations (e.g., Thorsson, Lindberg et al. 2007); the procedure to experimentally determine T_{mrt} is very complex, and is a very important variable within the human energy model (Matzarakis, Rutz et al. 2007). For this reason, and within the Rayman model itself, the Stephan-Boltzmann constant (σ), and the identification of mean radiation flux densities (S_{str}) (extrapolated from measured short (K) and long (L) wave radiation) as defined by Höppe (1992) (**Eq.2**) are utilised to calculate T_{mrt} as shown in **Eq.3**. For more detailed information on the formulas used within RayMan, see (Matzarakis, Rutz et al. 2007, Matzarakis, Rutz et al. 2010).

Equation:	$S_{str} = a_k \sum_{i=1}^{6} K_i F_i + a_l \sum_{i=1}^{6} L_i F_i$	**Eq.2**
Whereby:	K_i → shortwave radiation flux (W/m^2); L_i → longwave radiation flux (W/m^2); a_K → absorption coefficient for shortwave radiation; a_l → absorption coefficient for longwave radiation; Fi → angle factors of solid surfaces	
Note:	Upper bound of summation configured at 6 due to the six direction (4 cardinal directions, in addition to upwards and downwards) readings which would be required with the use of both a pyranometer and a pyregeometer to identify radiation fluxes upon a person within an actual/3D environment	

Equation:	$T_{mrt} = \sqrt[4]{((S_{str}/(a_l \sigma))} - 273.2$	**Eq.3**
Whereby:	$\sigma \rightarrow 5.67*10^{-8}$ W/m^{-2}K^{-1}	
Note:	As σ is presented in degrees Kelvin, the T_{mrt} equation converts the result into Celsius after radical	

Once overall thermal comfort factors were examined around the square through the use of the specified POIs, the study then examined the implementation of respective public space design measures. Again referring to numerous outputs obtained in Publication 4, three predominant measures were suggested within the four POIs which presented the highest levels of thermal stress, these being: vegetation, shelter canopies and water/misting systems. In order to quantify their potential attenuation upon identified thermal comfort levels, it was necessary to predominantly identify how the measures would influence 'in-situ' G_{rad}, RH and T_{amb}. Such an exercise was undertaken by investigating: (i) reductions of G_{rad} induced by introduced trees, nylon shade sails, and by acrylic flaps of the shelter canopies within the different POIs; and, (ii) reductions of T_{amb} levels as a result of increasing atmospheric RH through the **Exp.1** that was developed from (Ishii, Tsujimoto et al. 2008, Ishii, Tsujimoto et al. 2009).

Expression:	If $K_{amb} \rightarrow K_{amb} - a$, then RH → 21$a$/20 RH such that $0 < a < 7$, $a \in$ N	**Exp.1**
Note:	If K_{amb} is decreased by a where a is less than 7 and it is a natural number, then RH get increased by a*5%, i.e., a(RH + 5/100 RH) = 21a/20 RH	

As a result, modifications of thermal comfort levels were able to be obtained by re-introducing the projected microclimatic variables into RayMan, which in turn, presented PET/PS estimates from the direct implementation of the public space measures. In addition, it was also possible to examine how such quantitative results would influence qualitative factors (such as pedestrian thermal adaptation and personification) around the square by considering the results obtained from the PBR interviews.

Publication 7: Confronting potential future augmentations of the physiologically equivalent temperature through public space design: The case of Rossio, Lisbon

Author/s: A. Santos Nouri, A. Lopes, João Pedro Costa, & A. Matzarakis

Within this publication, the results obtained from Publication 6 were taken a step forward to consider how climate change projections could affect the identified thermal comfort thresholds within the square of Rossio. Publication 7 underpins a pilot analysis into how climatic scenarios such as $SRES_{A1FI}/RCP_{8.5}$ could influence existing local thermal comfort conditions (with or without the public space interventions disclosed in Publication 6) by 2100. Based upon the '*What if?*' approach discussed in Publication 3/5, the following interrogation was launched: '*If the $SRES_{A1FI}/RCP_{8.5}$ scenario came to fruition, what impacts could this have upon the local biometeorological environment in Rossio?*'

Based upon the study conducted by Matzarakis and Amelung (2008), who identified the impact of these scenarios upon projected PET values by processing T_{amb}, RH, V, and cloud cover values obtained for each global grid within RayMan; future estimations of PET and T_{mrt} were presented for the end of the century. It was revealed that within the Mediterranean region, PET values revealed substantial increases of between 10 ºC and 15 ºC, such outcomes were noted to be alarmingly higher than the estimated increase of up to 4 ºC in T_{amb} (IPCC 2014) for the same temporal period. Based upon the map outputs, within the case of Lisbon, an approximate increase of between 10 ºC and 12.5 ºC was also recognised.

When considering such implications for the acknowledged biometeorological environment in Rossio, and constructed upon a oscillation of +10 ºC from the existing values obtained in Publication 6; it became clear that (based upon the increment of roughly 5 ºC per physiological threshold) three new PS grades were required beyond the initial 'Extreme Heat Stress' to plot the projected PET results. Based upon the PET oscillations presented initially by the study to inform a projective description of PS stress around the entire square (and not only within the respective POIs), a hypothetical 5m by 5m grid network was established throughout the entire square. To preserve precision whilst assessing PS values around the square, the established gird enabled a more concise: (i) consideration of shade upon pedestrianized areas as a result of street trees; (ii) contemplation of hotter surface temperatures around the square; and, (iii) definition of shade patterns cast by encircling structures such as building façades and square amenities (including those resultant of the proposed solutions). Even though this approach indicated just a synoptic and initial estimation of thermal comfort distribution around the square, the results previously obtained in each POI were used to inform how similar locations could influence pedestrian PS thresholds. Finally, two public space design measures were extended from the previous study in order to consider how thermal comfort could be modified throughout the entire western and eastern sidewalks.

As a result, and throughout the entire square it was possible to compare four datasets at 15:00 (which was the hottest diurnal hour, described as C5) namely: (i) $\overline{PET\Delta_{\mathrm{D3(C5)}}}$ – Representing existing PET with public space design interventions; (ii) $\overline{PET_{\mathrm{D3(C5)}}}$ – Representing existing PET without public space design interventions; (iii) $\overline{PET\Delta_{\mathrm{A1FI(C5)}}}$ – Representing projected PET with public space design interventions in a scenario with no policy changes to reduce global emissions; and, (iv) $\overline{PET_{\mathrm{A1FI(C5)}}}$ – Representing projected PET without public space design interventions in a scenario with no policy changes to reduce global emissions. In addition, and to present an overall comparison of the different presented thermal environments in Rossio, the PET Load (PETL) parameter (**Eq.4**) developed by Charalampopoulos, Tsiros et al. (2016) was utilised to quantify the amount of thermal stress beyond that of a comfortable PET value. Moreover, and beyond the identification of intensity of thermal stress, the periodicity and duration of such stimuli was also discussed within both existing and future datasets, with a further association to the existing/future influences of UHI intensities.

Equation:	$PETL = PET_h - A$	**Eq.4**
Whereby:	PET_h → is the average hourly PET value; *A* → is representative of the PS grade of 'Comfortable'	
Note:	Since the *A* factor can be calibrated depending on the specified PET ranges, a PET value of 23.0ºC was selected to represent the upper limit of the 'Comfortable' classification in the publication	

Section 4: Projecting thermal attenuation priorities and 'in-situ' impacts within idealised/default urban canyons

Within the final section of the research, and based upon outputs obtained from the previous 3 sections, two principal objectives were established, namely to: (i) in Publication 8 - identify how climatic data from Lisbon's meteorological station could be utilised to establish Thermal Attenuation Priorities (TAP) for public space design within Lisbon's historical quarter; and, (ii) in Publication 9 - examine how a specific measure of public space design (i.e., vegetation) could influence thermal comfort levels, both during the summer and during the winter. Unlike the methods undertaken in Publication 6/7, which presented methods of registering/utilising only on-site measured climatic data, the approach undertaken in Section 4 explored how meteorological station data could be used to further consider canyons with different types morphological compositions.

In addition, two secondary objectives were also established within this section, these being to analyse/apply: (i) a modified version of the PET (mPET), which was developed by Chen and Matzarakis (2017) to present more accurate estimations of thermal comfort conditions, particularly during annual periods of accentuated PS; and, (ii) a new version of the SkyHelios model (Matzarakis and Matuschek 2011, Fröhlich 2017) as a new means to address microclimatic characteristics such as *V* as a result of the integration of a new three-dimensional diagnostic tool.

Publication 8: Examining default urban-aspect-ratios and sky-view-factors to identify priorities for thermal-sensitive public space design in hot-summer Mediterranean climates

Author/s: A. Santos Nouri, João Pedro Costa, A. Matzarakis

Undertaken in this study, an application-orientated analysis of Lisbon's bioclimatic environment was established to identify physiological risk factors within Lisbon's public spaces by: (i) examining Lisbon's annual climatic oscillations of diurnal thermal stress, with a recording interval of 3 hours between 09:00 and 15:00; (ii) constructing an hourly evaluation of July's climatic conditions between the diurnal hours of 09:00 and 18:00, with a recording interval of 1 hour; and, (iii) assessing how such conditions were affected by the different modelled default urban ARs and SVFs. Once established, the obtained bioclimatic conditions within the different outdoor urban open spaces were assessed through the application of different thermo-physiological indices to construct the TAP for public space design at local scales.

To obtain the data required for the study, meteorological recordings were obtained from the World Meteorological Station weather station (Index Nº08535) located in Lisbon. Such data consisted of total cloud (Oktas), T_{amb}, RH, and lastly *V* which were introduced within the RayMan model. With regards to *V*, once the values were converted to m/s, a further adjustment was undertaken to account for the type of urban conditions described within the study. As presented by the study undertaken by Oliveira, Andrade et al. (2011), when considering speeds beneath the Urban Canopy Layer (UCL), and within the streets themselves, modified *V* values are often considerably lower than those presented by the meteorological station. As a result, and to determine actual *V* influences upon the gravity centre of the human body as defined by Kuttler (2000), the obtained results from the station were adapted to a height of 1.1m. Correspondingly to the study undertaken by Algeciras and Matzarakis (2015), the formula presented in (Kuttler 2000, Matzarakis, Rocco et al. 2009) was utilised (**Eq.5**).

Equation:	$V_{1.1} = V_h^{*}\left(\frac{1.1}{h}\right)^{\alpha} \qquad \alpha = 0.12^{*}z_0 + 0.18$	**Eq.5**
Whereby:	V_h is the m/s at a height of h (10m), α is an empirical exponent, depending upon urban surface roughness, and z_0 is the corresponding roughness length	

In addition to these variables obtained from the station, and based upon a similar approach conducted in Publication 6/7, G_{rad} values were also introduced later in the study. Additionally, such calibrations were also further examined in order to approach and compare such results against the new mPET index. As discussed by Chen and Matzarakis (2017), the main differences of mPET is the thermoregulation model (based upon a multiple-segment model), and the clothing model thus enabling a more accurate analysis of the human bio-heat transfer mechanism.

With this established data, the study was divided into three sequential stages to evaluate Lisbon's thermal risk factors and resulting influences on public space design. Firstly, monthly modifications of diurnal PET/PS fluctuations were analysed in order to obtain an overall understanding of 2016, which served as a reference point to identify periods of both cold and heat stress variations throughout the year. Secondly, based upon the annual analysis, diurnal variations were analysed in more detail through the hour oscillations for July between 2012 and 2016 to obtain an understanding of such diurnal fluctuations over five years. At this stage, the results between the PET and mPET indices were compared, and in addition, the results obtained by Chen and Matzarakis (2017) were also corroborated. Thirdly, such data was then cross examined within the different default ARs established within the study (i.e., Height-to-Width ratios (H/W) of 2.00, 1.00, 0.50, 0.25, and 0.17). At this stage, the respective G_{rad} measurements were introduced intro RayMan model as well. Such an approach enabled the concrete hourly prioritisation for public space design measures to be established within the various morphological canyons which are commonly found within Lisbon's historical district. In addition, and once again utilising the '*What if?*' approach as undertaken in Publication 7, the subsequent interrogation was also investigated: '*If the assessment was based upon a particularly hot day, instead of the averages obtained for the* |*July*$_{2016}$| *dataset, how would this influence the obtained bioclimatic results?*'

Similar to existing bioclimatic studies, in order to facilitate the representation and reading of PET/mPET (and corresponding PS levels), the results were processed with the Climate Tourism/Transfer Information Scheme (CTIS). Based upon the calibrations of the desired thresholds and temporal period, this software facilitated the graphical interpretation and representation of values presented by the study. Finally, and in order to plot the TAP results, and similar to the methods used in Publication 7, adapted PETL (**Eq.4**) and cumulative PETL (cPETL) parameters were used in order to establish the amount of thermal stress at a specific period/hour of the day, within specific locations hosted within the various assessed default ARs.

Publication 9: The impact of *Tipuana tipu* species on local human thermal comfort thresholds in different urban canyon cases in Mediterranean climates: Lisbon, Portugal

Author/s: A. Santos Nouri, Dominik Fröhlich, Maria Matos Silva & Andreas Matzarakis

Within the last publication of the thesis, and in association with Publication 8, one type of public space design measure which was discussed in terms of assessing its 'in-situ' influence upon comfort thresholds within different default urban canyons. Again retrieving information from the meteorological station, one of the most common shading trees in Lisbon was examined, the *Tipuana tipu* species. In order to undertake this examination, and in addition to the use of the mPET index, a new approach was used within this publication through the updated version of the SkyHelios model elaborated by Fröhlich (2017).

As presented within the new version, the model was developed to analyse the spatial dimension of local climatic conditions. The short runtime and the possibility of dealing with different projected coordinate systems permitted the model to evaluate the comparisons of different urban canyons, tree compositions, and their effect on pedestrian thermal comfort thresholds. In processing terms, the new SkyHelios model essentially follows a similar approach to that of RayMan, but has the additional feature of also considering the spatial dimension of the parameters. More specifically, unlike in Publication 8, where *V* was 'assumed' to be equal within the assessed canyons and locations; the three-dimensional diagnostic wind model integrated within the updated SkyHelios version enabled 'in-situ' estimations of *V* measurements to be obtained.

Nevertheless, within the initial assessments undertaken in the study to determine general bioclimatic conditions (i.e., PET and mPET values) retrieved from the same weather stations used in Publication 8, the following parameters were inserted into RayMan: T_{amb}, RH, total cloud oktas, and *V*. Once again, **Eq.5** was utilised to obtain *V* values at pedestrian height from the those presented by the station. In addition to the preliminary climatic variables, site G_{rad} measurements were once again utilised to obtain hourly oscillations: (i) in specific locations within the different canyons; and, (ii) beneath the tree crowns of the *Tipuana tipu* to identify the amount of radiation that was diluted by the vegetative mass.

When constructing the canyon simulations within the 'Obstacle' plugin associated to both the RayMan and SkyHelios models, similarly to the previous publication, various canyons with dissimilar morphological compositions were established (i.e., H/W ratios of 2.00, 1.00, 0.50, and 0.17). In addition, each of these canyons was examined under two conditions: (i) without the presence of vegetation; and, (ii) with the presence of vegetation. In addition, and similar to Publication 8, each canyon was aligned into a north-to-south orientation and a west-to-east orientation to process the influence of the geo-referenced summer/winter sun paths upon the two alignments. Based upon the studies identified within the publication, the concrete dimensions of the *Tipuana tipu* were stipulated within the each simulation, and adjusted upon maintain a similar amount of Vegetative Coverage Ratio (VCR) (**Eq.6**).

Equation: $$VCR = \frac{(100^{*}CS)}{W} \qquad CS = n^{*}r^{*}2$$ **Eq.6**

Whereby: *W* is the width of the aspect ratio, *CS* is the crown spread, *n* is the number of trees, and *r* is the radius (5,6.5)

Similar to the methodology utilised within the previous study, three points of reference were once again stipulated in each canyon to identify the diurnal variation of solar radiation. Once established, and based upon the calibration of the three dimensional diagnostic wind tool within SkyHelios, the last of the 8 tree line was selected to permit the identification of the influence of the preceding trees in each urban stipulated canyon. Therefore, within the actual simulations undertaken in the publication, it was possible determine how such obstacles within each canyon would influence $V_{1.1}$ once it reached each of the designated reference points. As a result, it was possible to describe and evaluate the 'in-situ' influences of one of Lisbon's most common shading trees within specific urban canyons, during both the summer and winter derivative of a combination of collected site and meteorological station data.

Acronym List

ADM	Auckland's Design Manual	PETL	PET Load
AR	Aspect Ratio	POI	Point of Interest
CABE	Commission for Architecture and Built Environment	PPS	Project for Public Spaces
CBD	Central Business District	PS	Physiological Stress
CCIAM	Climate Change Impacts Adaptation and Modelling	RCM	Regional Climate Model
CFD	Computational Fluid Dynamic	RCP	Representative Concentration Pathways
cPETL	cumulative PETL	RH	Relative Humidity
CTIS	Climate-Tourism/Transfer-Information - Scheme	SBS	Shadow Behaviour Simulation
GCM	Global Circulation Model	SIAM	Climate Change in Portugal Scenarios, Impacts and Adaptation Measures
H/W	Height-to-Width Ratio	SRES	Special Report on Emission Scenarios
IPCC	Intergovernmental Panel on Climate Change	SVF	Sky View Factor
KG	Köppen Geiger	TAP	Thermal Attenuation Priorities
MEMI	Munich Energy-balance Model for Individuals	TP	Thermal Perception
mPET	modified PET	UHI	Urban Heat Island
MRF	Measure Review Framework	UNFCCC	United Nations Framework Convention on Climate Change
Oktas	Total Clouds	UP	Unitary Plan
PBR	Pedestrian Based Responses	VCR	Vegetative Cover Ratio
PET	Physiologically Equivalent Temperature		

Symbol List

'*Cfb*'	Temperate oceanic climate	T_{amb}	Ambient temperature
'*Csa*'	Hot-Mediterranean climate	T_{globe}	Globe temperature
'*Csc*'	Temperate with dry cold summer	T_{mrt}	Mean radiant temperature
G_{rad}	Global radiation	T_{surf}	Surface temperature
K	Short-wave radiation	V	Wind Speed
L	Long-wave radiation	σ	Stephan-Boltzmann constant

*Equation/Expression symbols excluded

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Publication 1:

Approaches to outdoor thermal comfort thresholds through public space design: A Review

A. Santos Nouri, João Pedro Costa, M. Santamouris, A. Matzarakis

Published review article in Atmosphere (2018), 9, 108 (MDPI) – (State-of-the art)

Article Preamble

Publication reviews existing approaches that have addressed local outdoor thermal comfort levels through public space design. The assessment is divided into two sequential stages, whereby: (1) overall existing approaches to thresholds are reviewed within both quantitative/qualitative spectrums; and, (2) different techniques and measures are reviewed and framed into four Measure Review Frameworks. The results of the publication lead to an encompassing assessment throughout the thesis of the current practices of public space design within three specific subcategories of the Köppen Geiger 'Temperate' classification.

Article Symbol list

$\#K_X$	Temperature difference of X variable	Q^*	Net of all-wave radiation
'*Af*'	Tropical rainforest climate	Q_E	Flux of latent heat
'*Aw*'	Tropical savannah with dry winter climate	T_{amb}	Ambient temperature
'*Bwh*'	Desert climate	T_{cold}	T_{amb} of coldest month
'*Cfa*'	Humid subtropical climate	T_{mon10}	# of months where T_{amb} is above 10 ºC
'*Cfb*'	Temperate oceanic climate	T_{surf}	Surface temperature
'*Csa*'	Hot-Mediterranean climate	V	Wind Speed
a	Albedo	ΔQ_A	Net heat advection
G_{rad}	Global radiation	ΔQ_S	Heat storage within urban fabric
P_{sdry}	Precipitation of driest month in summer	Q_F	Anthropogenic heat flux
P_{wwet}	Precipitation of wettest month in winter	Q_H	Flux of sensible heat

Article Acronym List

AR	Aspect-Ratio	OUT_SET*	Outdoor SET*
B	Beginning of Month	PCI	Park Cooling Islands
CFD	Computational Fluid Dynamic	Perm.	Permanent Measure
cPETL	cumulative PETL	PET	Physiologically Equivalent Temperature
E	End of Month	PETL	PET Load
ETCS	Ephemeral Thermal Comfort Solution	PG	Pergola
FP	Functioning Period	PMV	Predicted Mean Vote
GP	Group Plantation	PP	Pump Pressure
H/W	Height-to-Width	PPD	Predicted Percentage of Dissatisfied
IS	In-Situ	PPS	Project for Public Spaces
ITS	Index of Thermal Stress	PS	Physiological Stress
KG	Köppen Geiger	PSD	Public Space Design
LP	Linear Plantation	PT	Perceived Temperature
M	Middle of Month	RH	Relative Humidity
MEMI	Munich Energy-balance Model for Ind.	SET*	Standard Effective Temperature
MOCI	Mediterranean Outdoor Comfort Index	SMD	Sauter Mean Diameter
mPET	modified PET	SP	Surface Plantation
MRF	Measure Review Framework	ST	Solar Transmissivity
MRT	Mean Radiant Temperature	SVF	Sky View Factor
NA	Not Applicable	SW	Surface Wetting
ND	Not Disclosed	UHI	Urban Heat Island
NDI	No Detailed Information	UTCI	Universal Thermal Climate Index
NH	Nozzle Height	UV	Ultra Violet

*Tree acronyms not included

atmosphere

Review

Approaches to Outdoor Thermal Comfort Thresholds through Public Space Design: A Review

Andre Santos Nouri [1,*], João Pedro Costa [1], Mattheos Santamouris [2] and Andreas Matzarakis [3,4]

[1] Faculty of Architecture, University of Lisbon, CIAUD—Research Centre for Architecture, Urbanism and Design, Rua Sá Nogueira, Pólo Universitário do Alto da Ajuda, 1349-063 Lisbon, Portugal; jpc@fa.ulisboa.pt
[2] The Anita Lawrence Chair in High Performance Architecture, School of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia; m.santamouris@unsw.edu.au
[3] Research Center Human Biometeorology, German Meteorological Service, D-79104 Freiburg, Germany; Andreas.Matzarakis@dwd.de
[4] Chair of Environmental Meteorology, Faculty of Environment and Natural Resources, Albert-Ludwigs-University, D-79085 Freiburg, Germany
* Correspondence: andrenouri@fa.ulisboa.pt; Tel.: +351-919-247-292

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Abstract: Based on the Köppen Geiger (KG) classification system, this review article examines existing studies and projects that have endeavoured to address local outdoor thermal comfort thresholds through Public Space Design (PSD). The review is divided into two sequential stages, whereby (1) overall existing approaches to pedestrian thermal comfort thresholds are reviewed within both quantitative and qualitative spectrums; and (2) the different techniques and measures are reviewed and framed into four Measure Review Frameworks (MRFs), in which each type of PSD measure is presented alongside its respective local scale urban specificities/conditions and their resulting thermal attenuation outcomes. The result of this review article is the assessment of how current practices of PSD within three specific subcategories of the KG 'Temperate' group have addressed microclimatic aggravations such as elevated urban temperatures and Urban Heat Island (UHI) effects. Based upon a bottom-up approach, the interdisciplinary practice of PSD is hence approached as a means to address existing and future thermal risk factors within the urban public realm in an era of potential climate change.

Keywords: public space design; Köppen Geiger classification; thermal comfort; microclimates; climate change

1. Introduction

Given the increase of population living within cities, and extreme conditions and aggravations as a result of climate change projections, there has been a resultant response from the international scientific community. When approaching high urban temperatures at micro/local scales, it has so far been argued that "*most cities are not designed to ameliorate these effects although it is well-known that this is possible, especially through evidence-based climate-responsive design of urban open spaces*" [1] (p. 1). As a result, the bottom-up role of local urban spaces in accommodating urban liveability and vitality is continually receiving attention within the international community [2,3].

So far, top-down climatic assessments and thermal comfort studies have often resorted to more simplistic analysis tools. As an example of this incongruity, it has been identified that global entities such as the Intergovernmental Panel on Climate Change "*describe the effect of weather and climate on humans with a simple index based on a combination of air temperature and relative humidity. The exclusion of important meteorological (wind speed and radiation fluxes) and thermo-physiological variables seriously diminishes the significance of [presented] results.*" [4] (p. 162). Consequently, it can be argued that such discrepancies can hinder fairly 'evident' and important microclimatic considerations for a multitude of professionals at local scales, such as architects and urban planners/designers. For example, Katzschner [5] identified that irrespective of local ambient temperatures (T_{amb}), there was an acute disparity of thermo-physiological stress between areas exposed to the sun from those cast in the shade. The influences of such disparities were also confirmed by observed pedestrian behavioural patterns within outdoor spaces by Whyte [6] who suggested that "*by asking the right questions in sun and wind studies, by experimentation, we can find better ways to board the sun, to double its light, or to obscure it, or to cut down breezes in winter and induce them in the summer.*" [6] (p. 45). Similar perspectives were also established in other early studies (e.g., [7,8–15]).

Consequently, and embracing the significance of future horizons that shall likely witness ensuing aggravations of the climate system, principals such as the urban energy balance (Equation (1)) as presented by Oke [16] are particularly relevant when facing such challenges.

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

whereby: Q^* → net of all-wave radiation, Q_F → anthropogenic heat flux, Q_H → is the flux of sensible heat, Q_E → the flux of latent heat, ΔQ_S → heat stored within the urban fabric, and ΔQ_A → net heat advection.

Due to delicate equilibrium of the urban climate, existing variables such as UHI intensities and T_{amb} values should be approached as 'base values' that could be further offset by future modifications of the urban energy balance. As a result, existing studies have already identified the need to consider how (i) the projected increase in frequency, intensity, and consecutiveness of annual hot periods can impact Q^* (i.e., altering the incoming/outgoing balance between short wave and long wave radiation) (e.g., [4,17]); (ii) in addition to other anthropogenic emissions, the expected increase in need for urban cooling (e.g., air conditioning) can escalate Q_F (e.g., [18]); (iii) the heat storage (i.e., ΔQ_s) of surface materials can increase as a result of radiation variations (e.g., [19]); and, lastly, (iv) potential reductions in variables such as wind patterns (as a result of additional urbanisation) can lead to undesired urban reductions of ΔQ_A [20].

Adjacently, and in accordance with the 'climate-comfort' rational of [7], this review study focuses on merging the potentiality of bottom-up perspectives with those of local urban outdoor spaces. The term of 'locality' is utilised in this study to describe a scale on which public space measures can render relevant, yet direct, thermal modifications on pedestrian comfort thresholds, which can vary from those of an urban canyon to those of an urban park; regardless, and throughout the article, such types of settings are always identified. Taking this line of reasoning a little further in the context of local decision making and design, this raises two predominant concerns: (i) the requirement to improve and/or facilitate the design guidelines within such environmental perspectives for local action and adaptation; and (ii) given the growth of the climate change adaptation agenda, the growing cogency/necessity for local, thermal, climate-sensitive action. For these reasons, the breadth between theory and practice needs to continue to be developed to inform the better design and maintenance of Public Space Design (PSD) in an era that is vulnerable to potential climate change [17,21–23].

In addition, it can also be argued that the role of PSD with respect to the application of design/assessment guidelines can potentially, in the future, be partly associated with a top-down approach. More specifically, once consolidated, regulatory entities can issue generalist bioclimatic 'best practice' recommendations to address human thermal comfort thresholds in different urban circumstances and scenarios. Nevertheless, it is suggested by this review article that (i) the state-of-the-art in this field is not yet mature for such a generalist approach, particularly considering the delicate relationship with local settings and the intrinsically associated influences of microclimatic stimuli; and (ii) whilst the breadth between theory and practice must be reduced, such a reduction at this stage should be matured between urban climatology and urban planning/design at local scales before being transposed to such prospective top-down regimental approaches.

With the objective of discussing and organising the application of scientific knowledge when addressing thermal comfort thresholds through PSD, this article presents two sequential reviews of the state-of-the-art. Firstly, general existing approaches to pedestrian thermal comfort thresholds are described both at a quantitative level (i.e., the identification of thermo-physiological indices) and at a qualitative level (i.e., the identification of psychological thermal adaptation dynamics). Secondly, four Measure Review Frameworks (MRFs) are constructed that describe the actual application of different types of PSD measures within three subtypes of 'Temperate' climates according to the Köppen Geiger (KG) classification system.

2. Methods & Review Structure

2.1. Application of Köppen Geiger Classification System

Within this article, the KG classification system is utilised to determine the climatic context of thermal PSD projects within the international arena. Such an approach enables the organising of respective projects into different climatic contexts based on local micro/climatic characteristics.

As suggested by Chen and Chen [24], the KG climate classification (i) provides a more encompassing description of climatic conditions/variations and (ii) has been increasingly used by the international scientific community. The classification represents an empirical system and serves as a record by which to determine the climate for any particular region over thirty years as defined by the World Meteorological Organisation. The principal climatic variables considered are T_{amb} and precipitation, which are subsequently computed every decade to smooth out year-to-year variations. Consequently, the system is extensively used by researchers and scientists across a large range of disciplines as a method for the climatic regionalisation of climatic variables from top-down climatic assessments (e.g., [24–35]).

As identified in numerous studies (e.g., [36–40]), the scientific community has recognised a weakness in studies that focus on Mediterranean '*Csa*' climates with regard to local approaches to thermal comfort thresholds. Such a deficiency often generally relays to a lack of local scale design guidelines and precedents that could otherwise inform practices such as PSD to attenuate thermal comfort during dry and hot Mediterranean summers. Additionally, and commonly within regions such as southern Europe, many cities often present lapse of meteorological and climatological data that would prove useful in informing design and decision making within the public realm; in these regions, such gaps of knowledge are particularly evident within municipal Masterplans, as exemplified by cases such as Portugal and Greece.

Based on the most recent version of the KG system by Peel, Finlayson, et al. [27], an emphasis was made upon 'Temperate' climates, with the reviewed PSD measures pertaining to three specific subgroups within the '*C*' group as presented in Table 1. Although the focus was attributed to '*Csa*' climates, it was found that the other 'Temperate' climatic zones also presented valid case studies and projects. In the case of '*Cfb*', although summer temperatures are generally lower (and rarely surpass 22 °C during the summer), numerous studies still revealed that pedestrian comfort thresholds could be improved through numerous PSD interventions. With regard to '*Cfa*', which presents the same type of summer temperatures as '*Csa*', such studies also had to manage the additional aspect of considering high RH levels during the summer to cool T_{amb} levels, which was particularly relevant within the last MRF presented in this review study.

Table 1. Description and criteria for the three subgroups within the Köppen Geiger 'Temperate' (C) group | Source: (Adapted from [27]).

KG	Common Designation	Criteria **		
		Broad Climate Type	**PR and Aridity**	**Temperature Class**
'*Cfa*'	Humid subtropical climate	$T_{hot} > 10$ & $0 < T_{cold} < 18$	No dry season	(Hot summer) $T_{hot} \geq 22$
'*Cfb*'	Temperate oceanic climate	$T_{hot} > 10$ & $0 < T_{cold} < 18$	No dry season	(Warm summer) $T_{hot} < 22$ & $T_{mon10} \geq 4$
'*Csa*'	Hot-summer Med. climate	$T_{hot} > 10$ & $0 < T_{cold} < 18$	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$	(Hot summer) $T_{hot} \geq 22$

** T_{hot} = T_{amb} of the hottest month (°C), T_{cold} = T_{amb} of the coldest month (°C), T_{mon10} = number of months where temperature is above 10, P_{sdry} = PR (mm) of driest month in summer, and P_{wwet} = PR (mm) of wettest month in winter.

2.2. Measure Review Framework Construction

Established on the argument that adaptation is not a 'vague concept' [41–44], and that beyond top-down information, it also must be established on local scale observation and understanding [4,45], Figure 1 represents how the MRFs were approached as a means to organise different existing approaches to local thermal sensitive PSD. As adaptation invariably takes place 'locally', the MRFs were thus perceived as a means to review existing approaches through PSD measures to tackle similar climatic constraints and threats.

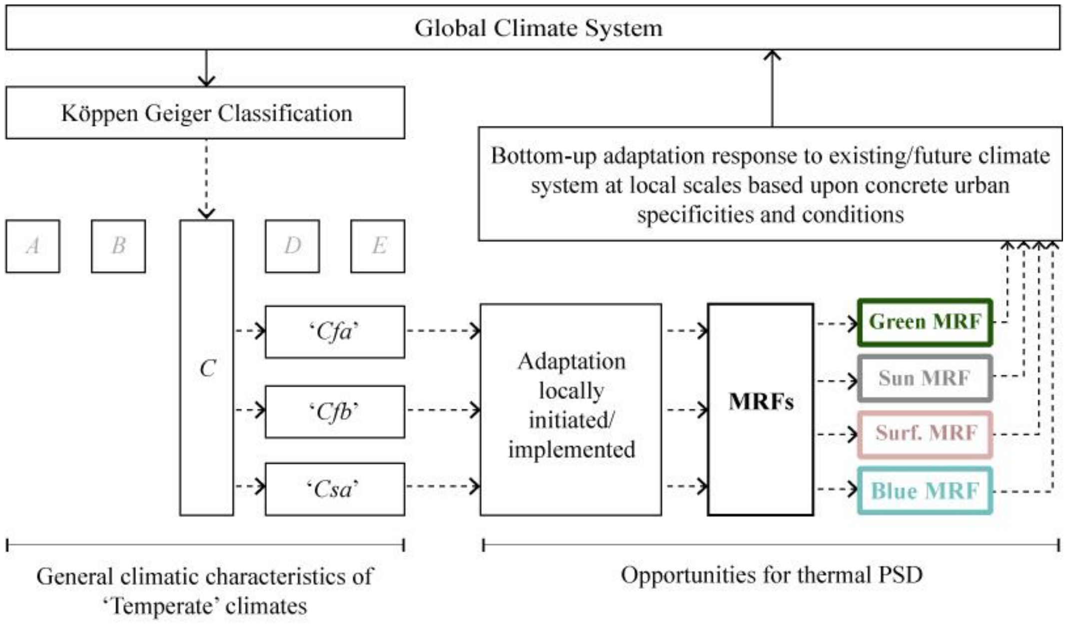


Figure 1. Identification of Measure Review Frameworks (MRFs) within bottom-up approaches to local thermal sensitive PSD within selected 'Temperate' climates.

In an effort to evaluate current available approaches to thermal comfort thresholds through PSD, this review article organises existing studies into four predominant sections. Within each section, specific types of PSD measures were organised into a respective MRF, with concrete details regarding their specificities, and resulting thermal outcomes. As represented in Figure 2, four MRFs were constructed that assessed projects that utilised different types of PSD measures, these being: (1) Green MRF—urban vegetation; (2) Sun MRF—shelter canopies; (3) Surface MRF—materials; and, (4) Blue MRF—water/misting systems. Such a division of measures was based on the similar distinctions discussed in [46–48]. Furthermore, as there are likely to be projects that have not been properly documented or published thus far within the scientific community, the aim of each MRF was to establish a representative selection of projects/studies within the specified 'Temperate' subgroups.

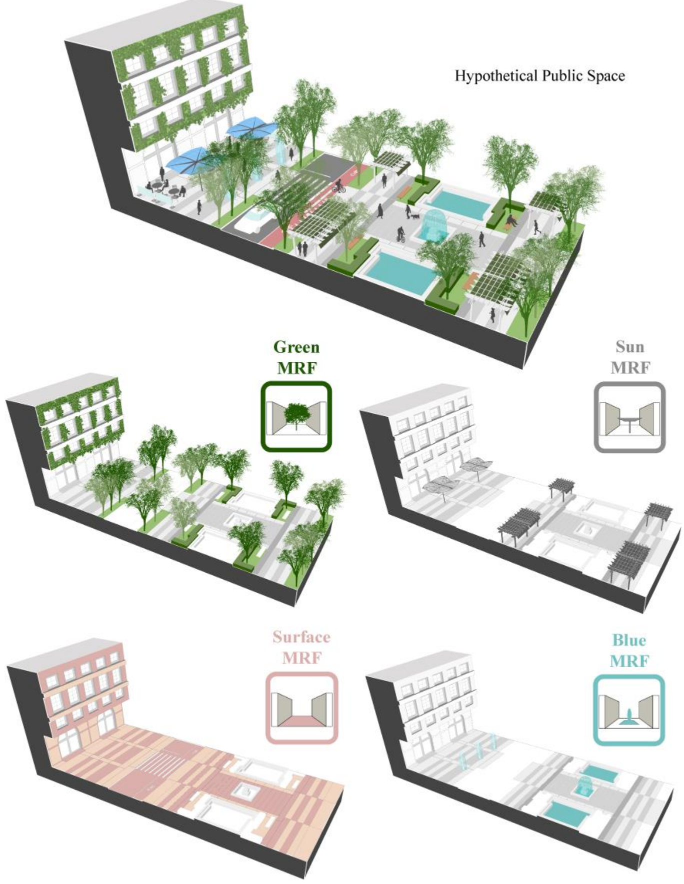


Figure 2. Representational division of thermal attenuation measures from a hypothetical public space.

3. Examining Thermal Indices and Adaptation Dynamics

Within the existing literature, it is a well-established fact that human thermal comfort is strongly correlated to outdoor urban environment [15,36,39,49–59]. In order to assess the effects of the thermal environment on humans, it has been argued that the most efficient means to undertake this evaluation is through the use of thermal indices that are centred on the energy balance of the human body [60]. So far, within the international community various indices have been developed and disseminated, including the (i) Standard Effective Temperature (SET*) [61]; (ii) Outdoor Standard Effective Temperature (OUT_SET*) [59,62]; (iii) Perceived Temperature (PT) [63]; (iv) Predicted Mean Vote (PMV) [64,65]; (v) Index of Thermal Stress (ITS) [8]; (vi) Predicted Percentage of Dissatisfied (PPD) [64]; (vii) COMFA outdoor thermal comfort model [66]; (viii) Universal Thermal Climate Index (UTCI) [67,68]; (ix) Wet Bulb Globe Temperature (WBGT) [69,70]; and (x) Predicted Heat Strain (PHS) [71].

It should be noted, however, that of these mentioned indices, many are designed for indoor use only, such as SET, PMV, and PPD. The justification for this is that the type of microclimatic stimuli is very different to those found outdoors where non-temperature variables must also be accounted for. As a result, indices that initially focused upon indoor conditions need to be 'modified' in order to accurately assess outdoor conditions, as exemplified by the creation of the OUT_SET* from the original SET index. In the case of PMV and PPD, and within the scope of approaching thermal comfort and indoor air quality, it is worth emphasising the significant contributions of Fanger [64] and, to some extent, the complementary aid of Gagge [72] with regards to specific thermal issues such as human perspiration and clothing vapour diffusion resistance. To date, the comfort equation of Fanger [64] is still widely used within the scientific community, and the PMV index continues to be the basis of several national and international standards.

Adjoining outdoor indices is the Physiologically Equivalent Temperature (PET) [15], which has been one of the most widely used steady-state model in bioclimatic studies [73]. Based on the

Munich Energy-balance Model for Individuals (MEMI) [10], it has been 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 perspiration rate, which are equivalent to those under the conditions to be assessed [74]. In addition, the default setting considers a clothing insulation of 0.9 and a metabolic rate of 80 Watts, yet such values can also be regulated. The justification for a greater use of this index can likely be attributable to (i) its feasibility in being calibrated on easily obtainable microclimatic elements, and (ii) its base measuring unit being (°C), which simplifies its comprehension by professionals such as urban planners/designers and architects when approaching climatological facets.

Recently, there have been numerous studies that have made adjustments to the PET index based on (i) determining additional variables, and (ii) refining the integrated thermoregulation model. Within the study conducted by Charalampopoulos, Tsiros, et al. [56], and recognising the fact that exposure to thermal stimuli is not typically momentary, cumulative aspects were integrated within the PET index. More specifically, and referring to their methodology, and amongst others, the PET Load (PETL) and the cumulative PETL (cPETL) were outlined, whereby (i) PETL refers to the outcome difference from optimum condition, hence permitting a specific value that denotes the amount of physiological strain on optimum thermal conditions, and (ii) cPETL ascertains the cumulative sum of PETL during a designated number of hours.

Oriented specifically towards improving the calibration of the thermoregulation and clothing models used within the PET index, Chen and Matzarakis [75] launched the new modified PET (mPET) index. As described in their study, the main modifications of mPET are the integrated thermoregulation model (modified from a single double-node body model to a multiple-segment model) and the updated clothing model, which relays to a more accurate analysis of the human bio-heat transfer mechanism. By referring to the ranges of Physiological Stress (PS) on human beings as described by Matzarakis, Mayer, et al. [76] (Table 2), it was identified that (i) unlike the mPET estimations, PET had the tendency to overestimate PS levels during periods of higher thermal stimuli, and (i) the likelihood of comfortable thermal conditions was higher through the application of the mPET index. Based on the bioclimatic conditions of Freiburg, the results from the study were also subsequently verified for the case of Lisbon by Nouri, Costa, et al. [36] and Nouri, Fröhlich, et al. [77]. Furthermore, and considering the calibration of the stipulated ranges of PS, variations of thermal indices and their associated calibration against stress levels have also been items of revision within various studies in the last decade (e.g., [51,56,78–80].

Table 2. Ranges of the Physiologically Equivalent Temperature (PET) for different grades of Thermal Perception (TP) and Physiological Stress (PS) on human beings; internal heat production: 80 Watts, heat transfer resistance of the clothing: 0.9 clo (according to [58])|Source: (Adapted from, [76]).

PET	Thermal Perception	Physiological Stress
<4 °C	Very Cold	Extreme Cold Stress
4~8	Cold	Strong Cold Stress
8~13	Cool	Moderate Cold Stress
13~18	Slightly Cool	Slight Cold Stress
18~23	Comfortable	No Thermal Stress
23~29	Slightly Warm	Slight Heat Stress
29~35	Warm	Moderate Heat Stress
35~41	Hot	Strong Heat Stress
>41	Very Hot	Extreme Heat Stress

Associated with the maturing know-how between human thermal comfort and that of urban climatic conditions, the continual extension and modifications of existing thermal indices shall very likely continue to grow. Such a phenomenon can be attributable to two predominant reasons: (i) the discovery of new developed methods to estimate thermal conditions, and (ii) the presence of new interrogations inaugurated by members of the scientific community. Adjoining the thermal indices already mentioned, and similarly to Fanger's model [64], Salata, Golasi, et al. [81] proposed a logistic relationship between the observed percentages of dissatisfied and the mean thermal sensation votes on the ASHRAE 7-point scale in Mediterranean climates.

Given the growing amount of research into the application of thermal assessment methods, there has likewise been a parallel attentiveness to the intrinsic correlations between the different indices themselves (e.g., [73,82–84]). Additional indices were also discussed, particularly in Pantavou, Santamouris, et al. [73], which presented an extensive comparative chart of existing indices, their respective formulae, and correlation coefficients.

In addition, psychological (i.e., qualitative) aspects have also been discussed in parallel to thermal index (i.e., quantitative) attributes and are presented within Table 3. Within the studies, and in different ways, it was identified that 'intangible' attributes can also present an important factor when evaluating thermal comfort thresholds. Although more associated with indoor climatic conditions, such attributes have also been assessed by numerous recent accomplished studies as well [85–87].

Table 3. Selected studies that assessed the relationship between thermal indices and qualitative attributes.

(No.)	Source	Selected Study Outcomes
#i	[88] (Review Article)	Analysed eight outdoor thermal comfort studies that combined thermal indices with behavioural aspects and concluded that the perception of thermal comfort should be approached through four interconnected levels: (i) physical, (ii) physiological, (iii) psychological, and (iv) social/behavioural
#ii	[89]	Identified that although the presence of comfort conditions generally led to a higher amount of pedestrians, only 35% of the interviewees were located within theoretical comfort conditions
#iii	[90]	Identified that transitory exposure and thermal expectation can present a major influence on pedestrian subjective assessments and thermal contentment, and that 'steady-state' models such as PMV were revealed to be inappropriate for the assessment of short-term outdoor thermal comfort
#iv	[91]	In line with the European Union project RUROS [92], it was identified that the behaviour of pedestrians was dependant both on the outdoor thermal conditions and individual expectations. Such a result was exemplified when people left air conditioned/indoor contexts for direct sunshine, even if such an exposure implied PET values that would exceed comfort ranges
#v	[79]	Within the study's field survey, it was identified that 90% of pedestrians chose to stay under shade trees or shelters. As a result, this both indicated the importance of shading availability, but more importantly, the capability of decision makers and designers to adequately ensure such an availability of choice for thermal adaptability.

In line with the presented outcomes, when considering PSD approaches, the deceptively elementary vision of "*What attracts people most, it would appear, is other people*" [6], (p. 19) is still, today, of key significance. The described attraction here can be approached as an 'adaptive thermal comfort process' that pedestrians undergo when exposing themselves to a given outdoor environment. Within the study conducted by Nikolopoulou, Baker, et al. [93], such a process was broken down into three key categories: physical, physiological, and psychological.

Furthermore, within a subsequent study by Nikolopoulou and Steemers [94] six intangible characteristics were identified and correlated to pedestrian psychology within outdoor environments, namely: naturalness, expectations, past experience, time of exposure, and environmental stimulation. As to be expected, since these qualitative attributes enter the 'intangible' sphere, the quantification of each parameter is complex. In order to translate these factors into PSD terms and by correlating the six characteristics with the three sets of potential preferences of thermal environments as described by Erell, Pearlmutter, et al. [48], Nouri and Costa [95] discussed an adaptation of the existing 'Place Diagram' by the Project for Public Spaces (PPS). Based on its universal 'What makes a great place' diagram [96], the category of 'Comfort' was expanded to describe how design can be approached in a three step approach in order to (i) address microclimatic constraints, (ii) present physical responses, and, lastly, (iii) recognise how such interventions could potentially influence pedestrian psychological attributes.

Critical Outlook

Grounded on existing studies pertaining to both physiological and psychological aspects of approaching outdoor thermal comfort thresholds, it is possible to verify both (i) the steady growth of knowledge associated to the influences of the urban climate upon humans, especially at local/micro scales, and (ii) the potential for further studies to take such promising breakthroughs even further, which shall likely continue to be instigated by the international community given the potential unravelling of future climate aggravations. More specifically, and constructed on the discussion within this section, this review article suggests that there is an opportunity to do the following.

Firstly, further develop means to explore how qualitative attributes (e.g., expectations and past experience) can be better integrated within quantitative indices, even as an indicative 'approach'. As a result, this effort could potentially present means to better predict (and account for) pedestrians willingly exposing themselves to thermal stimuli which would, in quantitative terms, imply surpassing their thermo-physiological comfort threshold. Such an approach would also present means for better approaching intricate elements such as 'thermal adaptation and personification' and using pedestrian behaviour simulation possibilities (e.g., agents).

Secondly, approach the necessity for the standardisation of a thermal comfort index for specific regions (such as MOCI) which caution. For although a standardised index could assist the establishment of a 'common language' between scientists, another perspective can be presented. More specifically, it can be argued that numerous existing thermal indices have already been identified as 'common language' within bioclimatic studies and, moreover, use the common unit of °C. As a result, a more 'interdisciplinary standardisation' should be reinforced, whereby the common language of one discipline (i.e., climatology/biometeorology) could be transposed on the sphere of urban design/planning through the continual dissemination of interdisciplinary studies and scientific collaboration.

4. Green Measure Review Framework

To date, numerous review articles have already discussed the capacity of urban vegetation (namely urban trees and 'green' areas) to attenuate urban temperatures and combat UHI effects, such as are summarised in Table 4. In addition to these review articles, other reviews of the state-of-the-art with a slightly different perspective have also been disseminated, namely the (i) specific thermal effects of reflective and green roofs [97,98], (ii) urban air quality and particle dispersion through the presence of vegetation [99] (research article), [100] (research article), and (iii) benefits and challenges of growing urban vegetation within the public realm [101].

At local scales, and within the scope of public space design, very little work has been carried out on vegetation influences at a micro level and how such contributions can positively influence the thermal comfort of users within the public realm [40]. To better grasp this relationship, it is here suggested that five characteristics need to be addressed when using vegetation as a direct means to cool T_{amb} and/or reduce solar radiation. Each of these characteristics is visually presented in Figure 3 and shall be associated with each project to construct and organise these specificities within the Green MRF (MRF 1). When certain characteristics were not included within the particular study, when available, different references were used in order to provide the reader an indication of such vegetative specifications.

Table 4. Existing review studies of urban vegetation benefits and their general conclusions.

(No.)	Source	No. of Studies *	Main Review Article Outcomes 
#1i	[102]	±16	▪ The effect of vegetation can be different under different planting schemes with regards to T_{amb}, G_{rad}, and V depending on the planting layout and species; ▪ In high density cities with limited allocation of vegetation, the influence on T_{amb} is small yet may still prove very useful in improving thermal comfort conditions using the casting of vegetative shading; ▪ Beyond these direct characteristics on pedestrian thermal comfort thresholds, other indirect positive influences on air pollution dispersion, noise control, and local socio-economic attributes were discussed.
#1ii	[103]	±50	▪ Most studies investigated the T_{amb} within green spaces and beneath trees generally indicated that such spaces generally present lower T_{amb} than surrounding sites; ▪ From the scrutinised studies, it was acknowledged that the cooling effect of parks resulted in an average diurnal T_{amb} reduction of 0.94 °C ▪ Further empirical research is required to examine specific recommendations on how best to incorporate urban greening within public realm at a local design guideline level.
#1iii	[104]	13	▪ The larger the green area, the lower the recorded T_{amb} within the surrounding area; ▪ Surrounding areas located downwind from the green space were more likely to be influenced, as the strong winds intensified the cooling effect of the respective green area; ▪ Use of vegetation in urban areas can reduce surrounding T_{amb} by 0.5 °C–4.0 °C.
#1iv	[105]	50	▪ The use of urban greenery is the most common technique that is used to mitigate UHI effects and urban T_{amb} temperatures; ▪ The average peak T_{amb} drop of all greenery case studies was ±1.6 °C (which included green roof and grass studies that were not considered in the identified study count). Around 50% of projects had a peak T_{amb} reduction below 1.0 °C, 78% below 2.0 °C, and almost 90% 3.0 °C; ▪ Urban trees were identified to present the highest mitigation potential from all types of considered types of urban greenery.

* No. of studies in review article (in the case of #1iv, 50 were selected based on their relevance to this study).

As a starting point, the first characteristic relays to the type of vegetative species used in each of the projects, thus giving an overall comprehension of the tree characteristics. So far, the stipulation of tree species has already been used by various authors to study local effects on solar transmissivity [13,48,106–110].

The second characteristic pertains to type of vegetative configurations and biomass (or vegetation coverage) utilised in each project. Such a stipulation was based on the study of Torre [111], who analysed the potentiality of using vegetation to modify outdoor microclimates, and moreover, to frame such potentials into design guidelines. These configurations were seen to be explicitly pertinent to the design of the public space in order to modify/optimise encircling microclimates, namely: (i) Linear Plantation (LP)—which is able to deflect radiation and wind currents; (ii) Group Plantation (GP)—which is able to deflect larger amounts of radiation and wind currents; (iii) Surface Plantation (SP)—which is able to change albedo, emissivity, and thermal storage/conductance; (iv) Pergola (PG)—which, depending on its configuration, is able to deflect radiation and wind. Pertaining to each configuration, similar results were also discussed in [112–117].

The third characteristic displays the dimensional features of the trees within each of the projects, including their crown spread, height, and growth speed. Such singularities become essential when determining the microclimatic contributions that the respective tree can present within the specific space. The fourth characteristic presents the vegetative shading coefficients of each species used in each project. As shown in the early studies conducted by McPherson [114] and Brown and Gillespie [117], different tree species vary considerably in transmissivity as a result of twig/leaf density and foliage development. Thus, and when available, the Solar Transmissivity (ST) is presented by percentage for each project/tree both for the summer and winter months.

The fifth characteristic provides information on foliation periods and seeks to present actual annual foliation and defoliation months for each species in the projects. Considering the case of deciduous trees as an example, although they may provide shade in the summer and permit solar exposure during the winter, they may not always provide shade precisely where desired, and the period in which many trees lose their foliage may not coincide with heating season at a respective location [48,116].

With regard to presenting the thermal results, as with all of the other MRFs discussed in this study, it is important to note that such reduction values were methodically approached differently by the authors in each project. In the interest of maintaining as much uniformity as possible, maximum reductions values (when available) were presented. In addition, such results were predominantly pertinent to the summer period, and, in most cases, were obtained on the same day or over the course of a set of specific days.

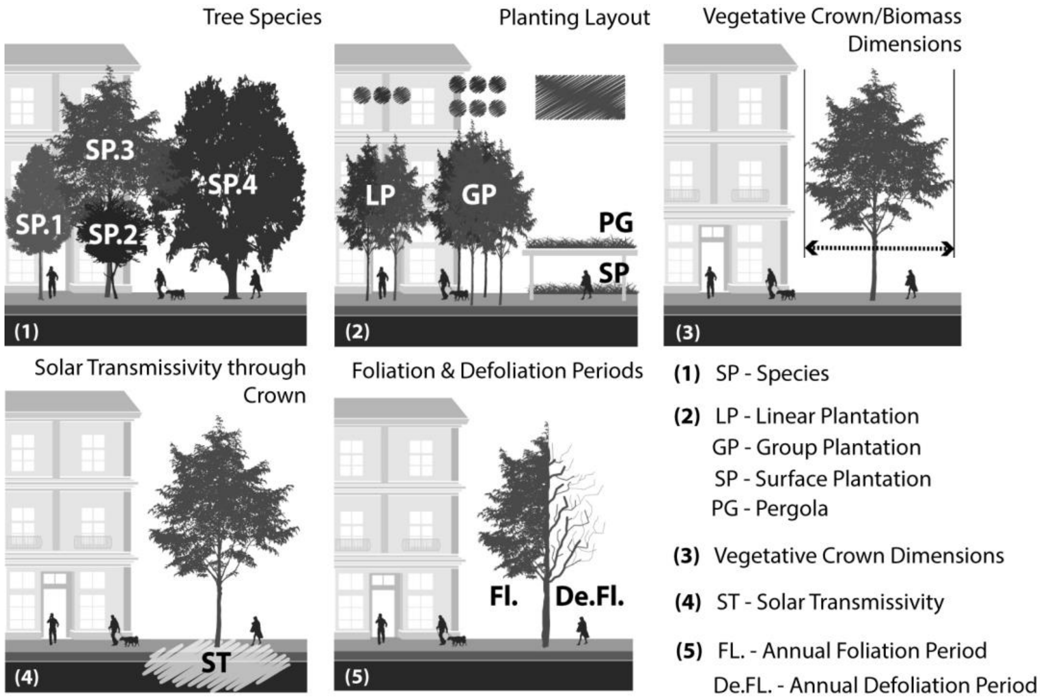


Figure 3. Vegetation crown dimension according to surface and human exposure characteristics.

4.1. Introduction of Projects

Within this section, the discussed projects shall be divided into two types: (1) scientific oriented—which explores how existing trees can reduce T_{amb}, either at their existing state or by tweaking their characteristics; and (2) design oriented—which explores the effects caused by the introduction of new trees as part of a wholesome bioclimatic project.

4.2. Scientific Oriented Projects

The studies were further sub-divided into two categories: those that identified the In-Situ (IS) effects of vegetation on site and those that evaluated the effects of Park Cool Islands (PCI) in which T_{amb} was evaluated against an adjacent stipulated 'comparison site'. Within such studies, the effects of IS and PCI were compared between areas principally cast in the shade by the vegetative crown and those generally cast in the sun. As this study was more focused on the direct influences of vegetation within a specific site, a larger emphasis was directed at the former. Nevertheless, some examples of PCI studies were also included based on the evaluated T_{amb} deviations, disclosed vegetation information, KG climate subgroups, and study scale. Outside of these established parameters, additional studies that have identified PCI T_{amb} variations between 1 °C and 3.8 °C can be consulted (e.g., [1,118–126]).

4.2.1. IS Effect Studies

At a pedestrian level, the study conducted by Picot [127] revealed that the growth of street trees led to a reduction in Global radiation (G_{rad}) as result of their incremental screening potential through their foliage, which reduced the amount of solar absorption on pedestrians within an outdoor plaza in Milan. Although the study revealed important thermal results through the use of the COMFA model, such energy budget results without a transposal upon more common measure units (such as °C) led the outcomes of the study to be harder to interpret for those less familiar with such budget thresholds (Project#1.1). Also, examining the screen potential of vegetation, Tsiros [40] analysed a limited set of T_{amb} measurements under tree canopies at a height of 1.70 m (slightly higher than the commonly applied height of 1.1 m) to examine the effect of shade trees within streets, which revealed different vegetative shading percentages. Grounded on a recognised limited set of data points, it was identified by the study that in a canyon (with a H/W of ≈0.90) with a shading area of 48%, the cooling effect was of a T_{amb} of 2.2 °C (Project#1.2). Also, considering other variables such as V and RH, and within a same climate subgroup, Taha, Akbari, et al. [128] revealed that vegetation could result in a T_{amb} decrease of up to 1.5 °C within a cluster (or GP) of orchards. It should be noted, however, that such results were obtained within an open field, and such results were recognised to likely vary within a more urban setting with a different morphological setting (Project#1.3). Nevertheless, and conducted within an urban setting in Melbourne, Berry, Livesley, et al. [115] identified a similar T_{amb} reduction of 1 °C as a result of a dense potted tall tree canopy in close proximity to a building façade. Although influences on other variables such as T_{surf} were also considered, it was recognised that a future study was needed to identify influences on additional variables. Such a necessity can be attributed to the low reductions in T_{amb}, which were likely due to atmospheric conditions diluting the magnitude of the presented results (Project#1.4).

In a different way to the previous four projects, Shashua-Bar, Tsiros, et al. [129] reported the potential of vegetative cooling through the use of thermo-physiological indices in addition to T_{amb} reductions. Within their study, four theoretical design interventions within Athens were examined to explore how different PSD means could influence pedestrian thermal comfort levels. Of the four, the two most successful solutions were (i) to increase vegetative coverage from 7.8% to 50%, and (ii) to elevate building façades by two additional floors, thus changing the Height-to-Width (H/W) ratio from existing 0.42 to 0.66. The increase in vegetation coverage demonstrated T_{amb}/PET reductions of 1.8 °C/8.3 °C (Project#1.5). Also established using additional variables (e.g., W/m^2, Mean Radiant Temperature (MRT), and (iii) within the city of Hong Kong, Tan, Lau, et al. [130] recently studied the use of urban tree design to mitigate daytime UHI effects as a result of the city's elevated urban density. It was identified that in locations with a high Sky View Factor (SVF) (i.e., with a low H/W ratio), the presence of a group of vegetation could lead to a maximum T_{amb}/MRT reductions of 1.5 °C/27.0 °C (Project#1.6). It was, however, identified that further study was required to examine the presence of other tree species to present more concrete recommendations for the urban placement of different tree species. Obtaining a comparable T_{amb} reduction in the city of Manchester, Skelhorn, Lindley, et al. [131] also identified a comparable reduction of 1.0 °C during the summer by increasing the amount of existing mature trees on site (Project#1.7). In addition, the study identified the risks with calibrations of ENVI-met [132] simulations in representing accurate readings of real-worlds measurements, as also identified in [133].

In addition to these projects, it is also worth noting that there were numerous studies that were not included in the framework due to (1) the identified T_{amb} reductions being <1.0 °C; (2) being located outside of stipulated KG climate subgroup; and (3) the analysis being set a larger meso/macro scale. Nevertheless a critical overview of their selected results is summarised below:

1. Tsilini, Papantoniou, et al. [134] identified that the hours revealing the greatest variations as a result of vegetation were between 12:00 and 15:00; (ii) Martins, Adolphe, et al. [135], who also identified low reductions of T_{amb}, presented noteworthy thermo-physiological reductions (e.g., a PET decrease of 7 °C); (iii) similarly, and by combining with other PSD measures, Wang, Berardi, et al. [136] also identified similar PET reductions of 3.3 °C and 4.6 °C even when reductions of T_{amb} did not surpass that of 1.0 °C
2. Abreu-Harbich and Labaki [137] identified that the most predominant influence on thermal comfort was the tree structure, regardless of the utilised thermal index (i.e., PMV and PET); (ii) in a later study, Abreu-Harbich, Labaki, et al. [138] again identified both the importance of tree species and the use of thermo-physiological indices such as PET for evaluating thermal comfort; beyond considering T_{amb}, they also considers factors such as solar radiation dynamics
3. Through satellite imagery, Jonsson [139] discovered that at a larger scale, urban T_{amb} varied between 2 °C and 4 °C as a result of the presence of vegetation; (ii) in the study conducted by Perini and Magliocco [140], it was also identified that at ground level and as a result of foliation, T_{amb}, MRT, and PMV values were also considerably lower (≈−3.5 °C in T_{amb} and −20.0 °C in MRT) in comparison to those identified in the rest of the city; and, finally, (iii) in an effort to determine influences of urban vegetation on local conditions within high density settings, Kong, Lau, et al. [141] identified maximum reductions of 1.6 °C in T_{amb}, 5.1 °C in MRT, and 2.9 °C in PET.

Although the disclosed studies were not included within the Green MRF, their results highlight the importance of vegetation even when variables such as T_{amb} varied beneath 1.0 °C, within other KG subgroups (i.e., within different climatic circumstances), and lastly, at larger urban scales in which the effects of vegetation are still salient when addressing high urban temperatures and UHI effects.

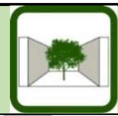
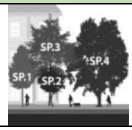
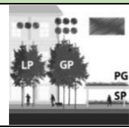
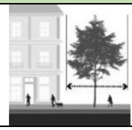
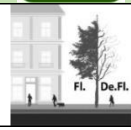
4.2.2. PCI Effect Studies

Accounting for the fact that the following studies compared the PCI effects with adjacent areas with generally no (or significantly limited) vegetation, the ensuing studies revealed higher reductions of local human thermal stress. Shashua-Bar and Hoffman [142] selected 11 outdoor public spaces in Tel-Aviv (located within a KG subgroup of '*Csa*') and identified that (i) in all locations, the maximum cooling effect from trees took place at 15:00, and (ii) the average T_{amb} cooling effect throughout the sites was of 2.8 °C, with a maximum of 4.0 °C (Project#1.8). A decade later, and still located in Tel-Aviv, the analysis carried out by Shashua-Bar, Potchter, et al. [107] also illustrated similar cooling potential from common street trees. When reaching their full vegetative biomass, and within a canyon with a H/W of 0.60, the cooling effect of the selected trees attained T_{amb} reductions of up to 3.4 °C (Project#1.9). A further study conducted in Tel-Aviv by Potchter, Cohen, et al. [143] also identified an almost identical T_{amb} reduction of 3.5 °C resultant of an urban park containing large high and wide trees (Project#1.10). A similar reduction was also identified by Skoulika, Santamouris, et al. [144] within an urban park in Athens '*Csa*', who revealed a T_{amb} reduction of up to 3.8 °C (Project#1.11). Lastly, and also within a '*Csa*' subgroup, Oliveira, Andrade, et al. [145] also identified a very strong and clear PCI effect within small urban park in Lisbon. The identified effect was determined within an urban built-up area (2479 buildings/km^2) within a district with an orthogonal urban geometry, with a small 95 × 61 m urban park centred between the urban blocks. In their study, and during specific days, it was identified that the green space led to reductions of 6.9 °C in T_{amb}, 39.2 °C in MRT, and 24.6 °C in PET (Project#1.12).

4.3. Design-Oriented Projects

Leaving the scope of scientific exploratory projects, the Parisian climate sensitive redevelopment project, 'Place de la Republique' aimed to address both pedestrian thermal comfort and UHI within the largest public space in Paris (Project#1.13). Although exact temperature reductions were not identified, the strategy consisted of implementing measures that would increase vegetative biomass in order to influence solar permeability and provide protection from winter wind patterns [146]. Similarly, and within a '*Csa*' subgroup, the 'One Step Beyond' winning proposal for the international 'Re-Think Athens' competition also used vegetation to cool T_{amb} within the public realm (Project#1.14). As part of a defined 'heat mitigation toolbox', the proposed greenery, such as grass, hedges, climbing plants, and trees, was aimed at mitigating the UHI effect through evapotranspiration and vegetative shading [147]. Still, within a '*Csa*' subgroup, a rehabilitation project was introduced in order to improve the environmental resilience to the intense summer sun and temperatures within Almeida de Hercules in Seville (Project#1.15). As part of the intervention, additional vegetation was introduced with a planting structure varying from LP to GP depending on the uses and activity threads. Lastly, located in Barcelona, the winning submission 'Urban Canòpia' aimed at proposing a new park-plaza that would introduce new contemporary dimensions, including means to address the thermal comfort levels (Project#1.16). The principal measure used was vegetation, in order to diminish T_{amb} and limit the amount of solar radiation during summer.

MRF 1. Urban Vegetation.

Green Measure Review Framework 														
(No.)	Source	KG	Thermal Results (Max)	H/W (≈)	 Species Acronym	 Planting Layout	Veg. Cover. (%)	Crown Spread (m)	 Overall Height (m)	Growth Speed (cm/year)	 Solar Trans. through Crown (%) Sum.	Win.	 Foliation Periods (Leaves Only) Fol.	Defol.
IS Effect Studies														
#1.1	[127]	'*Cfa*'	Increase in comfort levels *[1]	0.28	|*Tc*|	LP	-	6–12 (1)	21 (2)	30–60 (1)	7 (7), 13 (8), 17 (9)	46 (7), 70 (9), 62 (10)	B5 (7), M/E5 (14)	B12 (7), B10-M11 (14)
					|*Ls*|			≥12 (1)	18–30 (2)	60–91 (1)	18 (7)	70 (7), 84 (11)	Deciduous (NDI)	
					|*Tp*|			-	35 (3)	-	-	-	B5 (13)	B12 (13)
#1.2	[40]	'*Csa*'	−2.2 K_{amb}	0.90	|*Ma*|	LP	48	≥12 (1)	12 (2)	≥91 (1)	-	-	M4 (13)	B12 (13)
#1.3	[128]	'*Csa*'	−1.5 K_{amb}	NA	ND	GP	-	-	-	-	-	-	-	-
#1.4	[115]	'*Cfb*'	−1.0 K_{amb}	NA	|*Fe*|	LP	-	18–27 (4)	10 (3) 2.9 (16) *2	-	14 (7), 15 (12)	59 (7)	E4 (7), M5 (12)	B10-M11 (7), E11 (12)
					|*Af*|			-	30 (6) 3.8 (16) *2	-	-	-	Deciduous (NDI)	
#1.5	[129]	'*Csa*'	−1.8 K_{amb} −8.3 K_{PET}	0.42	|*Fc*|	LP	50	6–12 (1)	5–8 (2)	91 (1)	-	-	M4 (13)	E12 (13)
#1.6	[130]	'*Cfa*'	−1.5 K_{amb} −27.0 K_{MRT}	(SVF: 0.8)	|*Fm*|	GP	-	10–12 (1)	18 *2	60 (1)	-	93 *2	Evergreen	
#1.7	[131]	'*Cfb*'	−1.0 K_{amb}	ND	|*Ac*|	GP	-	7.6–10 (1)	>20 *2	30 (1)	-	-	-	-
					|*Ap*|		-	10–12 (1)	>20 *2	91 (1)	14 (7)	65 (7)	B4 (7)	M11 (7)
					|*Ap2*|		-	12–18 (1)	>20 *2	60 (1)	-	-	-	-
PCI Effect Studies														
#1.8	[142]	'*Csa*'	−4.0 K_{amb}	0.45	|*Fc*|	LP	61	6–12 (1)	5–8 (2)	91 (1)	-	-	M4 (13)	E12 (13)
#1.9	[107]	'*Csa*'	−3.4 K_{amb}	0.59	|*Fc*|	LP	-	6–12 (1)	5–8 (2)	91 (1)	-	-	M4 (13)	E12 (13)
					|*Tt*|			7–15 (1)	7–15 (1)	60–91 (1)	-	-	B5 (13)	M3 (13)
					|*Pd*|			6 (15)	30 (3)	30–91 (1)	-	-	Evergreen	
#1.10	[143]	'*Csa*'	−3.5 K_{amb}	NA	|*Fm*|	GP	95	10–12 (1)	12 (1)	60 (1)	-	-	Evergreen	
#1.11	[144]	'*Csa*'	−3.3 K_{amb}	NA	|*Oe*|	GP	-	7.6–9.1 (1)	7.6–9.1 (1)	30–60 (1)	-	-	Evergreen	
					|*Ak*|			9.1 (1)	12–18 (1)	≥91 (1)	-	-	Evergreen	
					|Cc|			15–30 (1)	15–40 (1)	≥91 (1)	-	-	Evergreen	

#1.12	[145]	'Csa'	−6.9 K_{amb}	0.30	|*Ca2*|	GP		21 (1)	25 (3)	60–91 (1)	-	-	M4 (13), M4 (7)	E12 (13), M/E11 (7)
			−24.6 K_{PET}		|*Cl*|		96.5	1.5–4.5 (1)	6–12 (1)	30 (1)	-	-	Evergreen	
			−39.2 K_{MRT}		|*Me*|			9–10 (1)	9–10 (1)	60 (1)	-	-	Evergreen	
#1.13	[146]	'Cfb'	ND	0.10	|*Pa*|	LP + GP	-	≥12 (1)	21 (2)	91 (1)	17 (7), 14 (8),	64 (7), 46 (8)	B4 (7), M5 (12)	M11 (7), B12 (12)
					|*Gt*|		-	5.5 (1)	24 (2)	91 (1)	32 (7), 30 (12)	48 (7), 85 (15)	M4 (13), M3 (7)	M10 (13), B10–M11 (7),
#1.14	[147]	'Csa'	−3.0 K_{amb}	0.15	|*Pa*|	LP + GP	-	≥12 (1)	21 (2)	91 (1)	17 (7), 14 (8),	64 (7), 46 (8)	B4 (7), M5 (12)	M11 (7), B12 (12)
					|*Rp*|			≥12 (1)	12–24 (2)	91 (1)	-	-	Deciduous (NDI)	
					|*Jm*|			22 (1)	10 (3)	60 (1)	-	-	B5 (13)	E2 (13)
					|*Pp*|			≥12 (1)	25 (3)	60–91 (1)	-	-	Evergreen	
					|*Cs*|			≤6 (1)	20–30 (3)	91 (1)	-	-	Evergreen	
					|*Aj*|			6 (1)	10 (3)	91 (1)	-	-	Deciduous (NDI)	
					|*Ma*|			≥12 (1)	12 (2)	≥91 (1)	-	-	Deciduous (NDI)	
					|*Cs2*|			≥8 (5)	15 (3)	-	-	-	Deciduous (NDI)	
					|*Kp*|			17 (1)	15 (3)	30–60 (1)	25 (7), 13 (12)	42 (7)	M4 (7), M4 (12),	M11 (7), M11 (12)
					|*Ca*|			10 (1)	9 (2)	60 (1)	-	-	Evergreen	
#1.15	[-]	'Csa'	ND	0.12	|*Pa2*|	LP + GP	-	6–12 (1)	24 (2)	91 (1)	-	-	M3 (13)	B12 (13)
					|*Ca2*|			21 (1)	25 (3)	60–91 (1)	8 (7)	53 (7)	M4 (13), M4 (7)	E12 (13), M/E11 (7)
#1.16	[-]	'Csa'	ND	−0.01	|*Pp2*|	LP + GP + SP + PG	-	≥8 (5)	≥12 (5)	-	-	-	Evergreen	
					|*Pp3*|			≥12 (1)	25 (3)	60–91 (1)	-	-	Evergreen	
					|*Qi*|			28 (1)	25 (3)	60 (1)	-	-	Evergreen	
					|*Ca2*|			21 (1)	25 (3)	60–91 (1)	-	-	M4 (13), M4 (7)	E12 (13), M/E11 (7)
					|*Ag*|			-	20–30 (3)	-	-	-	Deciduous (NDI)	
					|*Fa*|			≥8 (5)	≥12 (5)	-	-	-	Deciduous (NDI)	
					|*Tc*|			6–12 (1)	21 (2)	30–60 (1)	7 (7), 13 (8), 17 (9)	46 (7), 70 (9), 62 (10)	B5 (7), M/E5 (14)	B12 (7), M11 (13), B10-M11 (14)
					|*Pa2*|			6–12 (1)	24 (2)	91 (1)	-	-	M3 (13)	B12 (13)
					|*Sa*|			-	15–24 (2)	-	-	-	Deciduous (NDI)	
					|*Ph2*|			≥8 (5)	21 (2)	-	-	-	B4 (13)	E12 (13)
					|*Tt*|			7–15 (1)	7–15 (1)	60–91 (1)	-	-	B5 (13)	M3 (13)
					|*Ma*|			6–12 (1)	12 (2)	91 (1)	-	-	M4 (13)	M11 (13)
					|*Sm*|			22 (1)	10–15 (3)	91 (1)	-	-	Deciduous (NDI)	
					|*Jm*|			22 (1)	10 (3)	60 (1)	-	-	B5 (13)	E2 (13)

Key

Source:
(1) [148]
(2) [149]
(3) [150]
(4) [151]
(5) [152]
(6) [153]

Tree Acronyms:
|*Tc*| » *Tilia cordata* |*Ls*| » *Liquidambar styraciflua* |*Tp*| » *Tilia platyphillos* |*Ma*| » *Morus alba* |*Fe*| » *Fraxinus excelsior* |*Af*| » *Angophora floribunda* |*Fc*| » *Ficus carica* |*Gt*| *Gleditsia triacanthos* |*Pd*| » *Phoenix dactylifera* |*Pa*| » *Platanus acerifolia* |*Rp*| *Robinia pseudoacacia* |*Jm*| » *Jacaranda mimisfolia* |*Pp*| » *Pinus pinea* |*Cs*| *Cupressus sempervirens* |*Aj*| » *Albizia julibrissin* |*Cs2*| » *Cercis siliquastrum* |*Kp*| » *Koelreuferia paniculata* |*Ca*| » *Citrus auruntium* |*Pa2*| » *Populus alba* |*Ca2*| » *Celtis australis* |*Pp2*| » *Pinus pinsaster* |*Ph*| » *Pinus halpensis* |*Pp3*| » *Pinus pinea* |*Qi*| » *Quercus ilex* |*Ag*| » *Alnus glutinosa* |*Fa*| » *Fraxinus angustifolia* |*Um*| » *Ulmus minor* |*Pn*| » *Populus nigra* |*Sa*| » *Salix alba* |*Ph2*| » *Platanus hispanica* |*Pc*| » *Phoenix canariensis* |*Wf*| » *Washingtonia filifera* |*Tt*| » *Tipuna tipu* |*Lp*| » *Lagunaria patersonii* |*Ma*| » *Melia azedarach* |*Sm*| » *Schinus molle* |*Fm*| » *Ficus microcarpa* |*Ac*| » *Acer campestre* |*Ap*| » *Acer platanoides* |*Ap2*| *Acer*

Foliation & Layout:
B: Beginning of Month
M: Middle of Month
E: End of Month
1–12: Month # (January–December)
Planting layout

General:
ND: Not disclosed by project
NDI: No Detailed Information
NA: Not Applicable
-: No information

(7)	[154]	*pseudoplatanus* |*Cl*| » *Corynocarpus laevigatus* |*Me*| » *Metrosideros excelsa* |*Oe*| » *Olea europaea* |*Ak*| » *Acacia koa* |*Cc*| » *Corymbia calophylla*	Acronyms found in
(8)	[155]		Figure 3
(9)	[156]		
(10)	[157]		
(11)	[158]		Notes:
(12)	[114]		*[1]−Resultant of a decreased energy budget due to
(13)	[116]		reduced solar radiation
(14)	[159]		*[2]−Values obtained from study/project
(15)	[107]		
(16)	[115]		

4.4. Critical Outlook

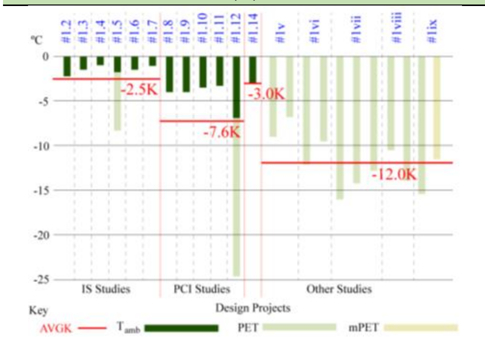
When approaching the effects of vegetation within the local public realm, it is clear that they provide numerous benefits within the built environment. Nevertheless, when approaching issue of thermal comfort, the identified quantity and type of effects depend predominantly on (i) tree characteristics, planting layout, and site conditions; and (ii) the utilised evaluation methods/variables. These two facets have been respectively summarised within the Green MRF.

When considering the results obtained by Projects#1.5/6, it was possible to identify that while IS T_{amb} reductions were low, thermo-physiological variables revealed substantial influences on thermal comfort thresholds. As a result, it is reasonable to assume that such influences would also be verified within Projects#1.2/3/7. As already discussed, such variances were also identified in studies that witnessed reductions of <1.0 °C and that were also located within different climate subgroups. When considering studies that identified PCI effects, similar conclusions could be drawn between Projects#1.8–12. Nevertheless, it was noted that the PCI effects generally rendered greater reductions of T_{amb} due to the greater cluster and/or arrangement of vegetation within the respective 'green site'. However, PCI studies also revealed comparably higher reductions in thermo-physiological variables (i.e., of up 24.6 °C in PET) as demonstrated by Project#1.12.

Within Table 5, and when available, the thermal results of each project were plotted to illustrate the maximum and average attenuation capacity (in T_{amb} and PET) between the IS studies, design project, and PCI studies. Adjoining these studies, the selected results from five additional studies were also plotted within Table 5. As they were either located within other KG subgroups, or more oriented towards thermo-physiological aspects, they were not included within the Green MRF. Within the last project of the five (Project#1ix), [77] revealed both the IS influences of PET and mPET from the *Tipuana tipu*, also within a '*Csa*' subgroup, in common default urban canyons within the historical quarter of Lisbon. The results from the additional studies served to demonstrate how thermo-physiological indices significantly varied IS, as they considered additional factors such as solar radiation. Additionally, and as verified by earlier studies (e.g., [9,13,114]) and confirmed by the reviewed studies in this section, T_{amb} variations as a result of vegetation can prove to be a less efficient method of evaluating thermal comfort conditions at pedestrian level as the encircling atmosphere quickly dissolves such variations.

Table 5. (A)—Supplementary study results that identified vegetation effects on PET. (B)—Overview of maximum and average reductions of T_{amb} and PET.

(A)



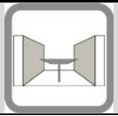
(B)

(No.)	Source	KG	Sel. Species (Ind)	Max Red. (≈)
#1v	[110]	'*Csa*'	*Tilia (spp.)* *Jacaranda mimosifolia*	−9.0 K_{PET} −6.8 K_{PET}
#1vi	[108]	'*Cwa*'	*Tipuana tipu* *Caesalpinia peltophoroides*	−12.1 K_{PET} −9.5 K_{PET}
#1vii	[109]	'*Cwa*'	*Caesalpinia pluviosa* *Hand. chrysotrichus* *Tipuana tipu*	−16.0 K_{PET} −14.2 K_{PET} −12.8 K_{PET}
#1viii	[54]	'*Csa*'	*Jacaranda mimosifolia* *Tipuana tipu*	−10.5 K_{PET} −13.9 K_{PET}
#1ix	[77]	'*Csa*'	*Tipuana tipu* *Tipuana tipu*	−15.6 K_{PET} −11.6 K_{mPET}

5. Sun Measure Review Framework

Again pertaining to the microclimatic characteristic of solar radiation, its intrinsic relationship with H/W with regard to local thermo-physiological thresholds has also received considerable attention within the scientific community. Amongst others (e.g., [160–166]), a summary of studies regarding canyon and bioclimates is summarised in Table 6, including those from other climate subgroups and those described in Table 1/Figure 1. Although the Sun MRF (MRF 2) deliberates specifically on the implementation of shelter canopies, Table 6, beforehand, presents selected outputs from such studies to inspect the broad-spectrum relationship between H/W and that of local thermo-physiological thresholds.

Table 6. Review of studies that identified thermal results from H/W and canyon analysis.

(No.)	Source	KG	Canyon Config.	Aspect Ratios	Selected H/W Thermal Study Outcomes 
#2i	[167]	'*Bwh*'	Symmetrical	0.50 1.00 2.00 4.00	▪ Slight T_{amb} reductions were identified given the increase of aspect ratio; however, changes in radiation fluxed provided a much more significant microclimatic variable for thermal comfort estimations; ▪ Given subtropical latitudes, the thermal environment within 0.50 canyons is much more stressful independent of orientation, although East-to-West proved to be slightly worse; ▪ Within the setting of wide streets, shading strategies through PSD must be considered; ▪ The period of thermal discomfort for intermediate orientations is reduced for intermediate orientations due to streets being always partially shaded.
#2ii	[168]	'*Cfb*'	Symmetrical	(0.38 to 3.00) (0.13 to 2.67)	▪ Simulations identified that the bioclimatic conditions in urban settings are strongly affected by canyon configurations, and that height, width, and orientation play an important role for the examination of specific thermal bioclimatic conditions; ▪ Estimations and simulations results can be derived that have significant for both basic research and that of estimating specific thermal conditions; ▪ North-to-South orientation revealed highest thermal stimuli at midday, while East-to-West revealed lowest stimuli.
#2iii	[169]	'*Cfa*'	Symmetrical	0.50 1.00 1.50 2.00 2.50 3.00 3.50	▪ Thermal conditions vary in street canyons with different aspect ratios; ▪ Height, width, and orientation play an important role in the examination of specific thermal bioclimatic conditions; ▪ Estimations and simulations results proved to have significant outputs for both basic research and that of estimating specific thermal conditions
#2iv	[170]	'*Af*'	A/symmetrical	(0.80 to 2.00)	▪ Taller façades of asymmetrical canyon play an important role in enhancing V at street level; ▪ High asymmetrical aspect ratios are ideal and are better than low symmetrical streets, and are an improvement over deep symmetrical canyons in tropical climates, since they store heat at night and block air flow; ▪ PSD and position of boulevard components at street level such as sidewalks and vehicle lanes should take advantage of the differences between high/low buildings instead of being organised in the traditional and symmetrical fashion.

#2v	[171]	'*Aw*'	Symmetrical	0.50 1.00 1.50 2.00 3.00 4.00 5.00	▪ Thermal conditions within lower aspect ratio canyons and East-to-West orientations revealed much higher susceptibility to thermal stress; ▪ Shading strategies through PSD, i.e., pergolas, awning, galleries, or vegetation, should be implemented when it is unfeasible to increase building heights; ▪ Commonly, North-to-South orientations revealed the most efficient strategy for attenuating thermal stress during summer; ▪ Those aspect ratios between 1.00 and 1.50 that are most favourable for PSD increase bioclimatic control during summer.
#2vi	[172]	'*Aw*'	A/symmetrical	0.50 1.50 2.00 3.00 5.00	▪ North-to-South, Northwest-to-Southeast, and Northeast-to-Southwest were the canyons that presented discomfort for smaller periods of time in comparison to East-to-West canyons; ▪ Optimal areas within the canyons are adjacent to north side of the East-to-West street, the northwest side of the Northeast-to-Southwest street, and the southwest side of the Southeast-Northwest street. When highest façade is located on the east side of the North-to-South canyons, then the 'subzone' adjacent to the east facing façade was also recommended for pedestrians.
#2vii	[36]	'*Csa*'	Symmetrical	0.17 0.25 0.50 1.00 2.00	▪ When approaching high to medium ARs, canyon orientation became a far more significant influence on thermal comfort conditions. ▪ Within the lower ARs, central regions generally presented a very high priority for PSD interventions. This being said, during various occasions, central canyons regions did not always correspond to the locations with the highest thermal stimuli within low ARs; ▪ Under almost all investigated conditions, it was identified that canyon locations with the generally lowest priority for PSD were the western regions within the North-to-South orientations and southern regions within the West-to-East orientations. Regardless, there were specific times of day in which PSD could potentially present important thermal attenuations in all analysed canyons and orientations.

From the studies presented in Table 6, two critical aspects were identified with regards to the relationship between urban canyons and solar radiation, namely, that (1) canyons within different aspect ratios, symmetry, and orientations can present acutely different influences on thermal comfort thresholds; and (2) within the canyons themselves, such thresholds can also vary significantly. For this reason, and given that the modification of H/W is often unfeasible within existing urban frameworks, PSD plays an important role in addressing such a limitation during annual periods of high thermal stimuli. Thus, and when addressing shade canopies and/or structures within public spaces, the main microclimatic factor that must be considered is its ability to address solar radiation. Although the correlation between solar radiation and T_{amb} can be deceptive, MRT has proven to be a complicated, yet effective, variable for understanding the effect of solar radiation in outdoor contexts [173]. Placing this within IS terms, while the registered T_{amb} under a canopy may be the same as one fully exposed to the sun, the amount of solar radiation will differ significantly. As a result, this variation in radiation will dramatically influence MRT, and thus, influence pedestrian thermo-physiological comfort levels. This being said, and within Figure 4, the broad characteristics of shelter canopies and their influence on respective variables (namely W/m^2) are generally described from a design point of view.

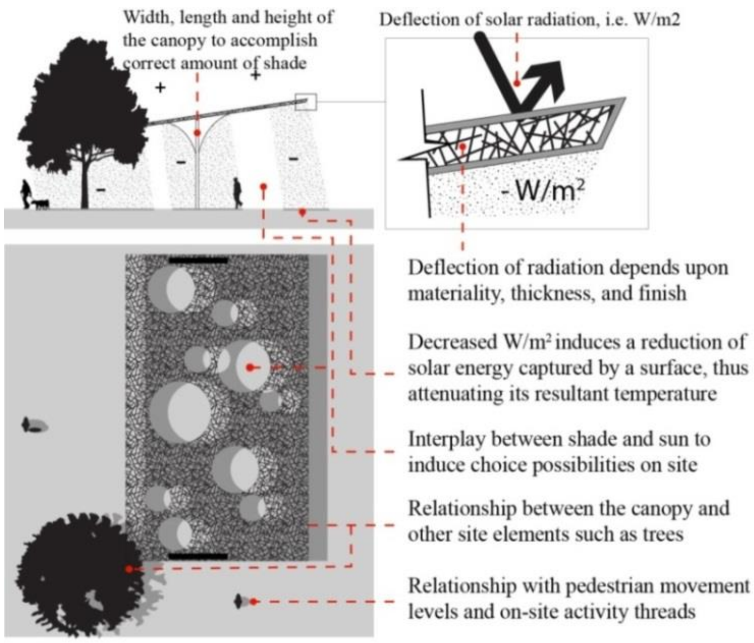


Figure 4. Variables that influence the performance of shade canopies.

5.1. Introduction of Projects

Currently, the use of shade canopies in the public realm is far from uncommon. However, and similar to the use of vegetation, very few of them originate as a result of a wholesome bioclimatic approach, and are often a product of urban 'cosmetic beautification'. In order to effectively examine the use of shade canopies as a means of attenuating thermal comfort levels, a differentiation between short-term and long-term interventions is required. Unlike most of the other thermal PSD measures, the design of shade canopies can be often interlinked with temporary solutions. Here, the design of the structure itself can be oriented as an Ephemeral Thermal Comfort Solution (ETCS) [28], which can provide short-term solutions during annual periods of higher thermal stimuli. When considering 'Temperate' climates and their general solar radiation implications on Mediterranean cities, one must similarly consider that there is an increased need for solar radiation during the winter as well. Resultantly, the implications between ETCS and permanent shading solutions are considerably different. While ETCS are only directed at addressing the need for solar attenuation during the hotter months, permanent solutions must also be evaluated in terms of their impact during winter periods, in which increased solar exposure often becomes more desired. Both typologies shall be incorporated into the Sun MRF to describe how the selected design solutions were elaborated by others to attenuate the amount of thermal human stress within the respective outdoor spaces.

5.2. ETCS Projects

Now concentrating on the ETCS scope, both the Mediterranean countries of Portugal and Spain have proposed creative and temporary solutions through the application of nylon in order to address the summer sun and simultaneously contribute to the quality of the urban public realm. Initiated in 2011, 'Umbrella Sky Project' was launched in order to decrease the amount of heat stress on the pedestrians throughout July to September (Project#2.1). Similar in nature, Madrid also deploys ETCS during the hotter months of the year in order to decrease the amount of solar radiation felt by pedestrians, exemplified in shopping streets such as 'Calle del Arenal' (Project#2.2). In addition, although not included within the MRF due to a lack of available specifications, a similar approach was also applied within the Spanish city of Seville, known as 'Calle Sierpes' within a commercial street to also reduce radiation fluxes at pedestrian level.

In 2008, and within Madrid, the conceptual project 'This is not an Umbrella' (Project#2.3) mimicked the idea shown in Project#2.1. Although a simple and low-cost solution, it enabled a way in which to attenuate thermal comfort levels in the patio of the Spanish Matadero Contemporary Art Centre. A similar approach was also undertaken in a contemporary art centre with the use of freshly cut bamboo to provide relief from the hot summers in New York (Project#2.4).

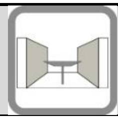
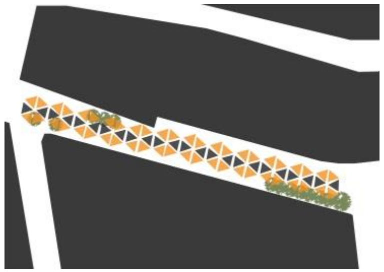
In an effort to explore the installation of light-weight and movable shading canopies, the recent project 'Urban Umbrella' in Lisbon also sought to introduce means of providing relief from the summer sun (Project#2.5). Resultant of their design, the pedestrians could open or close the canopies depending on their preference or time of stay within the exterior space. Lastly, Ecosistema Urbano architects launched a conceptual 'Bioclimatic urban strategy' to improve the pedestrian comfort in the public spaces of downtown Madrid (Project#2.6). Of the numerous measures proposed in the strategy, various types of canopies were suggested, including sheets of fabric/foliage supported by roof-cables and small shade canopies that were to be placed above new seating amenities within the different squares.

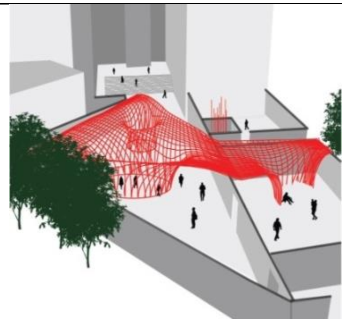
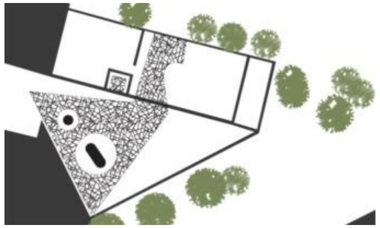
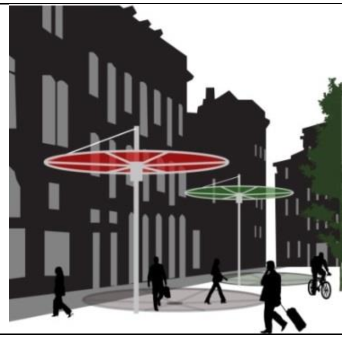
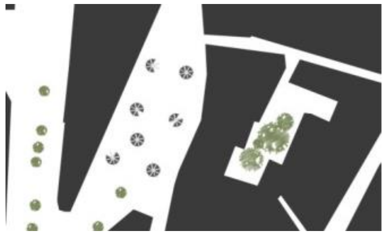
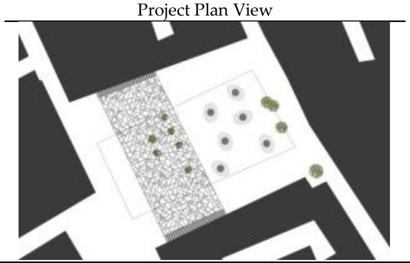
5.2.1. Permanent Solution Projects

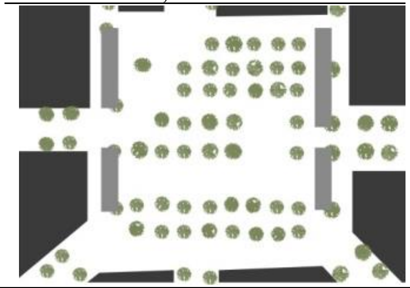
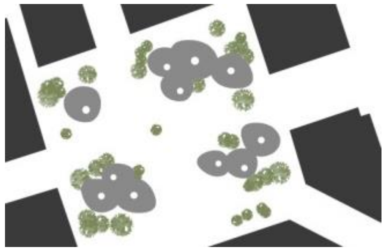
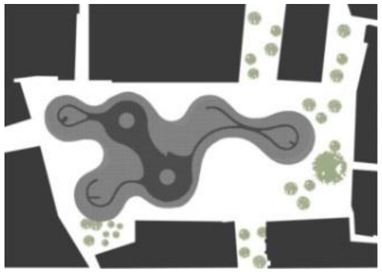
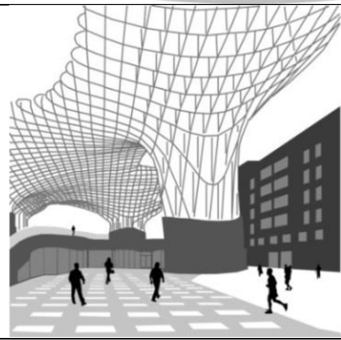
The following projects illustrate cases in which permanent shade solutions were projected and/or constructed. The first project refers back to the 'One Step Beyond' project entry (Project#1.14), where in one of the public spaces (Omonia square), a limited number of shading canopies were introduced. Although the four canopy structures shade less than 10% of the total area of the public space, they were strategically placed adjacent to food/beverages kiosks. Consequently, the associated risk of over-shading during the winter is null, and effective shading is accomplished year round. Still, within the 'Re-Think Athens' competition, another noteworthy entry was the 'Activity Tree' by ABM architects (Project#2.7). After an in-depth site analysis, the zones that would require attenuation from solar radiation were to be protected by 'Bioclimatic Trees'. These structures were designed to permit solar penetration during the winter through a structural celosias system.

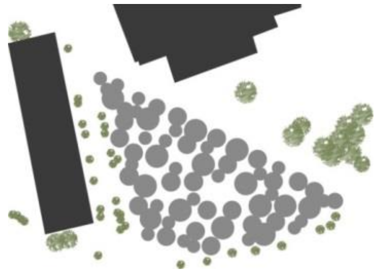
Within Seville, and also resultant of an international competition, the proposal 'Metropol Parasol' introduced a significantly larger structure and provided actual uses within its interior (Project#2.8). The principal idea behind the project was to offer shade within the previously sunny and hot square, and to enable more activity threads during the summer. Also in Spain, the last project is located in Cordoba, with a large open space that lacked shading measures and fell victim to elevated summer temperatures. As a result, ParedesPino architects installed prefabricated circular canopies that vary in height and diameter in order to represent that of an 'urban forest of shadows' (Project#2.9).

MRF 2. Shelter Canopies.

Sun Measure Review Framework									
(No.)	**Name/Status**	**Loc.**	**KG**	**H/W (≈)**	**Area of Canopy (s)**	**Choice**	**Material**	**Temporal Scope**	**Icon**
#2.1	'Umbrella Sky Project'/Constructed (2011)	Águeda	'*Csa*'	1.30	80%	Local	Nylon Project Plan View 	ETCS	
#2.2	Shopping street 'Calle del Arenal'/Constructed (-)	Madrid	'*Csa*'	1.10	70%	Local	Nylon Project Plan View 	ETCS	
#2.3	'This is not an Umbrella'/Conceptual (2008)	Madrid	'*Csa*'	0.12	28%	Local	Nylon Project Plan View 	ETCS	

#2.4	'Canopy'/Constructed (2004)	New York	'*Cfa*'	NA	26%	Local	Bamboo	ETCS	
							Project Plan View 		
#2.5	'Urban Umbrella'/Under Construction (2015)	Lisbon	'*Csa*'	0.32	9%*	Micro	Aluminium + Acrylic	ETCS	
							Project Plan View 		
#2.6	'Bioclimatic Urban Strategy'/Under Construction	Madrid	'*Csa*'	0.24	24%*	Micro	Aluminium + Acrylic + Flora	Perm.	
							Project Plan View 		

#1.14	'One Step Beyond'/Conceptual (2013)	Athens	'*Csa*'	0.15	10%	Local	Timber Perm. Project Plan View 	
#2.7	'Bioclimatic Trees'/Conceptual (2013)	Athens	'*Csa*'	0.15	24%	Local	Timber Perm. Project Plan View 	
#2.8	'Metropol Parasol'/Constructed (2013)	Seville	'*Csa*'	0.22	39%	Local	Timber Perm. Project Plan View 	

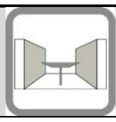
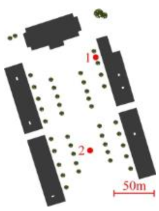
#2.9	'Urban forest of Shadows'/Constructed (2010)	Cordoba	'*Csa*'	NA	NA	Local	Aluminium + Acrylic Perm. Project Plan View 	

Notes: *—Based on project plans/representations, it should be noted, however, in this project that the precise number of canopies are not disclosed; thus, the canopy area and icons should be considered as indicative only. Acronyms: ETCS—Ephemeral Thermal Comfort Solution; NA—Not applicable; Perm.—Permanent Measure.

5.2.2. Critical Outlook

As shown within the Sun MRF, very few constructed projects have considered the thermo-physiological implications of either ephemeral or permanent shade canopies; thus, the inclusion of 'Thermal Results' was not justified. Nevertheless, and as exemplified by Projects#2.1–6, although the use of ephemeral shade canopies was perhaps more predisposed to artistic influence rather than precise scientific application, it can be safely assumed that their continual use is indicative of their capacity to reduce thermal stress levels. Although the quantification of such a reduction within these projects has not yet been identified or disseminated, two recent bioclimatic PSD studies examined how ephemeral shade canopies were able to concretely reduce IS thermo-physiological thresholds. These two studies were undertaken within two different urban canyons types, and are presented in Table 7.

Table 7. Result review of two bioclimatic studies that identified concrete thermo-physiological attenuation as a result of ephemeral shade canopies.

(No.)	Source	KG	H/W (≈)	Measure	Thermal Result (Max)	Icon & Plan Project View (Icons and Plan Adapted from Sources)		
#2viii	[17,54]	'*Csa*'	0.21	ETCS Sun Sails (Nylon) (1)	−20.0 K_{MRT} −9.9 K_{PET}		 (1)	 (2)
				Permanent Shelter (Aluminium, Acrylic) (2)	−22.0 K_{MRT} −12.3 K_{PET}			
#2ix	[174]	'*Cfb*'	0.22 *1	ETCS Sun Sails (Nylon) *1	−11.0 K_{MRT} −5.0 K_{PET}		*1 Icon/Plan not included, please refer to source	
			1.66	ETCS Sun Sails (Nylon)	−27.0 K_{MRT} −13.0 K_{PET}			

In Project#2viii, the study examined how the presence of canopies could reduce pedestrian thermal stress during the summer in a civic square (Rossio) in Lisbon by examining potential reduction of G_{rad} (W/m^2) within the lateral area of a canyon with a low aspect ratio. As revealed by the study, (i) the introduction of nylon canopies resulted in a projected MRT/PET decrease of 20.0 °C/9.9 °C within the eastern sidewalk at 15:00, an area prone to high physiological discomfort during the afternoon (results which are concomitant with the study outcomes presented in Project#2ii/vii); and, (ii) the introduction of opening/closing permanent shelters similar to those presented in Project#2.5 and constructed out of aluminium acrylic presented a potential MRT/PET reduction of 22.0 °C/12.3 °C within the centre of the canyon. Similarly, and as identified within Project#2ix, the study identified the effects of two ephemeral shelter canopies (identified as sun sails) on thermal comfort levels within two types of canyons in Pécs, Hungary. Within the first and lower canyon, maximum MRT/PET reductions were of 11.0 °C/5.0 °C, and the higher canyon revealed even greater reductions of 27.0 °C/13.0 °C.

Naturally, each project should be approached on a case by case scenario. However, the projects in Table 7 reveal a slightly different approach to those presented within the Sun MRF, as they considered concrete thermo-physiological impact that the shelters would have on pedestrians. As a result, it is thus suggested that further approaches and research of this nature are necessary with regard to the implementation of this type of PSD measure. Such a necessity becomes especially prominent for projects that utilise permanent shelter canopies and, moreover, when the canopies overcast a high percentage of the space (e.g., Project#2.8/9). In such cases, it becomes adjacently vital to consider how such shadows may lead to risks of over-shading within 'Temperate' winters, in which higher levels of solar radiation are often desired by pedestrians.

6. Surface Measure Review Framework

So far, the application of 'cool materials' in PSD has also progressively explored means to counterbalance elevated temperatures and UHI effects. More specifically, these materials are those that contain both high reflectivity and thermal emissivity values, thus performing better when exposed to high solar radiation and ambient temperatures [175]. Resultantly, the application of materiality on urban surfaces encounters its niche within the design and conceptualisation of the urban realm in 'Temperate' climates. Thus far, there has been considerable exploration into the increase of pavement albedo through the improvement of surface coatings and the use of aggregates/binders with lighter colours. Based on the study conducted by Santamouris [176], these examples include white reflective paint, infrared reflective coloured paint, heat reflecting paint, and, lastly, colour changing paints on pavement surfaces. The results of these studies showed considerable T_{surf} decreases of up to 24 °C during the day.

6.1. Introduction of Projects

In parallel to the discussed global studies regarding the thermal benefits of high albedo and emissivity materials, several bioclimatic projects have thus far incorporated such approaches to cool local temperatures and attenuate UHI effects. In these projects, the design goes beyond the execution of improved pavements and considers their integration within a wholesome design project to address thermal comfort levels. All of the projects in this section are situated within a climate KG subgroup of '*Csa*' and, interestingly, in either Athens or Tirana.

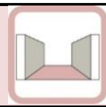
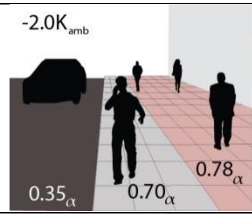
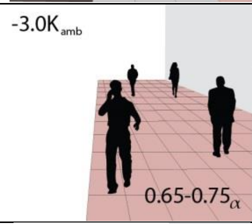
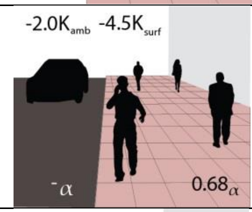
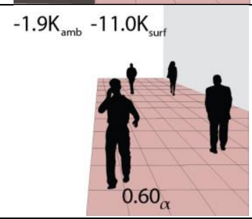
Approached as a bioclimatic rehabilitation project in Athens, in an effort to also attenuate temperature and UHI effects, Santamouris, Xirafi, et al. [177] demonstrated a T_{amb} reduction of 2.0 °C through the increase of shaded surfaces, evapotranspiration effects, and utilisation of cool materials (with albedo values ranging between 0.70 and 0.78) (Project#3.1). Also currently being constructed and located in Tirana, Fintikakis, Gaitani, et al. [178] investigated the use of cool pavements (the predominant PSD measure) that exceeded an albedo value of 0.65, along with the combination of other measures such as the increase of greenery and shading canopies, in an effort to achieve a T_{amb} reduction of 3.0 °C and reduce peak temperatures (Project#3.2).

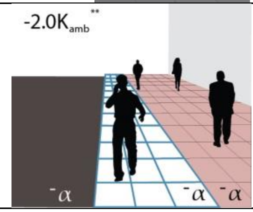
Returning to Athens, Gaitani, Spanou, et al. [19] studied the application of cool pavements in streets and squares in order to alleviate both T_{surf} and T_{amb}. Adjoining the changing of pavement materials, there was also an increase of vegetation and shading canopies. Yet, and similarly to the previous projects, these alterations were also secondary to the changing of pavement materials. The intervention led to an overall T_{amb} decrease of 2 °C and also improved temperature homogeneity within the public realm (Project#3.3). Similarly, and as part of the rehabilitation of an urban park within Athens, Santamouris, Gaitani, et al. [175] changed the dark paving to pavements coloured with infrared reflective cool paints (presenting an albedo of 0.60), which led to a T_{surf}/T_{amb} decrease of up to 11.3 °C/1.90 °C (Project#3.4). Adjoining to these studies within Athens and Tirana, other existing studies also within the 'Temperate' group revealed similar T_{amb} reductions of between 1.0 °C and 2.5 °C through pavement modification [179–181].

Similar to Projects#3.1–4, the two subsequent projects also integrate the use of materials as part of their bioclimatic approach. This being said, the use of materials has the same weight as other measures such as the implementation of vegetation, shading canopies, and water/misting systems. Both have already been mentioned in the previous sections/MRFs, yet also integrate cool pavements in their bioclimatic approach. The Parisian environmental redevelopment plan (Project#1.13) utilises the use of perennial materials, and the effects of UHI were directly used as a design generator to reconfigure the area's surface materials, whereby (i) the shaded zones of the square were predominantly in darker colours, and (ii) the open spaces were paved primarily with generally paler colours [146]. Along the same lines, the 'One Step Beyond' proposal (Project#1.14) also uses cool materials such as light asphalt, light concrete, and light natural stones specifically for their high albedo value and lesser absorption of radiation [147].

Within the Surface MRF (MRF 3), all of the bioclimatic projects that use materials to cool T_{surf}/T_{amb} were presented. With exception for the Project#1.13, all projects were implemented in public spaces that have hot-summer Mediterranean climates. The projects in this framework consider the energy balance of the pavements, namely, by (i) increasing albedo values, thus decreasing absorption of solar radiation on the materials; and (ii) decreasing the amount of radiation that the materials were exposed to by the presence of new shading measures (not shown in icons for simplification purposes). Both stone (marble) and concrete (with IRCP) surfaces led to the greatest increases of albedo as shown in Projects#3.1–4/1.14. More specifically, and as can be seen by the projects, the substitution of surface materials increased albedo by up to 51% (Project#3.1) and led to an overall T_{amb}/T_{surf} reduction of up to 3.0 °C/11.0 °C (Projects#3.2/4, respectively).

MRF 3. Materials.

Surface Measure Review Framework										
(No.)	**Source**	**KG**	**H/W (≈)**	**Existing Surface Material**	**Existing Surface Albedo**	**New Surface Material**	**New Surface Element**	**New Surface Albedo**	**Thermal Results**	**Icon**
#3.1	[177]	'*Csa*'	0.66–0.12	Black asphalt Concrete	$0.40_{\alpha}\leq$	Cool Asphalt Marble Concrete + (IRCP)	Road Pavement Pavement	0.35_{α} 0.70_{α} 0.78_{α}	−2.0 K$_{amb}$ Reduction of peak temp.	
#3.2	[178]	'*Csa*'	NA	Black asphalt Dark concrete Dark stone	$0.20_{\alpha}\leq$	Concrete + (IRCP)	Pavement	0.65_{α}–0.75_{α}	−3.0 K$_{amb}$ Reduction of peak temp.	
#3.3	[19]	'*Csa*'	0.30	Black asphalt Concrete	$0.45_{\alpha}\leq$	Asphalt + (PC) Concrete + (IRCP)	Road Pavement	ND 0.68_{α}	−2.0 K$_{amb}$ −4.5 K$_{surf}$	
#3.4	[175]	'*Csa*'	NA	Asphalt Concrete	0.20_{α}–0.45_{α}	Concrete + (IRCP)	Pavement	0.60_{α}	−1.9 K$_{amb}$ −11.0 K$_{surf}$	

#1.13	[146]	‘*Cfb*’	0.10	Asphalt	0.05_{α}–0.20_{α} (1)	Light concrete slabs	Pavement	ND	ND	
				Concrete	0.10_{α}–0.35_{α} (1)	Dark concrete slabs *1				
#1.14	[147]	‘*Csa*’	0.15 *2	Asphalt	0.05_{α}–0.20_{α} (1)	Permeable pavements	Pavement	ND	−2.0 K_{amb}	
				Concrete	0.10_{α}–0.35_{α} (1)	Concrete + (IRCP)	Pavement			
						Asphalt + (PC)	Road			

Key

Source: (1) [48]

Acronyms:
IRCP: Infrared Reflective Cool Paint, PC: Photocatalytic Compound, α: Albedo, ND: Not disclosed by study, NA: Not Applicable

Notes:
*1—Situated in shaded areas
*2—Ratio specifically in one of the public spaces enclosed in the overall project (Omonia Square)

6.2. Critical Outlook

When considering materiality interventions within PSD, and similarly to most fields within the spectrum of climatic adaptation, disagreement has arisen within the scientific arena. When approaching the urban canyon, certain authors have suggested that the decrease of temperatures referring to urban surfaces (such as pavements) may, in fact, not lead to a decrease in T_{amb} and, moreover, to 'adverse human health impacts' [182]. Such authors have also advised that the refection of radiation from high-albedo pavements can also (i) increase the temperature of nearby walls and buildings, (ii) augment the cooling load of surrounding buildings, (iii) lead to heat discomfort felt by pedestrians, and (iv) induce harmful reflected Ultra Violet (UV) radiation and surface glare issues.

Notwithstanding, this reflection suggests that these disagreements do not justify the hindrance of both the development and further incorporation of reflective pavements, including those of cool pavements. As illustrated by Project#3.3, researchers and manufacturers have also been developing cool coloured materials with higher reflectance values compared to conventionally pigmented materials of the same colour. Encouragingly, such materials have been applied in cases in which the use of light colours may lead to solar glare issues, or simply when the aesthetics of darker colours are preferred. Lastly, and unlike pavements, the thermal attenuation of building surfaces has been well documented; thus, if a wall or building surface is affected by the pavement's increased reflectivity, the buildings surface is, arguably, in itself thermally inefficient.

When considering the urban energy balance as suggested by Oke [16], factors such as urban heat storage (ΔQ_s) play a very important role within the urban environment. For this reason, and due to the shear amount of paving within the public realm, its heat flux has been a topic of study as identified within Surface MRF. More specifically, and due to the consensually established poor performance of materials such as asphalt and concrete, methods to increase pavement albedo are continually being explored, namely through modifying surface coatings and the aggregates/binders with lighter colours. Yet, another important aspect identified within Projects#3.1–4/1.14 was the integration with other PSD measures.

Thus, it can be suggested that PSD measures such as pavements should be approached as a two-step approach, whereby, depending on the identified susceptibility to solar radiation (i.e., as a result of IS aspect ratio and/or sky view factor) they could (1) integrate other PSD measures that can, beforehand, reduce the energy load upon the pavement; and (2) improve the thermal balance of the pavement. Based on the results obtained by Projects#3.1–4, such a pavement thermal balance can be approached by specifically considering their (i) absorbed solar radiation; (ii) emitted infrared radiation; (iii) heat transfer resultant of convection into the atmosphere; (iv) heat storage by the mass of the material; (v) heat conducted into the ground; (vi) evaporation or condensation when latent heat phenomena are present; and, lastly, (vii) anthropogenic heat caused by frequent urban factors such as vehicular traffic. As a result, and similar to the projects mentioned in the Green/Sun MRF, to accurately approach such cooling effects, variables such as T_{amb} and T_{surf} should be complemented by thermo-physiological indices to assess the influences of non-temperature elements on human thermal comfort as well.

7. Blue Measure Review Framework

In the past, the presence of water and misting systems was customarily focused on aesthetic and sculptural purposes in PSD. More recently, however, there has been a considerably greater emphasis on their interconnection with bioclimatic comfort in outdoor spaces in terms of adaptation efforts to climatic conditions [183]. For this reason, water and misting systems have since taken on a new meaning.

7.1. Introduction of Projects

Perhaps due to its early integration, the arena of existing projects has the tendency to fall into two predominant typologies. The first type, which is more oriented towards design, often falls short of explaining how their integrated water/misting systems can attain the correct balance between RH levels and those of T_{amb}. On other the hand, the second type, predominantly from Japanese literature, mostly focuses on the engineering aspect of equilibrating humidity levels with temperature thresholds and is less design oriented. Neither of these types is more important than the other, but this presents the opportunity to learn from both approaches in order to improve the incorporation of such PSD measures.

7.2. Design Oriented Approach

The first examples return to the Parisian and Athenian design projects (Projects#1.13–4), which also incorporate the use of water and misting systems as part of their wholesome bioclimatic approach. In Project#1.13, the use of water is not only utilised for aesthetic purposes but to address elevated temperatures during the summer. Project#1.14 integrates a 'Heat mitigation Toolbox' that implements the evaporation of micro water particles in order to reduce extreme temperatures and UHI effects.

Within Lebanon, Nunes, Zolio, et al. [183] propose to re-develop Kahn Antoun Bey in Beirut. The dominant conceptual bioclimatic measure used in the proposal was a misting system, which, in combination with other measures (i.e., vegetation, materiality, and canopies), was designed to tackle hot, yet humid, summers. Integrated within the study, an initial indicative expression was used to determine cooling effectiveness ranges based on T_{amb}, RH, and water temperature. As a result, after considering the high RH levels inherent to the site, it was considered that its microclimate could jeopardise the misting system (Project#4.1). Such a conclusion hence suggests that water spraying requires careful deliberation and thus will be analysed further within the ensuing projects.

Returning to the European context, the Expo of 1992 in Seville (Project#4.2) was approached as a method for synthesising bioclimatic techniques with PSD. Various innovative techniques are focused on the application of misting systems and bodies of water, namely, through (i) continuous blowing of moist air, (ii) 'micro' water nozzles in trees and structures, (iii) 'sheets' of water in the form of ponds and waterfalls [184,185]. In comparison with all of the other design-oriented projects, this project also accommodated a relatively strong engineering approach, yet it lacks the applicative detail that is presented by engineering projects discussed in this review article. Moreover, the project is also a case in which Surface Wetting (SW) is undesired, as it was argued that it would lead to stagnancy and resource wastage. However valid, such an approach should not lead to the conclusion that SW cannot be integrated within the systems overall design.

As an example of this incorporation, and situated within a '*Cfb*' climate, the French project 'Le Miroir d'Eau' (Project#4.3) was based on the concept of addressing thermal comfort levels and reflecting surrounding façades through a sheet of water and an integrated misting system (also based on a 'micro' nozzle system). To address the issue of stagnation, the water that temporarily floods the slabs is recollected after a few minutes, leaving the pavement surface dry. Through this method, wet surfaces become part of the design of the system, one which increases the climatic responsiveness of the once thermally problematic public space.

To finalise the design projects, and returning to the ephemeral perspective, one can also refer to the 'CoolStop' implementation in New York (Project#4.4). Simple in concept, constructed out of PVC piping, and operated through a fire hydrant unit, the misting system cooled the encircling microclimate during the summer months. Resultant of its ephemeral nature, resource wastage and stagnation was far less of a concern due to its on/off nature, seasonal use, and low consumption requirements.

7.3. Engineering Oriented Approach

In many cases, SW is undesired not only due to wastage/stagnation concerns but also because it can represent a direct result of exacerbating acceptable RH levels, in which water particles are unable to evaporate due to high atmospheric moisture content. As a result, this can lead to an undesired wetting sensation upon pedestrians. In order to effectively lower T_{amb} without imperilling acceptable humidity levels within PSD, the appropriate water pressure, nozzle type, and functioning period must be established [17,28,54].

As attested by Ishii, Tsujimoto, et al. [186] and Ishii, Tsujimoto, et al. [187], the formation of correct droplets with the adequate amount of temporal intervals becomes fundamental when approaching thermal comfort in areas that witness high humidity levels. Resultantly, and in order to explore these techniques a little further, the following projects are those that have adapted more of an engineering approach when establishing concrete temperature reductions through misting systems.

With goal of learning from ancient Japanese rituals such as 'Uchimizu', Ishii, Tsujimoto, et al. [187] developed an exterior misting system that would enable the reduction of air-condition loads without the use of vegetation (Project#4.5). Since Japan has a humid climate (i.e., '*Cfa*'), the system was designed to overcome high humidity whilst decreasing high ambient temperatures, hence the name 'Dry-Mist'. Within an outdoor environment, it was projected that (i) for every 1 °C drop in T_{amb}, RH would increase by 5%; and (ii) the system could lead to a total T_{amb} decrease of 2 °C that, subsequently, would lead to a reduction of 10% in energy consumption of interior air conditioners.

Situated within a different setting, (Project#4.6) takes the exploration of the 'Dry-Mist' system a little further; installed within a semi-open train station during the summer of 2007, a total of 30 nozzles were implemented in order to test their cooling effect. In their study, Ishii, Tsujimoto, et al. [186] reported an initial cooling potential T_{amb} average between 1.63 °C and 1.90 °C between 9:00–13:00, and 13:00–15:00, respectively. Nevertheless, and beyond these mean values, the maximum decrease in T_{amb} reached 6.0 °C and was accompanied by an increase of 28% of RH. These results illustrate that the consequential increase in humidity, although not in a fully exterior setting, accurately follows the ratio established in Project#4.5 (i.e., −1 °C in T_{amb} = +5% of RH). Similar to the application of cool pavements discussed in the previous section, there is limited knowledge regarding actual design and installation. An issue that often arises in this respective quandary is linked with the optimum amount, and size, of particles (i.e., the Sauter Mean Diameter (SMD) of the water particles).

To specifically address this issue of micro water droplets, Yamada, Yoon, et al. [188] discussed the cooling effect/behaviour of different particle sizes utilised within misting systems in outdoor spaces (Project#4.7). Through Computational Fluid Dynamic (CFD) studies, it was demonstrated that there is minor deviation in temperature for different particles sizes. Three different cases of SMD were examined, i.e., 16.9 μm, 20.8 μm, and 32.6 μm, and each displayed a similar T_{amb} reduction of ≈1.5 °C. Nonetheless, it was also identified that, due to their size and increased water mass, larger particles remained longer and at a lower position, thus suggesting the importance of particle size when deciding on the height of the misting system, especially if in circumstances whereby SW is undesired.

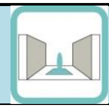
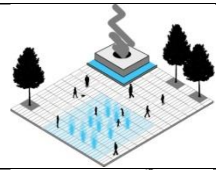
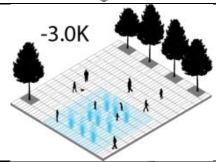
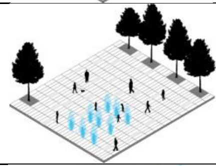
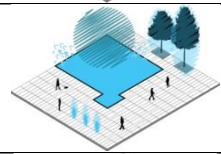
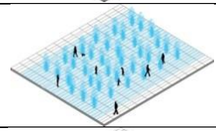
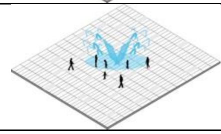
To approach the issue of height variation, Yoon, Yamada, et al. [189] studied the performance of a misting system in a semi-outdoor space, with three sprays placed at 1.5 m from the ground (Project#4.8). Through the application of CFD studies, and by assuming a wind speed of 0.1 m/s and solar radiation of 363 W/m^2, the following conclusions were reached: (i) T_{amb} of 30 °C with 80% RH scenario—water particles descended to near the ground before evaporating, reduction in T_{amb} of ≈2.5 °C; and (ii) T_{amb} of 30 °C/34 °C with 60% RH scenario—the water particles evaporated much faster, and led to a T_{amb} reduction of ≈1.75 °C. Resultantly, the study concluded that even if outdoor temperature was different, the distribution of the cooling effect would display similar behaviour; furthermore, when the RH exceeds 80% threshold, any misting system beneath that of 1.5 m will very likely lead to SW.

More recently, and carried out by Farnham, Nakao, et al. [190], both the pertinence of nozzle height and SMD was confirmed in Japanese city of Osaka (Project#4.9). Within a semi-enclosed space, this particular experiment achieved a total T_{amb} cooling of 0.7 °C without SW. This result was achieved by single nozzle spraying water particles with an SMD of between 41 μm and 45 μm. However, and even from heights of 25 m, if the respective SMDs were increased then an excessive amount of water particles would amalgamate close to the floor (thus exacerbating RH thresholds) and cause undesired SW.

The Blue MRF (MRF 4) was constructed to discuss two types of projects: those that allow SW and those that do not. Projects#1.13, #1.14, #4.3, and #4.4 demonstrated how SW is incorporated into the system in order to avoid issues of stagnation or water wastage. On the other hand, scientific Projects#4.5–8 show how high humidity levels can be overcome when cooling semi-enclosed and outdoor public spaces when SW is undesired. In light of their technical approach, design-oriented projects can thus learn from their methodical resolutions when addressing high T_{amb} and UHIs. Promisingly, and based on the disclosed results, although the already high atmospheric moisture levels beneath the UCL could discourage such applications, as a general rule of thumb, this can be overcome by a combination of (i) the correct nozzle height (1.5 m≥), (ii) the appropriate 'projected' water particle size (i.e., with a SMD below 45 μm), (iii) functioning beneath a microclimatic environment with a RH of 70–75%, (iv) assuming an increase of 5% RH for every decrease of 1.0 °C in T_{amb}, and (v) avoiding the use of the misting system if the average wind speed surpasses that of 1 m/s.

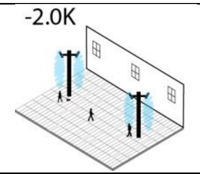
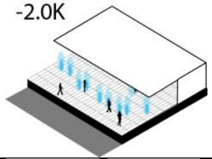
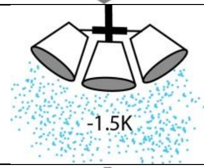
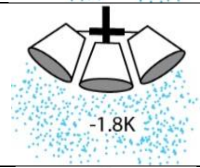
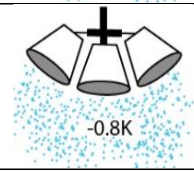
Promisingly, all of the scientific Projects are located in a KG subgroup of '*Cfa*', which also has a temperate climate and hot summers; its '*f*' subgroup portrays a climate without annual dry seasons. When considering these implications on '*Csa*' climates, and when cooling T_{amb} in dry summers, the evaporative cooling of water particles can thus be explored further without exacerbating acceptable RH levels.

MRF 4. Water/Misting Systems.

Blue Measure Review Framework									
Design Projects (Constructed or Conceptual)									
(No.)	**Source**	**KG**	**Thermal Results**	**H/W**	**Water Area**	**SW**	**SW Method**	**Temporal Scope**	**ICON**
#1.13	[146]	'*Cfb*'	ND	0.11	270 m^2	Yes	Thin layer of water is released then is left to evaporate	Perm.	
#1.14	[147]	'*Csa*'	−3 K_{amb}	0.20	792 m^2	Yes	Water features such as misting systems are intended to wet surfaces and induce evaporative cooling	Perm.	
#4.1	[183]	'*Csa*'	ND	0.42	795 m^2	No	-	Perm.	
#4.2	[184,185]	'*Csa*'	ND	NA	NA	No	-	Perm. *1	
#4.3	[-]	'*Cfb*'	ND	NA	2500 m^2	Yes	Surfaces are wet for a specified period and then re-absorbed into ground slabs	Perm.	
#4.4	[-]	'*Cfa*'	ND	NA	NA	Yes	Thin layer of water is released, then is left to evaporate during summer	ETCS	

Scientific Projects

(No.)	**KG**	**Thermal Results**		**SW**	**Limitation Method**	**SMD**	**PP**	**FP**	**NH (m)**	**Project Type**	**ICON**
		Avg.	**Max**								

#4.5	[186]	*'Cfa'*	−2 K_{amb}	-	No	Mechanism activation when: RH = 70% T_{amb} = 28≥	-	6.0 MPa	-	-	Field	
#4.6	[187]	*'Cfa'*	−2 K_{amb}	−6 K_{amb} *2	No	Temporal intervals	-	6.0 MPa	2 min with 3 min interval	1.5	Field	
#4.7	[188]	*'Cfa'*	−1.5 K_{amb}	-	No	-	16.9 μm 20.8 μm 32.6 μm	6.0 MPa	-	1.5	CFDs	
#4.8	[189]	*'Cfa'*	-	−2.5 K_{amb} −1.8 K_{amb} −1.8 K_{amb}	No	30 °C∣80% RH 30 °C∣60% RH 34 °C∣60% RH	-	6.0 MPa	-	1.5	CFDs	
#4.9	[190]	*'Cfa'*	-	−0.8 K_{amb}	No	-	41 μm −45 μm	5.5 MPa	5 min	25 (max)	Field + CFDs	

Key

PP: Pump Pressure
FP: Functioning Period
NH: Nozzle Height

Field: Study carried out on site
CFD: Study conducted in controlled environment using Computational Fluid Dynamics
SMD: Sauter Mean Diameter

*1: Although permanent, designed specifically for the Expo of 1992
*2: Value obtained if presented FP was extended

7.4. Critical Outlook

As with all of the types of measures presented in the studies discussed in this review article, it is important to remember that outdoor environments should not be designed to mimic indoor conditions [185]. Analogously, when approaching outdoor contexts, it is vital to consider that pedestrians often avert microclimatic monotony and frequently expose themselves to environmental stimuli that can surpass identified thermally comfortable thresholds [54]. For this reason, the application of misting systems through PSD must not be seen as a means of simply reducing T_{amb} because they surpass a certain benchmark during the day. Instead, they should be approached as a means of reducing temperatures in certain locations which, in turn, can offer an increased thermal versatility within an outdoor space. Naturally, the placement of such locations needs to be correct based on similar approaches such as those conducted within Projects#2i–2vii. Once established, their dimension and installation can be more effectively considered with regard to installation specifications (e.g., whether nozzles are installed within floor slabs in the centre of the square or above pedestrian level within the tree crowns above sidewalks). Thus far, however, the concrete application of such measures within the scope of thermal sensitive PSD is still significantly divided between design approaches (often lacking technical experience, namely in Projects#1.13/4/4.1–4.4) and those of a more engineering approach (often lacking the design approach, namely in Projects#4.5–4.9). Accordingly, it is thus suggested by this review study that, based upon existing knowledge, there is the fertile opportunity for future studies to dilute such segregation, even if initially based on rudimentary rules of thumb such as those mentioned in this section.

8. Conclusions & Critical Research Outlook

Bottom-up approaches to climate adaptation are continually becoming more essential for local urban design and decision making. Although often derivative from the global system, it is within local scales that adaptation efforts find their niche for addressing both existing and future microclimatic aggravations. For this reason, and in parallel to top-down approaches and assessments disseminated by the scientific community, the union between fields of urban climatology and planning/design must continue to be strengthened.

Promisingly, and perhaps as a result of a synergetic relationship with the overall climate change adaptation agenda, means of addressing local outdoor thermal comfort thresholds are continually increasing. Within this review article, such a development within the state-of-art has been based on the identification of how PSD can address thermal comfort thresholds in climates with the KG group of 'Temperate'. Within this class, the subcategories of '*Cfa*', '*Cfb*', and '*Csa*' were explored, with a greater emphasis on the latter due to its drier and hotter summers (i.e., Hot-summer Mediterranean climate). Although the link between PSD and urban climatology is still maturing, the state-of-the-art is progressively gaining posture in its efforts to form local design guidelines when approaching local thermal comfort thresholds. In summary, and as a result of this article, the following outlooks are presented:

- There is still an over dependence on singular climatic variables that do not effectively assess local thermal comfort implications, both within top-down and bottom-up perspectives. More urgently, and with regards to bottom-up approaches, there still needs to be a better integration of thermo-physiological indices to help guide more wholesome bioclimatic evaluations of the public realm. Such a requisite is particularly pertinent in design projects that exclusively depend on variables such as T_{amb} to assess the current and prospective conditions as a result of PSD interventions.
- The existing divergence between qualitative and quantitative evaluations of thermal comfort conditions needs to be addressed further. Although thermal indices have incontestably proven their importance in approaching pedestrian thermo-physiological stress, it has also been proven that socio-psychological factors can also influence pedestrian interpretations of thermal stress. In other words, while human-biometeorological thresholds have been well documented (and in

numerous ways), there is now the opportunity to further explore how simulations can potentially account for human qualitative criteria as well.

- It has been well documented that (i) tree characteristics and planting layout have a dramatic effect on thermal comfort levels; and (ii) thermal attenuations, as a result of 'green spaces', are higher than those obtained from IS individual trees. Yet, different methodologies have been utilised to identify these influences of vegetation on the urban microclimate. These approaches can be divided into two categories: those that consider non-temperature variables such as solar radiation and those that focus on modifications of T_{amb}. Although each have presented important results, it was found that studies that considered reductions in radiation fluxes were more beneficial for wholesome thermal comfort assessments.
- Unlike with vegetation, there has been very little work with regard to the influence of shelter canopies on thermal comfort levels. Although widely used, its bioclimatic application needs to be examined further. Thus far, there have been few studies that have examined the influences of ephemeral measures such as nylon/acrylic canopies. Yet, more permanent solutions (which also paradoxically present a higher need for such studies) have yet to be implicitly explored. On the other hand, and with regard to the synergetic relationship between urban canyons and solar radiation, extensive studies have been undertaken to examine influences on local thermo-physiological thresholds. Yet, with such a robust scientific foundation, and although studies are emerging, further investigation should be conducted on how different PSD measures can influence such local thresholds, including through the use of shelter canopies.
- With regard to the approach to surface elements such as pavements, although considerable work has already been undertaken, more investigation is needed. Such a task ultimately relays the requirement to consider (1) their symbiotic relationship with aspect ratios, and other PSD measures, especially in terms of susceptibility to global radiation (both continuous and episodic); and (2) further assessments into the actual thermal performance and reactions of such materials under set circumstances. Again, it is here that non-temperature variables shall continue to prove imperative when considering the direct, and indirect, influences that elements such as pavements can have on pedestrian thermal comfort thresholds.
- Lastly, and with regard to the application of water/misting systems within outdoor urban spaces for addressing thermal comfort thresholds, the link between design and engineering needs to be explored further. Moreover, it is suggested by this review study that enough is already known amongst the two approaches to launch initial investigations into how engineering approaches can be interlinked with design concepts, even if still based on basic rules of thumb that can be explored further in future thermal sensitive PSD studies.

Overall, although there has been a promising amount of studies within the scopes of urban design and urban climatology, there remains the opportunity to further interlace these two disciplines. As demonstrated within this review article, considerable work has been undertaken with regard to (i) approaching pedestrian comfort thresholds (both in quantitative and qualitative terms), and (ii) the influence of PSD on the bioclimatic responsiveness/behaviour of the urban public realm.

Especially within contexts such as southern Europe, such a synergy must also be reflected on planning policy and design guidelines. Such integration shall inevitably aid non-climatological experts to further consider how (i) bioclimatic site surveys can be undertaken to determine local thermo-physiological risk factors; and (ii) local information (such as that presented from meteorological stations) can form a base with which to approach initial appraisals—which can then be refined to a particular location, with its own specificities and characteristics. In this way, local bottom-up efforts can be approached as a fertile ground for accommodating creative PSD solutions, which are, moreover, backed by scientific knowledge, to maintain an active and safe urban public realm within an era prone to additional microclimatic aggravations.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

#Kx (in MRFs)	Temperature difference of X variable (°C)
'*Af*'	Tropical rainforest climate (-)
'*Aw*'	Tropical savannah with dry winter climate (-)
'*Bwh*'	Desert climate (-)
'*Cfa*'	Humid subtropical climate (-)
'*Cfb*'	Temperate oceanic climate (-)
'*Csa*'	Hot-Mediterranean climate (-)
a	Albedo (-)
AR	Aspect-Ratio (-)
B	Beginning of Month (-)
CFD	Computational Fluid Dynamic (-)
cPETL	cumulative PETL (°C)
E	End of Month (-)
ETCS	Ephemeral Thermal Comfort Solution (-)
FP	Functioning Period (min)
GP	Group Plantation (-)
G_{rad}	Global Radiation (W/m^2)
H/W	Height-to-Width (-)
IS	In-Situ (-)
ITS	Index of Thermal Stress (-)
KG	Köppen Geiger (-)
LP	Linear Plantation (-)
M	Middle of Month (-)
MEMI	Munich Energy-balance Model for Individuals (-)
MOCI	Mediterranean Outdoor Comfort Index (-)
mPET	modified PET (°C)
MRF	Measure Review Framework (-)
MRT	Mean Radiant Temperature (°C)
NA	Not Applicable (-)
ND	Not Disclosed (-)
NDI	No Detailed Information (-)
NH	Nozzle Height (m)
OUT_SET*	Outdoor SET* (°C)
PCI	Park Cooling Island (-)
Perm.	Permanent Measure (-)
PET	Physiologically Equivalent Temperature (°C)
PETL	PET Load (°C)
PG	Pergola (-)
PHS	Predicted Heat Strain (-)
PMV	Predicted Mean Vote (-)
PP	Pump Pressure (MPa)
PPD	Predicted Percentage of Dissatisfied (-)
PPS	Project for Public Spaces (-)
PS	Physiological Stress (-)
PSD	Public Space Design (-)
P_{sdry}	Precipitation of driest month in summer (mm)
PT	Perceived Temperature (°C)

P_{wwet}	Precipitation of wettest month in winter (mm)
Q^*	Net of all-wave radiation (W/m^2)
Q_E	Flux of latent heat (W/m^2)
Q_F	Anthropogenic heat flux (W/m^2)
Q_H	Flux of sensible heat (W/m^2)
RH	Relative Humidity (%)
SET*	Standard Effective Temperature (°C)
SMD	Sauter Mean Diameter (μm)
SP	Surface Plantation (-)
ST	Solar Transmissivity (%)
SVF	Sky View Factor (-)
SW	Surface Wetting (-)
T_{amb}	Ambient temperature (°C)
T_{cold}	T_{amb} of coldest month (°C)
T_{hot}	T_{amb} of hottest month (°C)
T_{mon10}	# of months where T_{amb} is above 10 °C (-)
T_{surf}	Surface Temperature (°C)
UHI	Urban Heat Island (-)
UTCI	Universal Thermal Climate Index (°C)
UV	Ultra Violet (nm)
V	Wind Speed (m/s)
WBGT	Wet Bulb Globe Temperature (°C)
ΔQ_A	Net heat advection (W/m^2)
ΔQ_S	Heat storage within urban fabric (W/m^2)
-	Tree acronyms not included

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Section 1

The emergence of the climate change adaptation agenda and the growing role of bottom-up approaches to local scales

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Publication 2:

An overall perspective on climate change adaptation agenda

João Pedro Costa, A. Santos Nouri, Andre Fernandes

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Chapter Preamble

Publication examines the obstacles and developments within the political and scientific arenas with regards to the emergence of the climate change adaptation agenda. Based more predominantly upon an initial top-down approach, the growing recognition for the necessity for action is discussed. Through a structured evaluation, the important contributions from global scientific entities are discussed, and the need for further bottom-up and localised action for urban planning and design is identified.

Chapter Acronym List

AAG	Adaptation Assessment Guidebook	KP	Kyoto Protocol
ACCSP	Australian Climate Change Science Program	LDCs	Least Developed Countries
ALGA	Australian Local Government Association	MRV	Measurement, Reporting and Verification
CEC	Commission of the European Communities	NAPAs	National Adaptation Plans of Actions
CPL	Climate Protection Levels	NASs	National Adaptation Strategies
CRI	Climate Risk Information	NCCAF	National Climate Change Adaptation Framework
DEFRA	Department for Environment, Food and Rural Affairs	NPCC	New York City Panel on Climate Change
EPA	Environmental Protection Agency	PEER	Partnership for European Environmental Research
GAL	Global Administrative Law	PlaNYC	New York City’s long-term sustainability plan
GCMs	Global Circulation Models	RCPs	Representative Concentration Pathways
GDP	Gross Domestic Product	RIBA	Royal Institute of British Architects
GHG	Greenhouse Gas	SRES	Special Report on Emission Scenarios
ICE	Institution of Civil Engineers	UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel on Climate Change	VROM	Ministry of Housing, Spatial Planning and the Environment

*Association/entity acronyms in tables not included

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Climate Change Adaptation in Urbanised Estuaries Contributes to the Lisbon Case

An overall perspective on the climate change adaptation agenda

J. Pedro Costa, A. Santos Nouri, A. Fernandes

Abstract

Before the turn of the century, the international community was convinced that efforts of mitigation were sufficient to solve the problem of climate change. Today, climate change adaptation is considered essential within the global political and scientific arena. This consensus is in itself a delicate conclusion that has, and must continue to, overcome scientific uncertainty through political and managerial cohesion.

Although challenged by political and scientific hurdles, climatic adaptation is already well underway in numerous countries around the globe. Moreover, and in this context, the pace has already been set for the rest of the world. This chapter discusses the obstacles and outcomes of what shall likely be an asset in the global endeavour towards climatic adaptation in both uncertain and eventful horizons.

Introduction

When considering the span of Earth's history in the last 100,000 years or more, it is evident that climatic variability has had significant contributions upon the planet. Similarly, when considering the long span of Man's occupation on Earth, adaptation to climate has been remarkably successful, where "*biologists, anthropologists and archaeologists often characterize humans as the most adaptable of animal species*" (Burton, Diringer and Smith, 2006, p.3).

On the other hand, the recent phenomenon of anthropogenic 'climate change' in the last 150 years has overlapped with the current averages through the actions of Man (Santos and Cruz, 2010). The global temperature increases has recently reached the 0.8ºC since the pre-industrial era and rising in accordance with the fast growth of GHG anthropogenic emissions (EEA, 2012). The warming effects of the climate system are already being observed and the magnitude of the phenomena is expected to increase along the 21st century. Under a summarised view, the current scientific research points towards a strong link between the human interference and the: (i) rise of the continental average temperatures; (ii) modification of the spatial and temporal distribution of precipitation and wind patterns; (iii) rise of the mean sea level; and, (iv) changes in the frequency and intensity of extreme weather events (IPCC, 2007). The consequences of such changes are far from innocuous. Projections and observations indicate several climate change phenomena with the potential to alter territorial characteristics, and impact both human and environmental systems.

In this context, the scientific and political arenas find their niche in confronting climate change. This chapter shall underpin an overall perspective of how the climate change agenda around the globe is maturing and challenging both the hazards and opportunities inferred by climate change.

1. A perspective upon international politics in light of future climatic impacts

Within the global scale, it is clear that climate related risks have considerably increased in recent decades through population growth, expansion of human settlements into now high-hazard zones, and society's consumerist attitudes. Correspondingly, and undertaking a cultural point of view, "*culture can be viewed as both a cause of climate change, for example consumerist culture, and as something that in itself will be affected by climate change – for example, demands for changes in patterns of consumption.*" (Oster and Starr, 2008, p.10).

Respectively, for more than a quarter of a century, the need for changing consumption patterns and addressing the risks related to climate has grown significantly in the international political arena. The current global institutional framework for managing the issue of climate change has made remarkable contributions to the elaborate mechanism of ensuring that countries actually implement their quantitative obligations (Gupta, Olsthoorn and Rotenberg, 2003). This is especially significant for two principal reasons: (1) Countries are generally reluctant to hand over 'enforcement power' to an international organisation, i.e. meeting foreign pre-established goals and targets (Sands, 1994; Tompkins and Amundsen, 2008); and, (2) the coordination is being accomplished given the uncertainties involved with accounting for greenhouse gas (GHG) emissions (Gupta, Olsthoorn and Rotenberg, 2003).

This delicate equilibrium between countries has been an outcome of various international institutions and entities who have guided both national mitigation targets and the more recently, the National Adaptation Strategies (NAS). In 1992, international politics concerning climate change took a substantial step forward when the international community set up the United Nations Framework Convention on Climate Change (UNFCCC). From the very start in 1992, the convention established that its ultimate goal was to achieve "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" (United-Nations, 1992). In order to enforce the conventions objectives, the Kyoto Protocol (KP) was set up in 1997 to delineate the binding quantitative obligations for each respective country (UNFCCC, 1997). With these obligations established, there was a new political thrust to implement policies and measures in such a way as to minimize adverse effects; including the adverse effects of climate change, effects on international trade, and social environmental and economic impacts on other Parties, especially developing country Parties (Breidenich, Magraw, Rowley et al., 1998). The catalysing force that propagated the emergence of this international framework in light of climate change has been a subject of dispute amongst various authors. Some theorists suggest that the multilateral environmental regimes (such as the UNFCCC) originated from nations wanting to control resources due to environmental degradation (Homer-Dixon, 1994; Gould, Weinberg and Schnaiberg, 1995). On the other hand, other approaches suggest that these environmental regimes originated from the changing attitude in world politics and global institutions in light of global warming (Meyer, Frank, Hironaka et al., 1997; Siebenhüner, 2003). Although the latter is more persuasive, it is likely that the former also contributed to institutions such as the UNFCCC. Conversely, Meyer et al. (1997) also highlight the importance of "*the worldwide expansion of scientific discourse and association over* [the twentieth century] *facilitated the rise of world environmental organization*" (Meyer, Frank, Hironaka et al., 1997, p.631). This invariably makes reference to the early scientific global disseminations from the Intergovernmental Panel on Climate Change (IPCC). At the time, some of the most prominent disseminations of the IPCC were the First Assessment Report (FAR) in 1990, and the 'future studies' in emission scenario exercises such as the (SA90) also in 1990, and the (IS92) in 1992[1].

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[1] In the first FAR of the IPCC, there was a clear objective of improving climatic predictive capabilities in order to: (1) understand better the various climate related processes; (2) improve

Today, scientific research (such as that of the IPCC) is still continuing to point towards an increase of climatic magnitudes until the end of the century. The extent of this increase will be however dependent on the concentration of GHG emissions. Furthermore, existing knowledge correspondingly suggests that future impacts will not be evenly distributed, and some regions shall be affected by determined climate events more than others. In summary, and without having in consideration local variants, impacts will be mostly driven by the progressive change of the climate, such as: (i) the increase of the average surface temperature all over the globe[2]; (ii) changes in the average annual precipitation, with some regions becoming up to 20% wetter or dryer (thus also influencing the probability of floods and droughts); (iii) the rise of sea level, increasing the coastal flood risk of all low lying areas and small islands; (iv) the intensification of draught in some areas and seasons such as those observed in Southern Europe and West Africa; (v) the increase of heavy precipitation in many regions; (vi) increased frequency of temperature extremes and warm spells all over the globe; and, (vii) the increase of tropical cyclones intensity on some basins and the shift of 'extratropical stormtracks', amplifying the potential damages in many coastal areas (IPCC, 2007).

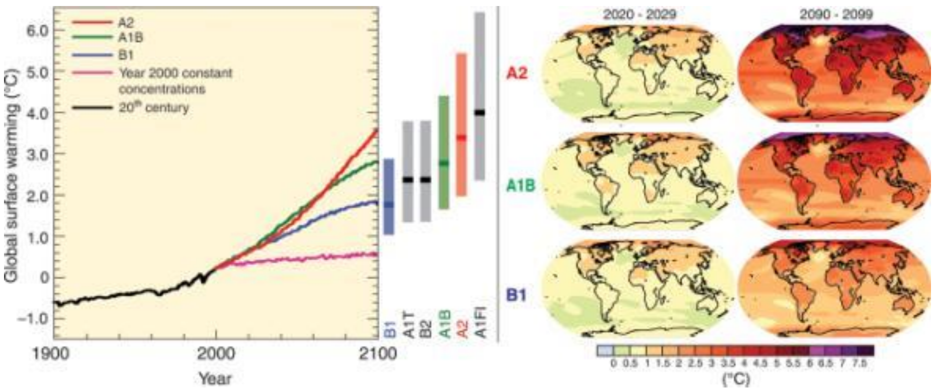

Figure 1 – IPCC's different climate scenarios and respective implications on global temperatures. Source: (IPCC, 2007)

Considering the actual path of global emissions (Fig.1), projections point to a probable warming between 2ºC and 3ºC by the end of century if no strong mitigation measures are taken (EEA, 2012). Regardless, even if current emissions could be completely ceased, many changes would still take place, namely the global increase in surface temperatures and rise of mean sea levels and occurrences of extreme events (Chart.1).

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the systematic observation of climate-related variables on a global basis; (3) develop improved models of the Earth's climate system (i.e. Global Circulation Models (GCMs)); (4) increase support for national and international climate research activities; and, (5) facilitate international exchange of climate data. IPCC (1990). IPCC First Assessment Report, Report prepared for Intergovernmental Panel on Climate Change by Working Group 1 Cambridge, New York, Melbourne, Cambridge University Press. Furthermore, the 1990 IPCC scenario A (SA90) explored four emission pathways, including a 'business as usual' future and three additional scenarios with policy interventions. This was then followed by the 1992 IPCC scenarios (IS92) that portrayed the implications of uncertainties in economic growth, population and technology in a number of 'business as usual' energy and economic futures. Moss, R., J. Edmonds, K. Hibbard, M. Manning, S. Rose, D. Vuuren, T. Carter, S. Emori, M. Kainuma, T. Kram, G. Meehl, J. Mitchell, N. Nakicenovic, K. Riahi, S. Smith, R. Stouffer, A. Thomson, J. Weyant and T. Wilbanks (2010). "The next generation of scenarios for climate change research and assessment." Nature **463**(11): pp. 747-756.

[2] To take place namely over land areas and the Northern Hemisphere, where a global mean rise between 1.1ºC and 6.4ºC is expected, affecting the water availability, ecosystems, human health, amongst others.

Furthermore, scientific endeavours also indicate that the effects of climate change are already being felt, namely through the emergence of an unusual high number of extreme events in the last decade (Rahmstorf and Coumou, 2012). Unprecedented heat waves, droughts, downpours and cyclones have broken several regional climate records and are problematic to justify when the influences of climate change are disregarded. The inferred causalities have been significant, as demonstrated by the European heat wave of 2003, which led to more than 70,000 deaths; and the Pakistani floods in 2010, leading to 3,000 deaths and 20 million people affected due to the sheer magnitude of the event.

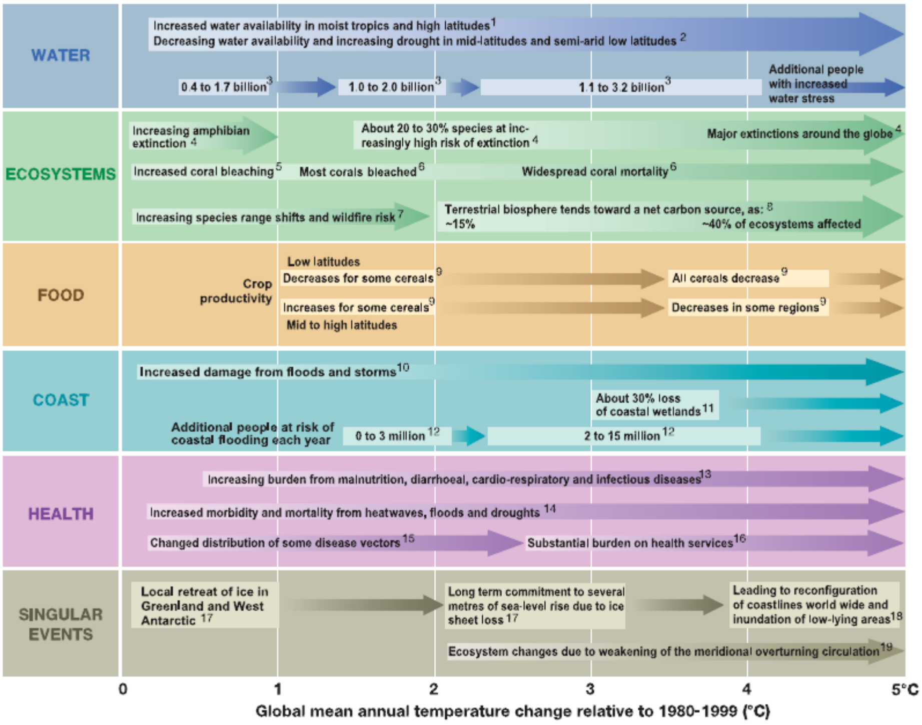

Chart 1 - Table of global impacts projected for changes in climate associated with different global average surface temperature increase in the 21st century. Source: (IPCC, 2007)

In light of such evidences, the international arena has made significant progress in global efforts regarding climate change. Nevertheless, scientific obscurities and political attritions are still identifiable. Moreover, assessing the actual effectiveness of entities such as the UNFCCC can also be challenging due to the obscurities in identifying causality between the existence of an institution and actual behavioural change (Tompkins and Amundsen, 2008). In other words, Tompkins et al. (2008) suggests that the difficulty inbuilt in this genre of analysis lies in distinguishing an entity's desired 'outcome' from the resultant and actual 'output'. As an example, when reviewing the conventions general objective of preventing 'dangerous anthropogenic interference', it can be argued that "*evaluating the consequences of climate change outcomes to determine those that may be considered 'dangerous' is a complex undertaking, involving substantial uncertainties as well as value judgements*" (Patwardhan, Schneider and Semenov, 2003, p.1). Additional to the lack of agreement on what exactly 'dangerous' climate change is, it is also argued that the convention does not address how this objective can be accomplished (Oppenheimer, 2005).

Nevertheless, this identified 'vagueness' on behalf of the convention likely originates from the uncertainty that is inherent in both climate change mitigation and adaptation. Depicting now on the former, the arena of global GHG reduction is significantly hindered by: (1) science – in the intrinsic uncertainty of the emissions themselves, i.e. margins of error in analytical statistics and in epistemic uncertainty of retrieved data;

and (2) politics – in the uncertainty of compliance of parties to the KP, and how to verify these compliances. These issues suggest that there needs to be a "*developing* [of] *accurate ways of measuring the emissions of GHG, including the developing of measures that verifiably reduce anthropogenic emissions of GHG*" especially when "*it is not unrealistic to assume that many Parties will opt to make uncertain reductions that enable them to claim they are in compliance with Kyoto.*" (Gupta, Olsthoorn and Rotenberg, 2003, p.482).

Furthermore, considerable debate has risen in light of the KP's methods of enforcing GHG emission reductions upon its Parties, especially when considering the institution's top-down political nature. With the division between developing countries and developed countries (Annex 1 countries), the latter are obliged to downscale their national GHG emissions until the pre-established deadline. Yet it has been suggested by a number of theorists that "*a far more effective (and presumably fairer) way to tackle climate change today is by bringing on board the major GHG emitters, irrespective of their GDP* [Gross Domestic Product]*, and ask them to reduce their GHG in an equitable manner without ignoring the historic responsibilities on the part of developed countries. Why? Because the Kyoto Protocol's stipulation that only Annex 1 countries reduce their GHG emissions does not reflect today's or tomorrow's climate change reality.*" (Leal-Arcas, 2012, p.3). This has raised the glance upon alternative approaches where "*GAL* [Global Administrative Law] *principles and practices of transparency, participation, reason giving, and review should be widely emulated in the governance of a bottom-up strategy's components including MRV* [Measurement, Reporting and Verification] *of their performance in achieving their objectives and in achieving GHG reductions, in order to build trust, create incentives and pressures to promote compliance, as well as enhance the efficacy of GHG reductions. One advantage of a bottom-up regime is that it has the ability to involve sub-natural actors that have little or no role within the UNFCCC.*" (Stewart and Oppenheimer, 2011, p.6).

2. An overview of representative cases: politics and reference documents

Focusing now on the politics of adaptation, who's' subject matter invoked little interest in the international arena until mid-1990's, has since became a fundamental global concern (Smit, Burton, Klein et al., 2000; Rübberlke, 2011; Cook, Nuccitelli, Green et al., 2013). Unlike mitigation, the global politics of climatic adaptation is inherently different and has distinct implications for the international climatic policy. This heterogeneity partly takes place because climatic adaptation is in the core interest of each individual country, requiring specific national (i.e. regional and more recently local) adaptation. This implies that although adaptation will probably always be backed by the international framework, its international 'enforcing' will not be required in adapting to climate change (Rübberlke, 2011). However, it can also be argued that national climate adaptation can also have valuable international benefits such as: (1) direct benefits – through early warning systems, climate monitoring systems, and afforestation programmes (Anantram and Noronha, 2005); and more importantly, (2) indirect benefits – learning from practical and theoretical precedence amongst respective international adaptation efforts through the cooperation within the international arena (Swart, Biesbroek, Binnerup et al., 2009; ENAAC, 2010; Costa, 2011). This resulted in institutions such as the United Nations Development Programme (UNDP) to aid countries with "*a number of multi-criteria decision-making tools* [to] *help countries identify, evaluate and prioritize technological means for both mitigation and adaptation*" (UNDP, 2011, p.50).

As already discussed, adaptation has become a legitimate and fundamental aspect in the international climate change agenda since the turn of the century. Nowadays, "…*adaptation is now recognised as inevitable*" (Burton, Huq, Lim et al., 2002, p.147), contrastingly to when "*ten or fifteen years ago, the international community was focused on mitigation,* [and] *everyone was convinced that this would solve the problem. It was politically incorrect to speak about adaptation. Today things have changed.*" (Santos *in* Ecosfera, 2011, author's translation).

Reflectively, although the UNFCCC has been discussed more in terms of efforts to mitigate climate change, the convention has also made significant contributions to the international climate change adaptation agenda. Amongst others, are the contributions made by the: (1) Buenos Aires Programme[3] (UNFCCC, 2005); (2) Nairobi five year programme of work on impacts, vulnerability and adaptation to climate change[4] (UNFCCC, 2007); (3) National Adaptation Plans of Action (NAPAs) (UNFCCC, 2013) for Least Developed Countries (LDCs); and (4) Bali Action Plan[5].

These contributions made by the convention have been significantly valued within the international framework, yet from a political stand point, constraints can be found regarding its efforts in climatic adaptation. The first constraint originates due to the fact that "*the climate regime has not traditionally engaged many of the agencies and actors whose participation in adaptation is essential. Even if the regime assigned a higher priority to adaptation, it still might not be the best channel for engaging relevant policymakers and stakeholders*", and secondly, "*the regime's inherent focus on climate change may not easily lend itself to a comprehensive effort addressing both climate change and natural climate variability*"[6] (Burton, Diringer and Smith, 2006, p.15).

Focussing now on the European scope, the European Commission published the Green Paper entitled 'Adapting to climate change in Europe – options for EU action' that sets four lines of action at the community level, those being:

1. "*Where current knowledge is sufficient, adaptation strategies should be developed in order to identify optimal resource allocation and efficient resource use which will guide actions at EU level…*"
2. "*…to recognise the external dimension of impacts and adaptation and to build a new alliance with its partners all around the world and particularly in developing countries. Adaptation should be coordinated with its neighbours and cooperation with international organisations should be further strengthened.*"
3. "*Where there are still important knowledge gaps, Community research, exchange of information and preparatory actions should further reduce uncertainty and expand knowledge base. Integration of research results into policy and practice should be reinforced.*"
4. "*Coordinated strategies and actions should inter alia be further analysed and discussed, in a European Advisory Group on Adaptation to Climate*

[3] Programme that originated from the convention's COP10 that focussed on strategic priorities for adaptation and enforcing relations with the Global Environment Facility (GEF)

[4] In the Nairobi five year programme, it is stated that "*sustained political momentum behind climate change is raising the level of resources for and activity in adaptation assessment. Furthermore, the scope and pace of climate change reinforces the need for more rapid development of assessment tools and methods, and of adaptation options for communities that integrate the consideration of such issues as sustainable development…and environmental impact*" UNFCCC (2010). Adaptation Assessment Planning and Practice: An overview from the Nairobi work programme on impacts, vulnerability and adaptation to climate change. Germany, United Nations Convention on Climate Change

[5] This plan was an outcome of the convention's COP13 that aims at enhanced action on adaptation regarding the "*international cooperation to support urgent implementation of adaptation actions…to enable climate-resilient development and reduce vulnerability of all Parties.*" UNFCCC (2007). Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007. Germany, United Nations Framework Convention on Climate Change.

[6] This point is also highlighted by the synthesis report of the IPCC in 2007 that underpins the differences in the conventions climatic focus, where *"climate change in IPCC usage refers to a change in the state of the climate that can be identified…it refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the [UNFCCC], where climate change refers to a change of climate that is attributed directly or indirectly to human activity…"* IPCC (2007). Synthesis Report - An assessment of the Intergovermental Panel on Climate Change - adopted section by section at IPCC Plenary XXVII (Valencia, Spain, 12-17 November 2007). Geneva, IPCC.

> *Change under the European Climate Change Programme.*" (CEC, 2007, p.13)

This paper was then followed by the dissemination of the White Paper in 2009 that aims at enforcing more concrete policy development within the European Union. As an example, following the UNFCCC stipulation that every effort must be made to adopt national or regional strategies; the White Paper establishes that "*the EU's framework adopts a phased approach. The intention is that phase 1 (2009-2012) will lay the ground work for preparing a comprehensive EU adaptation strategy to be implemented during phase 2, commencing in 2013…for phase 1 to be a success, the EU national, regional and local authorities must cooperate closely.*"[7] (CEC, 2009, p.7). Furthermore, it is also important to note that the concept of 'mal-adaptation' is introduced within this document as well, stating that "*some adaptation actions that are taken may increase vulnerability rather than reduce it. Some examples of this 'mal-adaptation' are sea level rise or flood protection infrastructure that may disturb the natural dynamic nature of coastal and river systems, or cooling or water supply technologies that may increase energy consumption.*" (CEC, 2009, p.6).

When reflecting upon both the Green and White Papers of the Commission of the European Communities (CEC), it is clear that climatic adaptation has enforced the collaboration with scientific knowledge and national policy constitution. It is in this arena where 'applied science' has found its niche and is integrating with policy development, into what can be described as 'socially robust knowledge' (Jasanoff, 2003). Furthermore, the increasing complexity of society into what can be defined as a 'third modernity' (Ascher, 2010 [2001]), and the shift from 'government to governance' (Folke, Hahn, Olsson et al., 2005), has increased the range of participants involved in creating their own national adaptation strategies.

As a result, a comprehensive number of countries have already embarked on their NASs. The Partnership for European Environmental Research (PEER) breaks down these programmes and projects into:

1. 'Climate System Research Programmes'
2. 'Impacts Research Programmes'
3. 'Vulnerability and Adaptation Research'[8] (Swart, Biesbroek, Binnerup et al., 2009)

The first stage of the NASs (Tbl.1) concentrates on understanding the climatic system, detecting climatic variation, modelling future climate, anthropogenic contributions (climatic forcing), and sources of GHG. Resultantly, it is suggested that the outputs from this phase were what probably invigorated the presence of climatic mitigation within international political arena. This once again strengthens Meyer's argument that the formation of entities such as the UNFCCC and IPCC were resultant of 'scientific discourse and association' before the turn of the century.

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[7] It is established in the White Paper that Phase 1 will focus on 'four pillars of action' i.e.: (1) building a solid knowledge base on the impact and consequences of climate change for the EU; (2) integrating adaptation into EU key policy areas; (3) employing a combination of policy instruments (market-based instruments, guidelines, public-policy partnerships) to ensure effective delivery of adaption; and (4) stepping up international cooperation on adaptation. CEC (2009). White Paper - Adapting to climate change: Towards a European framework for action. Brussels, Commission of the European Communities.

[8] It is worth noting that this approach suggested by PEER resembles the three stage framework at the COP1 in 1995 where: Stage I was to focus on identifying the most vulnerable countries (short term); Stage II was focused on preparing for adaptation (medium to long term); and, Stage III entailed implementing measures to facilitate adaptation (medium to long term). Burton, I., E. Diringer and J. Smith (2006). Adaptation to Climate Change: International Policy Options. USA, Prepared for the Pew Center on Global Climate Change.

Table 1 - Examples of the climate system research programmes in Europe from 1998 onwards

Stage 1 of NASs - Climate System Research Programmes			
Country	**Year**	**Programme**	**Budget (per annum)**
Denmark	1998-	Danish climate centre (part of the Danish Meteorological Institute)	€ 0.6M
	1998-2003	Various Danish climate system research projects	€ 24M
Finland	1990-1995	Finnish research programme for atmospheric change (SILMU)	€ 15M
Germany	1987-1994	Enquete Commission "Schutz der Erdatomsphare"	Unknown
Netherlands	1989-1995	National Research Programme on Global Air Pollution and Climate Change (NOP 1)	Unknown
Sweden	1996-2001	Swedish Regional Climate Modeling Programme (SWECLIM)	Unknown
	1990-1998	Climate change UV-B radiation	Unknown
	2007-	Bert Bolin Centre for Climate Research	Unknown
United Kingdom	1990-	Meteorological Office Hadley Centre (MOHC) for climate prediction and research	£ 74M for 5 years (since 2007)
	2001-2007	NERC Rapid climate change (RAPID)	£ 20M
	2003-2009	NERC Quantifying and understanding the earth system (QUEST) programme	£ 23M

Source: Adapted from (Swart, Biesbroek, Binnerup et al., 2009)

With the increased funding for examining options for reducing anthropogenic emissions of GHG (i.e. mitigation), a more focalised concern was established regarding climate change at national levels. This funding ranged from the private, public and governmental sectors to nationally monitor and reveal observed impacts of climate change in the environment (Swart, Biesbroek, Binnerup et al., 2009). It is important to note that these initial stages of the NASs were independent of the UNFCCC/KP and also made valid scientific contributions to the IPCC’s assessment reports; with the latest being the fourth assessment report published in 2007. Table 2 shows examples of the second phase research programmes and projects in Europe. It can be noted that this list is significantly larger than the former for two principle reasons: (1) mitigation alone was recognised to be insufficient to deal with the issue of climate change; and (2) in consequence of the first point, European (and global) stipends were increased due to the consensually established need for adaptation in light of scientific endeavours.

Table 2 - Examples of the Impacts Research Programmes in Europe

Stage 2 of NASs - Impacts Research Programmes			
Country	**Year**	**Programme**	**Budget (per annum)**
Denmark	1998-	Various national international climate	€ 10M

	2001	impact research projects	
Finland	1999-2002	Finnish Global Change Research Programme (FIGARE)	€ 6.7M
	2004-2005	Assessing the adaptive capacity of the Finnish environment and soceity under a changing climate (FINADAPT)	€ 0.3M
France	1999-2003	Gestion et impacts du changement climatique (GICC) 1	€ 4.0M
	2003-2006	Gestion et impacts du changement climatique (GICC) 2	€ 3.5M
Germany	2001-2006	DEKLIM - German Climate Research Program	€ 37M
	2008-	Federal research programme "Climate Impact and Adaptation in Germany"	€ 15M
	2007-	Federal research programme "Klimazwei: Research for climate protection and protection from climate impacts	€ 15M
	2007-	Klimzug - federal funding programme for research on regional climate impacts and adaptation	€ 75M
Latvia	2006-2009	National Research Programme KALME: Climate change impact on the waters of Latvia	€ 1.9M
Netherlands	1995-2001	National Onderzoek Programma Mondiale Luchtverontreiniging en Klimaatveranderin (NOP 2)	Unknown
	2004-2011	Climate Changes Spatial Planning (CcSP)	€ 100M
Portugal	1999-2002	Scenarios impacts and adaptation measures (SIAM) 1	Unknown
	2002-2006	Scenarios impacts and adaptation measures (SIAM) 2	Unknown
Spain	2003-2005	"Assessment report of the preliminary impacts in Spain due to Climate Change" (ECCE)	Unknown
Sweden	2008-	Swedish Research Programme on Climate Impacts and Adaptation (SWECIA)	€ 4.3M
United Kingdom	1997-	UK Climate Impacts Programme (UKCIP)	£ 3.8M for 5 years since 2005
	1992-2002	Nerc Terrestrial Initiative in Global Environmental Research (TIGER)	£ 20M

Source: Adapted from (Swart, Biesbroek, Binnerup et al., 2009)

With the increased understanding regarding the inevitability of climate change, the latest phase of the NASs has dramatically raised attention towards national adaptation approaches. As a result, more prominence has been attributed to the examination of adaptation options, thus requiring further research into economic, social and behavioural issues. This recent approach of countries focusing further on their own ‘pathway’ to climatic adaptation and resiliency (especially in frontrunner countries such as the UK, Finland, and the Netherlands) has also influenced the global scientific community concerning climate change endeavours. As an example, the latest Special Report of Emission Scenarios (SRES) that followed the scenarios (IS92), were launched by the IPCC to investigate the uncertainty of future greenhouse gas and short lived pollutant emissions given a wide range of driving forces has now given way to a new form of analysing global emission scenarios (Fig.1). This is due to "*end users, including policy makers, have new information needs that require changes in scenario focus…in addition, increasing attention to the impacts of climate change scenarios that focus for adaptation has spawned an interest in climatic scenarios that focus on the next two to three decades with higher spatial and temporal resolution and improved representation of extreme events.*" (Moss, Edmonds, Hibbard et al., 2010, p.750). As a result, the IPCC decided at its twenty-fifth session in 2006 against producing another set of emission scenarios, and leaving this responsibility to the global scientific community. It can be argued that this was to be expected as this intergovernmental agency had "*recommend*[ed] *that the new scenarios be used not only in the IPCC's future assessments of climate change, its impacts, and adaptation and mitigation options, but also as a basis for analyses by the wider research and policy community…*" (IPCC, 2000, p.viii). As a consequence, the new Representative Concentration Pathways (RCPs) were launched and has facilitated the most recent programmes of the NASs in Europe. Table 3 illustrates the discussed programmes that include more detailed assessments which are specifically directed on impacts on both the regional and local scales or in specific sectors to aid context-specific adaptation.

Table 3 - Examples of Vulnerability and Adaptation Research in Europe

Stage 3 of NASs - Vulnerability and Adaptation Research			
Country	**Year**	**Programme**	**Budget (per annum)**
Finland	2006-2010	Finnish "Climate Change Adaptation Research Programme" (ISTO)	€ 0.5M
Netherlands	2009-2014	Knowledge for Climate (KfC)	€ 100M (€ 50M subsidy)
Sweden	2006-2012	CLIMATOOLS	SEK 25M
	2001-2005	Communication, Organisation, Policy Issues and Efficiency (COPE)	Unknown
United Kingdom	2000-	Tyndall Centre for Climate Change Research	£ 19M to 2010
	Forthcoming five-year programme	Living with Environmental Change (LWEC) Programme	Nominal £ 1B

Source: Adapted from (Swart, Biesbroek, Binnerup et al., 2009)

Although there are still limited number European countries that are at the third stage of their NASs, it is expected that others shall join this list of Vulnerability and Adaptation Research. This meeting of different nations towards the common goal of climatic adaptation is a representation of an international effort that has ever since evolved from the late twentieth century. In the case of the EU, its enclosed research has played an important role in the international climate change agenda due to its developments both in the political and scientific arena. More concretely, the European scope alone portrays the tackling of complex translations from scientific insights into applicable and national information for policy makers. This translation exemplifies how the global political arena is evolving due to scientific discovery and with the dissemination of relevant knowledge towards mutual goals across international frontiers. It can also be acknowledged that the need for political enforcing upon different countries in light of climate change is continually decreasing, whereby these interactions are increasingly led instead by international cooperation towards mutual collaboration towards global resiliency in eventful horizons.

3. Case studies of National Climate Change Agendas

3.1 The Dutch Case

Considering now the Dutch case, the climatic-sector of coastal defence in the Netherlands also has a number of adaptation initiatives at both the policy and operational level. This policy arena is segregated into two main themes, firstly, spatial planning; and secondly, flood-risk management. At the operational level, four distinguished plans/programmes are orientated towards direct climate change adaptation, those being the: (1) Delta Plan; (2) National Flood Defence Construction Programme; (3) Sand Nourishment Programme; and lastly, (4) Delta Law and Delta Programme (European-Comission, 2009).

Policy initiatives in light of climate change (i.e. including flood-risk management) and spatial planning are mostly performed at national level with the support of the Ministry of Housing, Spatial Planning and the Environment (VROM). In regards to spatial planning research, amongst others[9], the most prominent within the Dutch NAS is the ‘Working Together with Water’ (Deltacommissie, 2008). These research initiatives contributed to the programme ‘Routeplanner’ which in turn significantly supported the NAS of the Netherlands published by the government in 2007.

As a result numerous adaptation initiatives have already been launched within the Netherlands, which are viable due to precautious planning and the continuous integration of scientific know-how in the challenging of local and regional risk factors (Figs 2,3,4,5).

[9] Such as the ‘Climate for Space’ and ‘Habiforum’ programmes

Figure 2 – Strategy Synthesis Plan of the Rotterdam Water City 2030. Source: (Rotterdam.Climate.Initiative, 2010)

Figure 3 – Concept of Water Plaza in challenging flooding scenarios. Source: (Boer, Jorritsma and Peijpe, 2010)

Figure 4 – Amphibious housing built upon resilient dikes in Holland. Source: (Dura Vermeer case study *in,* Robinson and Hamer, 2009)

Figure 5 – Floating Pavilion of the Delta Sync and Dura Vermeer, one of the seven projects of the Rotterdam's climate change adaptation strategy. Source: Author's photograph

3.2 The American Case

When considering the American approach to its national climate change agenda, it is clear that it has always had a different approach to the EU. These 'power struggles' in climate change negotiations have taken place due to Europe preferring a 'global government' solution, unlike the USA that has always pushed for a market-based solution (Tompkins and Amundsen, 2008). This was clear when the Bush administration pulled out of the KP in 2001, declaring that the protocol was too scientifically 'ambiguous' and 'costly'. Instead, the U.S. policy established only to rely on domestic and voluntary actions to reduce its 'greenhouse gas intensity'[10] (Fletcher, 2005).

[10] Refers to the ratio of emissions to economic output of the U.S. economy by 18% over the next decade; this is part of the new approach for meeting the long-term challenge of climate change, where it is also noted that "*if, in 2012, we find that we are not on track towards meeting our goal, and sound science justifies further policy action, the United States will respond with additional measures that may include a broad market-based program*" Fletcher, S. (2005).

Within the American scope, the years following 'post-Katrina' demonstrated clear progression in its climate change agenda. In terms of climatic precedent and impact, Hurricane Katrina in 2005 presented the most extreme meteorological event in the USA since 1928. This extreme climatic event reinforced the possible severity of meteorological impacts upon Mankind, and that if it "*taught us anything, it is that the worst-case scenario can happen. For the first time in human history, science has given us the ability to peer into a crystal ball of numbers and models and see what kind of a climate we'll be living in by mid-century if we continue to emit carbon at our current levels.*" (Cullen, 2010, p.xvii). Although less severe, further extreme events took place that further enforced the need for national action such as Hurricane Irene in 2011 and Hurricane Sandy in 2012. In 2009, the U.S. Global Change Research Program released the report 'Global Climate Change Impacts in the United States' that states that the USA "*has considerable capacity to adapt to climate change, but during recent extreme weather and climate events, actual practices have not always protected people and property…adaptation tends to be reactive, unevenly distributed, and focused on coping rather than preventing problems.*"(Karl, Melillo and Peterson, 2009, p.98). This report further entails that for the 2100 horizon, numerous and severe climatic impacts are expected[11], such as: (1) increase in average temperatures up to 2.0ºC; (2) sea level rise between at least 0.90 m and 1.20 m; (3) the occurrences of hurricanes with unprecedented ranges of wind and precipitation; (4) change in river flows due to reductions in snow deposits in the winter; an (5) more severe dry spells in the south-western regions and the Caribbean (Karl, Melillo and Peterson, 2009).

In this context, and with the need for adaptation approaches, the 'Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy' was launched the following year. This report recommended seven political steps that would aid the Federal government towards national resilience to climate change, namely:

1. "*Implement adaptation planning within Federal agencies to consider and address climate change impacts on missions, operations, and programs.*"
2. "*Strengthen interagency coordination to build a robust body of accessible science and tools to inform and support adaptation decisions.*"
3. "*Enhance the Government's ability to support and implement adaptive actions for the cross-cutting issues discussed in this report, and address additional cross-cutting issues over the next year (including coastal and ocean resilience and fish, wildlife and plants).*"
4. *"Develop an international adaptation strategy that builds on and enhances on-going efforts, supports the core principles and objectives of the President's new Global Development Policy, and coordinates resources and expertise across the Federal Government to support international adaptation initiatives.*"
5. "*Improve coordination of Federal efforts at the regional level to create efficiencies in climate science and services and to meet local, and regional adaptation needs.*" (Sutley, Lubchenco and Abbott, 2010, p.52)

Global Climate Change: The Kyoto Protocol. CRS Report for Congress. USA, Congressional Research Service.

[11] Including events such as: (1) increase in average temperatures up to 2.0ºC; (2) sea level rise between at least 0.90 m and 1.20 m; (3) the occurrences of hurricanes with unprecedented ranges of wind and precipitation; (4) change in river flows due to reductions in snow deposits in the winter; an (5) more severe dry spells in the south-western regions and the Caribbean Karl, T., J. Melillo and T. Peterson (2009). Global Climate Change Impacts in the United States. UK & USA, Cambridge University Press.

These points illustrate that the adaptation strategy started to play a strong role in the political agenda within the Federal Government. Yet what makes the North-American adaptation considerably distinctive is their dynamic bottom-up approach to the climate change agenda. Although the national the adaptation strategy (i.e. American NAS) was launched in 2010, various cities and estates had already been reviewing local and regional approaches to climate change. Two coastal cities are significant in this context, those being San Francisco and New York. Being in risk of sea level rise, San Francisco launched the report 'Living with a Rising Bay' in 2009 that initiated water related hazard assessments upon its waterfronts. These assessments are then reflected on: (1) how these risks can be inbuilt in city characterisation and infrastructure; and (2) suggesting possible strategies that can be applied to medium to long term (2009|2011).

The city of New York also presents an important precedence in the urban pursuit for climatic resilience, where since 2007, city planning enclosed endeavours towards climatic adaptation. Additionally, prominent competitions were launched that raised awareness and induced the creativity to tactically face climate change, this is exemplified by the New York Contest 'What if NYC?' (Fig.6). These efforts are enclosed within the New York City's long-term sustainability plan (PlaNYC), where Mayor Michael Bloomberg convened the New York City Panel on Climate Change (NPCC). This panel consists of experts to advice on issues related to climate change, and purposely structured to model the IPCC since its launch in 2008. In order to aid the foundation for climate change adaptation in New York, the NPCC launched three booklets, namely:

1. Climate Risk Information (CRI) – presents climate trends and projections for New York City and identifies potential risks on critical urban infrastructure in light of climate change.
2. Adaptation Assessment Guidebook (AAG) – outlines a process through which stakeholder can develop and implement adaptation plans
3. Climate Protection Levels (CPL) – evaluates some of the policies, rules, and regulations that govern infrastructure in New York City to determine how they could be affected by climate change (NPCC, 2009).

As a result of these strategically clear approaches to climate change at the regional and local level, it is argued that New York is clearly preparing for climate change as it: (1) Invests in adaptation and less in mitigation; (2) values defensive attitudes in light of civil protection, city infrastructure, and evacuation systems; and, (3) endorses the role of insurance schemes regarding the realisation of societies adaption (Costa, 2011).

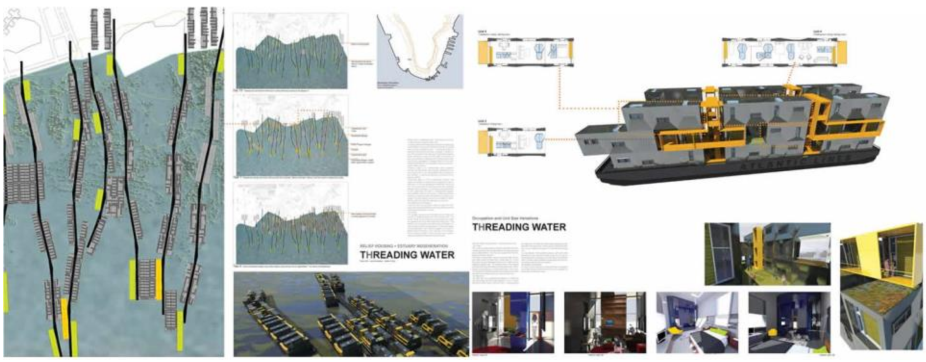

Figure 6 – Winning Proposal for the New York Competition 'What if NYC?', by David Hill with Laura Garofalo, Nelson Tang, Henry Newell, Megan Casanega. Source: (NYC, 2008)

3.3 The UK Case

Focussing now on case of the United Kingdom, one is presented with a country that has been one of the pioneers in climatic adaptation. In 2008 the Department for Environment, Food and Rural Affairs (DEFRA) presented UK's first NAS that was orientated towards amalgamating diverse existent adaptation initiatives. Nevertheless what makes this case especially relevant is the precautious approach to climate change such as the 'Think Thank' of the Royal Institute of British Architects (RIBA) and the Institution of Civil Engineers (ICE) that tests the: (1) impacts of extreme scenarios; and, (2) forming the possible strategies to be adopted in affected areas[12].

Focusing now on cases such as Kingston-Upon-Hull and Portsmouth, impacts scenarios are tested in urban areas to analyse the impacts of a 2.0 m sea level rise. Following this analysis, three strategic options are launched: (1) 'Retreat' – the abandonment of urbanised areas and from affected infrastructure through the relocation to hazard-free areas; (2) 'Defend' – utilizing new infrastructure to avoid flooding in the prone areas; and (3) 'Attack' – advancing into the water, and reflecting upon international approaches such as the 'living with the water'[13].

As a third, and representative case study, the River Thames (Fig. 7) is also a key example in flood management in light of climate change adaptation and resilience; it combines: (1) a defensive infrastructure approach that tackles possible impacts from the tides and meteorological over-forcing from the North Pole; with (2) protection of urbanised areas at risk in the 2100 horizon and of measures to be undertaken in different susceptible zones. Moreover, the 'Thames Estuary 2100 Plan', includes estimations that shall result in the increase in river flow by 40% by 2080. This is resultant of climactic impacts that are an amalgamation of the increase in precipitation levels, and of sea level rise ranging up to 0.90 m by 2100.

Presently, there are already documents that address the adaptation of private housing to climate change that tackle flooding, droughts, and overheating (Three Regions Climate Change Group, 2008). Along with other adaptation plans, London has started to methodically work in various aspects of climatic adaptation, namely its: (1) urban infrastructure with a flexible orientation; (2) urban planning that safeguards vital infrastructure and anticipates affected zones through delineating a categorical risk system; (3) built form that has resulted in innovative and activist resiliency documents in light of climate change.

Being a frontrunner country in the agenda for climate change adaptation, its local case studies allow contemplations to be made in regard to city design. When considering

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[12] This approach is "*designed to provoke longer-term thinking across a wide audience…Our proposals are extremes; and they need to be in order to tackle the scale of the problem…Clearly the urban context is where we find the most acute problem: one tidal flood event can damage so many people's homes and critical infrastructure in an extremely short period of time. Furthermore, the consequences will be long lasting.*" Robinson, D. and B. Hamer (2009). Facing Up o Rising Sea-Levels: Retreat? Defend? Attack? The Future of our Coastal and Estuarine Cities. Great Britain RIBA - Royal Institute of British Architects | Building Futures, Institution of Civil Engineers.

[13] This concept was launched by the Dutch, where Dutch Ambassador Renée Jones-Bos illustrates in his keynote speech that "*Our old 'higher dikes' approach is no longer sustainable or affordable. Whether we like it or not, we are learning to adapt, to live with water, and not to always fight against it. Our collective DNA is mutating, away from flood resistance at any cost to flood accommodation wherever possible.*" Jones-Bos, R. (2012). Dutch Ambassador Renée Jones-Bos Discusses "Living with Water" Approach to Water Management at APA conference in LA. L. A. C. Centre. USA, American Planning Association

the 2100 horizon, approaches such as the 'Think Thank' allow the architect / urban planner to make conceptual decisions concerning the adaptation of already existing urban zones. Although it is uncertain that the life cycle of these zones, infrastructures, and buildings will extend to such horizons, it is nevertheless prioritised that these elements anticipate the future need for adaptation and resiliency. This line of reasoning is one that demonstrates a clear and objective foresight into future horizons, and as a result, what makes the case of the UK particularly relevant.

Figure 7 – Water level control in London by the Thames Barrier. Source: Andy Roberts 2004

3.4 The Australian Case

Focusing now on the Australian case, in 1989 the Australian government established a National climate change science program entitled the Australian Climate Change Science Program (ACCSP). It aimed at comprehending and providing information on the climate change phenomena, and to also assist the planning process to account for climate change impacts.

Disseminated in 2007, the ACCSP launched the Technical Report 'Climate Change in Australia' that aimed at providing "*an up-to-date assessment of observed climate change over Australia, the likely causes, and projections of future changes to Australia's climate* [and] … *information on how to apply the projections in impact studies and in risk assessments* " (CSIRO, 2007, p.6). The report is grounded on the Fourth Assessment Report of the IPCC, and underlines that mean sea level rise in Australian coasts reached 1.2 mm per year during the twentieth century. Additionally, it defines El Niño's southern oscillation and the southern annular mode "*overlay the global mean sea level rise, resulting in significant regional variability in the magnitude and trend of sea level rise in the oceans surrounding Australia*" (CSIRO, 2007, p.92). Lastly, the document points out the combined effect of sea level rise, storm surges and changes in wind speed, namely by increasing the impacts due to flooding, erosion and damage, both on city infrastructure and natural ecosystems (CSIRO, 2007).

In 2007, the Australian NAS was also launched, whereby the ‘National Climate Change Adaptation Framework’ (NCCAF) established that “*the long term goal of this Framework is to position Australia to reduce the risks of climate change impacts and realise any opportunities. In the medium term (5-7 years), targeted strategies in this Framework will build our capacity to deal with climate change impacts and reduce vulnerability in key sectors and regions*” (NCCAF, 2007, p.4). This NAS is incorporated within the Australian ‘Plan of Collaborative Action on Climate Change’, in order to outline the future agenda of collaboration between governments to consensually address key demands in the business and community sectors.

More specifically, the framework adopted two priority intervention areas: building understanding and adaptive capacity, and reducing vulnerability in key sector and regions. The aim was to guide the action in several fields, such as: (1) to support decision-makers with practical guides and tools to assist in managing climate change impacts; (2) to establish a new centre for climate change adaptation to provide decision-makers with robust and relevant information on climate change impacts, vulnerability and adaptation options; (3) to work with stakeholders in key sectors to commence developing practical strategies to manage the risks of climate change impacts; and, (3) to assess the implications of climate change and possible adaptations for important regions such as the Murray-Darling Basin, the south-west Western region of Australia, the tropical north, and the drying regions of eastern Australia (NCCAF, 2007).

More recently, in 2010, the Australian Government Position Paper entitled ‘Adapting to Climate Change in Australia’ was published. This paper defines the following priorities for adaptation action: (1) coastal/water management; (2) infrastructure protection; (3) protection of valued natural systems, ecosystems and agriculture; and, (4) overall prevention, preparedness, response and recovery in light of natural disasters inferred by climate change (Australian-Government, 2010).

In conclusion to the Australian case, it is also important to note that processes of adaptation are also undertaken through a bottom-up approach where the Australian Local Government Association (ALGA) has identified climate change as a fundamental priority. Being proof that the Australian case are also in their third stage of their NAS, the ALGA focusses on:

- Enhancing the capacity of Local Government to adapt to climate change impacts by advocating for the establishment of Local Government Climate Change fund.
- Advocate for certainty in relation to litigation resulting from climate change particularly in coastal areas.
- Advocate for improved collaboration between the three levels of government on climate change issues (ALGA, 2011)

Table 4 provides a summary of some of the climate change adaptation projects being undertaken by other Local Government Associations around Australia.

Table 4 - Australian Local Government Association Adaptation Projects

Representative body	Support/initiatives
LGSA NSW	Climate Change Action Pack program with support from NSW Government Workshops/training for councils NSW Mayors Agreement on Climate Change
MAV	Members briefs provided on a needs basis covering climate change issues Environment Forum on Climate Change (2008) Workshop on adaptation for local government managers (Nov 09)
VALGA	Climate change working group to advise board
LGAQ	Advocacy role through government advisory groups Preparation of Climate Change Adaptation Guide (2007) and Climate Change Mitigation guide (2009)
LGA SA	LGA Climate Change Strategy 2008-2012 SA Local Government Sector Agreement – Climate Change Coordinating a risk management & adaptation program Local Government Climate change summit
WALGA	WALGA Climate Change Strategy Climate Change and Sustainability Annual review Integrated planning project for climate change management with WA Office of Climate Change and DPI Web-based Climate Change Management toolkit
LGANT	Through local government reference groups seek to influence planning and priorities, and learn of issues and concerns Acted as proponent for councils with federal LAPP funding applications

Source: Adapted from (LGAT, 2010)

3.5 The Indonesian Case

It is consensually recognised that Indonesia is one of the most vulnerable countries to climate change impacts. Moreover, it is also a prominent case study as Indonesia: (i) is the second biggest contributor to global GHG emissions due to land use and deforestation; (ii) hosts the fourth largest population in the world, hence implying that it is a major carbon emitter due to energy consumption; and, (iii) is still struggling with economic development, particularly poverty alleviation (Yusuf, 2010).

Taking these concerns into account, and amongst others, (e.g. the spatial planning, and management of natural resources/energy consumption levels), the Indonesian Government implemented, in 2007, the ‘National Action Plan Addressing Climate Change’ (Ministry-of-Environment, 2007). The agenda is constituted by three main pillars: (i) mitigation; (ii) adaptation; and, (iii) the improvement of institutional capacity to act upon developing and implementing both mitigation and adaptation programs. Respectively, the adaptation agenda is focused on the following issues: water resources, agriculture, fisheries, coastal/marine systems, infrastructure, settlement activities, health and forestry. In light of impending sea level rise in coastal areas, the agenda proposes the development of an inventory for all edified structures. Furthermore, a planning endeavour is also set in order to rearrange the coastal area which are prone to a high risks in light of sea level rise (Ministry-of-Environment, 2007).

Conclusion

Although there are still a limited number of countries that are already implementing actual national adaptation measures, it is essential that others adhere to approaches such as the European ‘Vulnerability and Adaptation Research’. Setting the stride, international precedential cases are already exemplified by countries such as the Netherlands, USA, UK, Australia, and Indonesia.

More concretely, these countries illuminate the confronting of intricate interpretations from scientific insights into applicable and national information for policy makers. This implies, by definition, that the comprehension of local and dynamic risk factors is backed by global knowhow. This two-way-relationship has allowed benchmark countries to both rely on international scientific knowledge, yet also, contribute towards it with their own national processes of climatic adaption. One of the most prominent contributions from these front runner countries is their approach to ‘down-scaling’ climatic adaptation. In this perspective, the invaluable contributions from organisations such as the UNFCCC, KP, and the IPCC (all representing global scientific ‘structures’), were taken a step further due to the recognised need for bottom-up and localised action.

On a similar note, the disclosed case studies in this chapter also suggest that efficient national adaptation can only be accomplished when precautionary approaches are established. Adjacently, this infers that looming levels of uncertainty are challenged by flexible and resilient long term planning and urban management.

Undertaking now a more encompassing and global view, this chapter has discussed the evolution of what was once a commonly overlooked and disregarded topic. Today, and contextualised within the twenty-first century, the climate change adaptation agenda has gained an unprecedented stature. This is evident firstly owing to the consensus that mitigation is no longer sufficient, and secondly, due to the advancement of the adaptation agenda by its own right as discussed in this chapter. Whereby, today, the ever-emergent agenda is constituted by scientific discovery, and backed by the international political arena – a clear representation of worldwide collaboration towards the mutual ambition of global resiliency in eventful horizons.

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Publication 3:

A bottom-up perspective upon climate change – approaches towards the local scale and microclimatic assessment

A. Santos Nouri

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Chapter Preamble

Publication launches the discussion of how bottom-up orientated planning assessments can approach climatic issues within local scales. In addition, it also synoptically examines how they can moreover contour obstacles such as climatic uncertainty by methodologically approaching local risk factors through numerous identified means and approaches.

Chapter Symbol List

T_{mrt}	Mean Radiant Temperature

Chapter Acronym List

GCM	Global Circulation Models	RCM	Regional Climate Model
IPCC	Intergovernmental Panel on Climate Change	SVF	Sky View Factor
PET	Physiologically Equivalent Temperature	UHI	Urban Heat Island

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A bottom-up perspective upon climate change – approaches towards the local scale and microclimatic assessment

A. Santos Nouri
Faculty of Architecture, Technical University of Lisbon, Portugal

Research Scholarship holder from the Portuguese Foundation for Science and Technology - Urbanised Estuaries and Deltas. In search for a comprehensive planning and governance.

ABSTRACT: Up to now, the issue of 'locality' has mostly been approached through a solely top-down planning perspective. This concentrates on methods of impact prediction by relying on global models as a starting point to anticipate climate change scenarios. Nevertheless, it is becoming consensually established that these models have little specificity and lack information regarding local assessment and adaptation. Although these more encompassing analytical top-down models are fundamental in global adaptation, significant meteorological variables are being frequently overlooked. Having the possibility to contribute to the quality of life and identity within cities, there is an unprecedented interest in the quality/resiliency of urban open spaces due to their role in establishing microclimatic thermal comfort levels. Moreover, this interest shall grow exponentially along with the impending climatic effects within urban outdoor environments. This article discusses how bottom-up orientated planning assessments can contour issues of climatic uncertainty by methodologically approaching these cumulative microclimatic manifestations.

To date, a considerable amount of research relating to 'locality' has been carried out through a top-down approach. This concentrates on methods of impact prediction through global models as a starting point to anticipate climate change scenarios. As these global models have little local specificity, there "*has been a growing interest, however, in considering a bottom-up approach, asking such questions as (1) how local places contribute to global climate change, (2) how those contributions change over time, (3) what drives such changes, (4) what controls local interests exercise over such forces, and (5) how efforts at mitigation and adaptation can be locally initiated and adopted.*" (Wilbanks and Kates, 1999, p. 601). Consequently, although climate change and uncertainty go hand in hand, climate change adaptation is not a 'vague concept' (Bourdin, 2010). Inversely, it is the concrete bond within specific localities that substantiates its preciseness (Costa, 2011); nevertheless, this means that climatic "*effects cannot be downscaled from a regional weather model, they are complex and require local observation and understanding.*" (Hebbert and Webb, 2007, p.125). This article shall discuss how analytical models that are bottom-up orientated can tackle uncertainty by focusing on climate impacts upon the local scale as the "*cities' sustainable development mainly depends on the capacity of the town planners to offer outdoor urban spaces with high environmental qualities (…) designing and modifying urban forms induce major and long-term transformations to the environment. The microclimate is one of the fundamental aspects of this process.*" (Reiter and Herde, 2011, p.1).

1 THE PARADOX OF SCALE

In a world of global environmental change, the variances between 'micro' and 'macro' scale perspectives are currently originating a considerable paradox between top-down and bottom-up approaches. The interchangeable scale at which environmental change has been assessed has been mostly top-down, where the methods of climatic impact analysis are derived from global models. Respectively, Global Climate Models (GCMs) are the primary tools for evaluating global change that provide 'reasonable' simulation accuracy of present climate when viewed from global and hemispheric scales; yet the data presented from these models at more micro scales are often considered erroneous (Hewitson and Crane, 1996). With notable regional and local specificity, there is now a growing interest in considering a reversal of this 'down-scaling' approach within the planning and scientific communities (Wilbanks and Kates, 1999). This elevated weight attributed to bottom-up approaches further underpin the micro-environmental process, socio-economic activities, resource management that arise within the local scale.

1.1 *Dominant top-down approaches and relationships with local contexts*

In accordance with GCMs, it has been established that the global temperature is to continually rise throughout the 21st century, and that there shall be significant changes in air humidity, wind speed and cloud cover around the globe. However, the Intergovernmental Panel on Climate Change (IPCC) report of 2001 describes the effect of weather and climate on humans with a limitative index that is based on a combination of air temperature and relative humidity. This originates a lack of significant information regarding: (1) meteorological factors including – wind speed and radiation fluxes; and (2) thermo-physiological factors including – activity of humans and clothing. Respectively, this suggests that although these top-down approaches are vital in establishing consequences of global climatic change, they have the tendency to overlook imperative thermo-physiological parameters in local contexts (Matzarakis and Amelung, 2008).

1.2 *The Downscale of Climate Change*

The GCM's seasonal mean temperature, precipitation and wind speeds within Europe are analysed by sixteen down-scaled Regional Climate Models (RCMs) simulations until the end of the century. These simulations are used to: "*(i) evaluate the simulated climate for 1961-1990, (ii) assess future climate change and (iii) illustrate uncertainties in future climate change related to natural variability, boundary conditions and emissions.*" (Kjellstorm, Nikulin, Hansson et al., 2011, p.24).

In the process of downscaling climate change examinations, the establishment of the third IPCC Assessment Report (IPCC, 2001), resulted in new data that scrutinise the possible national territorial impacts of climate change. This resulted in an array of countries establishing their own national studies, and in the case of Portugal, a new SIAM Project Report (Santos, Forbes and Moita, 2002) was thus established. This new outlook endorsed the amalgamation of local, regional, national and international adaptation agendas (Swart, Biesbroek, Binnerup et al., 2009).

2 THE POTENTIALITY OF LOCAL SCALES

When addressing the potentialities of local scales through a bottom-up approach, it is suggested that local dynamics are an important consideration in the climate change agenda (Hebbert and Webb, 2007; Costa, 2011). Although "*it is clear that some of the driving forces for global change operate at a global scale, such as greenhouse gas composition of the atmosphere and the reach of global financial systems. But it seems just as clear that many of the individual phenomena that underlie micro-environmental processes, economic activities, resource use, and population dynamics arise at the local scale.*" (Wilbanks and Kates, 1999, p.602). This approach by Thomas Wilbanks and Robert Kates presents various fundamental arguments that express not only why local scales are significant, but also how and where they respectively matter.

Firstly, when considering the domain (i.e. scale) of environmental change, one can reflect upon the global 'snowballing' changes that are resultant of the accumulation of widespread localised change. This presents the opportunity to investigate smaller-scale connotations in order to better comprehend the causes and driving forces of the global universal phenomenon (Root and Schneider, 2003).

Secondly, the previous consideration is strengthened when scrutinising the roles of 'agency' that are intentional human action; and where 'structure' is constituted by formal social affiliations or organisations. This differentiation enforces the prominence of 'agency' having a direct interest regarding local scales and their respective adaptation measures. This depicts upon the "*growing concern among local leaders about the long-term human health or social and environmental effects of inaction as well as the possibility to piggy-back climate change into more urgent local agendas such as improved local environments and liveability of cites...*" (Corfee-Morlot, Kamal-Chaoui, Donovan et al., 2009, p.33).

Lastly, it is suggested by Wilbanks and Kates that the interactionism between global structure and local agency through varying domains has raised significant interest in consolidating relevant climatic predictions and models. As a result, this suggests a need for both, a multi-scale climatic analysis and a multi-level governance in order to avoid gaps between local action plans and national and global policy frameworks. This approach "*allows two-way benefits: locally-led or bottom-up where local initiatives influence national action and national-led or top-down where enabling frameworks empower local players. The most promising frameworks combine the two into hybrid models of policy dialogue where the lessons learnt are used to modify and fine-tune enabling frameworks and disseminated horizontally, achieving more efficient local implementation of climate strategies.*" (Corfee-Morlot, Kamal-Chaoui, Donovan et al., 2009, p.3).

2.1 *Locally Initiating Analytical and Adaption measures*

Escalating now from the local scale to the global scale, one can note a significant difference in climate change awareness and regulatory practice. Nowadays, carbon mitigation and/or adaptation to global warming are part of many international agendas with monthly initiatives being disseminated throughout the global scientific community. Although this global dissemination is imperative, it is argued that it is frequently "*focussed* [on] *the exposure of cities to hazards that have a huge impact but low frequency. It has little to say about the high-frequency and micro-scale climatic phenomena created within the anthropogenic environment of the city.*" (Hebbert and Webb, 2007, p.126). Accordingly, this has diminished the comprehension of mitigation and adaptation within the local scale. Local factors such as microclimates are being considerably overlooked, where inclusively "*landscape architects and urban designers strive to design places that encourage* [urban] *activities, places where people will want to spend their time (...) however unless people are thermally comfortable in the space, they simply won't use it. Although few people are even aware of the effects that design can have on the sun, wind, humidity, and air temperature in a space, a thermally comfortable microclimate is the very foundation of well-loved and well-used outdoor places.*" (Brown, 2010, p.2).

Invariably, the considerations upon local climatic variables relays directly to the effects that the climate can have upon the liveability of cities (Hebbert and Webb, 2007). This suggests that urban form can enhance or reduce the quality of urban life, thus signifying the prominence between the spheres of local urban design and climatic adaptation. Issues such as street orientation, street width-to-height ratios, building spacing, architectural detailing in streetscapes, heat-reflectiveness from materials, the location of street trees, parks and water spaces have become a prominent niche for urban climatology and design (Givoni, 1998; Erell, Pearlmutter and Williamson, 2011). Where, with the aid of continual scientific outputs, respective investigations are integrating design concepts and climatic effects with 'biometerological' variables so human comfort levels can be estimated under different climate scenarios and design settings (Nikolopoulou, 2004; Schiller and Evans, 2006; Matzarakis, Rutz and Mayer, 2007; Grifoni, Latini and Tascini, 2010; Wong, Jusuf and Tan, 2011).

Having the possibility to contribute to the quality of life within cities, there is a strong interest in the quality of urban open spaces due to their role in establishing microclimatic thermal comfort levels (Katzschner, 2006). Moreover, this interest shall increase along with the progression of climatic effects upon urban outdoor environments.

In order to approach microclimatic comfort conditions (Fig.1), open spaces require a precise microclimatic analysis in order to evaluate people's reactions within a given thermal stimuli (Olgyay, 1963).

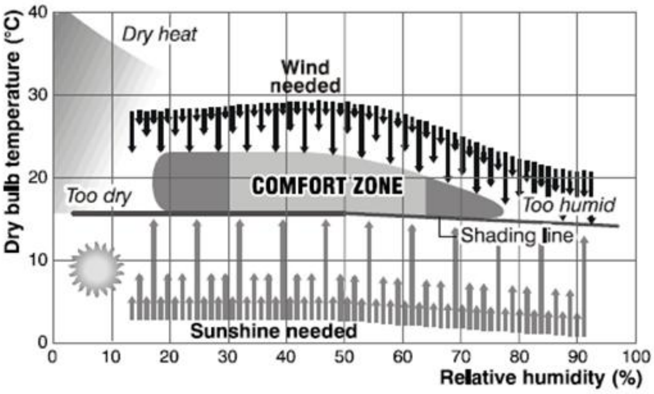

Figure 1. Olgyay's interpretation of moderate European climates – microclimatic requirements through PET values to determine thermal comfort in outdoor environments. (Olgyay, 1963)

More specifically, the thermal environmental effects upon humans can be determined with the aid of thermal indices based on the energy balance of the human body. One of the most common and used thermal indices is the Physiologically Equivalent Temperature (PET) (Höppe, 1999). This thermal index includes considerations upon meteorological factors such as air temperature, air humidity, wind velocity and short/long wave radiation that affects humans thermo-physiologically in outdoor environments (Table 1).

Table 1. PET Ranges within different grades of thermal perception and resulting physiological/thermal stress on human beings (Matzarakis and Mayer, 1996)

PET	Thermal Perception	Grade of Physiological Stress
≤ 4ºC	Very Cold	Extreme Cold Stress
4ºC	Cold	Strong Cold Stress
8ºC	Cool	Moderate Cold Stress
13ºC	Slightly Cool	Slight Cold Stress
18ºC	Comfortable	No Thermal Stress
23ºC	Slightly Warm	Slight Heat Stress
29ºC	Warm	Moderate Heat Stress
35ºC	Hot	Strong Heat Stress
41ºC	Very Hot	Extreme Heat Stress

Nevertheless, it is often that climatic assessments and thermal comfort studies have resorted to more simplistic and limitative analysis tools. As an example of this discrepancy, the IPCC Report of 2001/7 "*describes the effect of weather and climate on humans with a simple index based on a combination of air temperature and relative humidity. The exclusion of important meteorological (wind speed and radiation fluxes) and thermo-physiological (activity of humans and clothing) variables seriously diminishes the significance of the results.*" (Matzarakis and Amelung, 2008, p.162). Consequently, examples of such discrepancies can hinder fairly 'obvious' and important microclimatic considerations for a multitude of professionals such as urban designers and architects.

As an example, irrespective of air temperature, there is a constant variance of 5 ºC between PET values in areas exposed to the sun and those in the shadow (Fig.2). Interestingly, and comparing this to the fascinating results from Whyte's time-lapse photography (Fig. 3), it is suggested that "*by asking the right questions in sun and wind studies, by experimentation, we can find better ways to board the sun, to double its light, or to obscure it, or to cut down breezes in winter and induce them in summer. We can learn lessons in semiopen niches and crannies that people often seek.*" (Whyte, 1980, p.45).

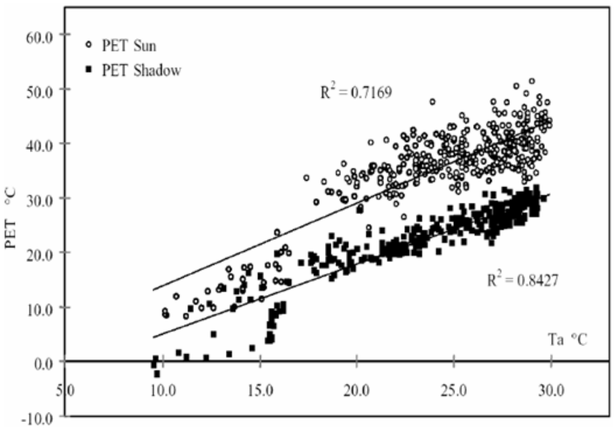

Figure 2. Relation between air temperature and thermal comfort index PET in sun and shadow (Katzschner, 2006)

Figure 3. William Whyte's time-lapse photography of sunlight patterns in New York (Whyte, 1980)

Pioneers of open space design and/or maintenance all indicate the inarguable relationship between microclimates and the vitality of urban spaces (Whyte, 1980; Carmona, 2003; Gehl, 2010; Erell, Pearlmutter and Williamson, 2011). Per se, public spaces can significantly benefit from microclimatic assessments that enable more efficient implementations of climatic strategies (both in analysis and policy criterion) in local contexts.

Although more encompassing analytical models are fundamental in the global adaptation to climate change, the local scale is: (1) where the effects of climate change will have their fundamental effects; and (2) directly where adaptation measures will find their niche to regulate these impending effects.

This being said, it is impossible to globally downscale climate change directly into local scales due to high computational demands and costs (Rummukainen, 2010). This 'limitation' is far from restrictive since those that are involved in urban planning and design can start with common meteorological data like air temperature, air humidity and wind speed in order to make significant improvements to the anthropogenic spaces of the city (Matzarakis, Rutz and Mayer, 2007). In terms of methodologically approaching these meteorological factors, one of the most accurate assessment models will be discussed below.

2.2 *RayMan Assessment Model*

One of the most comprehensive approaches in this analytical arena is the RayMan model, which calculates short and long wave radiation fluxes upon the human body. RayMan is able to deal with complex urban structures/compositions and is an effective tool for urban planners/designers when consulting the outdoor environments of the city.

Unlike other approaches and models, RayMan uses thermal indices such as PET to concretely address the urban bioclimatic and thermal comfort levels within local scales. This method permits "*the human-biometerological evaluation of the atmospheric environment*" and *"to clarify whether or not planning instruments are available for maintaining and improving the human-biometerological situation.*" (Matzarakis, Rutz and Mayer, 2007, p.1).

Beyond calculating mean radiant temperature (T_{mrt}), RayMan is able to calculate radiation fluxes due to the input of the following: (1) topography and environmental morphology (Fig.4a); and (2) fish eye lens photography to aid Sky View Factor (SVF) calculations (Fig.4b).

These input options allow the user to specify the topography of the area allowing the model to consider the geometric descriptors of the space/canyon. This is further heightened by the possibility to input fish eye lens photography in order to assess the local SVF. This calculation is a vital parameter in order to investigate the: (1) Urban Heat Island (UHI) effect; and (2) exposure of space to diffused solar radiation.

From this information and with the input of commonly accessible meteorological data such as air temperature, air humidity and wind speed - the T_{mrt} and PET can be respectively calculated. This is a significant step in linking urban climatology and urban design; enabling human comfort levels to be accurately calculated when assessing local climatic implications.

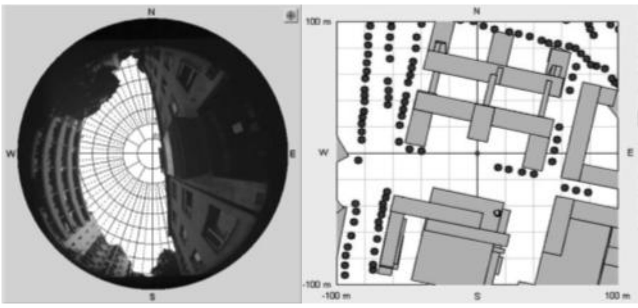

Figure 4. (a) Input window of urban structures and environmental morphology (b) Input window of fish eye lens photographs/drawings
Source: (RayMan Software by Matzarakis, 2000)

2.3 *Thinking "What if?"*

Although models such as RayMan only calculate existing microclimatic factors within the local scale, they are evidence that urban design and planning do not have to be hindered by climatic uncertainty. Approaches such as strategic '*what if?*' scenarios (Costa, 2011), allow the anticipation of possible impacts within future horizons. Correspondingly, the data input in models such as RayMan can be based on actual figures in order to understand whether a given space offers efficient comfortable PET values. Or, and more interestingly, investigate how these existing biometerological variables will be affected, by asking questions such as 'what if Europe's land temperature rises by 4.0 ºC by 2100?' This flexible approach is a pragmatic approach to uncertain climatic events in future horizons. Since these questions can be based on easily accessible meteorological information, local agents can start to comprehend how global climate change will affect the local and anthropogenic environments of the city through a bottom up approach. This endorses a new creative laboratory that fully exploits the potentialities and adaptability of local contexts.

3 CONCLUSIONS

Resultantly, it is becoming consensually recognized that top-down approaches are limitative for 'agencies' whose contributions to climate change lie fundamentally within the local 'domain'. This however does not mean that climatic assessments through GCM's or RCM's are not fundamental to Mankind's challenge in adapting to climate change. Yet it is suggested that these models often overlook fundamental climatic issues that are more applicable to microscale phenomenon. The often singular reflection and preoccupation with extreme weather effects greatly overlook the less severe yet constant meteorological repercussions such as wind patterns, solar radiation, and air temperature.

This article suggests that given climatic uncertainty, urban design and planning need to find new ways to analyse climatic phenomenon that take place within the local scale. This implies a change in the way in which climate change is to be approached for local entities such as architects and urban designers/planners. This article disputes an innovative reversal of the modern day 'top-down' approach, where microclimatic investigations can be used to combat climatic uncertainty. Implied by this approach, are new forms of thinking that consider both extreme weather effects, and the less severe but more constant effects of meteorological parameters on the public realm. It is consensus that air temperature is rising, yet there is little to be said regarding other meteorological parameters such as wind patterns and solar radiation. This lapse in the climate change adaptation arena therefore requires the understanding of the thermal environmental effects upon humans. This article suggests that this comprehension however can already be achieved, through local meteorological data, and can also be reflected into future contexts through flexible 'what if?' approaches.

Although the approach suggested by this article is still in its initial phases, the benefits are clear for those who are tasked with maintaining dynamic and healthy public realm. The theoretical discussion suggests that this approach raises the opportunity to reflect upon making dominant top-down approaches more useful for local contexts. For example, RCM assessments can be made more relevant for local agents by establishing the correct parameters and analytical scopes for local contexts. Furthermore, the differences in perspective between global structure and local agency can be reduced through multi-scale climatic analysis and multi-level governance in order to avoid gaps between local action plans/interventions and national and global policies. Yet in order to fine tune local implementation of climatic adaptation strategies and measures, microclimatic assessments need to play a more significant role in conjoining the spheres of urban climatology and urban planning/design.

4 ACKNOWLEDGMENTS

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Section 2

Examining existing measures and approaches to thermal sensitive public space design

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Publication 4:

A framework of thermal sensitive urban design benchmarks: Potentiating the longevity of Auckland's public realm

A. Santos Nouri

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Article Preamble

With the aim of approaching the often lack of bottom-up climatic indicators, tools and practical benchmarks, the publication launches a framework of international built and conceptual projects which address thermal comfort levels within specific climates. Based upon Auckland, such an organisation is cross-referenced with theory supporting its structure and respective division. Such frameworks were subsequently considered in terms of how they could launch new considerations within local policy and design guidelines.

Article Symbol list

$\#K_X$	Variation of X variable	*'Cfb'*	Tropical rainforest climate
'Cfa'	Humid subtropical climate	*'Csa'*	Net of all-wave radiation

Article Acronym List

ADM	Auckland's Design Manual	NYC	New York City
ARPHS	Auckland Regional Public Health Service	PET	Physiologically Equivalent Temperature
CFD	Computational Fluid Dynamics	PMV	Predicted Mean Vote
CBD	Central Business District	RH	Relative Humidity
ENSO	El Nino-Southern Oscillation	SMD	Sauter Mean Diameter
ET	Effective Temperature	SW	Surface Wetting
ETCS	Ephemeral Thermal Comfort Solution	UCL	Urban Canyon Layer
GCMs	Global Circulation Models	UHI	Urban Heat Island
IPO	Interdecadal Pacific Oscillation	UP	Unitary Plan
KG	Köppen-Geiger	UV	Ultra Violet
NIWA	National Institute of Water and Atmosphere		

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Article

A Framework of Thermal Sensitive Urban Design Benchmarks: Potentiating the Longevity of Auckland's Public Realm

Andre Santos Nouri

CIAUD, Faculty of Architecture, University of Lisbon, Rua Sa Nogueira, Polo Universitario, Alto da Ajuda, 1349-055 Lisbon, Portugal; E-Mail: andrenouri@fa.ulisboa.pt; Tel.: +351-213-615-884

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Abstract: One of the key objectives of contemporary urban design is to ensure the quality and activity within urban public spaces. Presented as a progressively emerging paradigm in this process, the effects of urban climatology are increasingly elucidating the need for further climate responsive environments. Moreover, this interest is one that shall increase along with the progression of climate change effects upon outdoor environments. Nevertheless, it is often that climatic assessments lack bottom-up climatic indicators, tools and practical benchmarks. As a result, this obstructs local decision making, and practices of localised adaptive design. In an effort to address such discrepancies, this paper launches a framework of international precedents of built and conceptual projects that address thermal comfort levels in public spaces. This organisation will be cross-referenced with theory that supports its structure and typological division. With Auckland as the focal case study, the solutions that are extracted from the framework will be scrutinised in order to shape new potential measures, and launch new considerations in Auckland's local policy and design guidelines. In this way, microclimatic concerns are hence framed into an opportunity to potentiate the use and longevity of Auckland's public realm.

Keywords: urban design; public space; microclimate; thermal comfort; climate change

1. Introduction

Before reaching the mid-twenty-first century milestone, it is expected that population, urban density and CO_2 emissions shall significantly increase in Auckland. Consequently, sustainable decision making becomes fundamental in amalgamation with the council's aim to make Auckland the world's most liveable city by 2040 [1]. In conjugation with this expansion, the practice of urban design is also presented with the interdisciplinary challenge of preparing for impending local "risk factors" as a result of climate change.

Although knowledge regarding outdoor thermal comfort has grown in recent years, its assimilation with climate responsive urban design has been considerably limited. As a result, local decision makers and designers often lack the design indicators and benchmarks to: (1) address existing microclimatic implications in public space design; and more prominently; (2) prepare for the invigoration of these respective insinuations as a result of climate change. With the aim of tackling such discrepancies, and through a Research for Design approach, this article reviews a range of international solutions that address similar microclimatic constraints similar to those found in Auckland.

This investigation is launched as part of an ongoing funded doctoral research with the title "*City Identity in Uncertain Climate Change Horizons: A Research Approach for Microclimatic Urban Design in Public Spaces*". As part of a chapter that explores the interaction between public space design and thermal comfort levels, this article launches a demonstrative case study on how a framework of thermal sensitive urban design can introduce new deliberations in both local policy and design guidelines for climate-responsive public spaces within the city of Auckland.

2. New Zealand's Climate and Future Implications

As a means to identify a basis for climatic regionalisation and comprehend variables from Global Circulation Models (GCMs) outputs, the Köppen-Geiger (KG) climate classification system has classified New Zealand as a Temperate/Mesothermal climate. More specifically, and supported by a top-down outlook, the updated world map of the KG system classifies this genre of climate as "Cfb", meaning a "Maritime temperate climate" or "Oceanic climate" [2]. Resultantly, this is concomitant with temperature fluctuations associated with large-scale climate patterns over the Southern Hemisphere and the Pacific Ocean. These meteorological phenomena have a temporal timeframe that can range from seasons to decades, such as the El Nino-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). Each of these oscillations can influence seasonal temperatures, wind patterns, and precipitation levels [3]. Consequentially, this natural variability invariably blurs the superimposition with long-term human-induced climate change trends.

Based on the disseminated figures from the National Institute of Water and Atmosphere (NIWA), New Zealand does not have a broad temperature range, and it lacks extreme values that are commonly found in most continental climates. Moreover, and due to being located in the Southern Hemisphere, northern cities experience higher temperatures throughout the year. As shown in Table 1, Auckland is one of these cities and is one of the warmest city centres in New Zealand.

Table 1. Summary of climate information for the six main City Centres in New Zealand (* Average Relative Humidity (RH) levels were taken at 9 am, hence these figures vary approximately if combined with afternoon RH levels—For the case of Auckland, this would decrease annual RH approximately to 76%. ** Annual count of "hot days" where temperatures exceeded 25 °C—values presented are annual averages since mid-twentieth century. Wet-days, sunshine, temperature, wind speed, and average relative humidity data are mean values from the 1981–2010 period). Adapted with permission from NIWA [4–6].

Location	Mean Relative Humidity	Wet-Days	Sunshine	Temperature				Wind Speed
	% (9 am *)	≥1.0 mm	Hours	Mean °C	Mean Max °C	Mean Min °C	Hot Days (Max Temp. ** > 25 °C)	Av. Wind Speed m/s
Auckland	82.3 *	137	2060	15.1	19.0	11.3	21	4.72
Tauranga	78.8	111	2260	14.5	19.1	10.4	21	4.44
Hamilton	85.0	129	2009	13.7	18.9	8.7	28	3.33
Wellington	82.3	123	2065	12.8	15.9	9.9	3	6.11
Christchurch	85.1	85	2100	12.1	17.2	7.3	21	4.17
Dunedin	73.1	124	1585	11.0	14.7	7.6	8	4.17

Due to being encircled by the Pacific Ocean, the country is expected to experience a delay in mean temperature change in comparison to global averages over the medium term [7]. This delay notwithstanding, national climate change projections indicate "very confidently" that until the end of the century there shall be: (1) a temperature increase of between 0.2 and 2.0 °C by 2040, and between 0.7 and 5.1 °C by 2090; (2) an increased frequency of high temperatures; and (3) an accelerated rate of temperature increase in comparison to the temperature patterns recorded for the twentieth century [3].

At a regional scale, and returning to the case of Auckland, it is a projected that by 2100, there will be at least 40+ extra "hot days" where maximum temperatures surpass 25 °C [7]. In retrospect with current values shown in Table 1, this implies that there will be a 200% increase in annual "hot days".

Furthermore, it is also worth noting that due to the proximate "ozone-hole", the county's peak Ultra Violet (UV) intensities can be 40% higher in comparison to similar latitudes in the northern hemisphere (e.g., the Mediterranean area). Although a UV index of 10 is already considered extreme, this index value can exceed 13 during the summer in cities such as Auckland.

In this light, perspectives towards the future adjoin the opportunity to deliberate upon more frequent and intense temperature levels in the city. Consequently, contemporary urban design embraces the need to certify that thermal comfort levels are addressed in the intricate balance between the urban microclimate, human characteristics, and the use of public spaces [8]. Regrettably, although the characteristics of urban climate have been well studied in the past two decades, there is little association with the possible application of physical urban design interventions.

In the scope of public space design, urban climatology is recognised as an essential component in the thermal analysis of open spaces in order to improve the collaboration between thermal physical attributes and the social environment as a whole [9]. Naturally, when presented with the risk factor of climate change, urban climate distribution becomes increasingly more important, and issues such as solar radiation, ventilation and heat islands present new challenges for local adaptation/intervention. More specifically to the local scale, the thermal environmental effects upon humans can be determined with the aid of thermal indices based on the energy balance of the human body. Thermal indices include considerations upon meteorological factors such as air temperature, air humidity, wind velocity and short/long wave radiation that affects humans thermo-physiologically in outdoor environments [10] Examples of such indices will be presented in Section 3.

As determined by Olgyay [11], thermal comfort is the balance of various microclimatic thermal stimuli. Consequently, if a stimuli such as ambient temperatures increase, then the balance of human comfort shall inevitably shift and require measures that cool ambient temperatures through the use of wind, shade, and/or evaporative cooling. Adjacently, the urban morphology can lead to local heat islands and thus require similar interventions to alleviate thermal stress levels. In the case of Auckland, although it shall face more attenuated climatic effects in comparison to global averages, its Unitary Plan (UP) invariably recognises the need to "*increase the resilience of Auckland's communities and natural and physical resources to the anticipated effects of climate change such as (...) more frequent and extreme weather events.*" ([1], p. 174). Moreover, and presented as a "Quality urban growth objective" in the UP, there is also an ardent interest in a "*high quality network of public open spaces and recreation facilities that enhances quality of life (...) and contributes positively to Auckland's unique identity.*" ([1], p. 178). Given the recognition of future climatic implications, and the importance of Auckland's public spaces, urban resilience and adaptability becomes a fertile scope of opportunity for local action. In this way, local decision makers and designers are hence tasked with considering the long-term longevity of the city's public realm that shall determinedly face climatic hurdles until the end of the century.

3. Urban Design Case Studies and Benchmarks

Since the turn of the century, the maturing climate change adaptation agenda has gained a new weight, and has instigated local decision makers and designers to search for measures to address local "risk factors" [12]. This early, yet developing bottom-up perspective, is one that explores how urban design and climatic adaptation can tackle meteorological implications through an interdisciplinary approach.

This section explores existing bioclimatic case studies that can potentially be used as benchmarks to address the impending threat of increased temperatures and heatwaves upon Auckland's public realm. In order to facilitate the typological differentiation between the discussed measures, and adapted from authors such as [13,14], four principal categories have been respectively established: (1) trees and vegetation; (2) shelter canopies; (3) materiality; and lastly (4) water and vapour systems. Of these four, a slightly greater emphasis shall be given to the categories of materiality and water/vapour systems. The reason for this is interlaced with their later appearance in urban design, and the considerable amount of scientific incongruity associated with their successful effects upon thermal comfort levels. During the ensuing section, existing international practices and/or projects shall be viewed as an opportunity to shape new potential measures, and additionally launch new considerations in Auckland's local regulatory and non-regulatory design guidelines. Given that Auckland shall experience meteorological aggravations such as increased hot days, the disclosed measures shall focus on how this can be overcome. With this objective in mind, and also taking into account the proposed alterations to microclimatic factors such as shading and wind patterns, the benefits of the projects shall be discussed in terms of reducing overall ambient temperatures (*i.e.*, K).

3.1. Trees and Vegetation

When considering the long term environmental adaptability of a city, there is a consensus that vegetation can significantly contribute to the improvement of the urban microclimate due to its ability to reduce air temperature through direct shading (Although there is still a limited amount of research pertaining to the direct effect of vegetative shading at pedestrian levels, the doctoral thesis of Ana Almeida suggests that "*trees, just like other green spaces inserted in edified areas can lower temperatures by approximately 3 °C*"), ([15], p. 54) and evapotranspiration. More specifically, these processes induce the decrease of radiant temperature, influence wind patterns (both in velocity and direction), air regeneration (such as CO_2 absorption), and filter both dust particles and noise. Moreover, and besides these environmental attributes, vegetation can also provide additional psychological benefits to humans through aesthetic, emotional and physiological responses [16].

In existing studies relating to vegetation as a form of microclimatic control in urban open spaces, four principal green "structures" can be identified: covering vegetation, isolated trees, and groves or lines of trees [17]. However, it is important to note that unlike inanimate devices, trees can change their dimension and degree of opacity during each season, and also during their lifetime. As a result, and although variations among trees may be considered aesthetically pleasing, the designer/planner needs to be aware of the shading pattern produced [14,17]. In terms of seasonal timeframes, there needs to be a consideration of: (1) how shade patterns can be provided in the summer when/where needed; (2) how solar penetration can be enticed during the winter period when/where needed; and (3) which specific trees provide these desired effects during the pertinent time of year.

Regrettably, and although recognized as an effective way to alleviate higher temperatures, the incorporation of these vegetation reflections upon thermal sensitive urban design is limited. Yet, authors such as Shashua-Bar, *et al*. [18] have explored the potential of passive cooling through the modelling of design options on outdoor thermal comfort in urban streets in the shade of both trees and buildings (Case #1). In their research, they analysed how street design scenarios benefited from the combination of vegetation with other measures in order to attenuate thermal comfort levels during the summer. To do so, the biometeorological index Physiologically Equivalent Temperature (PET) was used in order to assess levels in a typical street of Athens. Four theoretical design cases were undertaken: (1) increasing the tree's canopy coverage area from its actual net level of 7.8% to 50%; (2) reducing traffic load from two lanes to one and thus approximately reducing 1500 vehicles down to 750 per hour; (3) increasing the albedo of the adjacent side walls from the measured 0.4 to 0.7 by implementing lighter colours; and lastly; and (4) deepening the open space by increasing the aspect ratio (height/width proportions) from the existing 0.42 to 0.66 through elevating the side buildings by two additional floors (approximately 6 m) [18]. The results of the study illustrated that the most successful passive design solution was that of increasing the vegetative canopy coverage that resulted in a decrease of 1.8 K during noon hours. This is particularly interesting when comparing to the more drastic and expensive option of increasing the aspect ratio, which achieved a similar decrease of 1.9 K.

3.1.1. Application in Cooler Climates and Overcoming Risks of Overshading

Conversely, when applying this to Auckland, it is clear that, due to its more temperate climate, considerations would need to be made upon the issue of overshading. Nevertheless, the constructed Parisian climate sensitive redevelopment-project, "Place de la Republique" (also located in the KG classification of "Cfb") can be used as a practical example of how these issues can be resolved (Case #2). Trevelo & Viger-Kohler Architects and Urbanists aimed at addressing the thermal comfort and Urban Heat Island (UHI) effect within the now largest pedestrian square in Paris. Today, an overall 134 deciduous plane (Platanacease) trees and 18 deciduous honey locust (Fabaceae) trees encircle both the new perimeter and central area. Unlike the common segregation between vegetation and the thermal design of the public space, and in line with their environmental approach, the square is "*comfortable as a result of a strategy that is at once urban, landscaped and architectural*" ([19], p. 7). More specifically, this strategy consists of implementing measures that prevent the square from becoming a "heat island", namely by: (1) increasing planting and creating a unit of vegetation to provide maximum mass effect; (2) allowing the sun to penetrate and position the pedestrian areas in the sunniest areas; (3) blocking the colder winter winds by thickening the vegetation at the north of the square; and just as importantly, (4) linking the presence of vegetation in order to consolidate usage dynamics in the square to suit prevailing conditions [19].

3.1.2. Lessons for Auckland's CBD

Returning to the specific case of Auckland (and furthermore considering the temporal timeframe of 2040), the city is challenged with considering the specific implications of how vegetation can be appropriately introduced in order attenuate thermal comfort levels. Furthermore, and considering the responses from agencies such as the Auckland Regional Public Health Service (ARPHS) to the UP, the effects of UHI need to be considered further, especially given the future increases of both urban density and climatological impacts [20].

Respectively, and strengthened by the case studies presented in this first section, it is suggested that future projects (as an example, this will be particularly relevant in "Move 6" of the Auckland's Masterplan; that suggests an ecological "Green Link Network" that shall insert a "wave" of green vegetation to enhance the environmental sustainability at street level as part of the redesign of Victoria Street and adjacent open spaces) must consider vegetative: (1) annual shading patterns; (2) change in dimension and degree of opacity; (3) contributions to decreasing the UHI effect; and lastly (4) effects upon the activity threads, and usage of the urban realm in accordance with prevalent microclimatic conditions.

3.2. Shelter Canopies

When addressing canopies or roof structures in urban open spaces, the air temperature underneath the structure is predominantly affected by the existing solar exposure of the space. In turn, this directly relates upon the geometry of the structure, components, and the properties of its construction materials. The respective radiant temperature is interrelated to the temperature of the inner surface of the roof, which can be either lower or higher than the air temperature of the space underneath. Furthermore, the air velocity in the spaces underneath depends ultimately on the incoming wind/air patterns that are allowed to enter/penetrate the area.

In the case of Auckland's Central Business District (CBD), passive strategies to decrease solar radiation through shelter canopies are already present. Yet, and using Queen Street as an instance, most measures are only applied upon commercialised street sidewalks, and not within local open public spaces. With hindsight, civic spaces such as Aotea Square, Freyberg Square, and Queen Elizabeth Square are currently recognised by the UP as "*becoming increasingly important as Auckland's centres intensify and access to high-amenity open space is needed for residents*" ([1], p. 58). Perhaps due to the fear of overshading, these spaces do not accommodate passive structures that decrease and/or attenuate local solar exposure. Although this is beneficial during the winter months (*i.e.*, June to August), there is limited shading that would otherwise entice the increased usage of these spaces during the summer. Interestingly, prominent studies in the use of New York's public spaces suggest that "*the days that bring out the peak crowds on plazas are not the sparkling sunny days with temperatures in the [low 20 °Cs] (...) it is the hot, muggy days, sunny or overcast, the kind that could be expected to make people want to stay inside and be air conditioned, when you will find the peak numbers outside*" ([21], p. 44). Following this line of thought, the interplay of canopies regarding the provision of choice between experiencing sun, shade, or in-between areas becomes indispensable.

However, before any intervention can be considered, there needs to be a local and annual understanding of: (1) the patterns of existing solar radiation exposure (usually measured in hours); (2) the shadows that are cast from on-site elements (*i.e.*, such as vegetation and amenities); (3) the shadows that are cast from off-site elements (*i.e.*, such as contiguous structures and buildings); and (4) existing encircling wind patterns.

3.2.1. Permanent and Ephemeral Approaches to Passive Cooling

Once established, thermal sensitive urban design can present the opportunity to improve the current thermal response of these spaces in both colder and hotter months. More prominently, the long-term response to increased higher temperature and frequency in Auckland can be tackled through a precautious approach. In this scope, both permanent and temporary measures can be considered to increase local shading opportunities.

In the pursuit for case studies that have used shelter canopies in their bioclimatic approach to the public realm, permanent solutions can be extracted from the entries from the European competition "Re-Think-Athens". Although situated and tempered for a hotter climate (*i.e.*, "Csa" in the KG classification), many of the proposed measures can be adapted to Auckland's public realm and enclosing climate. The winning proposal "One Step Beyond" (Case #3) by OKRA Landscape Architects based their design upon a pedestrian-orientated space that incorporated contemporary ideas of climate control in order to address thermal comfort through microclimatic attenuation [22]. In one of the public spaces within the redevelopment proposal (Omonia square), a limited amount of shelter canopies were introduced into the space. Although the four canopy structures shade less than 10% of the total area of the public space, they are strategically placed on the extremities of the square alongside kiosks and food/beverage units. As a result, the risk of over-shading during the winter is null, nonetheless, effective shading is still accomplished during the summer in strategic locations.

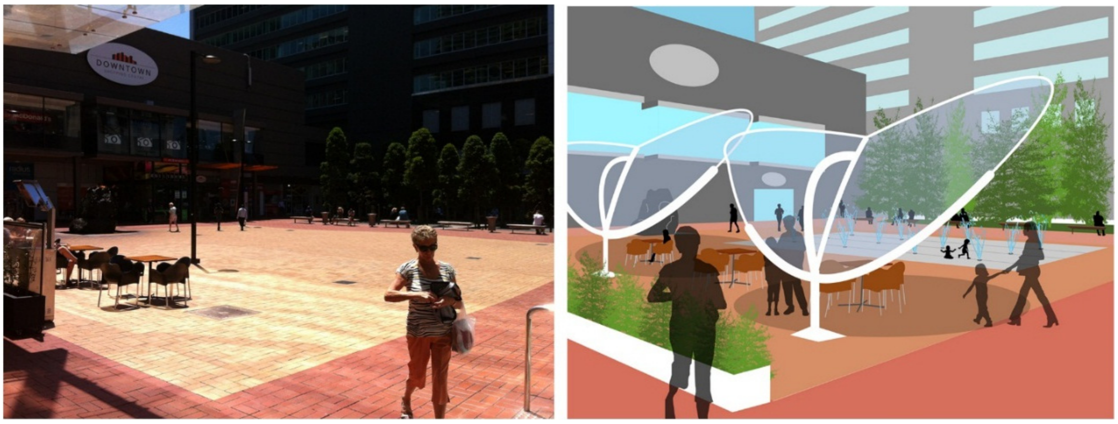
Another noteworthy and runner up entry was the submission of ABM Architects "Activity Tree" that, although it shall inevitably remain as a concept, offers, nevertheless, valuable precedents in terms of shelter canopies (Case #4). Established through an in-depth site analysis, the zones which would require protection/attenuation from solar radiation were to be protected by "Activity/Bioclimatic Trees". These canopies would cast shadows in specific areas and would serve as an advanced bioclimatic device that would be able to capture energy and water. Through a detailed analysis of sun patterns, and in order to permit solar penetration during the winter, the structural celosias system allowed the winter sun to penetrate the covered spaces.

Additionally, it is also worth noting that short-term interventions also find their niche in this category of thermal responsive urban design. Here, design can also be interlinked with ephemeral projects in order to tackle periods of higher temperatures and/or heat waves in public spaces. As an example of an Ephemeral Thermal Comfort Solution (ETCS), Ecosistema Urbano Architects launched the conceptual project "This is not an Umbrella" (Case #5). Although a simple concept, it is a lightweight and low cost solution, which enables the climatic control of a large outdoor space. The proposal is thought of as a citizen participation action that uses 1500 hanging umbrellas to shade the patio of the Spanish Matadero Contemporary Art Centre. Lastly and also erected in the exterior of a contemporary Art Centre in New York, Architects built an ETCS to provide relief from the hot summer weather. With the use of a precise 3D model, the "Canopy" was built with freshly cut green bamboo that provided armature for four different microclimates, which were also attenuated with three different water systems (Case #6).

3.2.2. Lessons for Auckland's CBD

Resultantly, both long-term and ETCS canopies find their role in attenuating urban thermal comfort levels. In the case of Auckland, this genre of intervention should be used to enhance availability of choice between exposed and shaded areas throughout the year. Moreover, the necessity of providing such choice shall increase along with the projected escalation of annual hot days in light of climate change. However, in order to avoid over-shading the city's public realm, careful analysis of existing solar patterns, shadows, and wind configurations is required. As demonstrated in the cases disclosed in this section, the tempering of thermal comfort levels can only be accomplished through the understanding of local annual microclimatic implications.

Figure 1 exhibits a conceptual bioclimatic intervention in Queen Elizabeth Square that, amongst other strategies, uses shelter canopies to improve thermal comfort levels during the summer. Photographed during the summer period, Figure 1a demonstrates a lack of activity and, moreover, a high exposure to solar radiation. Although there is vegetation on one side, the central square lacks the means to attenuate solar intensities and temperatures during the hotter months. As a result, Figure 1b shows a conceptual intervention that would be based around the use of: (i) mobile shelter canopies that could serve as temporary shading measures for the café's seating area; and (ii) a central water feature that would be turned on during hotter days, and which could entice an increase of foot fall/activity threads within the centre of the square. This simplistic conceptual intervention demonstrates an exploration of how microclimatic interventions could not only improve thermal comfort levels but also potentially increase activity threads through climate responsive public space design.



(**a**) (**b**)

Figure 1. Conceptual intervention in Queen Elizabeth Square (**a**) Existing square; (**b**) Square post bioclimatic intervention. Source: Author's rendering.

3.3. Materiality

The phenomena of UHI effects are becoming increasingly more intense in cities, and are consequentially coercing modifications upon the urban microclimate. As a direct result, the temperature disparities between urban and suburban/rural areas are continually increasing. This results from a positive balance within the urban environment due to increased heat gains consequential to the high absorption of solar radiation, the release of urban anthropogenic heat, decreased radiant heat loss under the Urban Canyon Layer (UCL), and lower wind velocities.

Through the design of both the public realm and public spaces, the global scientific community has already made significant progress in the endeavour to counterbalance UHI effects. More specifically, the proposed mitigation techniques and technologies involve the use of "cool materials" which present both high reflectivity and thermal emissivity values [23].

In this light, the application of such materials upon urban surfaces finds its niche within the design and conceptualization of the urban realm. Early investigations dating back to the 20th century already argued that the impact of pavements upon UHI was substantial, and furthermore played a considerable role in attenuating the overall urban thermal balance. The specific thermal balance of pavements is determined by the amount of: (i) absorbed solar radiation; (ii) emitted infrared radiation; (iii) heat transfer as a result of convection into the atmosphere; (iv) heat storage by the mass of the material; (v) heat conducted back into the ground; (vi) evaporation or condensation when latent heat phenomena are present; and lastly, (vii) inflicting anthropogenic heat through urban activity such as vehicular traffic upon roads [24,25].

Returning to the design of public spaces, decreasing the surface temperatures of elements such as pavements may thus significantly improve the thermal conditions in spaces suffering from elevated atmospheric temperatures. In practical terms, this can be achieved through the replacement of conventional paving surfaces that present higher surface temperatures during warmer periods.

3.3.1. The Impact of Material Reflectivity and Emissivity upon Ambient Temperature

Solar reflectivity (*i.e.*, albedo) of the respective material is, in general terms, influenced mostly by the colour of the material (another influencing factor can be the roughness of its surface, whereby those that present smoother/flatter surfaces are those with lower surface temperatures). In most cases, when a material is made of a lighter colour, it presents a higher albedo due to its lower absorptivity to the visual spectrum of solar radiation. In the study undertaken by Doulos, Santamouris, and Livada [26], numerous investigations were performed to correlate the impact of both the colour and roughness of various paving materials and their resultant surface temperatures. As part of their disseminated outputs, the investigation indicated measured air temperature, hence demonstrating the relationship between that of surface temperature and air temperature. The results of the study demonstrated that darker materials presented a significantly higher surface temperature comparatively to that of ambient temperature; thus, it can be concluded that this leads to the surfaces having a warming effect upon local ambient temperature. On the other hand, the surface temperatures of white concrete and marble are more analogous to local air temperature, especially in the case of white marble [26]. Similarly, the remainder of such temperatures in darker common materials can thus lead to elevated temperatures after peak hours due to convective heat dissipation from the pavement. This occurrence is a direct result of a combination of both low reflectivity and emissivity, whereby the radiation absorbed by the material is retained within its mass, and posteriorly dissipated back into the atmosphere, hence leading to elevating temperatures even after peak hours (materials with high emissivity correspond to good emitters of long wave radiation, and can, moreover, easily release the absorbed energy from solar radiation. For this reason, materials with lower emissivity rates are the principal reason for increased surface temperatures during the night as shown in [27]). Disseminated within the international scientific arena, further theoretical (and to some extent empirical) studies, both at local and regional scales, have enforced such relationships between materiality and surface/ambient temperatures [28,29].

3.3.2. Lessons Learnt from the Direct Application of Materials in Bioclimatic Projects

Analogous to the discussed global studies regarding the thermal benefits of high albedo and emissivity materials in contemporary cities, several bioclimatic projects have already incorporated such approaches to cool local temperatures and attenuate UHI effects.

The characteristics of such projects are demonstrated in Table 2, where it is worth noting that most projects are located in the same KG climate classification system (*i.e.*, “Csa”). Case #7 deals with the bioclimatic rehabilitation of a central area in the city of Marousi in Athens, and is currently under construction. Following the results of a microclimatic assessment, both innovative architectural and environmental techniques were used to attenuate local thermal comfort levels. Before the project was commenced, the area was known for its: (i) increased ambient temperatures during the summer period, and for its generally unsatisfactory thermal comfort levels; (ii) extensive use of black asphalt in streets, and the use of dark concrete tiles upon pavements; and (iii) susceptibility to medium intensities of UHI effects [30]. To overcome such issues, and to substantially improve the local microclimate, a bioclimatic plan was thus launched.

Table 2. Direct application of reflective pavements in existing bioclimatic projects. Adapted with permission from Elsevier [25].

Case #	City/Country	KG Climate Classification	Type of Existing Pavement	Type of New Pavement	Thermal Results
#7	Athens/Greece	"Csa"	Black asphalt and concrete pavements with albedo below 0.4.	(1) Cool asphalt in roads with albedo close to 0.35. (2) Natural reflective materials for pavements (marble), with an albedo of 0.7. (3) Concrete pavements coloured with infrared reflective cool paints with albedo 0.78.	(1) A decrease of 3.4 K in ambient temperature, whereby change in materiality contributed in 2.0 K. (2) Ambient temperatures in areas prone to higher temperatures were considerably attenuated.
#8	Tirana/Albania	"Csa"	Black asphalt and dark concrete/stone pavements with albedo lower than 0.2.	Concrete pavements coloured with infrared reflective cool paints with albedo between 0.65 and 0.75.	(1) A decrease in the average ambient temperature by 3 K. (2) Ambient temperatures significantly decreased in areas prone to maximum temperatures due to the presence of cool materials alone.
#9	Athens/ Greece	"Csa"	Concrete tiles initially of white colour with an initial albedo of 0.45; black asphalt on roads.	(1) Use of photocatalytic asphalt on the roads. (2) Concrete pavements coloured with infrared reflective cool paints with albedo 0.68.	(1) A decrease in average ambient temperatures of 2 K. (2) Decrease of the surface temperature of pavements by 4.5 K.
#10	Athens/ Greece	"Csa"	Asphalt, concrete and dark paving materials. The albedo of the paved surfaces was between 0.35 and 0.45 while in areas covered by concrete and asphalt the albedo was lower than 0.2.	Concrete pavements coloured with infrared reflective cool paints with albedo of 0.60.	(1) The use of cool paving materials reduces the peak ambient temperature during a typical summer day, by up to 1.9 K. (2) The surface temperature in the park was reduced by 11 K.

Table 2. *Cont.*

Case #	City/Country	KG Climate Classification	Type of Existing Pavement	Type of New Pavement	Thermal Results
#2	Paris/France	"Cfb"	Asphalt, concrete and dark paving	(1) Prefabricated cool concrete slabs. (2) Darker slabs are placed in more shaded areas of the square.	Not disclosed
#3	Athens/Greece	"Csa"	Asphalt, concrete and dark paving	(1) Permeable materials. (2) Cool materials with high reflectivity, high emissivity and low brightness. (3) Application of light coloured concrete and photocatalytic asphalt.	In combination with vegetation and water measures, an overall estimated reduction in ambient temperature of 3 K

In order to attenuate the temperature of the public realm, the proposed plan would integrate bioclimatic techniques with public space design through introducing: (i) an increase of vegetation in the area by planting new trees; (ii) the use of solar devices to improve/enhance shading; (iii) the use of water that would function as a cool sink; (iv) the use of earth to air heat exchangers to dissipate the excess urban heat to the ground; (v) photovoltaic panels; and finally, (vi) the use of materials with appropriate thermal properties such as cool materials.

With the exception of the earth to heat exchangers, most of the measures specifically considered the influences they would have upon the surface temperature of local materials. The thermal results of the project are shown in Table 2. The installed measures included the: (i) Extension of shading and solar control, aimed at reducing surface temperatures of pavements; (ii) use of tall trees and pergolas in order to improve the efficiency of local evapotranspiration; (iii) use of light coloured materials to decease the absorptivity of solar radiation, and thus decrease the surface temperature of pavements/streets; (iv) in continuation of the previous point, natural and artificial cool materials (albedo values of 0.70 and 0.78, respectively) were used in public spaces, and cool asphalt was applied on the roads; and lastly, (v) incorporation of water elements in most streets in order to promote the cooling effect through evaporation, and to directly cool local surface temperatures through the cooling effect of running water [30].

Case #8 examines the use of cool pavements in an effort to address thermal comfort in a public space located within Tirana. Currently under construction, apart from the increase of green spaces, solar control pergolas, and earth to air heat exchangers, reflective pavements were a fundamental bioclimatic design feature. Beforehand, the public realm accommodated pavements that were extensively made up of dark concrete and/or stone tiles with an albedo range of between 0.15 and 0.20 [31]. The climatic analysis determined that the area suffered from both elevated ambient and surface temperatures during the summer period, and, as a result, thermal comfort levels were compromised.

The proposed design solutions included increasing vegetation, the use of shading, and the use of materials with appropriate thermal properties. This specifically included the: (i) extended use of shading and solar control in the area in order to reduce the surface temperature of materials and resulting heat convection; (ii) high trees to enhance shading and evapotranspiration in the considered area; (iii) use of light coloured materials to decrease the absorption of solar radiation and surface temperatures of local pavements (the albedo of the chosen materials all exceeded the value of 0.65 and presented significantly lower surface temperatures then those to be expected from conventional materials of the same colour); and lastly, (iv) limitations on the amount of local traffic in order to decrease the amount of local anthropogenic emissions [31].

The outcomes of the interventions were measured at a height of 1.50 m (in order to simulate pedestrian level) through the use of Computational Fluid Dynamics (CFD), which illustrate that ambient temperatures were considerably reduced, especially, in areas already prone to maximum temperatures as shown in Table 2.

Case #9 is located in a highly populated area within the central zone of Athens, and it involves the use of cool pavements for streets and other open areas. Adjoining the changing of pavement materials, there is also an increase of greening/shading in the public spaces, and the use of earth to air heat exchangers. The original pavements were constituted of black asphalt on the roads, and the rest of the public realm was made of white tiles with an initial albedo of 0.45 (it should be noted, however, that the albedo decreased significantly as a result of wear and tear, especially in areas with heavier foot fall). After monitoring the local microclimate, it was concluded that the ambient and surface temperatures required alleviating, thus, presenting the opportunity for attenuation techniques. The overall bioclimatic approach included the use of: (i) concrete tiles which contained photocatalytic asphalt in the streets; (ii) concrete tiles coloured with infrared reflective paints; (iii) additional shading and green areas; and lastly, (iv) earth to air heat exchangers [32]. As shown in Table 2, such interventions suggest an overall decrease of up to 2 K, an improved homogeneity in temperature ranges within the public space; and finally, a significant decrease in temperatures in both the eastern and western areas of the square, owing considerably to the incorporation of cool materials [32].

Finally, Case #10 tackles the rehabilitation of an urban park in Athens that connects with the city's adjacent waterfront. Beforehand, most of the pavement in the park consisted of asphalt, concrete and dark paving, resulting in local albedo's ranging from 0.35 to 0.20 [23]. Through the monitoring of the existing microclimatic conditions during the summer, it was again concluded that a bioclimatic rehabilitation was required. In addition to the increase of vegetation and trees, cool pavements were the predominant measure used throughout the project. As a result, concrete pavements coloured with infrared reflective cool paints (presenting an albedo of 0.60) were installed in the park area. Through the use of visual infrared thermometer imaging, the difference in surface temperature between the shaded cool pavement, un-shaded cool pavement, and the surface temperature of a remaining, and moreover un-shaded, part of the previous pavement were examined. The temperature difference between the pavement specimens varied between 11.3 K, thus suggesting the importance of not only the shade, but the thermal benefits of the cool materials as well.

When an overall analysis was undertaken to determine the site's spatial distribution of temperature, it was already expected that the area adjacent to the sea would benefit less from the presence of the new "cool" materials. This is due to the influence of maritime breezes, humidity, and overall proximity to the water. On the other hand, the cool pavements in the park's interior play a significant role in decreasing both surface and maximum ambient temperatures, as depicted in Table 2.

Similarly to Cases #7–10, the following two cases integrate the use of materials as part of their bioclimatic approach in attenuating thermal comfort levels. Both cases also clearly aim at tackling UHI effects, and additionally, use it as part of their mission statement. The Parisian environmental redevelopment project (Case #2) underpins: "*A comfortable square, conscious of its environment—from an environmental point of view, traffic has been routed through the shaded area of the square to free up a large pedestrian area in the sunny part.* (…) *The process is underpinned by the use of perennial materials and economic techniques.*" ([19], p. 7). More specifically, local UHI was directly used as a design generator to reconfigure the area's surface materials, whereby: (i) the shady zones of the square were paved predominantly in darker colours; and, (ii) the open spaces were paved predominantly with generally paler colours. The "One Step Beyond Project" (Case #3) also state in their proposal that "*the benefit of using cool materials such as light asphalt, light concrete or light natural stones, is their high reflectivity and albedo. Cool materials guarantee less absorption of radiation and lower surface temperatures compared to other conventional materials. Through this reduction of heat storage in urban materials, the process of cooling down ambient air temperature at night accelerates…*" ([33], p. 14).

3.3.3. Scientific Incongruities between that of Surface Temperature and Ambient Temperature

As the bearings of thermal discomfort continue to gain weight in local decision making and/or design (both resultant of current temperatures, and in congregation with those to be expected as a result of climate change), numerous incongruities regarding the use of materiality have been raised. More specifically, recent studies are now questioning the overall advantages of reflective materials that reduce the temperature of urban surfaces, such as pavements. To date, the benefits of reducing surface temperatures through high albedo roofs have palpably proven to reduce summertime building cooling energy requirements (Such evidence led to the United States Department of Energy launching the "Cool Roof Initiative" in 2010, and in an effort to urge others to their cause, Energy Secretary Steven Chu stated "*Because cool roofs provide significant energy savings and environmental benefits, they should be used whenever practicable*") ([34], p. 2). Contrariwise, and turning our attention back to the urban canyon, certain authors have recently suggested that the decrease of urban surfaces (such as that of pavements) may, in fact, not lead to a decrease in ambient temperature, and additionally even lead to "adverse human health impacts" [35]. Such authors also suggest that the reflection of radiation from high-albedo pavements can moreover: (i) increase the temperature of nearby walls and buildings; (ii) augment the cooling load of surrounding buildings; (iii) lead to heat discomfort felt by pedestrians; and lastly, (iv) induce harmful reflected UV radiation and surface glare [35].

Similarly to most fields within the spectrum of climatic adaptation, further investigation is required. Notwithstanding, this paper suggests that these incongruities should not hinder both the development and further incorporation of reflective materials, namely, that of cool pavements.

Firstly, and as recognized by authors such as [36,37], cool pavements can in fact lead to discomfort due to the increased budget of solar radiation (*i.e.*, short-wave radiation) being approximately twice the decreased budget of long-wave radiation. As a result, this implies that relying only on the use of measures such cool materials can, counterproductively, lead to the thermal discomfort of pedestrians. Nevertheless, and as illustrated by Cases #2,3,7–10, the use of reflective materials was part of a successful and wholesome bioclimatic intervention that aimed at decreasing ambient temperatures, and not just surface temperatures. In other words, the decrease of surface temperatures was combined with other passive strategies, such as, increasing shading and solar control, increasing vegetation, and limiting traffic.

Secondly, as shown in (Case #9) researchers and manufacturers have also been developing cool coloured materials with higher reflectance values compared to conventionally pigmented materials of the same colour. These, encouragingly, have already been applied in cases where the use of light colours may lead to glare issues; or for simply when the aesthetics of darker colours are preferred [32].

Finally, and as classified by [27], cool materials for the built environment can be divided into two categories, cool materials for buildings, and cool paving materials. This paper suggests that the preoccupation with consequential thermal augmentation reflected from pavements onto nearby walls is, to some degree, controversial. Unlike pavements, the thermal attenuation of building surfaces has been well documented, and understood for almost half a century, hence architects/urban designers have recognised that reflective buildings' colours and/or materials can decrease building thermal loads. In juxtaposition, and when addressing outdoor thermal comfort, this infers that if a wall or building surface is affected by the pavement's increased reflectivity, the building surface is in itself thermally inefficient.

3.3.4. Lessons for Auckland's CBD

In the long term and when considering the implications of UHI effects in Auckland, it is essential to ruminate that the city is expected to grow by one million inhabitants by 2040. Naturally, the increased urban density in juxtaposition with increased temperatures will lead to the effects of UHIs becoming an increasingly pressing issue for local thermal urban design. Similarly to most arenas associated with climatic adaptation, the necessity for further investigation and presence of both incongruities and uncertainties shall continually afflict local design makers and designers. Nevertheless, and considering the relevant lessons for Auckland's CBD, the cases presented in Table 2 have shown that materiality can play an effective, yet economical, way of tackling challenges such as UHI effects and the increase of annual hot days.

In addition, and considering that most of Auckland's CBD has an extensive amount of dark pavements, the deliberation upon surface albedo becomes a key issue in order to reduce ambient temperatures during the summer. Returning now to the example of Queen Street, both sides of the street are paved with dark stone slabs, while the road itself is composed of asphalt as shown in Figure 2a. As an exploratory exercise, Figure 2b demonstrates how the street could look with the application of a cool pavement. In this fashion, the low reflectivity/emissivity rates of the previously dark pavement can be increased, where required, contingent on the extent of solar radiation exposure/hours.

(**a**) (**b**)

Figure 2. Conceptual intervention of cool pavements in Queen Street (**a**) Before the installation of cool pavements; (**b**) Post intervention. Source: Author's rendering.

In the case of Queen Street, Figure 2b demonstrates how the thermal inertia can be varied in order to decrease the surface temperature of the pavements. By increasing the albedo within the major foot fall area (*i.e.*, in front of retail frontages), the discharge of sensible heat and long-wave radiation can be reduced. When considering the energy balance of the pavement, the presence of shade (leading to a decrease in solar radiation/irradiance), and the increased albedo (leading to a decreased absorption and an increased reflection) the respective surface temperatures can be decreased. This decrease notwithstanding, it is also possible to consider the use of darker colours with a lower albedo under the shaded areas due to the decrease of solar radiation. This, however, would require careful consideration, as this could decrease the overall effectiveness of the pavement in lowering street temperatures.

3.4. Water and Vapour Mechanisms

This article has hitherto discussed the influences of vegetation, shelter canopies, and materiality upon thermal sensitive urban design. This section shall discuss the opportunities presented by water/vapour systems and shall examine their possible application in Auckland's public realm. In this section Relative Humidity (RH) levels will be used in order to address the evaporative cooling potentials and processes of water. As this relates to the relationship between actual vapour pressure and saturated vapour pressure, this percentage enables the understanding of how water can be used to cool ambient temperature without exasperating ambient moisture levels. Previously, the presence of water and misting systems were customarily focused upon aesthetic and sculptural purposes in public space design. More recently, however, there has been a considerably greater emphasis upon their interconnection with bioclimatic comfort in outdoor spaces in terms of adaptation efforts to climatic conditions [38]. As a result, water and misting systems have taken on a new meaning in public space design.

3.4.1. Lessons Learnt from the Direct Application of Evaporative Cooling Methods

The first examples in this genre of strategy return to Cases #2 and 3 that also incorporate the use of water and vapour systems as part of their bioclimatic intervention. In Case #2, water is used both for aesthetic purposes and for attenuating elevated temperatures during the summer. During this season: (i) a fine sheet of water is released and incorporates the use of spraying systems upon a 1% slope over an area of 270 m^2 (Figure 3a); and, (ii) the monument basin in the centre of the new pedestrian esplanade is filled with water through small water spouts (Figure 3b) [19]. As stipulated within the project brief, the utilization of water is primarily climatic, yet also designed to enhance the sociality, recreation and the aesthetics in the new Place de la Republique. It is worth reinforcing that this use of water in order to attenuate both temperatures, and UHI, is designed around a similar climate to that of Auckland, *i.e.*, with a KG climate classification on "Cfb".

Case #3 returns to the "One Step Beyond" project's "Heat mitigation Toolbox", that implements water measures that reduce the UHI effect and temperatures in its public spaces, such as Omonia square. More specifically, and serving as a focal point of the square, a fog-fountain is proposed to cool ambient temperatures through the evaporation of the water particles. Unlike Auckland, and due to its type of climate (*i.e.*, "Csa"), Athens has very low RH levels, hence evaporative cooling is considerably more effective. As a result, and during a microclimatic analysis field study, the ambient air temperature peaked at 39 °C, while RH remained at only 30%; with the aid of software projections, it was estimated that the evaporative system could aid lower surface temperatures down to 23 °C [22].

Counterproductively, the lower RH leads to another type of problem, the lack of water to sustain such systems. Yet with the use of other water elements, such as underground water storage systems, filtered rainwater can be used for both surface and greenery irrigation in periods of drought.

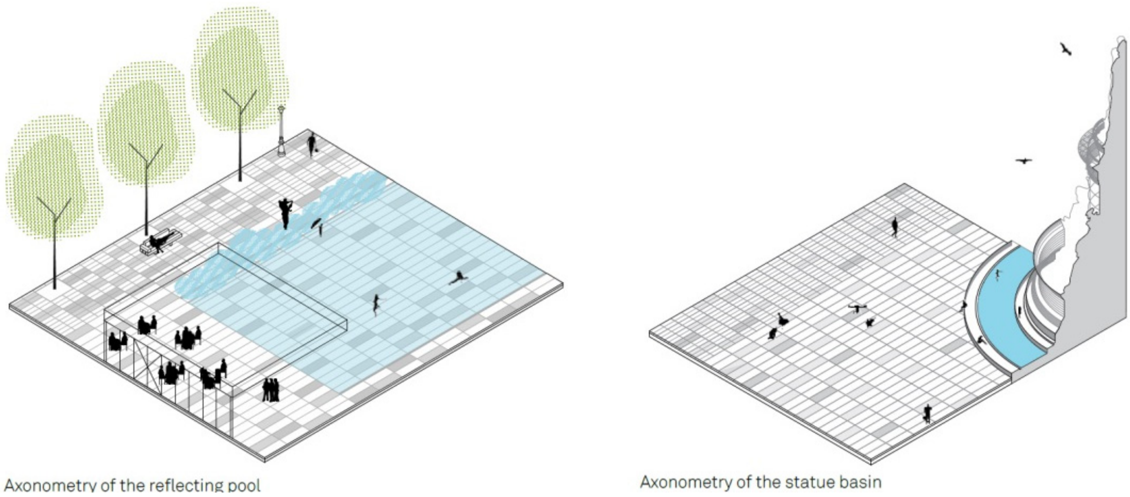


Figure 3. Axonometric of the (**a**) Reflecting pool; (**b**) Statue basin. Adapted with permission from Trévelo & Viger-Kohler [19].

Following onto the next case, and awarded the first prize in a local competition to re-develop the Khan Antoun Bey Square in Beirut, PROAP Landscape Architects (Case #11) explored a conceptual solution to improve outdoor thermal comfort standards. The dominant bioclimatic measure used in this project was a misting system, which in combination with vegetation, canopies and materiality, tackled hot-humid summers, and high solar radiation rates. This launched a deeper research into the effectiveness of temperature control systems in outdoor spaces by inducing evaporation through misting systems. The research concluded that misting-cooling systems can be complex, and its associated equilibrium with encircling air humidity is fundamental. In warm-humid summer climates, such as that of Auckland, water spraying and evaporation are more complex due to the existing amount of water already present in the atmosphere beneath the UCL.

3.4.2. The Equipoise between Evaporative Cooling and Relative Humidity Levels

The effectiveness of evaporative techniques is one that is contingent on a variety of factors. Namely, and in order to efficiently lower ambient temperature without imperilling acceptable humidity levels, the correct water pressure, nozzle type, and functioning period must be established. Ultimately, and as proved by [39,40], the formation of correct droplets with the adequate amount of temporal intervals becomes fundamental when addressing thermal comfort in areas with high humidity levels. In order to explore these techniques a little further, this paper shall discuss three case studies that adopt more of an engineering approach in order to establish actual temperature reductions through the means introduced in Table 3.

Table 3. Bioclimatic projects and studies that use evaporative cooling.

Case #	City/Country	KG Climate Classification	Surface Wetting (SW)	SW Method	Thermal Results
#2	Paris/France	"Cfb"	Yes	Thin layer of water is released then is left to evaporate	Not disclosed
#3	Athens/Greece	"Csa"	Yes	Water features such as misting systems are intended to wet surfaces and induce evaporative cooling	In combination with vegetation, and materiality an overall estimated reduction in ambient temperature of 3 K
#11	Beirut/Lebanon	"Csa"	No	–	Not disclosed
#12	Not Applicable /Japan	"Cfa"	No	–	Reduction of ambient temperature by 2 K
#13	Yokohama/Japan	"Cfa"	No	–	Reduction of ambient temperature by 2 K
#14	Not Applicable /Japan	"Cfa"	No	–	Reduction of ambient temperature of up to 3 K
#15	Seville/Spain	"Csa"	No	–	Reduction of up to 16 K in surface temperatures
#16	Bordeaux/France	"Cfb"	Yes	Surfaces are wet for a specified period and then reabsorbed into ground slabs	Not disclosed
#17	New York/USA	"Cfa"	Yes	Thin layer of water is released then is left to evaporate during summer	Not disclosed

Historically, in Japanese culture, a rudimentary cooling method called "Uchimizu" was used to cool outdoor temperatures through the scattering of water upon the entrances of residential dwellings. In an effort to profit from previous teachings, Ishii, Tsujimoto, Yoon, and Okumiya [40] developed an exterior misting system that would reduce the air-conditioning load of encircling buildings without resorting to the use of vegetation (Case #12). As Japan has a continental humid climate (*i.e.*, with a KG classification of predominantly "Cfa"), the system was designed to overcome high humidity when attenuating high ambient temperatures, hence the name "Dry-Mist". In an outdoor environment, it was projected that: (i) for every 1 K drop in ambient temperature, RH would increase by 5%; and; (ii) the system could lead to total decrease of 2 °C that, consequently, would lead to a reduction of 10% in energy consumption from air conditioners [40]. The atomization of the water particles resulting from the high pressure pump is connected to various meteorological sensors and control panels. Consequently, this enabled the automatic-control of the system, which would be triggered by certain pre-inserted environmental conditions. More specifically, the system would initiate when temperatures would surpass 28 °C, when RH was below 70%, and lastly, when the wind velocity was below that of 3m/sec without rainfall.

Although in a different setting, Case #13 takes the exploration of the "Dry-Mist" a little further. Installed in a semi-open train station platform during the summer of 2007, a total of 30 "Dry-Mist" nozzles were installed to test their thermal cooling effect. This investigation, carried out by [39], demonstrated an initial cooling potential mean of 1.63 K and 1.9 K between 9:00 and 13:00 and 13:00 and 15:00, respectively. Yet, after obtaining such results, it was concluded that the operation period (2 min with an interval of 3 min) was too short and that the mean cooling potential mean could thus be increased to 2 K. Interestingly, and beyond these mean values, the maximum decrease in temperature reached 6 K and was accompanied by an increase of 28% of RH. It is worth noting that this consequential increase in humidity, although not in a fully exterior setting, accurately follows the ratio established in Case #12 (*i.e.*, −1 k = +5% of RH).

The analysis of the "Dry-Mist" was accompanied by various questionnaires in order to evaluate how the users of the platform reacted to the system. The results obtained from the questionnaires (Figure 4) demonstrated that: (i) 80% of the 200 respondents found the system at least "somewhat comfortable"; (ii) only 1% stated that they wanted the misting system to be stopped, and 98% stated that they enjoyed the presence of the system; and lastly; (iii) of this 98%, 21% asked for more mist, and another 57% said that it was just right [39]. Hence, this case study has shown that even in conditions with high humidity, the careful and attuned use of misting systems can be both effective and successful.

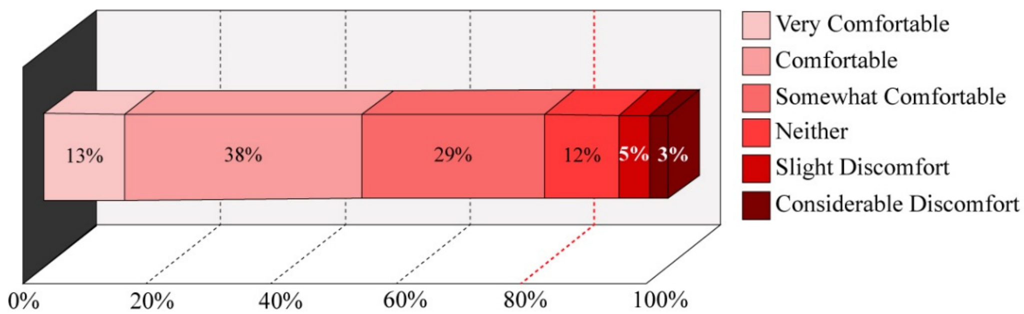


Figure 4. Results from thermal comfort questionnaire. Adapted with permission from CiNii [39].

3.4.3. The Variation of the Sauter Mean Diameter and Spraying Height

As seen from the previous cases, misting systems can act efficiently in attenuating thermal comfort even in conditions with high humidity. Notwithstanding, and similar to the application of cool pavements discussed in the previous section, there is limited knowledge regarding actual design and installation. A quandary that often arises in this context is associated with the optimum amount and size of the particles, *i.e.*, the Sauter Mean Diameter (SMD) of the water particles. In order to approach this issue, and for simplification purposes, Case #14 joins three similar Japanese studies of misting systems together.

In the study undertaken by Yamada *et al*. [41], and through the use of CFD analysis, it was demonstrated that there is no significant difference in temperature reduction for different SMD sizes; however, it was identified that larger water particles (≈32.6 μm) remain longer in the air. In design terms, this implies that since larger particles take longer to evaporate, spray height becomes a very important parameter. In the study of Yoon *et al*. [42], it was furthermore concluded that in any outside air temperature condition, when the RH goes beyond that of 80%, and with the nozzles at a height of 0–0.25 m, water particles would remain without evaporating. Consequently, ground surface wetting is to be expected, thus indicating that when Surface Wetting (SW) is undesired, the respective environment would not be suitable for spraying. Yet at a height of 1.5 m, and given an RH of no more than 75%, the misting system can efficiently cool ambient temperature without compromising overall thermal comfort [42]. Interestingly, and based on these results, it was considered that Japanese cities such as Tokyo, Osaka, and Fukuoka (all of which prone to elevated RH levels beneath the UCL) can considerably benefit from this evaporative cooling technique.

More recently, the last example in this case study was carried out by Farnham *et al*. [43], who verified both the importance of nozzle height, but also the fundamental role of SMD. Carried out in Osaka, and within a semi-enclosed space, this particular experiment achieved a total of cooling 0.7 K without SW. This was accomplished by single nozzles spraying mists with a SMD of 41–45 μm; moreover, the resultant increase of encircling humidity had little or no effect on the thermal comfort as demonstrated by the identified Effective Temperature (ET). These results notwithstanding, even from heights of 25 m, if the SMDs were to be increased, an excessive amount of water particles would amalgamate close to the floor (hence over-increasing RH), and also cause undesired SW.

Cases #12–14 have shown how Japan has overcome high humidity levels when cooling its public and semi-enclosed spaces. Inspired by an ancient and cultural practice, Japan is a front-runner country in the application of misting systems. Due to their technical approach, design orientated projects can learn from their methodical resolution to attenuating ambient temperatures and UHI through the use of misting systems.

Earlier, and within the European context, developed by an interdisciplinary group led by the department of Energy Engineering and Fluid Mechanics from the College of Industrial Engineering of Seville, the Expo of 1992 in Seville (Case #15) was approached as a method to synthesis bioclimatic techniques with public space design. The various new techniques that were tested and installed concentrated on misting systems and bodies of water, namely the: (1) continuous blowing of air through a fan that was permanently kept moist; (2) installation of "micro" water nozzles in tree branches that created droplets with an average SMD of around 20.0 μm, where colder air then flowed downward, hence cooling the shaded areas; (3) "sheets" of water in the form of ponds and waterfalls that cooled the spaces through evaporative cooling and strategically placed irrigation outlets [44]. Integrated with vegetation, canopies, and materiality, the public realm of the Expo was divided into three different types of spaces: (1) "Passage Areas"—with the prime functionality of supporting the main flow of pedestrians, with an expected "use timeframe" of below 15 min; (2) "Rest/Stay Areas"—with the primary goal of offering places for resting, eating, and social congregation, with an expected "use timeframe" of over 15 min; and lastly, (3) "Adjacent Areas"—that were spaces of interconnectivity between the former. This theoretical division between Passage, Rest, and Adjacent areas aided thermal comfort design to be divided into medium level, high level, and low level thermal conditioning, respectively.

3.4.4. SW within the Design Spectrum of Cooling Systems

In the case of Seville, SW was undesired as it was argued that it would lead to stagnancy and resource wastage [44]. Although this is a valid argument, this does not imply that SW cannot be part of the system's overall design. In other words, the actual act of controlled surface wetting can be the method to cool down ambient temperatures and mitigate UHI effects. Respectively, Table 3 determines which cases allow SW, and additionally, how they assimilated this within the design of the cooling system.

A successful example of this tactic, and situated in a "Cfb" climate, the project Le Miroir d'Eau (Case #16) by Michel Corajoud, Pierre Ganger, and Jean-Max Llorca, was initially aimed only at reintroducing vegetation into the space in order to attenuate the local microclimate. However, and based on the concept of addressing thermal comfort levels and reflecting surrounding facades, the "water mirror", and an incorporated on-site fog system (also based on a "micro" nozzle system) were installed. In order to avoid algae and water wastage, the water that temporarily floods the square recedes back into the slabs after a few minutes, leaving the surface dry like in any other square. Grooves were installed in-between the granite slabs, to allow the water to be recollected, and re-prepared for the next induced "flood". In this way, wet surfaces become part of the design of the system that increases the climatic responsiveness of the once thermally problematic public space.

Returning to the ephemeral perspective, and as already discussed through the "Canopy" project (Case #6), misting systems and water bodies have also been translated into ETCSs within the public realm. In this scope, one can also refer to the "CoolStop" project (Case #17) by Chat Travieso Design, which in collaboration with the NYC Department of Transportation, designed a temporary misting system during an annual event that pedestrianized seven miles of the city's streets. Constructed out of PVC piping, and operated through a hydrant unit, the misting system cooled the microclimate during the summer heat in New York's public spaces. Due to its ephemeral nature, resource wastage and stagnation is far less of a concern due to its on/off nature, seasonal use, and low water requirements.

3.4.5. Lessons for Auckland's CBD

Accordingly, and referring back to Table 1, Auckland's relatively high humidity levels need to be carefully deliberated when considering the application of water and misting mechanisms. As identified by Yoon, Yamada, and Okumiya [42], such mechanisms tend to be more intricate in attenuating thermal comfort levels when the RH surpasses the 75% mark. Nonetheless, this does not infer their inapplicability. Instead, three approaches can aid their applicability in Auckland's public realm, whereby: (1) SW is undesired—requiring careful consideration of necessary water pressure, nozzle type, altitude, and functioning period/intervals; (2) SW is desired and water is reused within the system—requiring hence water runoff deliberation; (3) ETCS are installed as a temporary measure during the summer period. Respectively, and referring to Table 3, local designers and decision makers can refer to examples such as: (1) Cases #11–15 to learn from existing studies and projects that contour high humidity levels and avert SW; (2) Cases #2,3,16 to learn from precedents that incorporate SW into the design of the respective cooling mechanism; (3) Cases #6 and 17 which present ephemeral evaporative solutions during the hotter months of the year.

These cases notwithstanding, it is still necessary in all approaches that local microclimatic factors are considered in order to fully exploit the potentiality/efficiency of such measures in attenuating thermal comfort levels through evaporative cooling.

4. Framework Illustrations and Discussion

As aforementioned, climate change adaptation has grown exponentially within both the global scientific and political arenas. Accordingly, one can witness the increasing global ambition amongst decision makers and designers to diminish the gap between theory and action with regards to local adaptation measures [45]. As shown in Figure 5, in order to introduce effective local climatic measures in Auckland's public realm without the risk of ineffectual adaptation (*i.e.*, maladaptation), local agents must focalise their adaptation endeavours around specific local risk factors through a bottom-up attitude. In this way, existing knowledge within the adaptation agenda must subsequently be refined into an appropriate response through a "case by case" attitude.

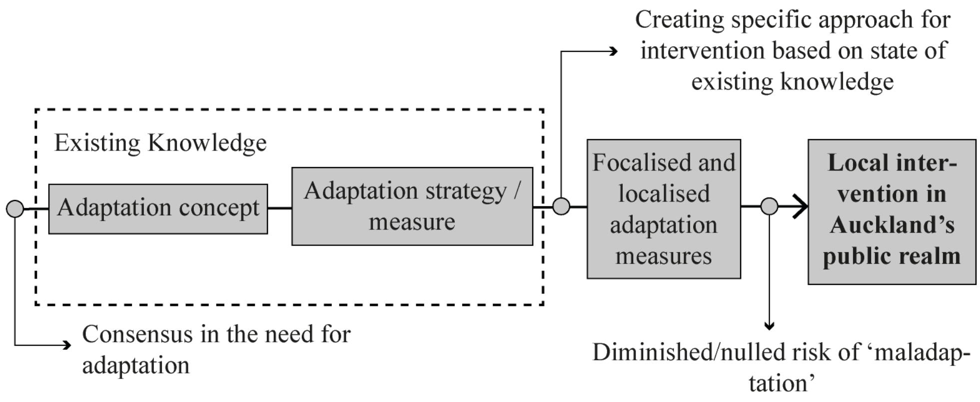


Figure 5. Proposing adaptation measures which focus upon Auckland's public realm and local risk factors. Adapted with permission from Taylor & Francis [45].

All the same, the gap between theory and action with regards to thermal comfort attenuation is extensive, leading to a lack of precedential benchmarks, indicators, and examples that could otherwise aid local decision making and design. To address this issue, Table 4 divides the 17 bioclimatic case studies into built, conceptual, and scientific projects. In this way, the practical experience from actual construction, convergent thinking through conceptual exploration, and the empirical outcomes of scientific methodologies can be presented in the framework. Having Auckland as the central case study, the framework demonstrates know-how within the international arena with regards to similar microclimatic constraints that are already, or shall soon be, witnessed in the city.

Table 4. Framework of relevant bioclimatic case studies within the international arena.

Case #	Project Title	Genre/Status	Location	Predominant Measure Used *	KG Climate Classification	Temporal Scope
#1	Not Applicable	Scientific (2012)	Athens/ Greece	V & M	"Csa"	Long-Term
#2	"Place de la Republique" Redevelopment	Constructed (2013)	Athens/ Greece	V & M & W	"Csa"	Long-Term
#3	"One Step Beyond"	Under Construction (2013–2015)	Athens/ Greece	V & S & M & W	"Csa"	Long-Term
#4	"Activity Tree"	Conceptual (2013)	Athens/ Greece	V & S & M	"Csa"	Long-Term
#5	"This is not an Umbrella"	Conceptual (2008)	Madrid/ Spain	S	"Csa"	ETCS
#6	"Canopy"	Constructed (2004)	New York/USA	S & W	"Cfa"	ETCS
#7	Not Applicable	Under Construction (2012)	Athens/ Greece	V & S & M	"Csa"	Long-Term
#8	Not Applicable	Scientific (2011)	Tirana/ Albania	V & S & M	"Csa"	Long-Term
#9	Not Applicable	Scientific (2011)	Athens/ Greece	V & S & M	"Csa"	Long-Term
#10	Not Applicable	Constructed (2012)	Athens/ Greece	V & M	"Csa"	Long-Term
#11	"Khan Antoun Bey Square"	Scientific/ Conceptual (2010)	Beirut/ Lebanon	V & W	"Csa"	Long-Term
#12	Not Applicable	Scientific (2009)	-/Japan	W	"Cfa"	Long-Term
#13	Not Applicable	Scientific (2008)	Yokohama/ Japan	W	"Cfa"	ETCS
#14	Not Applicable	Scientific (2008/11)	-/Japan	W	"Cfa"	Long-Term
#15	Expo'92 Seville	Constructed (1992)	Seville/ Spain	V & S & M & W	"Csa"	Short-Term
#16	"Le Miroir d'Eau"	Constructed (2006)	Bordeaux /France	W	"Cfb"	Long-Term
#17	"CoolStop"	Tested Prototype (2013)	New York/USA	W	"Cfa"	ETCS

* V = Trees and Vegetation; S = Shelter Canopies; M = Materiality; W = Water and Vapour Mechanisms.

Methods of Incorporating the Framework

Although some of the case studies were indeed based on warmer climates, they nevertheless suggest very pertinent benchmarks that can be adapted to New Zealand's more temperate climate. As discussed in the different sections of this article, these revisions can straightforwardly be undertaken by considering the microclimatic implications encircling Auckland's public realm. In this way, documents such as the regulatory UP, and non-regulatory Auckland's Design Manual (ADM), can introduce more concrete guidelines on how public spaces could be made more responsive in light of increased hot days, heat waves and managing UHI effects. More specifically, and now considering the ADM's "Section 4—Design for Comfort and Safety", the presented framework launches existing applicable bioclimatic solutions which can be made applicable for Auckland's CBD. Figure 6 demonstrates a possible online extension of Section 4 that is explicitly orientated towards "Dealing with Thermal Comfort & Climate Change".

Figure 6. Extending the ADM through the incorporation of the framework.

Firstly, in order to provide both guidance on microclimatic assessment, and to avoid issues of maladaptation, a section on "General Guidelines for Microclimatic Assessment" was introduced. This aims at demonstrating simple and effective ways of examining local microclimate conditions, and to moreover explain the importance of such considerations both now and in the future.

Secondly, the tackling of increased hot days, heat waves and UHI effects can be met by different approaches and options which are discussed in the respective case studies. At the moment, the site contains references to the redevelopment of Aotea Square and Lumsden Green, yet this can be considerably extended in order to provide bioclimatic guidance on incorporating comfort and safety into the design and maintenance of Auckland's public spaces.

Respectively, this method shall advise means to, namely: (i) maximise the effects of local evapotranspiration in areas increasingly prone to UHI; (ii) effectively reduce/enable solar penetration and wind patterns; (iii) design suitable annual availability of choice between exposed, semi-shaded, and shaded areas (iv) support urban activity threads through passive strategies, evaporative cooling systems, and vegetation; (v) reduce surface temperatures through the implementation of cool materials; and, (vi) install misting systems that induce (or not) SW in order to attenuate local thermal comfort levels. In this light, the local design manual could hence form the basis for future action in Auckland's public spaces, which shall very likely require investigations into their: (i) use of passive strategies and/or vegetation to attenuate the effects caused by the increase of annual hot days; (ii) overcoming of difficulties presented by high RH levels when cooling the public realm; and, (iii) decreasing urban surface temperatures by rethinking the extensive use of dark pavements through the introduction of cool surfaces and materials (Figure 6).

5. Conclusions

As with most sectors in the maturing climate change adaptation agenda, there is considerable theory, yet limited practical benchmarks that can directly aid local decision making and design. Nevertheless, this article has argued that there is sufficient existing knowledge to respond to the growing need for thermal comfort attenuation in Auckland. Moreover, and although New Zealand shall witness more attenuated climate change over the next few decades, the discussed existing national projections nevertheless indicate that adaptation is still essential. On top of these meteorological projections, the considerable increase in population, urban density and CO_2 emissions until 2040 augments such needs even further. To address such requirements, the presented framework of bioclimatic case studies has demonstrated a range of benchmarks that were developed by cities facing similar microclimatic issues to those that are present or expected in Auckland.

As a result, existing guidelines such as those pertaining to the city's public realm's comfort and safety can hence be developed further in order to aid local designers and decision makers to learn from existing approaches, and more importantly, to launch their own focalised approach. In this way, thermal sensitive urban design is launched into a fertile arena, whose application in a world of climate change is required in building a better New Zealand.

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Author Contributions

The photographs and renderings illustrated in Figures 1 and 2 were taken and created by the author. Figure 5 contains adapted material that was created by the author during a previous conference presentation. The graphics of Figure 6 are based on the existing layout of the ADM's website, yet its content was altered for demonstrative purposes.

Abbreviations

GCMs	Global Circulation Models
KG	Köppen-Geiger
ENSO	El Nino-Southern Oscillation
IPO	Interdecadal Pacific Oscillation
NIWA	National Institute of Water and Atmosphere
UV	Ultra Violet
UP	Unitary Plan
PET	Physiologically Equivalent Temperature
UHI	Urban Heat Island
ARPHS	Auckland Regional Public Health Service
RH	Relative Humidity
SMD	Sauter Mean Diameter
SW	Surface Wetting
UCL	Urban Canyon Layer
CFD	Computational Fluid Dynamics
PMV	Predicted Mean Vote
ET	Effective Temperature
ADM	Auckland's Design Manual

Conflicts of Interest

The author declares no conflict of interest.

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Publication 5:

Placemaking and climate change adaptation: new qualitative and quantitative considerations for the "Place Diagram"

A. Santos Nouri & João Pedro Costa

Published article in Journal of Urbanism: International Research on Placemaking and Urban Sustainability (2017), 10, pp. 356-382 (Taylor & Francis)

Article Preamble

Focuses upon improving urban design guidelines by reviewing existing theoretical and empirical research of how pedestrian comfort levels can be addressed through public space design. New qualitative and quantitative interrogations were examined against a generic tool which resulted in the introduction of six intangible criteria, and subsequently, six measurable attributes. New generic design tool considerations were established for existing and future public spaces in light of climate change.

Article Symbol list

$\#K_X$	Variation of X variable	$PET_{(y)}$	Projected PET levels
CI	Clearness index	T_{amb}	Ambient temperature
G_{Rad}	Global radiation	T_{globe}	Globe temperature
$PET_{(x)}$	Existing PET levels	V	Wind speed

Article Acronym List

AR4/5	Assessment Report 4/5	PET	Physiologically Equivalent Temperature
CABE	Commission for Architecture and Built Environment	PG	Pergola
CNTRL	Control Period	PPS	Project for Public Spaces
GHG	Green House Gas	RH	Relative Humidity
GP	Group Plantation	RUROS	Rediscovering the Urban Realm and Open Spaces
H/W	Height-to-Width Ratio	SP	Surface Plantation
IPCC	Intergovernmental Panel on Climate Change	SRES	Special Report on Emission Scenarios
LP	Linear Plantation	SVF	Sky View Factor
PCZ	Physiological Comfort Zone	UHI	Urban Heat Island

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Placemaking and climate change adaptation: new qualitative and quantitative considerations for the "Place Diagram"

A. Santos Nouri and João Pedro Costa

Universidade de Lisboa, Faculdade de Arquitetura, CIAUD, Centro de Investigação em Arquitetura, Urbanismo e Design, Lisboa, Portugal

ABSTRACT
Today, although most of the international research community considers climate change adaptation to be essential, there is limited knowledge on its concrete integration with contemporary placemaking. Yet, with the emergence of the adaptation agenda, the effects of urban climatology are continually coercing the need for concrete action to increase the climatic responsiveness of urban environments. This article is constructed upon a "Research for Design" approach, and focuses upon improving urban design guidelines by reviewing existing theoretical/empirical research on how pedestrian comfort levels can be addressed through public space design. The objective is to incorporate such qualitative and quantitative interrogations into a generic tool such as the "Place Diagram" by the PPS. A total of six intangible criteria, and six measurable attributes, are explored and structured in order to introduce new generic design considerations which can contribute to the responsiveness of urban outdoor spaces in an era of expected climate variability.

KEYWORDS
Placemaking; public space; urbanism; climate change adaptation; thermal comfort

Introduction

The art of contemporary placemaking is one which draws upon the early teachings of authors such as Whyte (1980), Gehl (1987) and Carmona et al. (2003). These lessons were marked by the merging of not just interdisciplinarity, but that of different professional spheres. Through time, the process of placemaking has accompanied issues intrinsically associated with the physical, social, ecological, cultural and "spiritual" qualities of the urban realm. However, and adjoining such interdisciplinarity, new obstacles and issues are continually raising the need to rethink the process of placemaking.

The very conception of what makes a public space "successful" requires a continuous adjustment given the unrolling of obstacles presented before contemporary cities. In this article, the phenomenon of temperature escalations due to possible climate change shall be approached in order to identify how public spaces can meet such challenges both today, and in the future. It is here where new spheres such as climatology, biometeorology, and

CONTACT A. Santos Nouri andrenouri@fa.ulisboa.pt

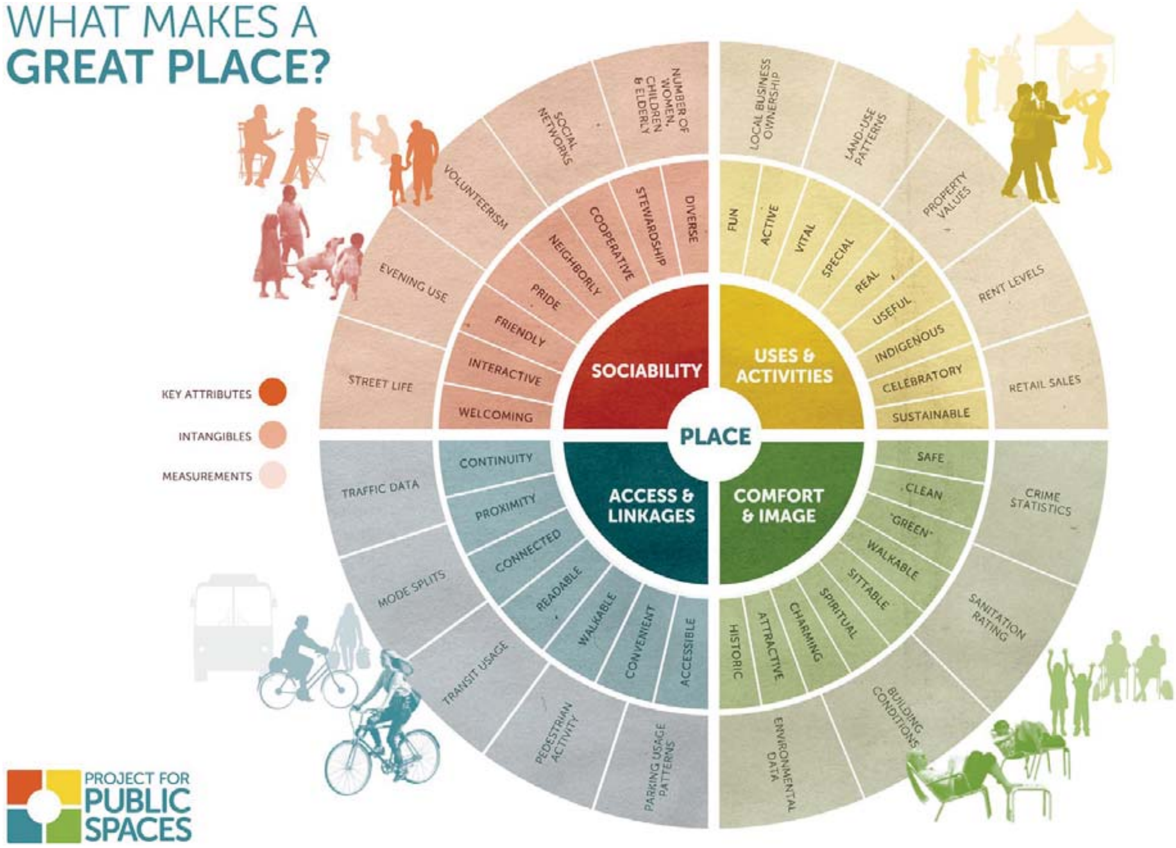


Figure 1. The existing "Place Diagram" by the PPS. Source: (PPS 2003b).

physiology raise new considerations in ensuring the comfort, safety and activity threads in a century which may witness increased occurrences/intensities of heat waves, temperature thresholds and urban heat island (UHI) effects.

Serving as an obstacle, however, and within the local scale, although there is a consensual need to act, there is often a lack of knowledge on how such adaptation measures can improve the experience and comfort of pedestrians in outdoor environments. For this reason, placemaking approaches such as the "Place Diagram" disseminated by the Project for Public Spaces require revision and require new considerations that aid local decision-making and design.

This article will be divided into three principal sections, the discussion of the existing diagram, the establishing of new qualitative/quantitative criteria and the respective restructuring of the diagram. Consequently, this draws upon the integration and organisation of new necessary "intangible" and "measurements" within a generic tool for contemporary placemaking in a century prone to potential impacts resultant of climate change.

The Place Diagram

Based on the work of Whyte (1980) and Jacobs (1961), the PPS have used techniques such as observation, surveys and interviews to study and transform public spaces into vibrant outdoor spaces that pedestrians enjoy (PPS 2000). Their work was considered to establish major groundwork in changing the way in which public spaces were built and planned. As

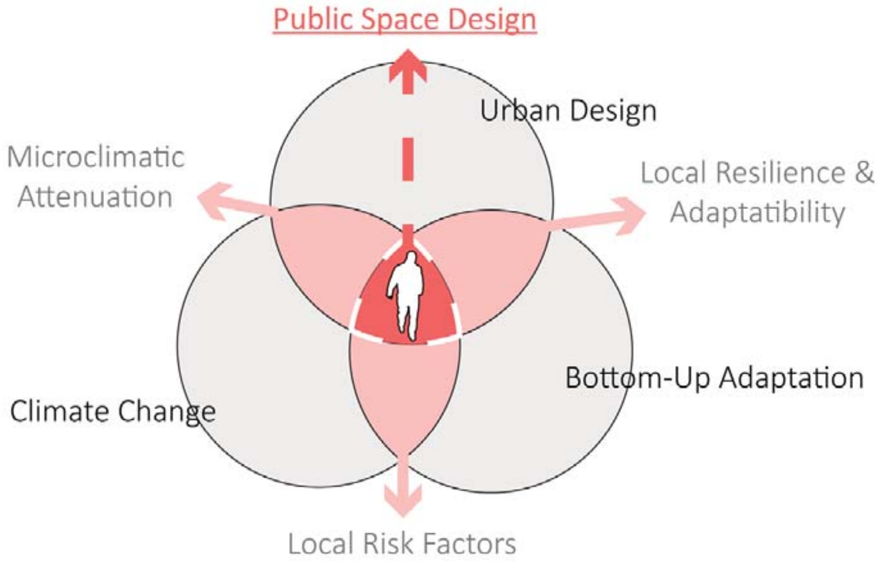


Figure 2. Public space design in the scope of urban design, climate change and that of user-based adaptation. Source: Author's figure.

part of their placemaking process, the PPS stated that "[their] approach to placemaking is based on [their] belief that it is not enough to simply develop design ideas and elements to improve or develop a public space (…) Improvements need to reflect community values and needs" (PPS 2003a, 3). Thus, in the eyes of the PPS since its establishment in 1975, societal necessities play a crucial role in creating a vision around the places which are part of the daily life of pedestrians. As a result, and in an attempt to respond to the issues that communities face in urban contexts, the organisation launched the polemic question: "What makes a Great Place?"

To answer this question, and after evaluating thousands of public spaces worldwide, the PPS created a diagram which refers to the significance of four principal urban qualities: (1) Sociability; (2) Uses and Activities; (3) Access and Linkages; and lastly, (4) Comfort and Image (PPS 2003b). This is summed in their "Place Diagram" as shown in Figure 1.

The diagram departs from four key attributes which can be scrutinised by both qualitative (termed as intangible) and quantitative (termed as measurable) criteria. It is worth noting that the "Place Diagram" is a generalist approach to considering the qualities of a public space. For this reason, the intention of the diagram is not to lead to answers, but instead, to aid local designers and decision makers in considering general factors which compose that of a successful public space.

Today, one of the distinctive characteristics of the PPS is their involvement in linking communities with not only placemaking, but also place-keeping (Dempsey and Burton 2012). Once the PPS first started working with local communities, it was evident that a lot of information could be extracted from people that worked or lived close to the respective spaces. This user-based approach was also one that allowed local officials and designers to access a large database or "portfolio" of successful spaces, both in terms of public space design, but of community engagement as well. These respective "exemplar spaces" are those which proved to be analogous to the expectations/requirements of the surrounding communities with regards to overcoming a certain urban challenge.

However, and when looking into the future, it is here questioned – How can this user-based approach continue to meet the expectations and requirements of local communities in light of new urban challenges?

Within what is considered a "third modernity" where, "the contemporary society witnesses rapid transformations and, resultant of this evolution, the degree and velocity of this transformation is often underestimated (…) in the domain of Urbanism, such comprehension is even more challenging to appreciate due to the slow evolution of the edified fabric, and because of the comparatively small amount of new annual contributions to the existing fabric …" (Ascher [2001] 2010, 19, author's translation), it is here argued that the "Place Diagram" needs to consider new factors in the light of the volatile urban climate until the end of the century. This being said, and although the physical attributes of public spaces may not have changed, they must nevertheless continue to reflect the values and needs of an ever evolving society. When regarding this evolution, although

> cities have grown gradually for hundreds of years, rooted in many years of experience and an intuitive feeling for human senses and scale (…) this knowledge was lost somewhere in the process of industrialization and modernization, which led to dysfunctional city environments for the important and yet ignored segment of city life on foot. (Gehl and Svarre 2013, 3)

Following this line of thought, if one is to consider public spaces to be a "founder of urban form, the space between buildings, that configures the domain of socialisation and 'common' experiences, and likewise of a collective community" (Brandão 2011, 34, author's translation), then one must "recognise the important role that public spaces play in extreme temperatures/combating climate change." (CABE and Practitioners 2011, 3). For this reason, and when considering future horizons and the progressively ensuing opportunities presented for climate change adaptation, new deliberations must be made upon the ability of public spaces to: (1) contribute to the alleviation of impacts within the built environment; and, (2) incorporate adaptive means in their own design without sacrificing their existing positive attributes (illustrated by approaches such as the "Place Diagram"). Either way, this introduces new challenges for public space design, and presents the opportunity for user based approaches to add to the quality and value of future outdoor spaces (Figure 2).

Before the turn of the century, the relationship between physical comfort and meteorological conditions was already considered an important factor. It was recognised that such approaches could potentially enable the ensemble of physically comfortable weather conditions (Olgyay 1963; Höppe 1999). Issues such as sunlight and temperature were considerably debated by authors who expressed the significance of daylight, and the implementation of attenuation measures in circumstances of overexposure (Whyte 1980; Marcus and Francis 1990). Moreover, the importance of wind patterns upon local conditions was also established in studies conducted by (Whyte 1980; Arens 1981; Gehl 1987).

As a result, and when assessing the existing structure of the "Place Diagram," if existing public space precedents were used to build the four existing criteria, then this raises the question of – how can new lessons be learnt when user-based adaptation efforts that combine urban climatology and urban design are still in their early stages?

Methods

In order to facilitate such guidelines, the breadth between theory and practice needs to be diminished in order to inform the better design and maintenance of public spaces in an era

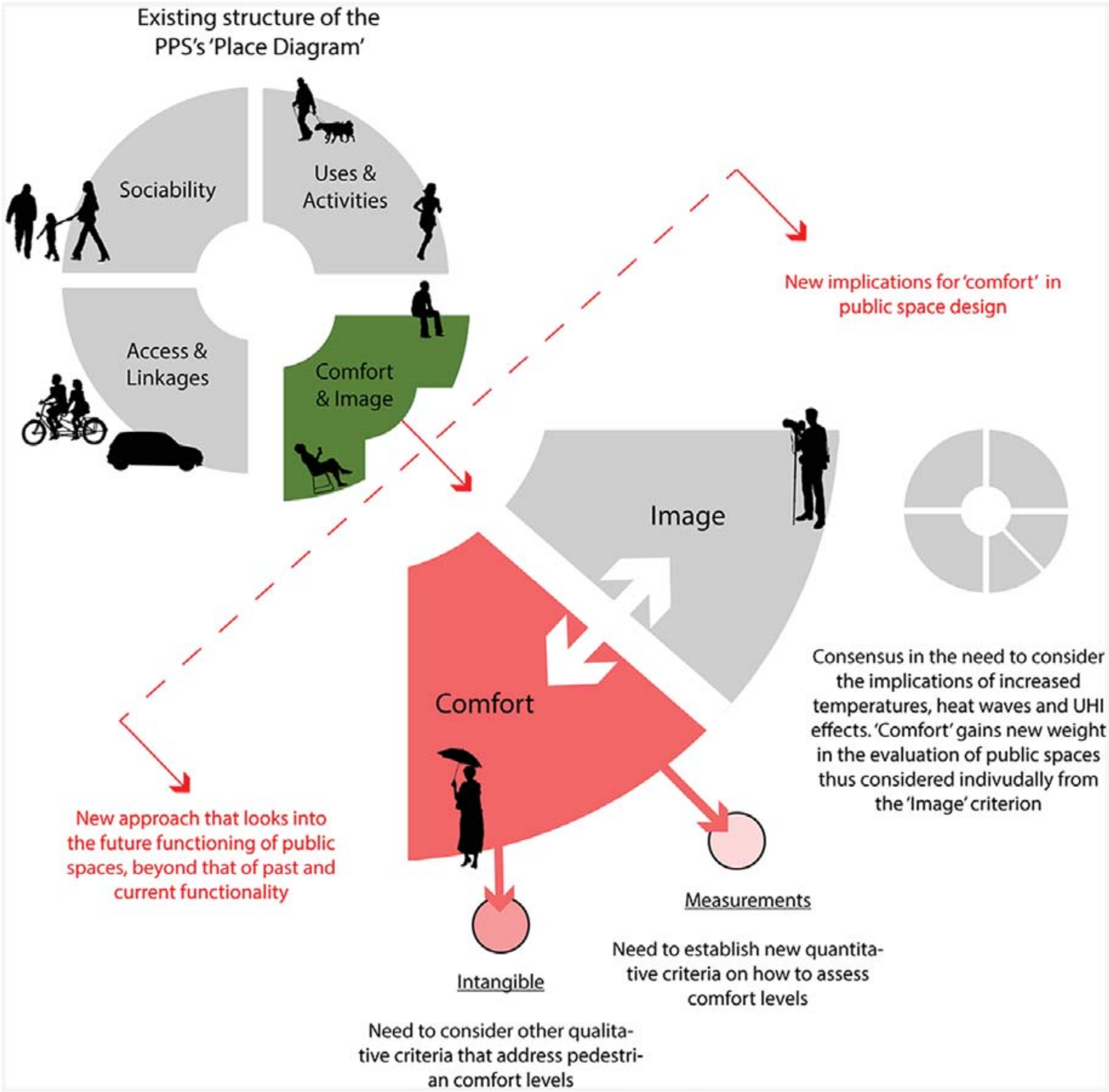


Figure 3. Extending the "Place Diagram" to consider new implications on pedestrian comfort in the light of climate change. Source: Author's figure.

of prospective climate change (Matos Silva and Costa 2016). As a result, this conjures the challenge of applying scientific information into readily available design guidance within the real-world process of public space design. It is here, within the user-based spectrum of adaptation to climate change, where microclimatic phenomena such as air temperature, radiation, humidity and wind patterns adjoin the important consideration of both the usage and longevity of public space. Considering the broad nature and the existing criteria of the "Place Diagram," an alteration is thus proposed in Figure 3.

Figure 3 demonstrates how the existing structure of the PPS's diagram can incorporate the increasing need to consider the possible impacts brought on by climate change. Given the "questions to consider on comfort & image" by the PPS, the only question that relates specifically to that of pedestrian comfort refers to the issue of safety and choice between sitting in areas in the sun or shade. In addition, since safety is directed at the presence of on-site security personnel, it falls short in considering how a space can transpose a sense of safety with regards to climatic hazards. As a result, it is here argued that there is an opportunity to raise new questions that specifically consider pedestrian comfort. Naturally, such questions require new qualitative and quantitative assessments in order to correctly assess comfort levels.

In order to approach these assessments, this article uses what Katzschner (2006) determines as a "research for design" approach. This methodology focuses upon improving urban design guidelines by reviewing existing theoretical and empirical research with regards to how pedestrian comfort levels can be addressed through public space design. In addressing and incorporating these questions into a generic tool such as the one used by the PPS, this "research for design" is approached through a twofold progression method.

Firstly, and in order to overcome the lack of existing knowledge within the scientific community, the authors associate theories of psychological adaptation with that of thermal preference. The outcome of this cross-examination is a three-step approach that endeavours to aid urban designers to better comprehend qualitative criteria through a design orientated approach. Subsequently, and based on the six determined socio-psychological criteria, the three step approach is compared to eight existing empirical studies that examine thermal adaptability and psychological preference in outdoor urban spaces.

Secondly, and once the three-step approach is established, the quantitative aspects are investigated in order to determine how urban design can improve the identified "built environment layer." This stage concentrates upon establishing the quantifiable criteria that directly influence the qualitative attributes of thermal comfort. Also summing up to six criteria, each is assessed against empirical and theoretical studies that all suggest their prevalence in improving the qualities of contemporary urban outdoor spaces. To conclude, these six quantitative criteria are extrapolated into three tiers of attributes which enable the inspection of the exact values/measurements that can be registered through site visits or computer simulations.

Establishing qualitative criteria

When considering qualitative criteria, it is worth noting that most (if not all) enter the psychological and sociological perception of man to his surroundings. Nevertheless, there is a considerable lack of knowledge on how to approach such a subjective area of study, and a limited amount of research has been carried out within the scope of urban design.

The concept of thermal comfort, or thermal acceptability, is crucial in urban design as it establishes the boundaries of ideal climatic conditions that should be achieved. For example, this may establish lower and upper temperature limits, maximum wind patterns and exposure to a certain level of solar radiation. As expected, and when considering local risk factors, such considerations of acceptability must always be context sensitive (Olgyay 1963; Matzarakis and Amelung 2008).

In the scope of thermal comfort in public space design, this may involve all of the processes which people go through to improve the fit between the environment and their preferential requirements. To grasp this intricate relationship, Nikolopoulou and Steemers (2003) suggest that there are six psychological factors: (1) naturalness; (2) expectations; (3) past experience; (4) time of exposure; (5) perceived control; and, (6) environmental stimulation. As these are attributes that enter the "intangible" sphere, the quantification of each parameter is complex. People perceive the environment differently, and psycho-sociological factors have a heavy influence upon the thermal perception of a space. In addition, the same respective person can have different reactions to the encircling climate during different periods of their lives. In order to analyse such factors in design terms, one can address the study conducted by Erell, Pearlmutter, and Williamson (2011) who established three sets of potential preferences which relate to the thermal environment of public spaces. These preferences are defined as the combination of factors which influence the outdoor thermal sensation of a person, namely the:

(1) Climatic Environment – Relating to the direct influence of the air temperature, radiation, humidity and wind patterns
(2) Built Environment – Relating to the buildings, technology, amenities by which the climate set of preferences can be addressed
(3) Human Environment – Relating to a wide range of aspects referring to people's behaviours which affect their thermal preferences, which can range from clothes selection and activity levels at a day to day level, to wider scope which can refer to the general satisfaction thresholds of a city in a specific type of climate.

Linking psychological adaptation with thermal preference

By cross-examining the six psychological factors with the three environments, one can get a better understanding of each factor with the built environment. Naturalness is strongly associated to the character of place, although a much debated concept, it is here depicted as locally distinctive patterns of development, landscape and use (Cowan 2005). Resultantly, this qualitative criterion is strongly attached to the built environment layer, and where the implementations of thermal attenuation measures require congruence with the rest of the site.

Past experience is strongly related to the human environment as it is a "variable" carried by pedestrians. Furthermore, and as stated by Nikolopoulou and Steemers (2003), design approaches can also influence short-term past experience. Although this would be at a larger scale, the urban fabric can offer spatial variety in the city, whereby a rich diversity of different environments/thermal stimuli can be experienced.

Perceived control is also a mixture between the human and built environmental layers, whereby such control can be introduced by the provision of opportunities through the physical adaptation of a place. In other words, this could be accomplished by pedestrians having the choice between differing microclimatic conditions, such as areas with more sun/shade (Carmona 2014), and more or less wind (Clément and Rahm 2007).

Time of exposure is a combination of all three environments, whereby the climatic environment is the continuous variable. The built environment layer enables the means to address such microclimatic phenomenon, which in turn, affects the human environment (ie time of exposure). As an example, one can refer to the Expo of 1992 in Seville, where the public realm of the Expo was divided into three different types of spaces: (1) "Passage Areas" with the prime functionality of supporting the main flow of pedestrians, with an expected "use timeframe" of below 15 min; (2) "Rest/Stay Areas" with the primary goal of offering places for resting, eating and social congregation, with an expected "use timeframe" of over 15 min; and lastly, (3) "Adjacent Areas" that were spaces of interconnectivity between the former. This theoretical division between passage, rest and adjacent areas aided thermal comfort design to be divided into medium-level, high-level and low-level thermal condition, respectively (Velazquez, Alvarez, and Guerra 1992).

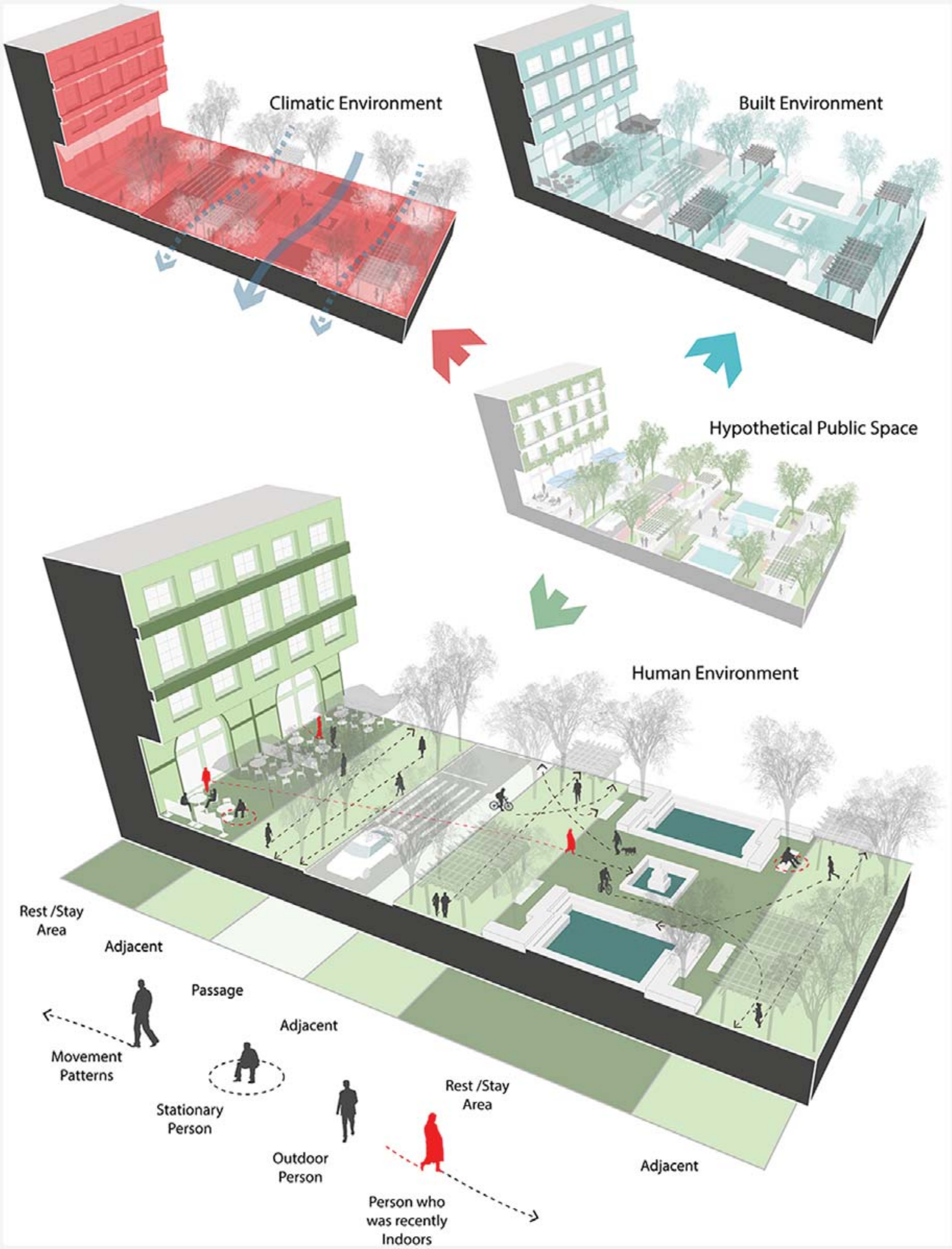


Figure 4. Representation of different environmental layers. Source: Author's figure.

Environmental stimulation is a mixture of the climatic environment and the human environment, whereby it is the pedestrian that chooses the amount of stimulation to a given microclimatic stimuli. As indicated by Gomez-Azpeitia et al. (2011), such choices can be considerably influenced by factors such as transitioning between indoor and outdoor environments.

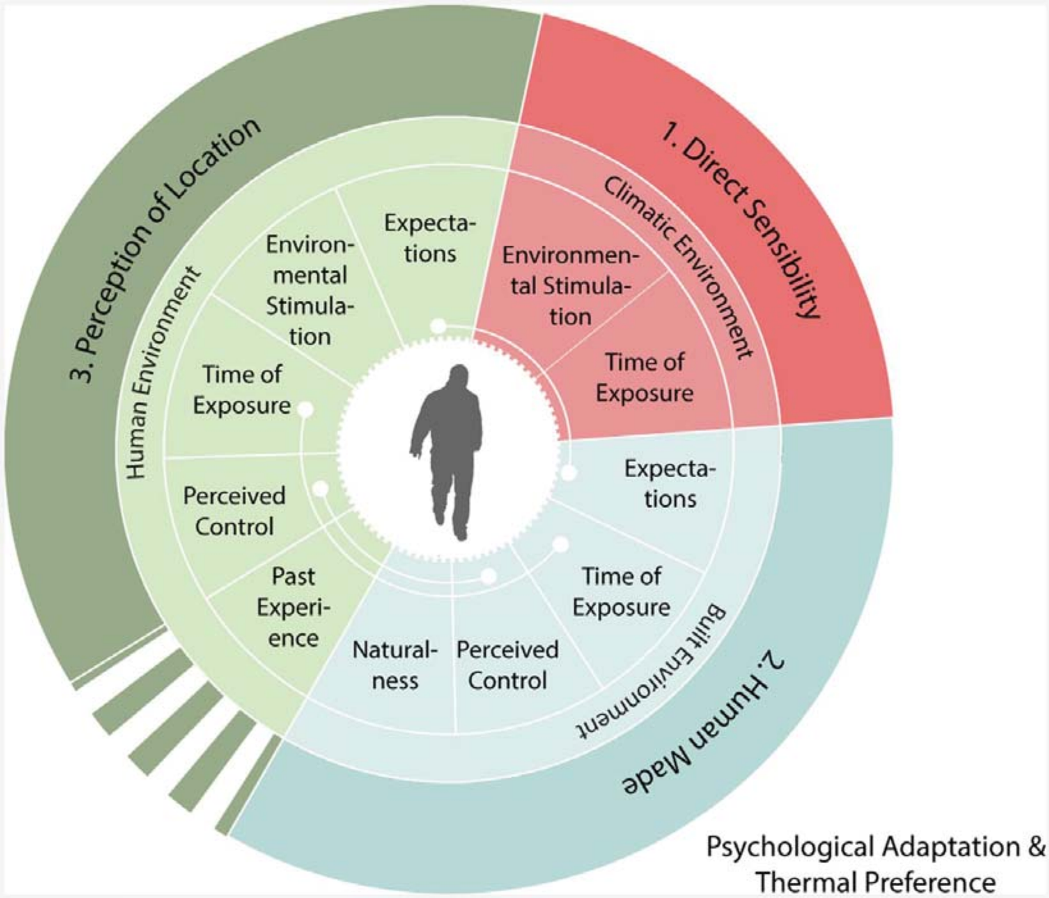


Figure 5. Cross-referencing the theory of psychological adaptation and thermal preference. Source: Author's figure.

Lastly, expectation is a factor that is associated to both the built environment and human environment, due to the relationship between a person's preconceived anticipation, and what they actually experience in a given space. Naturally, if a person expects to have the ability to "hide" from intense sun exposure or higher temperatures, tolerance levels are decreased due to the consequential obligation to withstand such thermal stress. As a result, factors such as time of exposure can also be affected due to the built environment not providing the means to address such attenuation measures.

In order to communicate these relationships in visual terms, a hypothetical public space is presented in Figure 4. Within the figure, the climatic environment illustrates the direct sensibility to climatic phenomenon, such as the influence of vegetation upon wind speed (blue lines), the formation of shade as a result of the tree crowns/canopies (white surfaces) and the areas exposed to solar radiation (shown in darker red). The built environment illustrates all of the built form which inevitably influences the climatic environment, such as the canopies (shown in grey) and/or trees (shown in light blue). Lastly is the human environment, containing the largest amount of aspects due to its intrinsically emotive relationship with the former layers. This layer presents the opportunity to comprehend movement patterns, areas for stationary activities, past thermal history and also the different type of areas which each influence staying times as suggested by Velazquez, Alvarez, and Guerra (1992).

Taking this line of reasoning into the practical sphere of public space design, the relationship between the six psychological criteria and the three environmental layers, can be seen as a three step process in influencing each of these qualitative criteria through a design-orientated approach (Figure 5).

As shown in Figure 5 the first psychological attributes that are affected are the amount of time and environmental stimuli the pedestrians choose to expose themselves to within the public space. Initially, these mental manifestations are those that are directly influenced by microclimatic occurrences in a given outdoor space. In order words, if pedestrians are exposed to too much thermal stress/stimuli, regardless of the built surroundings, they shall inevitably choose to leave. At a second stage, the built environment can be seen as a means to address pedestrian preferences in the light of the environmental stimuli. Respectively, it is here where comfort thresholds can be addressed by improving the amount of control pedestrians have upon personalising their susceptibility to a respective stimuli. In addition, if this perceived control is achieved in a natural way, ie through passive or vegetative means, then the stimuli tolerance can be increased further. Lastly, the last phase of the process is the result of the interventions within the built environment in combination with the climatic environment. As can be seen in the psychological factors, such as expectations, time of exposure and perceived control, each are situated in both the second and third phases. For this reason there is a direct impact that physical interventions and design opportunities can have upon the perception of an outdoor space. Furthermore, environmental stimulation and time of exposure are also part of the human environment, thus also suggesting that these criteria can also be influenced through local intervention.

Existing empirical studies of pedestrian thermal comfort

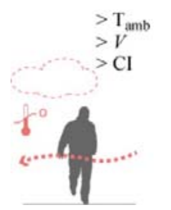
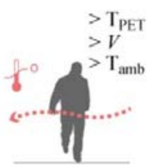
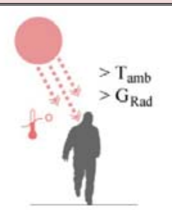
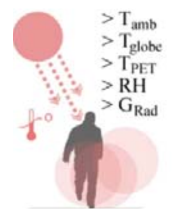
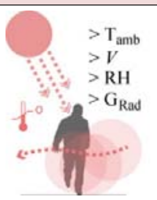
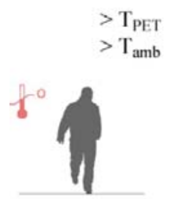
In order to assess the validity of this three-step approach in defining qualitative criteria, the three layers were analysed against existing empirical studies that examined pedestrian behaviour, and thermal comfort thresholds to outdoor microclimatic stimuli. This approach permitted the subjective processes of thermal preferences and psychological adaptation to be categorically organised.

Table 1 shows how eight existing studies can be divided into the three environments, whereby the: (i) first step illustrates the environmental stimulation that was assessed in each of the studies; (ii) second considers how the built environment affected activity patterns in light of the assessed environmental stimulation; and, (iii) third step shows how the previous steps influenced pedestrians to behave in a certain way, enticing them to stay longer (or not) in the space. As shown in Figure 5, the six psychological criteria are dispersed and repeated amongst the different layers due to an intrinsic "cause-and-effect" relationship between one another.

To date, empirical research with regards to pedestrian comfort thresholds and thermal adaptation is still in its initial phases. As a result, it is still problematic to produce concrete design guidelines based upon solely qualitative criteria. Nevertheless, it is here suggested that there is sufficient knowledge to provide reflections that can aid, and syndicate, local placemaking with climatic adaptation efforts.

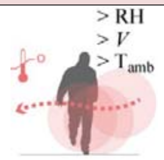
Also acknowledging this lack of studies with regards to psychological response and thermal comfort thresholds, Eliasson et al. (2007) identified in their research that air temperature, wind speed and cloud index had significant impact upon pedestrian behaviour. When considering the built environment, the interviewees revealed that they had different expectations with regards to the different microclimatic environments between an urban outdoor public space (comprising of higher temperatures and lower wind patterns), and a waterfront

Table 1. Applying the three step process in existing studies of pedestrian comfort thresholds and thermal adaptation.

Std.	1. Direct Sensibility **Climatic Environment**	2. Human Made **Built Environment**	3. Perception of Location **Human Environment**
(Eliasson, Knez et al. 2007)	Environmental Stimulation  > T_{amb} > V > CI	Expectations > Pedestrians expected waterfront plazas to have increased wind speed and reduced temperature > Pedestrians expected the urban square to have lower wind speed and increased temperature Naturalness > Wind patterns were considered by the pedestrians to be part of the '*positive aesthetic and symbolic value*' in the waterfront plaza	Environmental Stimulation > Higher wind speeds were accepted in waterfront plaza > Higher temperatures are accepted in urban square > Areas were considered more pleasant when sky was clear Expectations > Waterfront plaza was expected to be more pleasant as a result of higher wind speed and lower air temperature > Open square was expected to be more "*beautiful*" as a result of lower wind speeds and higher air temperature
(Katzschner 2006)	Environmental Stimulation  > T_{PET} > V > T_{amb}	Perceived Control > Given the possibility to choose between indoor and outdoor seating areas, pedestrians chose to sit outside in order to experience hotter temperatures	Environmental Stimulation > Higher temperatures were both accepted and pursued by workers in their lunch break who had been in an air-conditioned setting Past Experience > Pedestrians desired increased environmental stimulation due to their past experience of being inside of a building
(Zacharias, Stathopoulos et al. 2004)	Environmental Stimulation  > T_{amb} > G_{Rad}	Perceived Control > The increase of seating alone had a very small impact on pedestrian numbers in the area > It was demonstrated however that the seating located in the right locations in light of temperature and sun patterns were extensively used by pedestrians	Expectations > In the case where the seating was not used, the pedestrians revealed that proposed design solution failed to meet expectations when microclimatic conditions (such as shade and temperature variations) were not considered
(Lin 2009)	Environmental Stimulation  > T_{amb} > T_{globe} > T_{PET} > RH > G_{Rad}	Perceived Control > 90% of the pedestrians in the study that visited the space chose to stay under trees or shelters during the summer	Environmental Stimulation > As values of thermal indices increased, the number of people frequenting outdoor public spaces also increased in the summer/winter Perceived Control > When the individuals autonomously chose to visit the square, the thermal tolerance was high. On the other hand, when obliged to visit the square (such as being obliged to cross it), the tolerance was significantly lower
(Nikolopoulou, Baker et al. 2001)	Environmental Stimulation  > T_{amb} > V > RH > G_{Rad}	Perceived Control > Although appreciated during the winter period, a street with limited or no areas to sit in the shade decreased the amount of pedestrians during the summer. Moreover, the ones that did sit, sat for shorter periods.	Environmental Stimulation > Once pedestrians decided to sit outside, they had an increased thermal tolerance to environmental stimuli Past Experience > Pedestrians desired increased environmental stimulation due to their past experience of being inside of a building
(Thorsson, Honjo et al. 2007)	Environmental Stimulation  > T_{PET} > T_{amb}	Time of Exposure/Naturalness > Pedestrians demonstrated a shorter stay in the square, and used it to "*commute through*" or "*make a short phone call*" or to "*charge-up their body in the sun*" > Pedestrians demonstrated a longer stay in the park, and used it to "*relax*", "*exercise*", and "*eat lunch*" Perceived Control	Expectations/Time of Exposure > Pedestrians avoided the square due to the expected poor thermal comfort conditions Perceived Control > Park was perceived as a location that allowed greater adjustment of thermal conditions by moving in or out of the shade Environmental Stimulation/Time of Exposure

(Continued)

Table 1. *(continued).*

		> Pedestrians did not seek for shade in the square due to a general lack of choices to be in the shade > In the park, it was identified that 80% of the visitors pursued shade in temperatures above 20°C	> Pedestrians only saw the square as a destination when they desired elevated yet short amounts of environmental stimulation
(Thorsson, Lindqvist et al. 2004)	Environmental Stimulation	Perceived Control	Perceived Control
		> Pedestrians were registered to visit the park in order to expose themselves to the sun, but when temperatures go too high, people moved out of the sun and into the shade of the trees	> Pedestrians considered park to be a location that offered a wide variety of microclimates
		Naturalness	Expectations
		> The wide variety of exposed and sheltered areas in the park were considered very effective in 'naturally' offering individual control in overcoming thermal discomfort	> Pedestrians demonstrated that they 'feel better' or 'much better' when visiting the park, and stated that they liked its size, combination of open and wooded areas, peacefulness, and its suitability for a wide range of activities
(Nikolopoulou 2007)	Environmental Stimulation	Perceived Control	Expectations/Time of Exposure
		> Pedestrians revealed that they preferred shaded areas at higher air temperatures, and as air temperature rose, areas with shading measures became busier	> Pedestrians were found to increase around sunset due to considering the 'square as a much cooler'

| T_{amb} - Ambient Temperature | T_{PET} - Physiological Equivalency Temperature | T_{Globe} - Globe Temperature |
| V - Wind Speed/Direction | G_{rad} - Global Radiation | RH - Relative Humidity |

area (comprising lower temperatures and higher wind patterns). In addition, it was also perceived by the majority of the interviewees that the higher wind speeds added to the naturalness of the built environment. When assessing the human environment, both environmental stimulation and expectations played a fundamental role in constructing an overall image of the spaces. Beyond accepting both higher wind speeds and temperatures in the different locations, these stimuli led to the waterfront area being considered more "pleasant," and urban square as more "beautiful".

Integrated within the Rediscovering the Urban Realm and Open Spaces (RUROS) project, Katzschner (2006) investigated the use of an outdoor space located close to a small café. The study concluded that the behaviour of pedestrians was significantly dependent upon encircling microclimatic conditions, and past experience. When analysing the psychological attributes disclosed in the study, it was identified that the built environment layer had strong influence upon thermal adaptation as a result of perceived control. More concretely, the possibility of choosing between indoor or outdoor seating areas led pedestrians to choose to sit outside in higher temperatures. When considering these implications within the human environment, this resulted in higher temperatures being both accepted and pursued. These responses can be both interlinked with environmental stimulation and past experience.

Notwithstanding, it should not be assumed that merely placing seating will increase the thermal tolerance of pedestrians as shown in Zacharias, Stathopoulos, and Wu (2004). In their study, it was shown that as part of a redesign project to increase pedestrian numbers in a public space, it was not sufficient to increase the numbers of seating areas in the space. It was verified that this increase in seating facilities had to be done with an understanding of microclimatic constraints such as sun patterns and temperature variations. In cases where the seating provision was placed in the correct locations (in regards to these outdoor characteristics), the amount of pedestrians using the seats/benches increased significantly.

Within a humid subtropical climate, Lin (2009) identified that as opposed to a temperate climate, cool temperature and weak sunlight were generally desirable during the hot season. More specifically, the recognised thermal comfort threshold for an entire year lied between 21.3 and 28.5 $°C_{PET}$, which is significantly higher than the European threshold of 18–23 $°C_{PET}$ (Matzarakis and Mayer 1996). Here, it was identified that the built environment played a particular role in influencing pedestrian behaviour by the provision of choice. In addition, it was identified by the study that 90% of pedestrians chose to stay in the shade of trees/shelters, which implies that given the absence of this choice; a significant amount of pedestrians would either avoid, or stay shorter periods in the outdoor space. It was also noted that although thermal indices continued to increase due to the gradual augmentation of ambient temperatures, so did the amount of pedestrian attendance in the square. Such patterns are thus associated to the human environment. In contrast, the interviewees also revealed that the pedestrians that were obliged (ie required to cross the space to reach their destination), had a much lower thermal tolerance to the existing microclimatic conditions.

On the other hand, and as identified in a study conducted by Nikolopoulou, Baker, and Steemers (2001), this lack of perceived control in the built environment layer led to a very low amount of pedestrians during the summer due to a lack of shading facilities. Notwithstanding, the human layer revealed that pedestrians nevertheless presented a higher tolerance to environmental stimuli, particularly when they had recently exited the interior of a building.

In the study conducted by Thorsson et al. (2007), and similar to the first study by Eliasson et al. (2007), two types of Japanese public spaces were compared to one another in terms of pedestrian behaviour and thermal adaptation. The first public space was a square that had no trees, and very little shade during midday. The second was a park that contained a forested area, grassed locations and a playground. Although located close to one another, pedestrian behaviour varied significantly between the two. In terms of the built environment, the limited choice of shaded areas immediately influenced the pedestrians to not seek any comfortable conditions in the square, and led pedestrians to use the square only to undertake short activities, such as smoking, making a phone call or commuting through the square. On the other hand, the built environment of the park led pedestrians to partake in considerably longer activities such as "relaxing," "exercising" and "eating lunch." Furthermore, and dissimilarly, it was identified that 80% of the visitors pursued natural means of shade when ambient temperatures surpassed 20 °C (ie through sitting beneath a tree). This perceived control was also communicated into the human environment, whereby the park was generally perceived as an outdoor location that allowed greater adjustment of thermal conditions.

A similar reaction in both the built and human environments can be found in the study conducted by Thorsson, Lindqvist, and Lindqvist (2004), who also investigated the behaviour patterns of pedestrians in an urban park in Gothenburg, Sweden. Their survey revealed that pedestrians also wished to visit a green site in order to expose themselves to the sun, yet when temperatures became too high, they had the possibility to choose to move to a natural shade beneath a tree crown. As a result, and within the human environment, the interviewees also revealed that: (i) they perceived the park as location that offered a wide variety of microclimates; and (ii) they "felt better" or "much better" when visiting the park.

Finally, and also inserted within the RUROS project, the study conducted by Nikolopoulou (2007) also revealed the significance of perceived control in the built environment in influencing the conduct of pedestrians. Given the choice, pedestrians also revealed their preference for shaded areas when temperatures increased, and thus shaded areas became busier. Nonetheless, it was still noted that during the summer period, and particularly during early summer afternoons, pedestrians perceived the space to still be too hot. This perception changed significantly, in the summer evenings where pedestrians were found to exit indoor environments to experience a cooler outdoor microclimate.

In the light of these studies, when considering the qualitative behavioural aspects of pedestrians, approaching outdoor comfort thresholds can be complex. Yet, this should not invalidate their applicability as potential tools in aiding public space design, and their improved integration with the urban climate. The cross-examination of the three layers with existing empirical studies enables a simplification of the complex relationship between climatic dynamics, built form and that of human perception.

While referring to the built environment layer, two psychological aspects were the most common in influencing pedestrian behaviour in the light of climatic stimuli. The first was perceived control, which allowed pedestrians to personify their stay within a respective space. Such personification ranged from being able to choose where to sit, to choosing whether to be in the shade or sun. As a result, this reinforced the existence of different climatic alternatives within public spaces.

As a result of addressing this psychological characteristic, the time of exposure can also be increased as evidenced by Nikolopoulou and Steemers (2003). Their study illustrated that spaces which offered these types of choices witnessed an average pedestrian staying time of 50 min, opposed to 16 min when no choices were made available. In addition, it is clear from the empirical studies that when the environments were considered natural, thermal comfort thresholds were also increased. This was particularly visible in cases which in some way integrated some type of natural feature, ie such as trees and water bodies (Thorsson, Lindqvist, and Lindqvist 2004; Eliasson et al. 2007; Thorsson et al. 2007; Lin 2009). In addition, expectations also played a significant role both before and during the pedestrians visit to the sites. In empirical terms, pedestrians that visited the spaces expected to have the ability to regulate their thermal thresholds either through moving to the shade, standing in a windier location during the summer or sitting in the sun during the winter (Nikolopoulou, Baker, and Steemers 2001; Eliasson et al. 2007).

When reflecting upon the human layer, the amount of desired environmental stimulation was very variable in all of the case studies. More specifically, every case shown in Table 1 salient that pedestrians adapt to their surroundings, and accept conditions that would appear to lie outside their physiological comfort zone (PCZ). In turn, this indicates that people are comfortable in a wide range of environments as they respond to diverse situations which lead them to have higher thermal comfort thresholds. This increased lenience is what is termed as "the adaptive approach" (Humphreys, Nicol, and Raja 2007; Erell, Pearlmutter, and Williamson 2011), which suggests that although laboratory investigations may indicate "typical" or "expected" comfort zones, this does not mean that such thresholds cannot be surpassed in the light of other factors. Furthermore, and as shown in Table 1, existing empirical evidence has demonstrated that pedestrians also choose to surpass their expected comfort zones. In addition to these examples, one can also refer back to the studies carried out in New Yorks' public spaces which showed that

> the days that br[ought] out the peak crowds on plazas [were] not sparkling sunny days with temperatures in the [low 20°Cs] (…) it [was] the hot, muggy days, sunny or overcast, the kind

> that could be expected to make people want to stay inside and be air conditioned, when you [would] find the peak numbers outside. (Whyte 1980, 44)

For these reasons, it is here suggested that multi-agent software programs such as "BOTworld" (Bruse 2007) must be used with caution, as they often assume that pedestrians only accept environmental stimulation when it is within their thermal comfort thresholds. Therefore, this raises the need to formulate better "predicting tools" that better explain the relationship between outdoor climatic stimuli and the subsequent reaction of pedestrians (Givoni et al. 2003; Chen and Ng 2012).

In order to move towards such tools, it is fundamental to consider that pedestrians are organisms which avert climatic monotony, even if this implies that such desired fluctuations may expose them to environmental stimulation that surpass their PCZ. From the empirical studies, it is possible to establish that a pedestrian that desires to visit an outdoor space will also expect to personify their visit in numerous ways, including adjusting their thermal regulatory system. For this reason, regardless of their decision for more or less environmental stimulation, the crucial aspect in prolonging their stay in the outdoor space is to consider their expectations. As to be expected, and due to being an idiosyncrasy correlated to the human psyche, it would be naive to assume that one could acknowledge every expectation that pedestrians may have when visiting the space. However, this obscurity should not be mistaken with the ability to consider general microclimatic implications, and how they affect urban outdoor spaces. As a result, it is here where space personification becomes essential through the introduction of choice in public space design. When introducing such means to increase perceived control, urban designers must thus consider design solutions that substance such fluctuations of environmental exposure. When considering this in empirical terms, and as shown in Zacharias, Stathopoulos, and Wu (2004), in these circumstances, it is here where quality over quantity may lead to dramatic increases in pedestrian numbers in urban outdoor spaces.

Although all the psychological factors are indeed intrinsically qualitative, it is nonetheless argued that they can be influenced through public space design. It is here where design can be approached in a three step approach that understands the microclimatic constraints, provides physical responses and lastly influences the comfort of pedestrians. However, in order to successfully insert such interventions within the built environment, or "Human Made Phase," a quantitative approach is also required and thus extrapolated in the ensuing section.

Establishing quantitative criteria

Moving from qualitative aspects, pedestrian comfort is also attained through quantitative criteria in order to introduce measures that can improve comfort levels. In this scope, different measurable data can raise deliberations into the aspects that need to be considered, and/or modified, when considering pedestrian comfort. Figure 6 demonstrates the measurable data, and their specific characteristics which can be attained by field studies and/or research.

Local microclimatic data

The first data group is the "Local Microclimatic Data," which presents the local meteorological characteristics of the site. The measurements of the characteristics can be made through a mixture of 3D modulation, and direct measurement through climatological equipment.

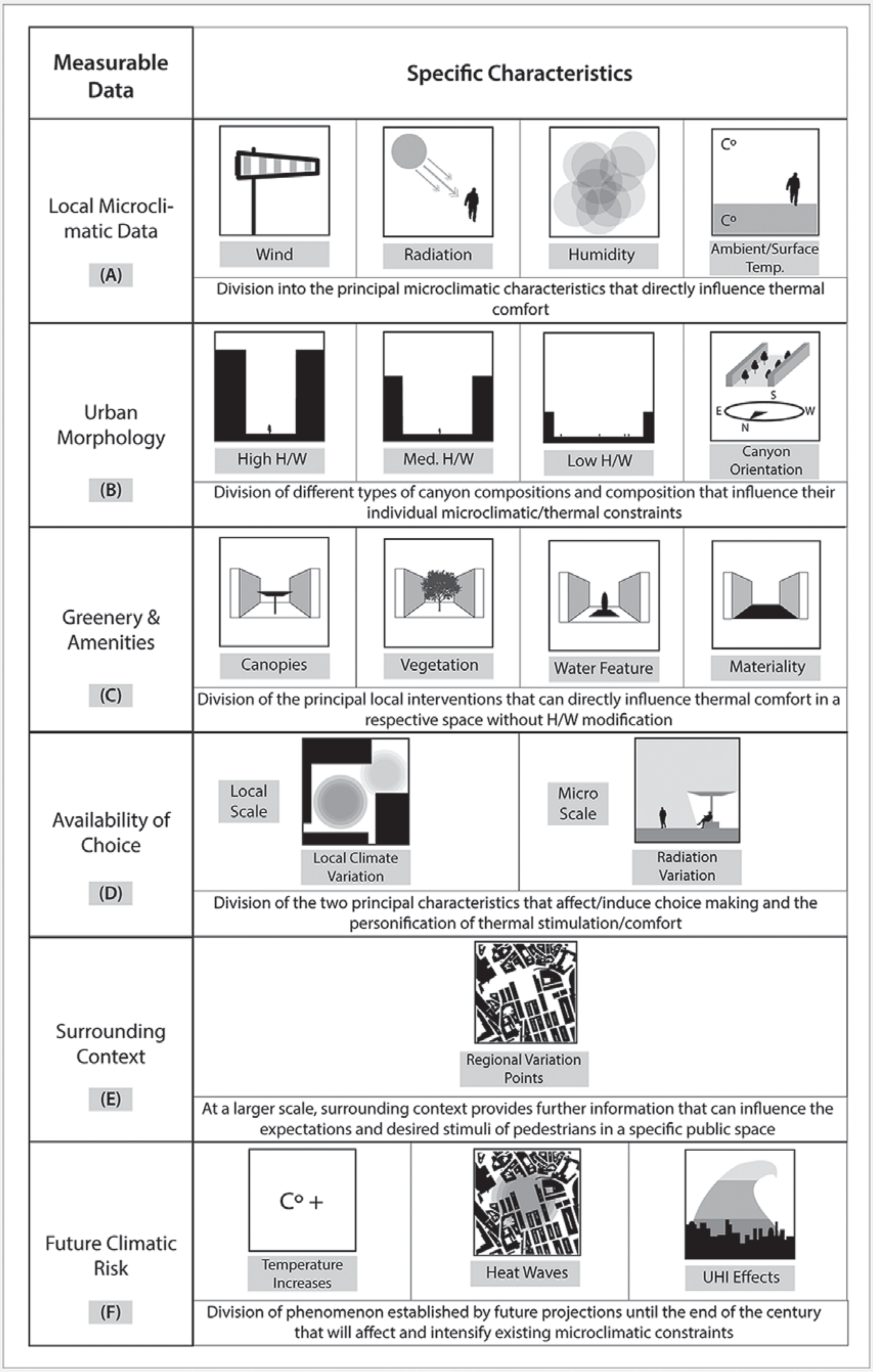


Figure 6. Specific characteristics of the quantitative criteria for pedestrian comfort. Source: Author's figure.

The influence of wind on pedestrian comfort can be seen as twofold: (1) decreasing a given surface temperature through convective heat transfer; and, (2) the effect it can have upon the mechanical functioning of the human body at higher speeds (Esch 2015). The effect of solar radiation incoming from the sun (ie short wave) upon pedestrians and surfaces is likely to be the principal determent in influencing thermal comfort in a respective urban space (Erell, Pearlmutter, and Williamson 2011). Relative humidity is the relationship between actual vapour pressure and saturated vapour pressure, this intrinsic balance can either decrease ambient temperature or exacerbate ambient moisture levels, and consequently decrease comfort levels (Nouri 2015). Lastly, ambient and surface temperatures also play a significant role, and furthermore, have an intrinsic "cause and effect relationship" with one another (Georgakis and Santamouris 2006; Santamouris 2013).

It should be noted that in order to accurately measure "Local Microclimatic Data" in terms of establishing a wholesome understanding of pedestrian comfort, the human energy balance must be considered. It is here where the Physiologically Equivalent Temperature (PET) can provide significant aid to local designers through the application of the software platforms such as the "Rayman" model (Matzarakis 2000). This platform permits the actual microclimate to be evaluated in terms of its influence upon the human biometeorological system, thus leading to an understanding of pedestrian comfort given a set of meteorological stimuli in a specific urban locus.

Urban morphology

When considering urban morphology, and despite the heterogeneity of a street (urban canyon henceforth), when considering the fabric of buildings and open spaces in quantifiable terms, the variations of canyons can produce significant modifications to the microclimate. As a result, this raises the need to consider the aspect ratio, or Height-to-Width Ratio (H/W), which describes the sectional proportions of the urban canyon. More specifically, it represents the ratio between the average height of adjacent building façades and the average width of the space. One of the biggest dissimilarities between high, medium and low H/W ratios is the quantifiable exposure to the sky, which is termed as the sky view factor (SVF). The higher the SVF, the more amount of sky is seen in a given area/surface, which directly correlates to the higher exposure to solar radiation. Nonetheless, orientation is also a fundamental quantitative factor both in terms solar radiation and wind exposure. For example, if the orientation of a high H/W canyon is perpendicular to predominant wind flow, then the wind tunnel effect will be replaced with the more attenuated occurrences of wind eddies permeating from the top of the street. Furthermore, orientation has a dramatic influence upon solar exposure and shadow behaviour due to the dominant positioning of the sun in the sky.

Greenery & amenities

As the climate change agenda continually gains new weight, local designers are increasingly exploring the capacity of "Greenery and Amenities" to address pedestrian thermal comfort. In recent decades, the dissemination of new knowledge has thus strengthened the contributions "Greenery and Amenities" can provide to thermal comfort in public space design. In this light, four different types of options shall be considered: shade canopies, vegetation, water and vapour systems and materiality (Nouri 2015).

In the case of shade canopies, such knowledge has aided the strategic placement of structures that can also attenuate solar radiation levels. Yet, such decisions should be accompanied by the local and annual understanding of public space's: (1) pattern of solar radiation exposure; (2) shadows that are cast from on-site elements (ie such as vegetation and amenities); (3) shadows that are cast from off-site elements (ie such as contiguous structures and buildings); and, (4) encircling wind patterns.

So far, a substantial amount of research has revealed that urban vegetation may be employed as a method to considerably reduce urban temperatures. Nevertheless, within the scope of public space design, there is very limited knowhow at the design guideline level with regards to microclimatic interaction between outdoor spaces and vegetation. To successfully assess this interaction in more detail, it is here suggested that two focal elements need to be understood in the application and measurement of trees in attenuating ambient temperatures and/or reducing solar radiation. The first factor is discussed by Ochoa de la Torre (1999), who analysed the potentiality of using the effects of specific vegetative configurations, namely: individual/linear plantation (LP), group plantation (GP), surface plantation (SP) and pergolas (PG). The second quantitative factor is the species of the vegetation, which accounts for important characteristics such as tree size, growth dimensions, crown density, biomass and foliation periods. Studies undertaken by (McPherson 1984; Almeida 2006) examined 47 tree species and were cross-examined to verify that the transmissivity of plants varied considerably as a result of twig/leaf density and foliage development.

With regards to the third characteristic in this group, the presence of water and misting systems is increasingly being used as a means to improve climatic conditions in outdoor spaces (Nunes et al. 2013). The wholesome effectiveness of evaporative cooling techniques is one that is contingent upon a variety of quantitative factors. Namely, and in order to effectively lower ambient temperature without imperilling acceptable humidity levels, the correct water pressure, nozzle type and functional period must be established. When relative humidity (RH) is too high, the rate of evaporative cooling of sweat is reduced, thus impeding the body's natural process of thermoregulation. On the other side of the spectrum, although measures that enable surface wetting (such as a fountain, or a another surface that contains water) are more simplistic in their applicative nature, relative humidity levels should still be considered in order not to exacerbate ambient moisture, and thus diminishing pedestrian comfort levels.

Through the design of the public realm, the use of "cool materials," which contain both high reflectivity and thermal emissivity values, can lead to the decrease of surface/ambient temperatures and thus significantly improve the thermal comfort in public spaces (Santamouris et al. 2012). Thus, and undertaking a quantitative approach, such improvements can be made through the replacement of conventional paving surfaces that present higher surface temperatures. Such replacements aim to introduce materials with higher solar reflectivity (ie albedo) and emissivity. In quantitative terms, and within the considerable range of projects that have already introduced such materials to diminish both ambient temperatures and disperse effects of UHI; reductions of up to 5 K in ambient temperature and 11 K in surface temperature were achieved (Santamouris 2013; Nouri 2015).

On this note, it is worth concluding the success of "Greenery and Amenities" is dependent on the combination of the different measures. Respectively, although each of the specific characteristics should be understood differently in terms of addressing pedestrian comfort, their crucial efficacy lies in their applicative permutation with one another.

Existing (i.e. CNTRL Values)			Future Projection under the IPCC's A1F Scenario for the northern hemisphere summer season		
PET (*x*)	Thermal Perception	Grade of Physiological Stress	$PET_{(x)} + PET_{(10\,°C)} = \mathbf{PET_{(y)}}$	Thermal Perception	Grade of Physiological Stress
≥ 4 °C	Very Cold	Extreme Cold Stress	4 °C + $PET_{(10\,°C)}$ = **14 °C**	Slightly Cool	Slight Cold Stress
8 °C	Cold	Strong Cold Stress	8 °C + $PET_{(10\,°C)}$ = **18 °C**	Comfortable	No Thermal Stress
13 °C	Cool	Moderate Cold Stress	13 °C + $PET_{(10\,°C)}$ = **23 °C**	Slightly Warm	Slight Heat Stress
18 °C	Slightly Cool	Slight Cold Stress	18 °C + $PET_{(10\,°C)}$ = **28 °C**	Slightly Warm	Slight Heat Stress
23 °C	Comfortable	No Thermal Stress	23 °C + $PET_{(10\,°C)}$ = **33 °C**	Warm	Moderate Heat Stress
29 °C	Slightly Warm	Slight Heat Stress	29 °C + $PET_{(10\,°C)}$ = **39 °C**	Hot	Strong Heat Stress
35 °C	Warm	Moderate Heat Stress	35 °C + $PET_{(10\,°C)}$ = **45 °C**	Very Hot	Extreme Heat Stress
41 °C	Hot	Strong Heat Stress	41 °C + $PET_{(10\,°C)}$ = **51 °C**	Very Hot	Extreme Heat Stress
≤	Very Hot	Extreme Heat Stress	< $PET_{(x)} + PET_{(10\,°C)} = \mathbf{PET_{(y)}}$	Very Hot	Extreme Heat Stress

Figure 7. Comparison of existing PET and a modest projection of PET for the Mediterranean area by 2100. Source: Author's figure + content adapted from (Höppe 1999; Matzarakis and Amelung 2008).

Availability of choice

Availability of choice is the most subjective of the quantitative factors because the facilitation of choice is resultant upon a combination of elements. The first characteristic in this data group is the presence of areas with different microclimatic conditions which result from the combination of the previously discussed climatic environment and built environment layer. In other terms, this employs designers to exploit the interplay of their proposals with the

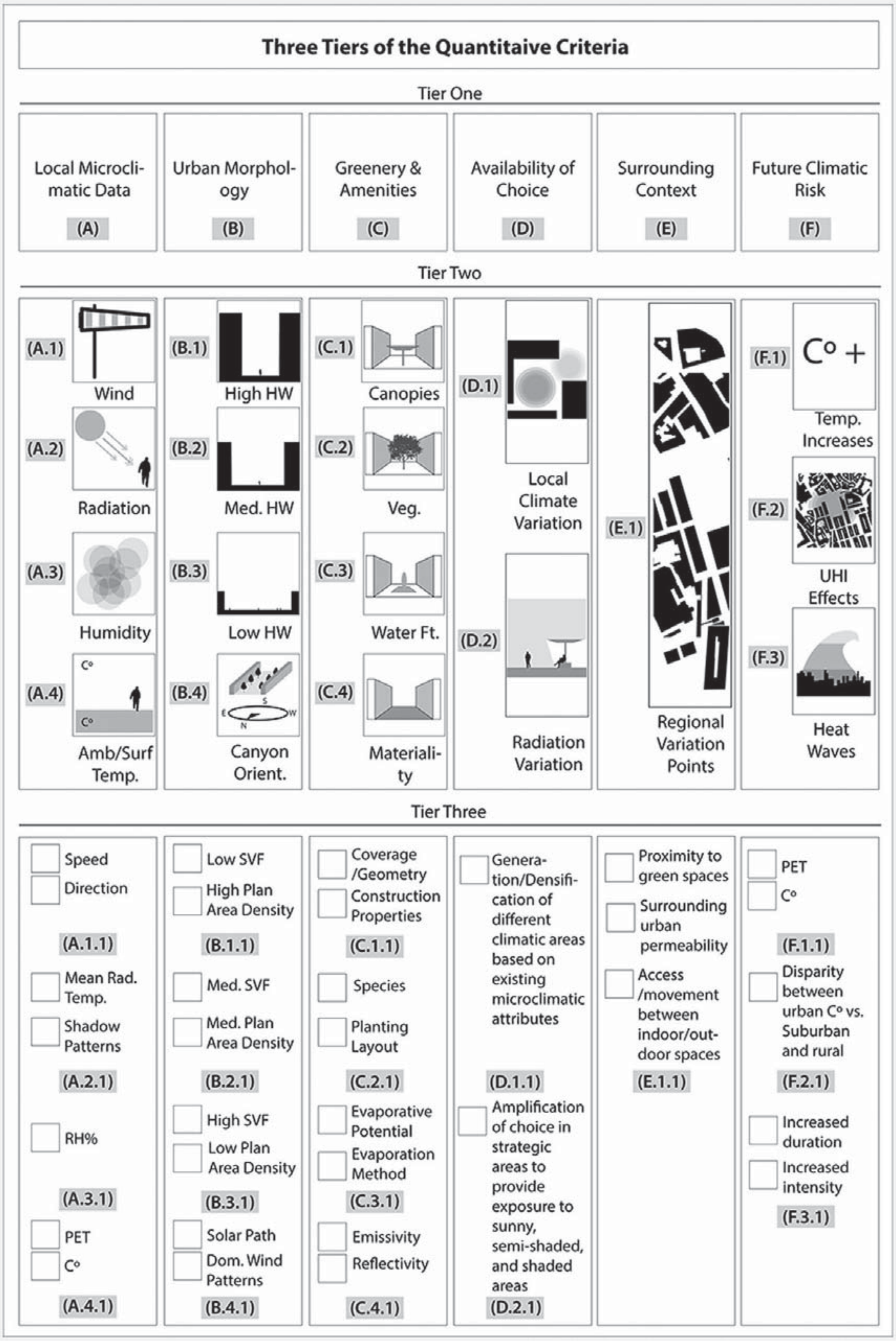


Figure 8. Three tiers of the quantitative criteria. Source: Author's figure.

microclimatic properties that "sometimes overlap, separate, regroup, densify, dilute, generating a variety of atmospheres where the users can choose and appropriate as they see fit." (Mosbach, Rahm, and Liu 2012, 2). The second characteristic can be quantifiable by the amenities to amplify such personification behaviours by the pedestrians (Knuijt 2013;

Carmona 2014). In turn, this narrates to the strategic placement of each of the interventions disclosed in the "Greenery and Amenities" categories.

Surrounding context

At a larger scale, the surrounding context can provide very useful quantitative data which can aid the addressing of pedestrian comfort within a relevant public space. In addition, this characteristic can be broken down further into sub-characteristics such as proximity to green spaces, the surrounding permeability and/or H/W and the intrinsic relationship with surrounding interior spaces. In general terms, context can have an influence upon many of the qualitative factors of pedestrian comfort, and can significantly affect the amount of time pedestrians choose to spend on site. Moreover, and now specifying upon that of microclimatic implications, the surrounding context can also provide information on larger scale meteorological behaviour, which may salient obstacles/opportunities for the public space (Alcoforado and Andrade 2006).

Future climatic risk

Future climatic projections provide a basis of quantifiable data, which in this scope, pertains to the projected increases in temperature, augmented effects of UHI and amplified heatwaves. Nonetheless, there shall always be a certain amount of uncertainty associated to possible future climate change due to the presence of unpredictable factors which can considerably influence forthcoming climatological trends. Acknowledging this uncertainty, and in order to approach possible climatic outcomes until the end of the century, a range of scenarios were developed by the Intergovernmental Panel on Climate Change (IPCC). This global scientific institution undertook an exploration into the possible changes in socio-economic conditions that would thus lead to a range of possible scenarios, known as the Special Report of Emission Scenarios (SRES) (IPCC 2000). Resultant of these scenarios, greenhouse gas (GHG) emissions and atmospheric concentrations of greenhouse gases could be estimated, thus allowing the comprehension of the reactions within the global climate system. Among the four main SRES, the A1F represents the case with the fastest and most dramatic effects upon climate change predictions, while the B1A and B2A scenarios represent more attenuated levels of climatic variation until the end of the century. For this reason, the A1F scenario, one which portrays a "world of fast economic development and rapid introductions of innovative efficient technologies" (IPCC 2000), can be used to consider the most pessimistic future situation through a "What if?" approach (Costa 2011; Costa et al. 2014).

In this scenario, many parts of the world, including the Mediterranean, show increases in PET by at least 10 °C (some areas Mediterranean witness an increase of up to 15 °C). These quantitative conclusions were disseminated by Matzarakis and Amelung (2008) who utilised GCM's and emission scenarios for the period 2071–2100 in comparison to the normal climate period, ie 1961–1990 (CNTRL). These quantitative outputs are of quintessential significance, as they demonstrate that the expected changes in air temperature, for the same period, are acutely lower (ie of around 4 °C).

In Figure 7, a combination of sources was used to demonstrate how existing thermal perception and physiological stress can be quantifiably influenced by the end of the century. $PET_{(x)}$ represents existing levels and the associated thresholds of pedestrian thermal perception, and the resulting physiological stress. It is worth noting here that $PET_{(x)}$ levels are adapted to the Mediterranean context, and thus do not require modification within most of the southern European region.

Based on an increase of 10 °C in PET, future projected PET (ie $PET_{(y)}$) is presented, and subsequently cross-referenced to that of thermal perception and physiological stress. As can be seen, this modification leads to a considerable increase in physiological strain for humans based on $PET_{(x)}$ thresholds. Solemnly, this implies that where a "comfortable" threshold may hold today at around 18 °C, this would translate into a "comfortable" threshold of located at around 4 °C by the end of the century. It is worth reinforcing that this is under a modest scenario.

As such, projections of "solely" increases in temperature provide considerably less precise data in the local and user based scope of public space design, thus enforcing the need to consider quantitative human bioclimatic indices such as PET.

In addition, considering UHI during the discourse of the twenty-first century, it is recognised within the scientific community that global climate change can interact with the future enveloping of the built environment, and shall inevitably affect urban bioclimates (Wagner 1994). To date, numerous studies have shown that UHI effects have increased during the twentieth century (Brázdil and Budiková 1999; Philandras, Metaxas, and Nastos 1999). The former study identified a quantifiable annual increase of 0.01 °C in the UHI effect during the summer until the 1960s, which later came to stagnate. Nevertheless, and as indicated by Oke (1976), the magnitude of UHI growth are limited due to new urban structures requiring the demolishing of others once a certain level of urban development is attained. This being said, designers should have such quantitative values in consideration as they are sufficient to intensify already high temperatures in urban regions.

Lastly, and following the AR4 of the IPCC, it is established that within the twenty-first century, the occurrence of both hot extremes and heatwaves are "very likely" (IPCC 2007). Furthermore, it is also suggested by the IPCC in its AR5 that the influence of prospective climate change upon heatwaves shall be more significant than the impact upon global average temperatures (IPCC 2013). In addition, quantitative studies have shown: (1) an increase in the duration, frequency and intensity of heatwaves observed in the Mediterranean region (Kuglitsch et al. 2010); and, (2) a doubling in the length of European heatwaves between 1880 and 2005 (Della-Marta et al. 2007). Respectively, and in conjunction with increased temperatures, and UHI patterns, the effects of heatwaves must also be considered when addressing pedestrian comfort levels through contemporary public space design.

In summary, each of the six quantitative factors can be assessed and/or measured through different means. Furthermore, and as shown in Figure 8, each of the factors is presented within a three tier system of values which directly, or indirectly, influence pedestrian comfort, where: (1) Tier One illustrates the six factors (ie A–F.#.#); (2) Tier Two shows the specific characteristics of each of the factors (ie #.1–4.#); and lastly, (3) Tier Three demonstrates how most of the characteristics can be broken down further into exact measurable quantities/extents (ie #.#.1–3).

Results and discussion

Based upon the integration of new qualitative and quantitative criteria when addressing comfort levels in public spaces, this article suggests that existing approaches such as the "Place Diagram" can, and should, be modified in the light of the opportunities presented by climatic adaptation. Given the projected impacts of climate change, the importance of developing alleviation recommendations at design guideline level shall inevitably escalate for placemaking (Costa 2013; Nouri and Matos Silva 2013). For this reason, it is argued that the

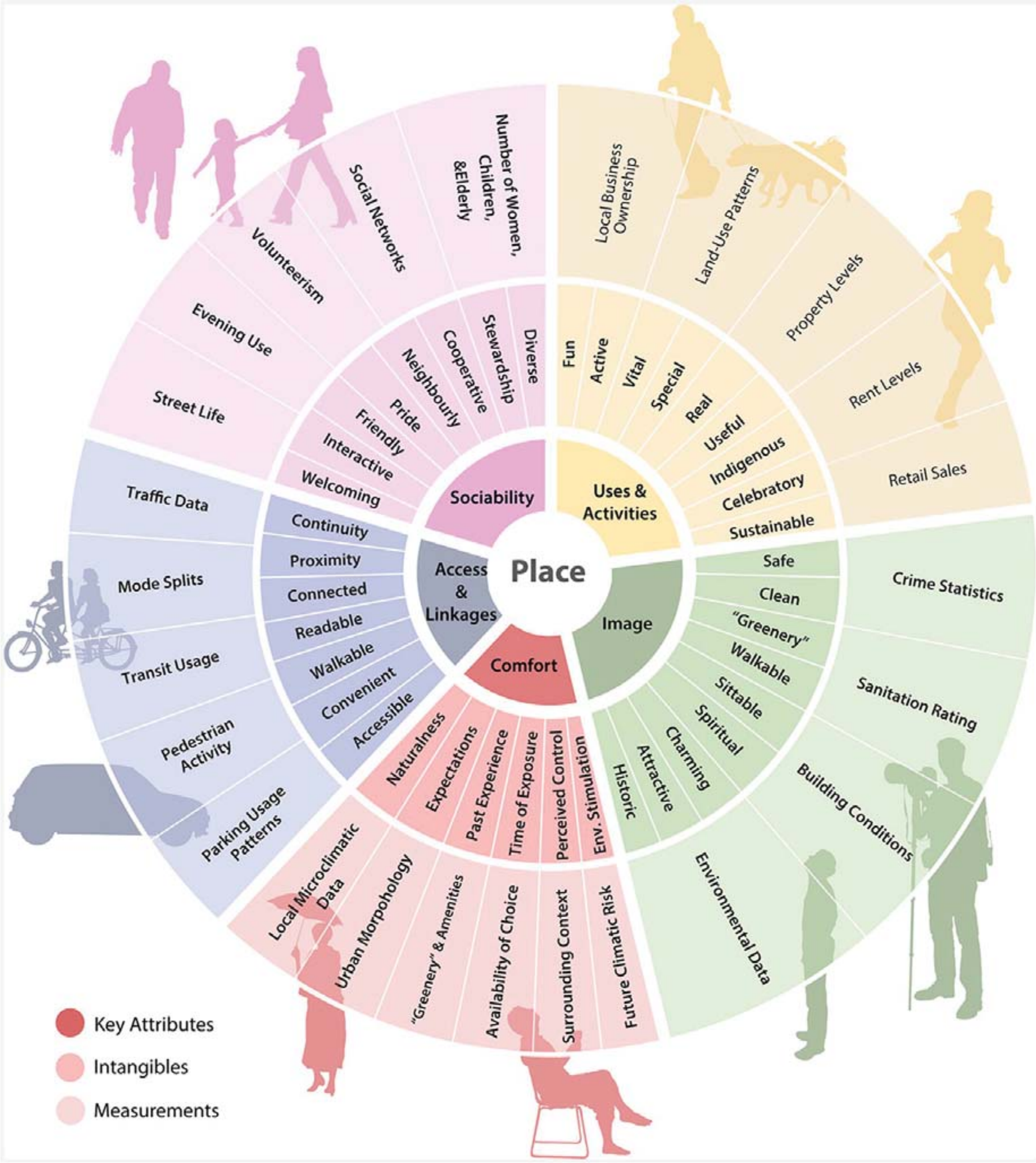


Figure 9. Restructured Place Diagram. Source: Author's figure + content adapted from (PPS 2003b).

attribute of "Comfort" in a world of possible climate change shall become a continually pressing factor for designers and decision makers. This thus implies that facilitating the provision of design guidance in generic public space evaluation models must consider such obstacles when evaluating the long term "success" of a public space. Invariably, although a present public space may demonstrate "successful" characteristics, without addressing pedestrian comfort, such characteristics in the future may no longer be sufficient in sustaining public life and affluence.

As shown in Figure 9, the objective of restructuring is not to compete with the other factors as established by the PPS. Instead, the goal is to complete a generic approach in identifying the wholesome "success" of a respective public space in a century that can witness continually growing climatic threats.

Conclusion

This article argues that approaches such as the "Place Diagram" need to be modified in order to consider the ever-growing importance of pedestrian comfort given events of increased temperatures, heat waves and UHI effects. This by no means advocates the invalidation of the previous criteria established by experts in the field. Instead, it is here disclosed how user based approaches to microclimates and prospective climate change can add to the constituents of a "successful" place in order to certify its future use and socio-economic prosperity. As a result, the triangulation between climate change, urban design and user-based approaches to adaptation can lead to the fortification of design guidelines in light of local risk factors. Although a lot of the knowledge is not new, there is, however, an acute lack of knowledge between scientific expertise and its respectful application in design terms. In this respective subject area, this pertains to designers often lacking the indicators to: (1) address existing microclimatic implications in public space design; and more prominently, (2) prepare for the invigoration of these respective insinuations as a result of potential climate change.

As a result, and within the generic scope of the "Place Diagram" new quantitative and qualitative factors were introduced to stimulate new important interrogations with regards to placemaking and that of pedestrian comfort. Through the cross-examination of theories in order to approach intangible factors, and the overview of measurable data, knowledge regarding outdoor thermal comfort can be more efficiently assimilated with climate responsive public space design in an eventful twenty-first century.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

A. Santos Nouri is an urban designer with an architectural background, he holds an MA in Urban Design from the University of Westminster, and an MArch from the University of Lisbon. He has worked in both the private and public sectors within the UK, including various councils and architectural offices before turning to his interest in research. Currently terminating his doctoral studies, the author's research interests focus upon microclimatic and thermophysiological characteristics within that of public space design in an era of potential climate change. After terminating his research grant within the project 'Urbanised Estuaries and Deltas' (funded by the Portuguese Foundation for Science and Technology FCT), he was awarded an international doctoral scholarship to New Zealand (through the Doctoral AUSMIP+ Programme) for one year in order to carry out a section of his research and lecture as a visiting doctoral fellow to architectural/urban design students. Upon return from New Zealand, he initiated his individual doctoral scholarship (also funded through FCT), and collaborative membership with CIAUD – Research Centre of Architecture, Urbanism and Design and has thus far published in various indexed international conferences and journals.

J. Pedro Costa is an architect (TU Lisbon, 1993), master on Contemporary Architectonic Culture (TU Lisbon, 1998) and PhD on Urbanism (TU Catalonia, Barcelona, 2007). He has as pos-PhD on Architecture and Urbanism (TU Lisbon, 2011) and a habilitation to full professor (Agregação) in Urbanism (ULisbon, 2012). He is a professor of Urbanism at the Faculty of Architecture, University of Lisbon, where he develops his teaching, research and expertise activity, and member of the Direction Board of the CIAUD – Research Centre of Architecture, Urbanism and Design, as well as visiting professor at the Barcelona University (PhD Programme). He is also the director of the Portuguese professional journal Arquitecturas, since 2005. From 2002 to 2004 he was advisor and head of cabinet of the Portuguese Secretary of State for Spatial Planning. Maintaining a general interest in urban and territorial planning issues, his current areas of research are waterfronts, climate change adaptation, urban morphology and urban regeneration.

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Section 3

Addressing existing and future thermal comfort thresholds within the square of Rossio, Lisbon

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Publication 6:

Addressing thermophysiological thresholds and psychological aspects during hot and dry Mediterranean summers through public space design: The case of Rossio

A. Santos Nouri & João Pedro Costa

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Article Preamble

Orientated at a specific case study, this publication presents results of an empirical analysis undertaken within Rossio. Such an analysis is constructed upon the identification of: (i) ascertaining the principal local risk factors within the square which could influence pedestrian thermal comfort thresholds; and (ii) assessing how the identified risk factors could be translated into creative solutions and opportunities for local public space design.

Article Symbol list

$\#K_X$	Variation of X variable	r	Regression coefficient
'*Csa*'	Hot-Mediterranean climate	T_{amb}	Ambient temperature
clo	Cloud cover	T_{surf}	Surface temperature
G_{rad}	Global radiation	V	Wind Speed

Article Acronym List

C	Cycle	NH	Nozzle Height
CD	Crown Dimension	PBR	Pedestrian Based Response
CFD	Computational Fluid Dynamics	PCZ	Physiological Comfort Zones
ETCS	Ephemeral Thermal Comfort Solution	PET	Physiologically Equivalent Temperature
FP	Functioning Period	PL	Planting Layout
GP	Group Plantation	POI	Point of Interest
H/W	Height-to-Width Ratio	PP	Pump Pressure
IMPA	Portuguese Institute of Sea and Atmosphere	PS	Physiological Stress
IPCC	Intergovernmental Panel on Climate Change	RH	Relative Humidity
JJA	June July August	SBS	Shadow Behaviour Simulation
KG	Köppen Geiger	SVF	Sky View Factor
LM	Limitation Mechanism	SW	Surface Wetting
LP	Linear Plantation	TH	Tree Height
MEMI	Munich Energy balance Model for Individuals	TP	Thermal Perception
NC	No Clouds	UHI	Urban Heat Island

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Addressing thermophysiological thresholds and psychological aspects during hot and dry mediterranean summers through public space design: The case of Rossio

A. Santos Nouri*, João Pedro Costa

Universidade de Lisboa, Faculdade de Arquitetura, CIAUD, Centro de Investigação em Arquitetura, Urbanismo e Design, Lisboa, Portugal

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ABSTRACT

Within the contemporary city, the effects of urban climatology are increasingly elucidating the need for further climate responsive environments. So far however, and as global climate studies often present limited local specificity for urban planning and design, there has been a growing interest for complementary bottom-up perspectives which describe how efforts of adaptation can be locally initiated. Accompanying this interest, and orientated at a specific case study, this article presents the results of an empirical analysis that was undertaken during July of 2015 within one of Lisbon's iconic historical public spaces, Rossio. The study was built upon two foundational interrogations: (1) What are the principal microclimatic risk factors within the square that can affect pedestrian thermal comfort thresholds?; and, (2) How can the identified risk factors be translated into opportunities for public space design?

In order to obtain an initial understanding of thermal comfort conditions, Computational Fluid Dynamic (CFD) and Shadow Behaviour Simulations (SBS) simulations were undertaken to establish six Points of Interest (POI) within the square. Subsequently, ambient temperature, surface temperature, relative humidity, wind speed, global radiation and Sky-View-Factor (SVF) were measured with on-site meteorological handheld equipment. In order to complement these examinations, Pedestrian Based Response (PBR) interviews were also conducted. Finally, through the application of the biometeorological RayMan model, the Physiologically Equivalent Temperature (PET) index was used in order to: (i) obtain approximations of diurnal physiological stress around the square; and subsequently, (ii) propose conceptual public space design solutions to improve existing thermal comfort conditions in the square.

1. Introduction

With the arrival of the climate change adaptation agenda, local decision makers and designers are continually focusing upon the implementation of measures to address local 'risk factors' [19]. This maturing bottom-up perspective is one that enables an exploration into how the sphere of urban design can improve the bioclimatic conditions within local scales. Thus, this developing bottom-up perspective is one that explores how the spheres of urban design and climatology can tackle meteorological implications through modifications of the urban public realm [10,31,46,49,66]. Used as a means to evaluate such modifications, numerous recent studies have incorporated the use of biometeorological studies to examine thermal comfort conditions as part of the public space design process of (e.g., [1,9,16,32,35,42,62,70]).

When considering the specific case of Lisbon, it is already recognised that urban planning and design need to adapt to future possible aggravations of climatic conditions which are presently raising implications upon its public realm [5,8,39]. Thus far, such studies have focused upon general bioclimatic conditions within the public realm (e.g. [11,57]), effects and intensities of UHI's (e.g.

Abbreviations: C, Cycle; CD, Crown Dimension; CFD, Computer Fluid Dynamics; ETCS, Ephemeral Thermal Comfort Solution; FP, Functioning Period; GP, Group Plantation; H/W, Height-to-Width ratio; IPCC, Intergovernmental Panel on Climate Change; JJA, June, July, August; KG, Köppen Geiger; LM, Limitation Mechanism; LP, Linear Plantation; MEMI, Munich Energy balance Model for Individuals; NC, No Clouds; NH, Nozzle Height; PBR, Pedestrian Based Responses; PCZ, Physiological Comfort Zones; PET, Physiological Equivalent Temperature; PL, Planting Layout; POI, Point Of Interest; PP, Pump Pressure; PS, Physiological Stress; RH, Relative Humidity; SBS, Shadow Behaviour Simulation; SW, Surface Wetting; SVF, Sky View Factor; TH, Tree Height; TP, Thermal Perception; UHI, Urban Heat Island; clo, cloud cover; Kamb, Change in Ambient temperature.

* Corresponding author.
E-mail addresses: andrenouri@fa.ulisboa.pt (A.S. Nouri), jpc@fa.ulisboa.pt (J.P. Costa).

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[3,5,38]), wind studies (e.g. [7,37]), and, the integration with planning policy (e.g. [6,8]). In addition, and inherent to the developing climate change adaptation agenda, studies relating to potential future climate change impacts upon the urban realm have also been disseminated (e.g. [4]).

Also located in Lisbon, this study presents the results of a bioclimatic analysis within one of the city's oldest civic spaces, Rossio. Based upon accessible meteorological equipment, and easy-to-use models/software for urban design and planning professionals, the study concludes a set of public space design solutions which were based upon the square's microclimatic risk factors. Undertaken in the summer of 2015, the empirical aims of the study were to: (i) identify the microclimatic risk factors within different areas of Rossio; (ii) to propose conceptual interventions that could potentially improve pedestrian thermal comfort during periods of annual higher climatological stress (i.e., JJA) in Rossio. Notwithstanding, the more encompassing objective of this study is to determine the lessons that the case of Rossio can bring in an era where urban climatology is becoming a continually important factor for local scale decision making and design.

2. Method

2.1. Study area

Lisbon is located close to the western coast of Portugal at 38°42′N and 9°08′W, with a climatic Köppen Geiger (KG) classification of '*Csa*' which implies that it has a Mediterranean climate with dry and hot summers [59]. During the year, and as presented by Refs. [48] and [15], the city witnesses: (i) between 10 and 20 'very hot days' days with ambient temperatures above 35 °C; (ii) between 100 and 120 'summer days' where maximum ambient temperatures exceed 25 °C; and lastly, (iii) up to two annual occurrences of ambient temperatures surpassing 32 °C for at least 16 days, corresponding to an urban heatwave. In terms of wind regimes, N and NW wind directions are the most common during the year, especially during the summer [2].

When considering the site of Rossio, although located just north of Lisbon's Tagus River (Fig. 1B), the square is located in the city's historical district which witnesses the strongest effects of UHI within the city [11], and often the highest ambient temperatures during the summer [6]. In addition, and within this district, most canyons present relatively high H/W ratios (i.e., of ≈1.66) (Fig. 1D), yet in the case of Rossio, this ratio is considerably lower (i.e., of ≈0.21) (Fig. 1E) thus increasing the susceptibility to microclimatic variables such as solar radiation during the summer. Such susceptibility of canyons with low H/W ratios has also been considered a high priority for thermal sensitive urban design (e.g. [52]), which in turn, summons the opportunity for public space design [23]. (■ See Appendix A.1/2 for Project Data Sheet).

2.2. Initial computer simulations

In order to establish the locations for the on-site meteorological measurements, two types of preliminary computer simulations were undertaken in order to: (i) identify areas that were more prone to microclimatic risk factors; and, (ii) validate the simulation results with subsequent onsite measurements. The selection of these two simulations were focused upon obtaining a synoptic comprehension of wind patterns, and radiation fluxes which: (i) are the most influenced by morphological and physical properties of the urban environment [42]; (ii) have proven to be the strongest parameters upon urban thermal comfort [12,16,34,35,72]; and, (iii) are often overlooked in top-down climatic assessments [41].

The first simulation was established to provide an initial indication of summer wind currents within the square through the use of Computational Fluid Dynamic (CFD) studies. In order to calibrate the wind tunnel study, four parameters were introduced into the CFD simulation: predominant wind direction, wind speed, horizontal height of the simulation plane, and lastly, sufficient 'contextual roughness' around the square.

As a starting point, and based upon data from the Portuguese Institute of Sea and Atmosphere (IPMA), wind rose studies indicated that the predominant wind direction for the July period varied between 315°–337.5°, i.e., ranging between NNW and NW (Fig. 1C). Such data was also utilised in numerous studies that explore wind regimes in Lisbon (e.g. Refs. [2,6,38]). When considering such implications upon the case of Rossio, it was noted that orientation of '*Avenida de Liberdade*' (Fig. 1A/B) aligned with the predominant wind direction for the summer period (i.e., JJA). Such an alignment raised an initial concern that this could generate a wind tunnelling effect, and propagate very strong wind speeds upon northern region of Rossio. When deciding upon the appropriate wind speed for the simulation, it was noted that mean values at street level are often considerably lower than those presented by meteorological stations [58]. Thus, and based upon previous studies that identified summer daily wind regimes within Lisbon for this time of year (e.g. [7,38]), a maximum wind speed of 5 m/s was applied to the simulation.

As concrete pedestrian height has varied slightly amongst existing microclimatic studies (i.e., by ± 0.50 m) in the last decade (e.g. [21,35,61,65]), the simulation plane for the CFD study was established at a height of 1.50 m. Finally, and when considering the size of the simulation, in order to consider the influence of surrounding buildings and roads before the wind patterns reached the square with an area of 30,000 m^2, the total simulated area was of 185,000 m^2. Due to the calibrated wind direction, a particular interest was considering the impact of the possible wind tunnelling effect projected from the north.

The second simulation was directed at obtaining a basic understanding of solar radiation within the square through Shadow Behaviour Simulations (SBSs). Also through the introduction of a geo-referenced massing model, the solar path was used in order to obtain the behaviour of shadows that were cast by the squares built form. As building heights were very much uniform in the square (i.e., 5 storeys), a synoptic building height of 18 m was used within the massing model. Within each simulation, the calibration of the simulation was adjusted in order to obtain the desired temporal scope and required precision. The first study was regulated to present a complete diurnal analysis of shading hours around the square (i.e., 08:00–17:00). In order to obtain a more precise result (such as vegetative shadows cast upon adjacent sidewalks and façades), the simulation was configured to assess resulting shadow patterns every 15. Subsequently, two more simulations were undertaken to analyse maximum shadow extents in the morning (i.e., 08:00–12:00) and afternoon (i.e., 12:00–17:00).

2.3. On-site meteorological measurements

Through the use of handheld/portable weather instruments (■ See Appendix B.1/3 for Equipment & Measurements), five different types of measurements were undertaken, i.e., Wind Speed (*V*), ambient temperature (T_{amb}), Relative Humidity (RH), global radiation (G_{Rad}), and surface temperature (T_{surf}). Although more sophisticated equipment could yield more accurate results, the focus of the selected equipment was also their ease of use and portability. Established upon an analytical timeframe of 10 min (where measurements were recorded every minute for 8 min, and a subsequent 2 to allow for relocation and set up time) a total of six POIs were permitted in order to obtain enough mean results around the site

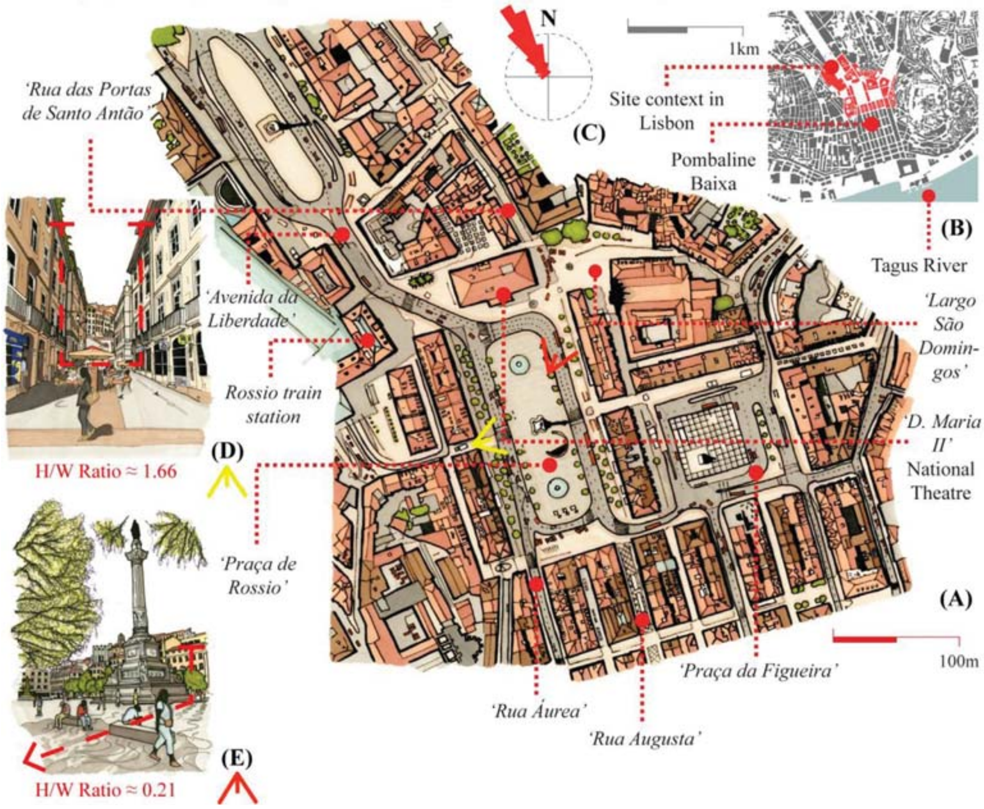


Fig. 1. **(A)** Site location and surroundings | **(B)** City context map | **(C)** Wind Rose with predominant wind direction | **(D)** H/W of surrounding canyons | (E) H/W of Rossio (perspective) | Source: Author's renderings.

every hour. This site assessment was repeated 6 times (thus forth termed as Cycle) in order to register diurnal microclimatic oscillations in the square. (■ See Appendix B.2/3 for Daily measurement method at each POI & C.1 for POI Equipment Layout).

During the hottest month of the year, a total of 6560 measurements were evenly distributed throughout 8 visits during the month of July. This distribution method was designed to: (i) obtain an overall climatic assessment throughout the entire month; (ii) enable a constant interval between visits (i.e., 2.5 days); and, (iii) allow for the collected data from each field visit to be subsequently processed. (■ See Appendix B.2/3 for Daily measurement method at each POI & C.1 for POI Equipment Layout).

2.4. Pedestrian based response interviews

Based upon similar studies (e.g. [17,33,68]), this section was aimed at determining psychological aspects that could complement both the thermophysiological analysis, subsequent design recommendations, and the generic bioclimatic guidelines at the end of the study. On the final site visit, two predominant methods were used to obtain the Pedestrian Based Responses (PBR):

- The first section, and based upon obtaining a sample of quantitative responses to evaluate human perception of the microclimate in-situ, 30 interviews were conducted to assess how pedestrians would mark from 1 to 7 (1 representing perfect, and 7 represent unsupportable) the following characteristics: ambient temperature, wind, strength of the sun, and overall comfort (■ See Appendix C.2 for Questionnaire Composition).
- The second section, was directed at assessing pedestrian cognitive mapping of the squares entire microclimatic conditions, whereby a total of 80 interviewees were informed that: (i) each person could only draw one circle for projected the cool area (in blue), and one circle for the hot area (in red); secondly, (ii) the circle could be as small or as large as they desired.

2.5. Thermophysiological analysis

To determine the effects of the thermal environment upon pedestrians, the study referred to the energy balance of the human body within the urban environment. This biometeorological approach is one that considers how the human body perceives a combination of atmospheric elements, through the use of a thermophysiological index, the Physiologically Equivalent Temperature (T_{PET}) [46].

Undertaking a similar methodical approach found in Refs. [1,2], in order to quantify thermal comfort of pedestrians, collected meteorological data from field measurements were assessed to identify PET values. This was achieved through the use of the RayMan Pro© software [44,45], that processed T_{amb}, RH, V, G_{Rad}, and T_{surf}. Furthermore, and in order to establish the grade of Physiological Stress (PS), a comparative chart was used (Table 1).

This being said, and although Physiological Comfort Zones (PCZ) were used as a means to quantify the thermal comfort of pedestrians, various studies have shown that pedestrians are comfortable within a wide range of environments as they react to numerous situations which induct higher comfort thresholds [20,30,34]. For this reason, although the physiological stress grade aided the evaluation of the exposure of environmental stress; it was just as important to recognise that pedestrians also avert microclimatic monotony in outdoor contexts, even if this implied that such desired fluctuations could bare them to environmental stimulation that exceeded their designated PCZ.

3. Results and discussion

3.1. Simulation results

When considering the initial outputs of the CFD study, and as shown in Fig. 2A, it was identified that the surrounding urban morphology led to: (i) wind advection rather than a tunnelling effect from '*Avenida de Liberdade*'; and, (ii) a wind tunnelling effect from the '*Portas de Santo Antão*' street, just north of the square. Within the centre of the square, the central statue leads to both the acceleration and deceleration of the predominant wind flow. This variation is due to the shelter effect from the base of the statue, resulting in a wind speed of ≈0.5 m/s, and the displaced acceleration of the wind that travels around the statue with a speed of around ≈2.1 m/s. Lastly, it is also noted a similar displacement effect of the trees, that led to a decrease of wind speed to almost ≈0.5 m/s beneath the crown, and an acceleration effect a few metres away.

With regards to SBS study, the identified hours of shading revealed 0 h within the centre of the square as a result of the squares low H/W ratio, and between 3 and 5 h of shade on either western-eastern sidewalk. It was noted, however, that shading hours did increase slightly directly beneath the tree canopies on both sidewalks Fig. 2B. In addition, and as shown in Fig. 2C/D, it was revealed that between: (i) 08:00 and 12:00 the western region of the site is completely exposed to solar radiation with exception of the shadows cast from the vegetative crowns; and, (ii) 12:00–17:00 the eastern side was exposed to solar radiation with exception of the shades cast by the trees. For this reason the amount of shading hours on either side is fairly balanced, yet it does not account for solar heat gain which most likely renders very different surface and ambient temperatures between the morning and afternoon.

3.2. Point of interest specification

The establishment of the POI was intended to provide a specific analytical location within the square that could examine pedestrian thermal comfort thresholds in that concrete area. By basing this selection upon the results obtained from the simulations, the locations of the meteorological recordings could be based upon anticipated microclimatic risk factors.

Fig. 3 presents the general distribution of the six allocated POIs which would register diurnal sequential bioclimatic fluctuations, whereby POI: (1) would confirm the absence of the wind tunnel effect within the NW region; (2) would test the impact of solar radiation with no vegetation shading, and the influence of the northern wind currents; (3) would assess the impact of the central fountain upon humidity levels and the lack of shading hours; (4) would analyse the impact of central higher wind speeds and lack of shading hours; (5) would examine the impact of street trees upon sidewalk temperatures and humidity levels; and (6) would test the impact vegetation upon central temperatures, and humidity levels. Moreover, this strategic distribution also enabled the on-site meteorological measurements to evenly spread around the site.

3.3. Meteorological results

3.3.1. Ambient temperature

As shown in Fig. 4A, both POI 1 and 5 presented the highest overall ambient temperatures between 10:00 and 14:00, particularly between 12:00 and 13:00. In addition it was noted that irrespective of their elevated exposure to solar radiation, and zero hours of diurnal shade (as demonstrated in Fig. 2B), POI 3 and 4 had a lower ambient temperature in comparison to the other locations that were over-cast by shade. In addition, and based upon the classification system of [48]; all site visits were considered 'Summer Days' since they obtained maximum ambient temperatures that exceeded 25 °C. Although the measurements on any site visit did not lead to a 'Very Hot Day' classification (i.e., where T_{amb} exceeded 35 °C), Day 3 presented a close maximum of 32.9 °C in POI 2 during C6.

3.3.2. Relative humidity

The measured relative humidity patterns revealed a strong correlation with that of ambient temperature during the day. Specifically, it was possible to verify that the POI's with the lowest temperature during the initial cycles correspond to those with the highest relative humidity percentage. In addition, modifications in the graph's trend between both microclimatic variables illustrated a strong relationship with one another.

When considering the possible influences of vegetative evapotranspiration and of the water fountains at the respective POIs, it was possible to confirm that they did not have a noticeable effect upon encircling RH levels or ambient temperature. Such results thus confirmed that single street trees were less effective in cooling when not in a group/cluster as also revealed by Ref. [66].

3.3.3. Wind speed

When comparing the measured wind patterns with the ones simulated in Fig. 2A, it was possible to conclude that the CFD simulations were generally analogous with those identified by the on-site measurements. In agreement with the CFD simulations, POI 1 revealed that '*Avenida de Liberdade*' did not generate a wind tunnel effect. In fact, and in conjunction with POI 5, POI 1 presented the lowest wind speeds as shown in Fig. 4C. In the case of POI 2, in comparison to other locations, and considering the possible wind tunnel effect from '*Portas de Santo Antão*' street, the location revealed only intermediate wind speeds. Furthermore, and located in the centre of the square, POI 3, 4 and 6 revealed the highest wind speed, particularly POI 4 which reached an average velocity of 2.0 m/s between 14:00–15:00 and 16:00–17:00.

3.3.4. Global radiation

The recording of global radiation during the day demonstrated a large variation both in POI 1 and POI 2 (Fig. 4D). This variation was resultant of sun patterns, and the resulting shade cast by the buildings on the east and western side of the square (Fig. 2B/C/D). Until 12:00, the western side of the square was fully exposed to solar radiation until it was overcast by the shade of the adjacent buildings. The measured global radiation in POI 1 and 5 were indicative of this change in radiation (i.e., from 660 to 63 W/m^2, and 159 to 39 W/m^2, respectively), whereby the variation witnessed in POI 5 was a lot smaller due to the continuous shade cast by the vegetative crown. On the other hand, as the shade receded from the eastern side of the square between 11:00–12:00, the radiation measured in POI 2 dramatically increased and began to drop after 14:00. Such results obtained from the on-site meteorological equipment complement the initial outcomes presented by the SBS study.

3.3.5. Surface temperature

Fig. 5A shows the variation of average surface temperatures during the day, where all temperatures were amalgamated for simplification purposes. In Fig. 5B, due to containing every material found in the square, POI 6 was used in order to provide an indication of how each of the different surfaces performed during the

Table 1
Ranges of the thermal index Physiologically Equivalent Temperature (T_{PET}) for different grades of Physiological Stress (PS) on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to [40]) | Source: (Adapted from [43]).

T_{PET}	PS
	Extreme Cold Stress
4°C	
	Strong Cold Stress
8°C	
	Moderate Cold Stress
13°C	
	Slight Cold Stress
18°C	
	No Thermal Stress
23°C	
	Slight Heat Stress
29°C	
	Moderate Heat Stress
35°C	
	Strong Heat Stress
41°C	
	Extreme Heat Stress

six cycles. Fig. 5A shows that the average temperatures in the POIs can reach differences of up to $25K_{surf}$, as illustrated between 16:00 and 17:00 in POI 5 and POI 4. Overall, POI 3 and 4 both had the highest surface temperatures throughout the day. Contrariwise, POI 2 proved to have significantly lower surface temperatures during most of the day.

As illustrated in Fig. 5A–C, the three hottest POIs were all those that incorporated Basalt paving. Finally, and when comparing the measured results in the shade, it was clear from Fig. 5B that there was a significant variation in surface temperature. The road surface, made of granite, reached the highest temperature in the shade, i.e., ≈30 K between 12:00–13:00.

3.4. PBR and psychological results

In accordance with numerous existing studies (e.g. [20,50,51,66,75]), the comprehension of psychological aspects related to thermal comfort thresholds can provide a very useful tool when evaluating outdoor environments. More specifically, this directly relates to the fact that a pedestrian that desires to visit an outdoor space will correspondingly wish to personify their visit in numerous ways, including adjusting their thermal regulatory system [54]. As a result, and independently of the desire for more or less climatic stimulation on behalf of the pedestrian, the crucial factor is enabling thermal 'choice', a factor which can easily be influenced by careful public space design that can substantiate such fluctuations of environmental exposure/simulation.

Correspondingly, when evaluating the results obtained from the PBR interviews, it was evident that potential idiosyncrasy correlated to the human psyche of 'choice making', could be effectively comprehended and related to the physical characteristics of the square. As shown in Fig. 6, by reviewing short term history (i.e., enquiring if the pedestrian had recently been in indoors), it was revealed that pedestrians who had recently been inside a building: (i) considered all microclimatic factors as at least 'pleasant'; and, (ii) considered the overall comfort as either 'perfect' or 'very pleasant'. On the other hand, the feedback obtained from pedestrians that had not been inside a building prior to the interview were substantially different, revealing: (i) classifications of 'unpleasant', 'very unpleasant' and even 'unsupportable'; and, (ii) the overall comfort of these pedestrians was noticeably lower and only 65% of pedestrians considered the microclimate as either 'perfect' or 'very pleasant'.

Such outcomes as revealed in Fig. 6 disclose that although the two groups were exposed to identical climatic conditions, psychological decisions can induce pedestrians to: (1) adjust their thermal perception differently; (2) lower or higher their desire for environmental stimulation accordingly; furthermore, and in the absence of other reasons to stay in the square, (3) if such availability of choice is not present, decide to leave.

The second segment of the PBR also revealed strong correlations between physiological and psychological decision making, particularly with regards to the pursuit of environmental stimulation and time of stay. Fig. 7 reveals how pedestrians perceived the general microclimate within the square. The presented map was built by overlapping the circles that were drawn by the pedestrians to identify either 'hot' or 'cool' areas. As demonstrated in both Fig. 7A/B, and contrary to the results obtained from meteorological instruments (shown in Fig. 4), the pedestrians: (i) found the middle of the square to be the hottest area; and (ii) considered the western region to be one of the coolest areas.

Furthermore, and as demonstrated in Fig. 7C, when complementing such results with the location of the interviewees, it was also identified that: (i) 50% of the interviewees were located in their designated cool area – of this percentage, 85% were seated; and, (ii) 13% of the interviewees were situated in their designated hot area – of this percentage, 80% were seated. Such results indicate that the majority of pedestrians located in either area, made the psychological decision to expose themselves to such stimuli, and more interestingly, to do so for a longer period of time.

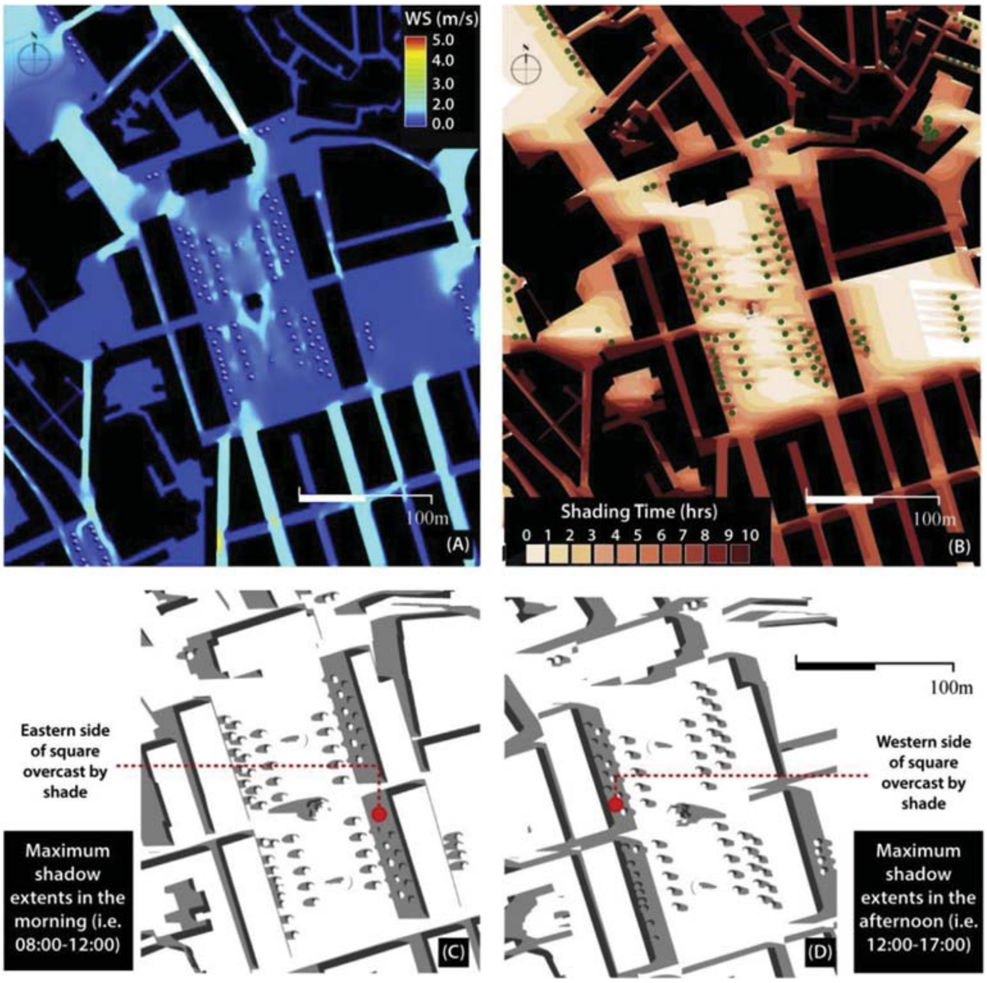


Fig. 2. **(A)** Wind Pattern simulation through Computational Fluid Dynamic (CFD) studies | **(B)** Shading time simulation through Shadow Behaviour Simulation (SBS) | **(C)** Maximum morning shadow extents through SBS | **(D)** Maximum afternoon shadow extents SBS | Source: Author's simulations.

This being said, and when considering the group of pedestrians which were neither in their designated cool or hot zone, and if sitting is assumed to be a behavioural indicator of thermophysiological acceptance; then the low percentage of seated pedestrians strengthens the adjoining importance of psychological aspects.

3.5. Thermophysiological results

3.5.1. Physiologically equivalent temperature and physiological stress

As indicated by the psychological results in the previous section, certain incongruities were identified between the data obtained from the meteorological recordings with those expressed by the interviewees. As a result, the RayMan model [44,45] was used in order to analyse the influences of the identified microclimatic elements upon the human biometeorological system within the six POIs.

The primary input parameters that were introduced into the model were T_{amb}, RH, V, G_{rad}, and T_{surf}. The first four of these microclimatic elements were the average values of the seven measurements undertaken at each POI during the six daily cycles. On the other hand, due to the amount of different surfaces, and their respective temperature disparity (Fig. 5B), the use of average values was considered to be excessively vague. For this reason, and as only one value could be introduced into the model; with the objective of always considering worse-case-scenarios, the highest surface temperatures were thus introduced. Furthermore, and in order to evaluate PET at the specific location and desired time, other parameters were also accounted for. Namely, and in addition to introducing geographical coordinates and altitude, and similar to the methodology used in studies by Ref. [6]; polar diagrams were taken at each location in order examine sky-view-factor values.

In order to determine the physiological stress levels throughout the day within each respective POI, Table 2 presents the mean PET over all seven days, expressed as $(\overline{PET})$. In addition, and when compared to the physiological stress grades presented in Table 1, it was identified that the hottest PET values and physiological stress grades varied between 14:00–15:00 and 15:00–16:00, resulting in ‘Strong Heat Stress’ predominantly in POIs with high SVF values. It should be noted that in the case of POI 2, which although obtained a slightly lower SVF comparably to POI 1, its exposure to the sun in the afternoon led to comparatively higher physiological stress grades (Fig. 2D).

3.5.2. Comparison with PBR results

When comparing such physiological and PBR outcomes, the locations with the highest PET/physiological stress levels were those in the centre of the square, namely POI 3/4. Correspondingly, and although recorded T_{amb} values were the lowest amongst these POIs, the PBR also identified these areas as the hottest in the square.

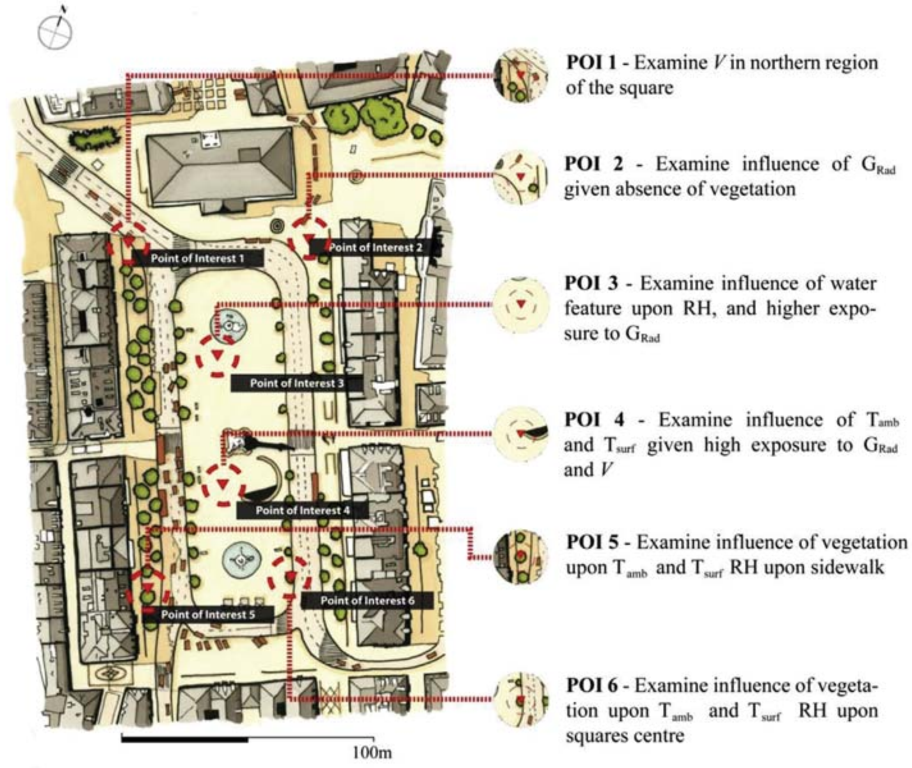


Fig. 3. Establishing specific Points of Interest (POI) based on initial simulations around the square | Source: Author's rendering.

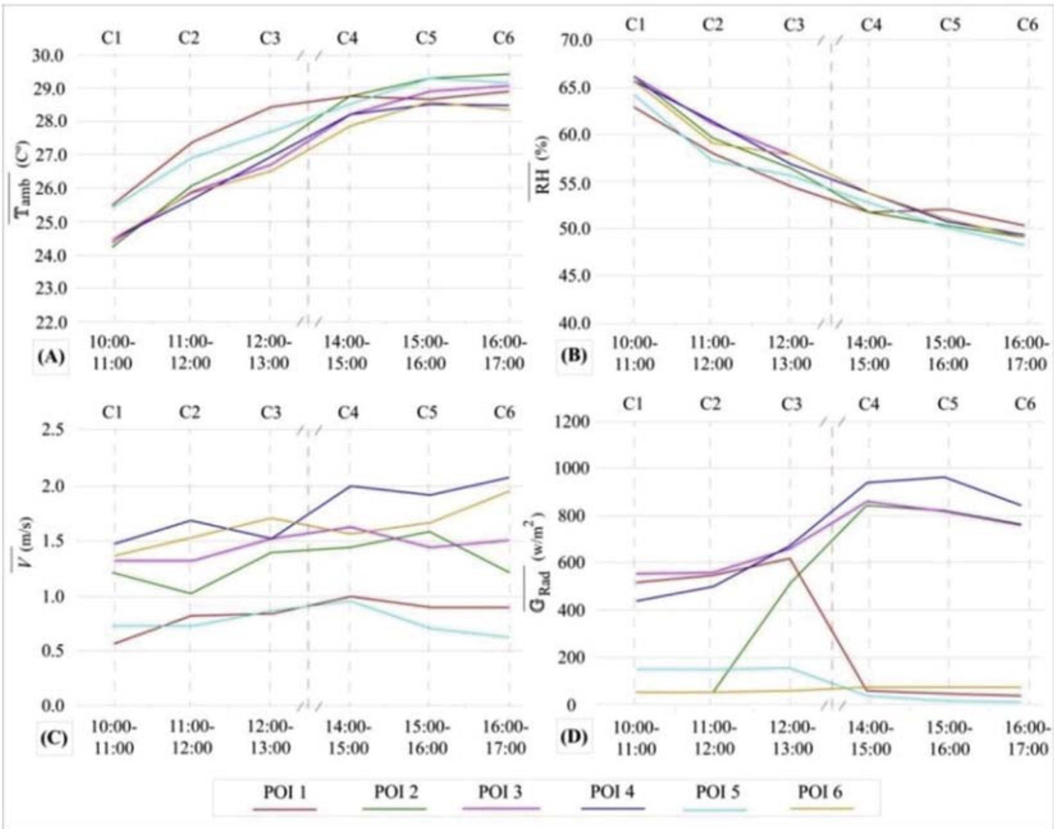


Fig. 4. Mean results obtained from meteorological instruments between 10:00–13:00 and 14:00–17:00 with a break during 13:00–14:00 (UTC +0) for pedestrian footfall count (displayed by red line) | **(A)** – Ambient Temperature | **(B)** – Relative Humidity | **(C)** – Wind Speed | **(D)** – Global Radiation | Source: Author's charts.

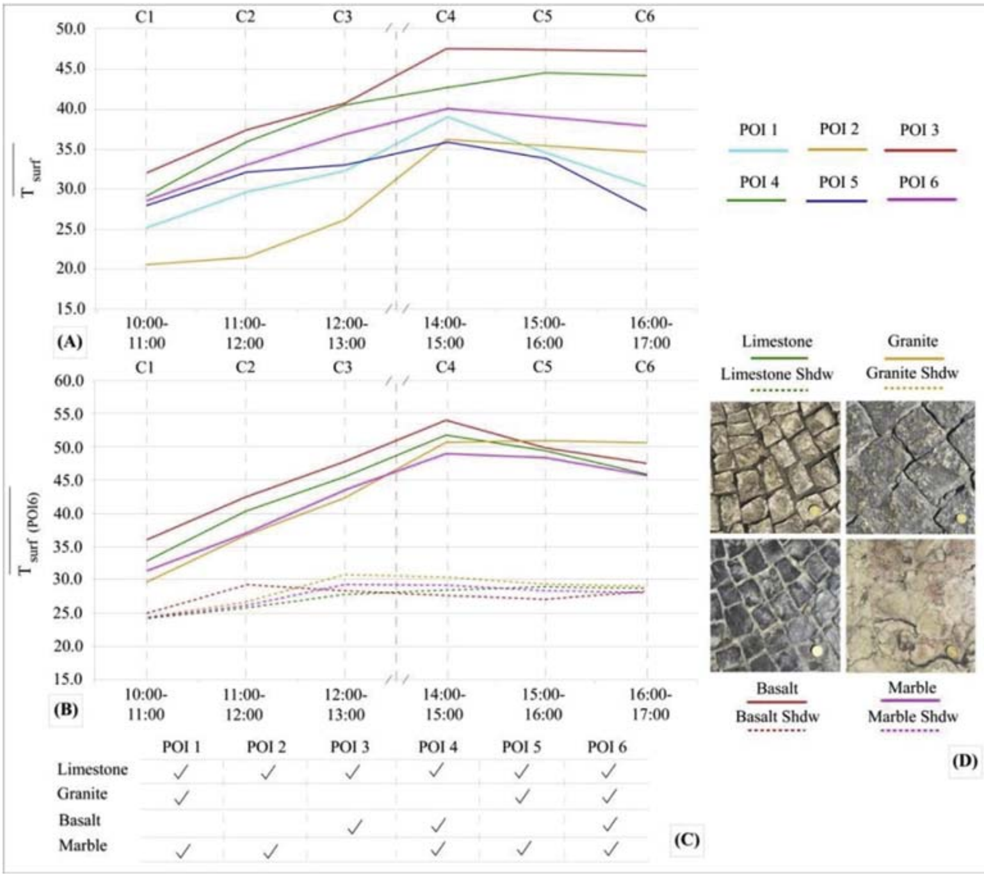


Fig. 5. Mean results obtained from meteorological instruments between 10:00–13:00 and 14:00–17:00 with a break during 13:00–14:00 (UTC +0) for pedestrian footfall count (displayed by red line) | (**A**) – Average POI Surface Temperatures | (**B**) – Average Surface Temperatures for POI 6 | (**C**) – POI surface composition | (**D**) – Surface appearance (coin in bottom-right corner used for visual scale comparison) | Source: Author's charts and photographs.

Equally, POI 1/5 which were located in the cooler zones as identified by PBR, also revealed considerably lower PET values. Set apart by only a small margin, POI 6 revealed the overall lowest PET values, which was also considered one of the coolest locations in the square. These results revealed both the effectiveness of the RayMan model, and the notable capacity of pedestrians to evaluate the microclimatic environment around them.

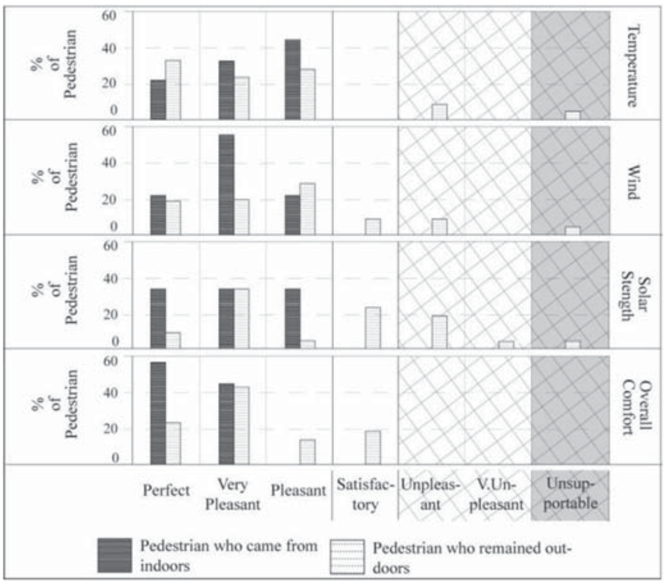


Fig. 6. PBR results which compares identified 'thermal classifications' of different variables against pedestrians who had been indoors at least 30 min before the interview with those who remained outdoors | Author's chart.

Fig. 8A reveals the footfall results that were undertaken between 13:30–14:00 during every site visit. Although it may initially induce the notion that pedestrian footfall was a direct result of comfort thresholds (i.e., hottest locations revealing the least amount of pedestrians, and vice-versa), other factors lie behind such results, particularly the psychological aspect of 'choice'. As an example, although POI 6 was considered one of the coolest areas of the square (both by physiological and PBR results), its adjacent mass cement bench that evoke the design concept of "*you sit right here and you sit there*" ([73]; p. 36) revealed the limited (yet used to maximum capacity) seating options to be found in the shade (Fig. 8B). On the hand, and in the case of POI 3/4, even pedestrians who desired to sit in the sun were met with a lack of seating options, and a security scolding for sitting upon the edge of the northern/southern water fountains just adjacent of the POIs. Such outcomes reveal the importance of also considering psychological aspects such as 'choice' in addition to thermophysiological factors such as pedestrian PCZ.

3.5.3. Regression studies

Taking the comparative studies a little further (■ See Appendix D for Variable Regression Study Results), the relationship strength between the different microclimatic variables was identified within each of the six POIs. This exploration was enthused by the

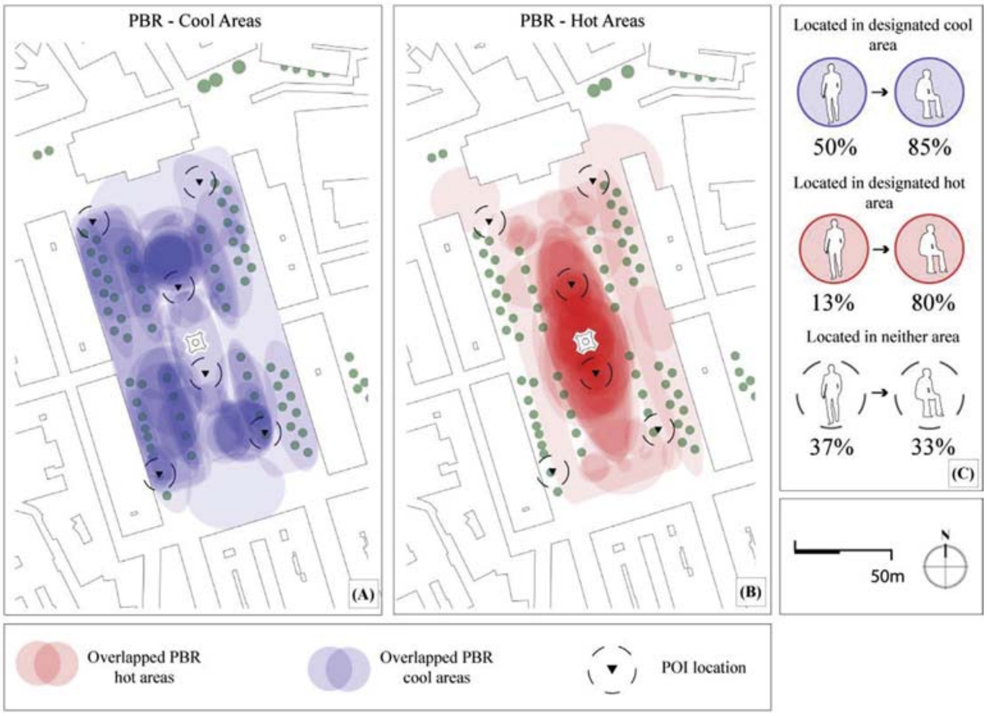


Fig. 7. Pedestrian Based Response (PBR) drawings of perceived cool and hot areas in the square | **(A)** – Cool areas | **(B)** – Hot areas | (**C**) – Percentage of pedestrians located in cool/hot areas, and seating percentage | Source: Author's rendering.

methodology used in the study conducted by Ref. [67] who used similar linear regression (r) examinations to determine the relationship between microclimatic variables and vegetative crowns in urban outdoor spaces. In this study, the analysis of both r, and its mean value during all POIs (expressed as $\bar{r}$), indicated the relationship strength between different microclimatic variables, and under which concrete conditions. It was demonstrated that both type of coefficients played an important role in understanding the: (i) intrinsic equilibrium between the microclimatic elements themselves; and, (ii) how urban structures (i.e., building configurations and vegetation) influenced such associations within outdoor urban spaces.

In the case of PET and mean-radiant-temperature, the intrinsic association to one another was a result of the direct 'cause-and-effect' relationship within the Rayman analysis model [45]. As to be expected, and resultant of the cooler morning air being closer to saturation, relative humidity and ambient temperature also displayed an 'Outstanding' negative mean coefficient in all POI's (expressed as $\bar{r}$). This outcome was also revealed in studies disseminated by Refs. [64,67]; and [60].

Similarly, a 'Very Strong' relationship was identified between ambient and surface temperature which substantiates the imperative correlation between the two microclimatic variables. Also verified in numerous studies, such 'cause-and-effect' relationship was attributed to the sensible heat released into the atmosphere when surface temperature surpasses that of ambient temperature [27,63,69].

Opposingly, the assessment of the relationship between wind patterns and other microclimatic variables revealed that: (i) $\bar{r}$ results indicated that wind patterns had a generally weak effect on other variables throughout the six POIs; (ii) higher P values (as was the case with ambient temperature and wind speed) illustrated statistical weakness between the data sets; and, (iii) individually, and in the case of POI 3/4, the obtained r values revealed stronger correlations. However, and as identified in studies disseminated by Ref. [74]; general wind measurements proved to be difficult due to the intrinsic and periodic fluctuations of wind speed at pedestrian level. Reflectively, a complementary future wind study with increased meteorological measurements and variables (such as wind gusts) could potentially better explain such general $\bar{r}$ wind correlations. Regardless of such $\bar{r}$ outcomes, the important influence of wind was still clear within the individual regressions. As an example, when considering POI 3 and 4, PET and wind speed revealed 'strong' and 'very strong' r values of 0.6414 ($P = 0.05$) and 0.7006 ($P = 0.03$). Similar results were also presented by Ref. [12]; who identified that summer winds between 1.0 and 2.0 m/s had a: (i) strong influence on thermal sensation when a pedestrian was in direct solar radiation conditions; and, (ii) considerably weaker effect in shading conditions. Interestingly, it was furthermore noted that the velocities during a windier day in the study of [12] were almost identical to: (i) those measured by the meteorological device in POI 3/4 (particularly between 14:00–1600) as shown in Fig. 4C; and similarly, (ii) those projected by the early CFD studies shown in Fig. 2A.

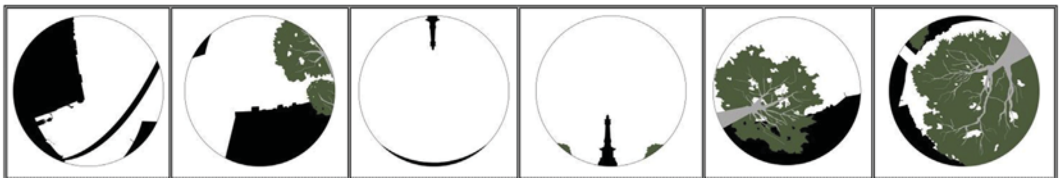
In general, while it was demonstrated that the r values between all of the microclimatic variables were stronger in POI 3 and 4; POI 1 and 5 revealed 'nugatory', 'very weak' and 'weak' r values. The reason for such weak correlations can be attributed to the change of global radiation between 12:00–13:00 (Fig. 4D) causing disparity between the microclimatic variables. In POI 1 and 5, the drop of solar radiation upon the two locations led to a delayed, yet significant, drop in surface temperatures between 14:00–15:00 and 16:00–17:00 by 8.8K_{surf} and 8.6K_{surf}, respectively (Fig. 5A).

3.6. Conceptual solution proposals

Thus far, numerous similar studies have explored the potential of passive urban design options within outdoor public spaces (e.g., [22,24,34,53,66,75]). Within such practices, such options refer directly to the improvement of climatic conditions through the

Table 2
Identification of mean PET from all site visits and resulting correlations with physiological stress grades | Source: Author's Table.

	POI 1		POI 2		POI 3		POI 4		POI 5		POI 6	
	$\overline{PET}$	PS	$\overline{PET}$	PS	$\overline{PET}$	PS	$\overline{PET}$	PS	$\overline{PET}$	PS	$\overline{PET}$	PS
10:00-11:00	30.0	Moderate Heat St.	21.5	No Stress	28.6	Slight Heat St.	28.2	Slight Heat St.	30.9	Moderate Heat St.	26.2	Slight Heat St.
11:00-12:00	32.6	Moderate Heat St.	24.0	Slight Heat St.	32.6	Moderate Heat St.	30.8	Moderate Heat St.	34.3	Moderate Heat St.	29.0	Slight Heat St.
12:00-13:00	34.6	Moderate Heat St.	29.7	Moderate Heat St.	33.8	Moderate Heat St.	33.8	Moderate Heat St.	35.8	Strong Heat St.	28.6	Slight Heat St.
14:00-15:00	30.7	Moderate Heat St.	34.9	Moderate Heat St.	37.8	Strong Heat St.	37.1	Strong Heat St.	33.0	Moderate Heat St.	33.4	Moderate Heat St.
15:00-16:00	31.7	Moderate Heat St.	36.2	Strong Heat St.	39.4	Strong Heat St.	38.2	Strong Heat St.	32.5	Moderate Heat St.	33.9	Moderate Heat St.
16:00-17:00	29.2	Moderate Heat St.	37.7	Strong Heat St.	39.2	Strong Heat St.	37.5	Strong Heat St.	30.6	Moderate Heat St.	31.1	Moderate Heat St.



SVF : 0.47	SVF : 0.42	SVF : 0.94	SVF : 0.93	SVF : 0.19	SVF : 0.06

Key:	PS	Physiological Stress Grade	$\overline{PET}$	Mean PET over all seven site visits	SVF	Sky-View-Factor

design and implementation of urban measures that attenuate thermal comfort conditions for pedestrians. Within this study, and in order to consider the worse-case-scenario, the obtained $\overline{PET}$ in Day 3 (hottest day out of the seven visits) was used to consider how conceptual public space interventions could attenuate the encircling microclimate in each of the four hottest POIs (i.e., POI 2/3/4/5). These locations were established by considering those which obtained at least a ‘Strong’ physiological heat stress grade from the $\overline{PET}$ data set, as shown in Table 2. Thus, and focusing on public space design recommendations, three types of passive urban design applications were recommended for the four hottest POI's of the square, namely, vegetation, shelter canopies, and water/misting systems. (■ See Appendix E & F for Solution Datasheet I & II).

3.6.1. Vegetation

The use of vegetation was recommended in both POI 2 and 3. In POI 2, the extension of the Linear Plantation (LP) configuration by three trees was recommended in order to prolong the tree line on

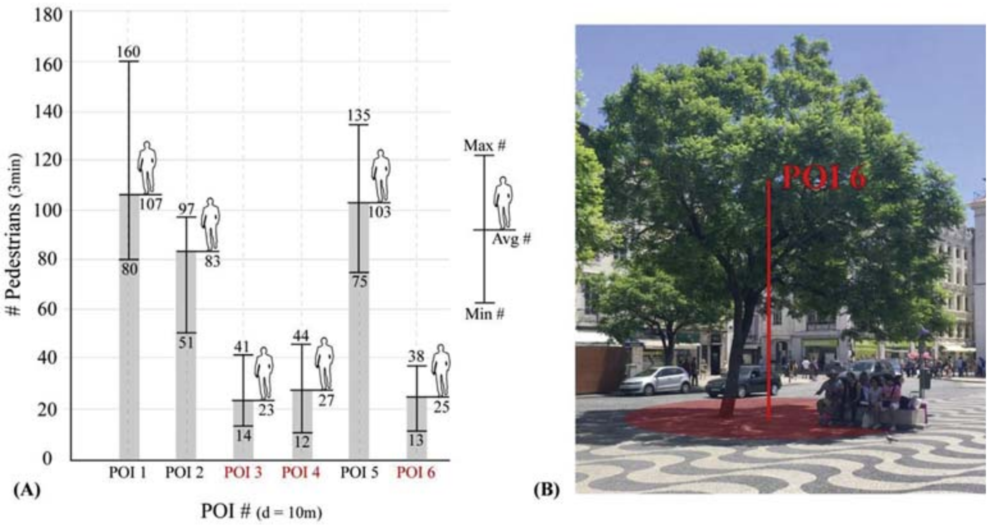


Fig. 8. Pedestrian Foot-count results and POI 6 bench use.

the eastern sidewalk into '*Largo São Domingos*' (Fig. 1). The added trees were the same species as those already present upon the sidewalk. The choice to maintain the species was not only for vegetative uniformity, but also based upon the positive thermal contributions of the *Tipuana Tipu* species, as evidenced in bioclimatic projects and studies in identical '*Csa*' climates [18,65]. The decision to continue the LP was based upon such planting configurations being able to effectively deflect: (i) radiation, especially when the tree line is parallel and close to a building frontage (e.g. [13,14,26,47]); and, (ii) wind patterns which occur perpendicularly to the tree line (e.g. [24,56,71]).

In POI 3, a Group Plantation (GP) of six *Tipuana Tipu* was recommended for the centre of the square (Fig. 10) which would deflect higher amounts of radiation, and moreover elevated wind currents as identified by both the CFD/SBS studies (Fig. 2A/B), and meteorological equipment (Fig. 4). (■ See Appendix F for Measure Specifications).

3.6.2. Shelter canopies

The usage of shelter canopies was suggested both in POI 2 and 4 in order to augment and/or provide shading provisions within the two locations. In the case of POI 2, and in addition to increasing the sidewalk's tree line, nylon canopies were suggested between the branches of the trees in order to create a continuous shaded area upon the sidewalk. The type of canopy used in this location is deemed as an Ephemeral Thermal Comfort Solution (ETCS), which encompass short-term solutions during annual periods of higher thermal stimuli [53].

When approaching POI 4, the objective of the intervention was to provide both seating and shading options for pedestrians within the centre of the square. As a result, this would augment pedestrian perceived control beyond the choice between shaded and sunny areas in the square, and provide a location that could be 'thermally personified'. In order to enable pedestrians to close and open the four introduced shelter canopies, a pull-string mechanism was suggested for each of the seven acrylic flaps which are supported by a central aluminium structure (Fig. 11). When shade is undesired, the flaps remain in an up position until the pull-string mechanism is triggered. (■ See Appendix E.1 for Calculation Methods).

3.6.3. Water/misting systems

The application of water/misting systems was divided into two types, those which caused Surface Wetting (SW), and the other that used micro water droplets intended to cool ambient temperature without exacerbating acceptable RH levels. Normally, and within the existing literature, these types of systems are discussed in have the tendency to fall into two segregated disciplines, namely that of: (i) design, which often fall short in explaining how their integrated water/misting systems can concretely attain the correct equilibrium between RH and ambient temperature (e.g., [55]); and, (ii) engineering, which solely focus upon equilibrating humidity levels with temperature thresholds without considering the design characteristics [28]. Neither of these disciplines is more important than the other, accordingly and undertaking an interdisciplinary approach, this section sought to combine both in the recommendations suggested for both POI 3 and 5.

The measure proposed for POI 3 integrated SW as a design feature in order to form a surface of water that would not only address pedestrian thermal comfort levels, but moreover, reflect the surrounding façades of the square. In addition, this measure can be triggered during the summer period (JJA) only, thus allowing the surface to remain dry during the rest of the year (Fig. 10).

Within POI 3, and over a total area of 160 m^2, a sheet of water would be spayed through a micro nozzle system over a new configuration of slabs which imitates the traditional Portuguese 'waved' paving pattern (Fig. 10). In order to avoid stagnation of the static water once on the ground, the flooded water would be recollected through the new paving slabs leaving the pavement surface dry. More concretely, both Limitation Mechanisms (LM) and Functioning Periods (FP) were stipulated for the operation of the misting systems throughout the day. Firstly, the LM was based upon detecting encircling RH, and if this value surpasses 70% then the mechanism would remain off. This is exemplified between 10:00 and 11:00 where the measured $\overline{RH}$ demonstrated percentages superior to 70% (Fig. 4B), thus the mechanism for this time of day remains off by default. Subsequently, and as diurnal RH levels lower, the potency of the mechanism would subsequently increase during the day based on the stipulated FP. By 17:00, where RH is at its lowest, the system would be at maximum strength with a FP of 4 min, and with an interval of 1 min between sprays. In addition, in order not to exceed the optimal amount of water upon the slabs, the frequency of water collection would be increased from 14:00 onwards.

Given that SW was not permitted in POI 5 (due to the coffee areas below), in order to effectively lower ambient temperature without imperilling acceptable humidity levels, the appropriate micro-droplet SMD, Pump Pressure (PP), Nozzle Height (NH), and FP were calculated and proposed (Fig. 12). (■ See Appendix E.2 for Calculation Methods).

3.7. Point of interest results

Within this section, the conceptual solutions were introduced into the four hottest POIs in order to test the potential reductions in T_{PET} and physiological stress thresholds. Through the use of the RayMan model, and in amalgamation with other parameters as discussed in previous sections, the principal PET calculation inputs were presented for each location. These inputs were divided into two sets, those pertinent to existing circumstances, and those which were projected as a result of the passive design applications. With regards to the projected input values, the following was deliberated:

- Unlike existing T_{surf} which was based upon highest surface temperatures; since the T_{surf} values were too ambiguous to project after the proposed design solutions (particularly in POI 3), this attribute was not included within the calculation. However, it was considered that this would not rebut the projections as this input was a complementary parameter for PET calculation within the RayMan model [45].
- With regards to projecting radiation values, in: (i) POI 2, based upon the nylon study as discussed in (■ Appendix F.3), the obtained hourly W/m^2 was used as an input within the RayMan model; (ii) POI 3, G_{Rad} inputs were based upon the average diurnal measurement of (i.e., of 67.5 W/m^2) obtained in POI 6 (i.e., also located beneath a tree in the centre of the square), this average was used due to the limited daily variation of solar radiation within the centre of the square; (iii) POI 4, established on the acrylic study as discussed in (■ Appendix F.3), the obtained hourly W/m^2 was used as an input within the RayMan model.
- In the case of POI 3/5, the inputs of relative humidity and ambient temperature were based upon the ratio of [28,29] as presented within (■ Appendix E).

Fig. 9 shows the difference between the existing $\overline{PET_{DAY3}}$ against the estimated diurnal T_{PET} for POI 2 ($\Delta T_{PET(2)}$) with the application of the nylon shelter canopies, and the introduction of the three *Tipuna Tipo* trees in POI 2. Due to being in the shade until 11:30, the $\Delta T_{PET(2)}$ only starts to lower once the location is cast in the sun, and the amount of solar radiation upon pedestrian level is decreased. As

Input Parameters	T_{amb} (°C)		T_{surf} (°C)		G_{Rad} (W/m^2)		V (m/s)		RH (%)	
	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Pro .
1 :00- 11:00	23.5	23.5	19.7	-	55	53.4	0.6	0.6	69.1	69.1
11:00-12:0	26.3	26.3	22.2	-	57	55	0.7	0.7	59.0	59.0
12:00-13:00	26.6	26.6	28.4	-	515	75.2	1.2	1.2	60.9	60.9
14:00-15:00	30.1	30.1	45.2	-	843	75.6	1.3	1.3	48.7	48.7
15:00-16:00	31.7	31.7	43.6	-	820	94.7	0.8	0.8	46.3	46.3
16:00-17:00	32.4	32.4	45.7	-	760	96	0.8	0.8	42.2	42.2

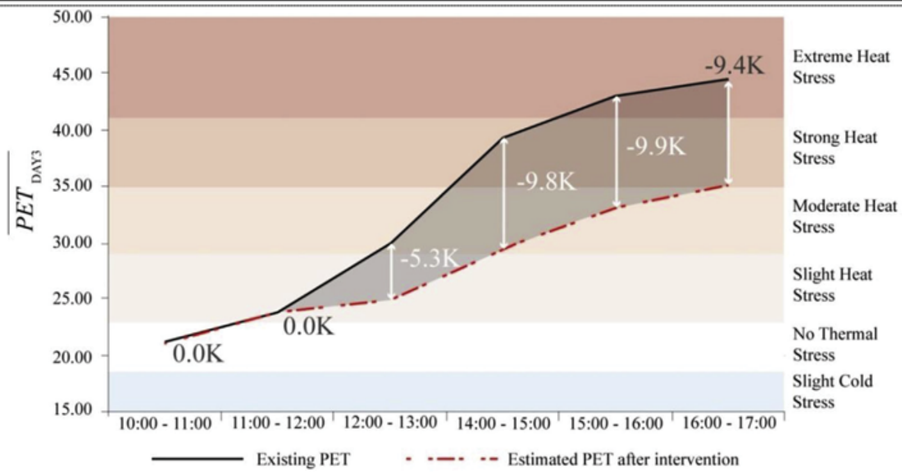


Fig. 9. Conceptual intervention in POI 2 and $\Delta T_{PET(2)}$ variation | Author's rendering & table.

shown in Fig. 9, where the original PS varied between 'Moderate Heat Stress' and 'Extreme Heat Stress' after 12:00–13:00, the estimated PS after the suggested intervention varies between 'Slight Heat Stress' and just surpasses the 'Moderate Heat Stress' in C6. Such variation is resultant of the reduced T_{PET} values, which reaches a maximum difference of $-9.9K_{PET}$ between 15:00–16:00. (■ See Appendix F.2/3 for Measure Specifications).

Fig. 10 demonstrates the resulting $\Delta T_{PET(3)}$ for POI 3 which initially revealed to be one of the hottest locations in the square. In accordance, POI 3 witnessed the highest decrease in T_{PET} after the proposed intervention which combined six shade trees with a SW water measure, leading to a maximum decrease of $-16.6K_{PET}$. This variation from existing T_{PET} occurred between 15:00–16:00, where the potency of the water system was at its maximum (under the compliance of the stipulated LM). Furthermore, and as can be seen from the physiological stress thresholds, the $\Delta T_{PET(3)}$ varied between 'Slight Heat Stress' and 'Moderate Heat Stress' which originally varied predominantly between 'Strong Heat Stress' and 'Extreme Heat Stress'. (■ See Appendix F.4 for Measure Specifications).

Fig. 11 shows the respective T_{PET} reduction for POI 4 with the four installed shelter canopy structures in the centre of the square. Although the $\Delta T_{PET(4)}$ values are based upon being beneath the shelter, pedestrians are able to close the acrylic flaps if they choose to sit in the sun. The maximum reduction in T_{PET} was measured between 15:00–16:00 which reached $-12.3K_{PET}$ as a result of the attenuated radiation upon the pedestrians beneath the shelter. Similar to POI 3, the existing T_{PET} almost reached 50 °C, a value that was accountable to the very high mean-radiant-temperature which reached 66 °C. Yet, with the presence of the canopies, and the reduction of W/m^2 upon the pedestrians, the resulting mean-radiant-temperature of 43.6 °C led to a $\Delta T_{PET(4)}$ of 36.3 °C. (■ See Appendix F.3 for Measure Specifications).

Fig. 12 shows the last suggested intervention that took place in

Input Parameters	T_{amb} (°C)		T_{surf} (°C)		G_{Rad} (W/m^2)		V (m/s)		RH (%)	
	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.
10:00-11:00	24.2	24.2	32.4	-	555	67.5	0.8	0.8	67.5	67.5
11:00-12:00	26.3	25.3	37.9	-	565	67.5	0.8	0.8	61.3	66.3
12:00-13:00	27.1	25.1	42.6	-	660	67.5	1.0	1.0	55.8	65.8
14:00-15:00	31.0	28.0	50.6	-	860	67.5	0.9	0.9	46.4	61.4
15:00-16:00	30.6	27.6	50.9	-	898	67.5	0.8	0.8	48.2	63.2
16:00-17:00	30.7	26.7	51.4	-	780	67.5	1.6	1.6	44.6	64.6

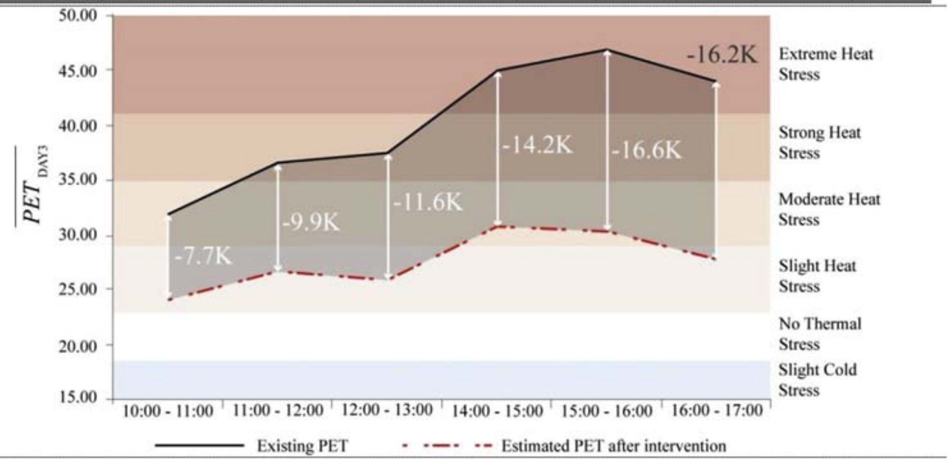


Fig. 10. Conceptual intervention in POI 3 and $\Delta T_{PET(3)}$ variation | Author's rendering & table.

POI 5, which consisted exclusively of evaporative cooling to attenuate thermal comfort levels. Since POI 5 proved to be coolest of the four locations, $\Delta T_{PET(5)}$ led to more modest reductions in comparison to the estimated T_{PET} in the other locations. Nevertheless, one of the objectives of the intervention was to decrease the physiological stress between 12:00–13:00 from 'Strong Heat Stress' which was what identified the location as one of the hottest locations as shown in Table 2. As shown by the presented $\Delta T_{PET(5)}$, the resulting diurnal values vary between 'Moderate Heat Stress' and 'Slight Heat Stress', with a maximum decrease of $-4.7K_{PET}$ between 14:00–15:00. (■ See Appendix F.5 for Measure Specifications).

4. Informing bioclimatic public space assessment and design guidelines

By investigating the observed microclimatic risk factors and their respective translation into opportunities for public space design, this study suggested numerous interventions for a specific case study in Lisbon. Furthermore, and as stated in the introduction, an analogous objective of this study was to contribute to general thermal sensitive public space guidelines. Such guidelines were intended to aid local design and decision making when tackling meteorological aggravations associated to Mediterranean climates with both hot and dry summers through public space design. Furthermore, and since thermal sensitive urban design has been identified as a high priority for canyons with low H/W ratios (e.g. [52]), the set guidelines are based upon assessing squares with similar characteristics to those found in Rossio.

4.1. Assessment guidelines

- In order to construct an overall comprehension of a site's bioclimatic condition, initial simulations such as CFD (i.e., Computational Fluid Dynamic) and SBS (i.e., Shadow Behaviour Simulation) should be undertaken to indicate areas which present the risk factors for pedestrian thermophysiological comfort. With regards to CFD, such studies require the correct calibration of the area's predominant wind direction/speed, simulation size and height. With regards to SBS, two types of geo-referenced studies should be undertaken with the appropriate analytical precision times: (i) a diurnal assessment to determine total hours of shading; and, (ii) a morning/afternoon simulation in order to account for diurnal shading oscillations.

- Based on the initial simulations, POIs should be established in order to develop the initial appraisal of thermal comfort conditions around the canyon. Reflectively, and based upon a recommended analytical timeframe of 10 min at each POI (eight minutes for meteorological recordings, plus 2 min to allow for relocation and set up time), a maximum of six POIs are suggested in order to obtain results around the site every hour (i.e., constituting an analytical 'Cycle'). Such Cycles should be distributed along the day in order to register diurnal sequential climatic fluctuations.
- With regards to on-site meteorological equipment selection, decision makers and designers should not be limited by the inability to obtain excessively sophisticated and expensive machinery to undertake microclimatic measurements. Once correctly selected and calibrated, accessible, affordable, and easily operated equipment are available to carry out a sufficiently detailed bioclimatic study to inform public space design.
- The use of the thermophysiological index PET should be used to inform the assessment/design of existing and projected modifications through easy-to-use biometeorological software platforms, such as RayMan. Such assessments permit the exploration of how pedestrians perceive a combination of atmospheric characteristics within the different zones of the canyon. Such assessments become particularly relevant for '*Csa*' climates, where evaluations of elevated T_{amb} levels (which can be further aggravated by UHI effects) can be combined with other climatic characteristics in order to obtain a wholesome evaluation of thermophysiological implication upon pedestrians. Such a cross-analysis of variables becomes predominantly vital as the evaluation of T_{amb} values can be particularly deceptive as an indicator of outdoor comfort thresholds when evaluated on its own.

4.2. Design guidelines

4.2.1. Designing to enhance 'choice'

- In thermophysiological terms, designers and decision makers should note that although PCZ (i.e., Physiological Comfort Zones) provide an effective method to quantify physiological stress, it should also be noted that pedestrians also avert microclimatic monotony. For this reason, design solutions should provide a base of 'choice' that enables a wide range of thermal stimuli.
- In psychological terms, and in order to address the potential provision of thermal 'choice' through public space design, psychological aspects can become a potent tool to aid design decisions by evaluating: (i) pedestrian cognitive mapping; (ii) in-situ evaluations of individual climatic stimuli; and, (iii) registering basic information of their time of stay, activity and recent thermal history.
- In order to influence choice, public space design must incorporate solutions that substantiate such desires for oscillations in thermal exposure. In the example of seating, their integration with thermophysiological considerations can induce pedestrians to stay longer, or even induce pedestrians to expose themselves to a thermal stress which would, customarily, surpass that of their designated PCZ. This is especially pertinent for canyons with low aspect ratios.

4.2.2. Designing for low aspect ratios

- When considering design options for the centre of the canyon, the susceptibility of elevated G_{Rad} must be considered. Such vulnerability is a result of high SVF values which lead to reduced shading hours, which consequentially result in dramatic increases in other variables such as T_{surf}, T_{mrt}, and T_{PET}. On the other hand, when considering proposals for the lateral areas of the canyon, such considerations of susceptibility should be more focused upon implications of dramatic G_{Rad} oscillations upon other variables.
- Given the higher susceptibility to physiological stress, and since canyons with lower aspect ratios often present higher activity threads in the lateral areas of the canyon, when approaching central areas, public space interventions must always reinforce 'choice' both in terms of activity threads (such as seating), and of 'thermal personification' (such as provision of shaded and non-shaded areas).

4.2.3. Designing with vegetation

- When considering vegetative shading of species/options (such as *Tipuana Tipu*) it should be noted that even at full maturity individual street trees do not lead to reductions of T_{amb}, nor sequential increases of RH at pedestrian height (as a result of latent evapotranspiration). On the other hand, such trees provide sufficient vegetative density (or Leaf Area Index (LAI)) to reduce SVF, and attenuate G_{rad} levels that, in turn, reduce T_{mrt} and T_{PET}.
- In cases where the trees are configured in a linear configuration, and resulting shadows do not intersect due to their plantation spacing, it is necessary to consider higher radiation fluxes in-between these shadows upon the sidewalk. However, the use of shade upon the pedestrian areas should also be approached as a means to increase the 'choice' of climatic stimuli, and not create a monotonous conditioned environment. Furthermore, when introducing trees within the sidewalk, the increased shading cast from adjacent buildings must be analysed since the amount of Watts/m^2 will be considerably lower than those found beneath a tree within the centre of the canyon. When approaching *V* shielding, when parallel to building façades, linear configurations present a promising potential capability to diminish perpendicular air currents.
- In circumstances where group configurations are proposed, particularly for the centre of a canyon, it becomes synonymously important to consider the extension, and diurnal oscillation, of cast shadows. Since the area will very likely witness limited shading hours, their strategic placement in the square must also consider factors such as existing/projected footfall patterns, activity threads, and seating provisions. When approaching *V* shielding under such circumstances, group plantations are able to deflect higher *V* patterns, which are customarily found within the centre of low aspect canyons. It should be noted, however, that as this type of intervention shall be present all year round; foliation and defoliation periods must also be considered during colder seasons.

4.2.4. Designing with shelter canopies

- Similar to designing with vegetation, the use of shelter canopies must always consider annual variations of the squares microclimatic conditions. For this reason, the design of permanent

Input Parameters	T_{amb} (°C)		T_{surf} (°C)		G_{Rad} (W/m^2)		V (m/s)		RH (%)	
	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.
10:00-11:00	24.3	24.3	29.1	-	440	139	0.5	0.5	65.9	65.9
11:00-12:00	24.8	24.8	38.0	-	501	145	1.7	1.7	68.8	68.8
12:00-13:00	27.5	27.5	42.5	-	670	144	0.8	0.8	57.7	57.7
14:00-15:00	30.7	30.7	50.0	-	940	156	0.9	0.9	47.3	47.3
15:00-16:00	31.1	31.1	52.1	-	960	159	0.8	0.8	46.7	46.7
16:00-17:00	30.6	30.6	51.0	-	840	155	2.2	2.2	43.8	43.8

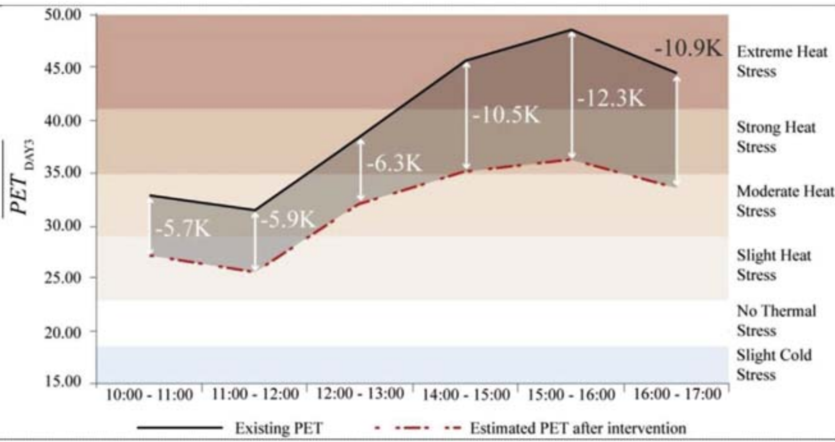


Fig. 11. Conceptual intervention in POI 4 and $\Delta T_{PET(4)}$ variation | Author's rendering & table.

solutions must also be evaluated against their impact during colder months where greater exposure to solar radiation is likely to be desired by pedestrians. Such constraints can be overcome by providing the option to modify or 'close' the respective structure during the winter.

- The main contribution of shelter canopies is the reduction of G_{rad} which subsequently reduces other variables such as T_{surf}, T_{mrt} and PET. For this reason, and within a bioclimatic perspective, even with rudimentary examinations, it is useful to evaluate the projected amount of reduced Watts/m^2. Such an exercise can be undertaken by previously examining the obstructive capacity of the shelter material before the canopy is introduced and/or constructed. At a design level, such ameliorations should reinforce pedestrian 'choice', both in terms of activity, and of 'thermal personification'; together characteristics which often fall short within the centre of canyons with low aspect ratios.

4.2.5. Designing with water/misting systems

- The application of Water/Misting Systems within public space design for climates with hot and dry summers should be based upon the decision of whether SW (i.e., Surface Wetting) is desired or not. Although locations with a '*Csa*' classification witness dry summers, it is still imperative to not risk exacerbating atmospheric water content which can induce pedestrian discomfort.
- In order not induce the risk of exacerbating atmospheric moisture content, numerous LMs (i.e., Limitation Mechanisms) should be established when considering the application of water/misting systems: (i) a RH benchmark of 70% should be set as a maximum value in which to adjust to potency of the system; (ii) in order to estimate the cooling effect of the mechanism, the following ratio should be used, for every decrease of 1K_{amb} a subsequent increase in 5%K_{RH} should be assumed. As a result,

Input Parameters	T_{amb} (°C)		T_{surf} (°C)		G_{Rad} (W/m²)		V (m/s)		RH (%)	
	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.	Exist.	Proj.
10:00-11:00	24.5	24.5	30.1	-	150	150	0.7	0.7	67.2	67.2
11:00-12:00	26.0	25.0	35.8	-	154	154	0.5	0.5	62.9	67.9
12:00-13:00	27.1	25.1	40.4	-	157	157	0.6	0.6	58.6	68.6
14:00-15:00	29.3	25.3	42.5	-	39	39	1.3	1.3	48.8	68.8
15:00-16:00	31.2	27.2	45.5	-	20	20	0.7	0.7	45.2	65.2
16:00-17:00	31.6	27.6	32.7	-	16	16	0.5	0.5	42.2	62.2

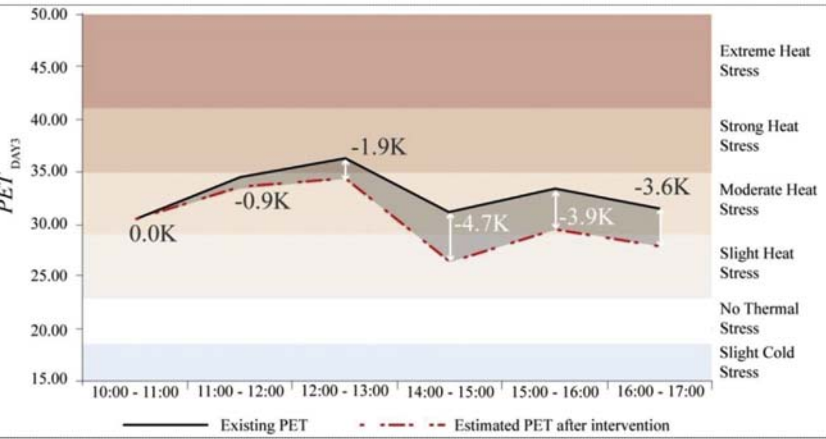


Fig. 12. Conceptual intervention in POI 5 and $\Delta T_{PET(5)}$ variation | Author's rendering & table.

and as RH decreases during the day, the potency of the mechanism can be increased without exacerbating a RH of 70%.

- Relating again to the features integrated within the LM, the fluctuation of the mechanism's potency can be attained by varying: (iii) the F/IP (i.e., Functioning/Interval Period) to periodically increase throughout the day; and, (iv) the PP (i.e., Pump Pressure) which will lead to a modification of the SMD of water droplet's. Lastly, and in order to ascertain the desired wetting effect under the correct conditions (especially in cases where SW is undesired), the following LM should be considered, to activate only: (v) when local T_{amb} values surpass that of 25 °C; (vi) when V is beneath 1 m/s, due to droplet over-dispersal; and lastly, (vii) when global radiation is below 300 W/m^2, due to the over-accelerated evaporative effect upon the micro-droplets, rendering the cooling sensation ineffective.
- In the case where SW is permitted, introduced measures should not permit static water as this can lead to stagnation issues. For this reason, the movement or recycling of projected water should be integrated within the design of the measures system. In the case of artificial flooding a designated surface, designers must also consider the frequency water recollection. Lastly, even in cases of SW, if misting systems are introduced close to pedestrian height, then droplet SMD should not surpass that of 500 μm, as this can lead to excessive pedestrian wetting.

5. Concluding remarks

The findings of this paper support that when addressing the bioclimatic characteristics of our public realm, bottom-up approaches can prove an effective means to address local risk factors, and that of pedestrian thermal comfort through public space design. From the results of this study, the following encompassing conclusions can be drawn:

- The combination between the thermophysiological PET, psychological PBR, and meteorological examinations enabled a wholesome understanding of the site's meteorological risk factors, and how they can be potentially improved through public space design. Such results further indicated the potentiality of integrating the disciplines of urban climatology with that of public space design to ensure the safety and quality of the public realm.

- The variety of the undertaken examinations indicated their complementarity and significance with one another. Namely, the association between psychological and physiological aspects proved to be imperative to go beyond quantitative assessments such as PCZs, and also consider more qualitative aspects such as pedestrian desired stimuli, and of 'choice' making.
- In this way, and based upon site specific characteristics and measurements, the proposed public space design interventions were believed to: (i) have enabled both PET and physiological stress levels to be improved; but moreover, (ii) enhance pedestrian thermal personification and activity threads in the centre of the square, which are normally synonymous with higher microclimatic aggravations and lower activity threads, exemplified by POI 3/4.
- Nevertheless, and one of the larger contributions of the study, was the contribution of bioclimatic public space guidelines, which consider how relatable squares (or canyons) with low aspect ratios can both assess, and explore the application of similar passive design solutions to ameliorate the symptoms witnessed in hot and dry Mediterranean summers.

Acknowledgements

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Appendix A. Project data sheet

A.1	Location Details				
Country	**City**	**Cord.**	**Altitude**	**Climate Classification**	**Köppen Geiger Acronym**
Portugal	Lisbon	38° 42′ 50″ N, 9° 8′ 22″ W	AMSL = 10m	Mediterranean climate with hot and dry summers	'Csa'

A.2	Site Visits		
Site Visit	**Date**	**Weekday**	**Data Collected**
1	6th July 2015	Monday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
2	10th July 2015	Friday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
3	13th July 2015	Monday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
4	17th July 2015	Friday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
5	20th July 2015	Monday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
6	24th July 2015	Friday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
7	27th July 2015	Monday	T_{amb} | WS | RH | T_{surf} | G_{Rad} + Foot Fall Count
8	30th July 2015	Friday	Pedestrian Based Response Interviews

FURTHER SIMULATION OBSERVATIONS

A.3	CFD Observations
Square Extremities	Wind speed accelerated in the north and south of the site as a result of wind channelling effect due to higher canyon height-to-width ratios (i.e., of ≈ 1.66)
Centre of Square	Central statue leads to both the acceleration (reaching ≈ 2.1m/s) and deceleration (reaching ≈ 0.5m/s). This variation is due to the shelter effect from the base of the statue, and the displaced acceleration of the wind that travels around the statue.
	As result of a displacement effect caused by the trees, wind speed decreased to almost ≈ 0.5m/s beneath the crown, and subsequently accelerated a few metres away.

A.4	SBS Observations
Square Extremities	Between 08:00 - 12:00 the western region of the site is completely exposed to solar radiation with exception of the shadows cast by the vegetative crowns
Centre of Square	Between 12:00 - 17:00 the eastern side was exposed to solar radiation with identical exception of the shades cast by vegetative crowns
	Zero hours of solar radiation was observed due to the squares low height-to-width ratio

Appendix B. Equipment & measurements

B.1	Equipment used during the field study					
	Equipment Name / Model #	**Measurement**	**Value Output**	**Accuracy**	**Resolution**	**Equip. Symbol**
1	KESTREL 4600BT©	V	m/s	± 3% (of displayed reading)	0.1 m/s	□
		T_{amb}	Cº	± 0.5	0.1 Cº	
		RH	%	± 3.0	0.1 %	
2	KKMOON SM206©	G_{Rad}	W/m^2	± 10	0.1 W/m^2	△
3	BENETECH GM550©	T_{surf}	Cº	± 1.5%	0.1 Cº	○

B.2	Daily measurement method at each point of interest						
	C1 10:00-11:00	**C2 11:00-12:00**	**C3 12:00-13:00**	**FOOT FALL 13:30-14:00**	**C4 14:00-15:00**	**C5 15:00-16:00**	**C6 16:00-17:00**
POI 1	10:00-10:08	11:00-11:08	12:00-12:08	13:30/3	14:00-14:08	15:00-15:08	16:00-16:08
POI 2	10:10-10:18	11:10-11:18	12:10-12:18	13:35/8	14:10-14:18	15:10-15:18	16:10-16:18
POI 3	10:20-10:28	11:20-11:28	12:20-12:28	13:40/3	14:20-14:28	15:20-15:28	16:20-16:28
POI 4	10:30-10:38	11:30-11:38	12:30-12:38	13:45/8	14:30-14:38	15:30-15:38	16:30-16:38
POI 5	10:40-10:48	11:40-11:48	12:40-12:48	13:50/3	14:40-14:48	15:40-15:48	16:40-16:48
POI 6	10:50-10:58	11:50-11:58	12:50-12:58	13:50/8	14:50-14:58	15:50-15:58	16:50-16:58

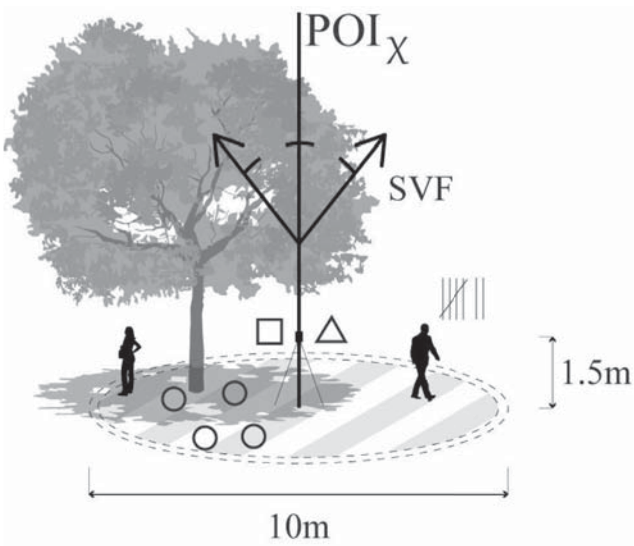
B.3 Notes

In order to attain averages at each POI during each of the Cycles, a total of 8 minutes was spent at each point. This method allowed every POI to be assessed within one hour, with a 2 minute breadth to set up the equipment at the subsequent location. At each point, wind speed, ambient temperature and RH values were measured at a height of 1.50m by the KESTEL 4600© every minute for eight minutes.

This technique enabled for average values to be logged by the equipment, and also for the other required data to be obtained. Two other examinations were undertaken with the use of the KKMOON SM206© and the BENETECH GM550©. Firstly, and also at a height of 1.50m, global radiation was measured in order to determine the amount of radiation that was present at each location. Secondly, all paving surfaces were tested in order to define their surface temperature, both in the sun and in the shade.

Appendix C. Equipment layout & PBR section 1 questions & sky view factors for poi

C.1	POI Equipment Layout



Although each POI was established at a specific location in the square, a 10m diameter was allowed in order to retrieve all of the temperatures of surrounding surfaces. This was particularly relevant when the POI was beneath a tree, In addition to these assessments, the Sky View Factor (SVF) was obtained through a fish-eye-lens camera at the centre of each of POI. After the first three Cycles were concluded, a footfall count was undertaken (again using the 10m diameter around each location) to determine the amount of pedestrian footfall during the busiest time of day, between 13:30 and 14:00

C.2	Questionnaire Composition						
PBR Section 1, Quantitative Questionnaire,	Perfect	Very Pleasant	Pleasant	Satis-factory	Unpleasa nt	Very Unpleasa nt	Unsupp-ortable
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
How do you find the **temperature** at the moment?							
How do you find the **wind** at the moment?							
How do you find the strength of the **sun** at the moment?							
How comfortable are you **overall** at the moment?							

Appendix D. Variable regression study results

D.1	POI 1	POI 2	POI 3	POI 4	POI 5	POI 6			
Microclimatic Variables $\overline{X}$							$\bar{r}$ / P	±	$\bar{r}$ Strengh
$\overline{T_{amb}} \cap \overline{RH}$	r = 0.9604	r = 0.8836	r = 0.9941	r = 0.9691	r = 0.9709	r = 0.9617	0.9566 / $P < 0.001$	-	Outstanding
$\overline{T_{amb}} \cap \overline{T_{PET}}$	r = 0.0186	r = 0.8278	r = 0.9909	r = 0.9753	r = 0.0005	r = 0.8546	0.6112 / $P < 0.001$	+	Strong
$\overline{T_{amb}} \cap \overline{T_{surf}}$	r = 0.5959	r = 0.8191	r = 0.9584	r = 0.9874	r = 0.2925	r = 0.9801	0.7722 / $P < 0.001$	+	Very Strong
$\overline{T_{amb}} \cap \overline{WS}$	r = 0.7215	r = 0.3557	r = 0.6951	r = 0.6053	r = 0.002	r = 0.5874	0.4944 / $P = 0.551$	+	Weak
$\overline{T_{amb}} \cap \overline{T_{mrt}}$	r = 0.0264	r = 0.8411	r = 0.9862	r = 0.9897	r = 0.2281	r = 0.8535	0.6541 / $P < 0.001$	+	Strong
$\overline{T_{PET}} \cap \overline{T_{surf}}$	r = 0.1191	r = 0.9903	r = 0.9483	r = 0.9408	r = 0.3031	r = 0.7739	0.6792 / $P < 0.001$	+	Strong
$\overline{T_{PET}} \cap \overline{WS}$	r = 0.0032	r = 0.3774	r = 0.6414	r = 0.7006	r = 0.3202	r = 0.2186	0.3769 / $P = 0.017$	+	Weak
$\overline{T_{PET}} \cap \overline{T_{mrt}}$	r = 0.9071	r = 0.9886	r = 0.9906	r = 0.9842	r = 0.7706	r = 0.9999	0.9402 / $P < 0.001$	+	Outstanding
$\overline{T_{PET}} \cap \overline{RH}$	r = 0.0028	r = 0.9573	r = 0.9826	r = 0.9458	r = 0.0041	r = 0.7277	0.6033 / $P < 0.001$	-	Strong
$\overline{T_{surf}} \cap \overline{T_{mrt}}$	r = 0.0197	r = 0.9777	r = 0.9808	r = 0.9708	r = 0.0961	r = 0.7712	0.6361 / $P < 0.001$	+	Strong
$\overline{T_{surf}} \cap \overline{WS}$	r = 0.6569	r = 0.3901	r = 0.8108	r = 0.6121	r = 0.4536	r = 0.6101	0.5889 / $P < 0.001$	+	Average
$\overline{RH} \cap \overline{WS}$	r = 0.7423	r = 0.2838	r = 0.6199	r = 0.6032	r = 0.0038	r = 0.6535	0.4844 / $P = 0.3628$	-	Weak

Outstanding	Very Strong	Strong	Average	Weak	Very Weak	Nugatory
0.99 – 0.90	0.89 – 0.70	0.69 – 0.60	0.59 – 0.50	0.49 – 0.30	0.29 – 0.10	0.09 ≤

Focused solely upon microclimatic characteristics, the table determines both the r between two variables in each location, and subsequently, identifies the mean r in all POI's, expressed as $\bar{r}$. Along with the $\bar{r}$, the following variables are also presented: (i) the trend of the linear regression in order to determine whether the two respective variables had a positive or negative influence upon one another (i.e., leading to a ± Pearson Coefficient); (ii) the P value in order to assess the statistical relevance of each $\bar{r}$ (i.e., to ensure that $P \leq 0.05$); and lastly, (iii) the overall relationship strength which was determined from the established key below.

The table illustrates clear strengths and weaknesses between numerous variables. The two strongest identified $\bar{r}$ relationships were between: ($T_{PET} \cap T_{mrt}$, $\bar{r}$ = +0.9566, $P < 0.001$), and ($T_{amb} \cap$ RH, $\bar{r}$ = -0.9402, $P < 0.001$). The weaker $\bar{r}$ examples were those that considered wind patterns, i.e.: ($T_{amb} \cap$ Wind, $\bar{r}$ = +0.4944, $P = 0.551$), ($T_{PET} \cap$ Wind, $\bar{r}$ = +0.3769, $P = 0.017$), ($T_{surf} \cap$ Wind, $\bar{r}$ = +0.5889, $P < 0.001$), and, (RH $\cap$ Wind, $\bar{r}$ = -0.4844, $P = 0.3628$).

Appendix E. Solution datasheet I (Calculation methods)

E.1	Shelter Canopies **Watts/m² reduction calculation**
POI 2	Global radiation was tested beneath a segment of nylon fabric (4m x 2m) which was attached to the branches of two existing *Tipuana Tipu* trees. Although merely indicative and necessitating further study, the average diurnal amount beneath the fabric was of 75 W/m².
POI 4	Acrylic panel was tested in order to rudimentarily determine the amount of global radiation beneath the proposed structure. Unlike the former location, as the shelter canopy was not combined with vegetation, the amount of radiation beneath canopy was slightly higher, and presented an average of 150 W/m². Nevertheless, and compared to the existing diurnal variation (i.e., 440-960 W/m²), this obtained result reveals promising potential in attenuating solar radiation upon pedestrians in the centre of the square during the summer.

E.2 — Water / Spray System

Establishing Limitation Mechanisms for POI 3 & 5

As SW was permitted in POI 3, the preoccupation with the projected water droplets was not of great concern. However, and in order to permit pedestrians to walk through the feature without getting overly wet (Fig.9); micro-droplets with a maximum Sauter Mean Diameter (SMD) of 500 µm was integrated into the LM. (▪ See Appendix F.4)

In order to quantify the balance between decreasing T_{amb} through the increase of RH levels, the ratio identified by Ishii, Tsujimoto et al. (2008) and Ishii, Tsujimoto et al. (2009) was used in order to propose an initial estimation on the correct amount of mist throughout the day for POI 5.

Expression:	If $K_{amb} \rightarrow K_{amb} - a$, then RH $\rightarrow 21a/20$ RH such that $0 < a < 7$, $a \in$ N
If K_{amb} is decreased by a where a is less than 7 and it is a natural number, then RH get increased by a*5%, i.e., a(RH + 5/100 RH) = $21a/20$ RH	
Source: Expression adapted from (Ishii, Tsujimoto et al. 2008, Ishii, Tsujimoto et al. 2009)	

Projected decrease of T_{amb} in POI 5 was established upon a concrete rise in RH in order to estimate the effects of the misting system upon the locations atmospheric moisture content. Accordingly, when providing the new projected T_{PET} for POI 5, this ratio was introduced into the biometeorological model, ensuring that the new RH never surpassed that of 70%. This maximum value is based upon two rationales presented by Yoon, Yamada et al. (2008), namely: (i) a superior RH would very likely lead to the thermal discomfort of pedestrians, regardless of T_{amb}; and, (ii) the sprayed micro-droplets would be unable to evaporate effectively due to high atmospheric water content and thus lead to SW. In order to determine the correct SMD of the mechanism, the study of Farnham, Nakao et al. (2011) was used to indicate the correct SMD given the nozzles being installed in the tree branches (i.e., with NH of approximately 3m). The LM of the system is also designed to respect the limitations that were identified by the respective studies, namely: (i) turn off given a RH higher than 70% to avoid exacerbating atmospheric moisture; (ii) only turn on when temperatures surpass a T_{amb} of 25; (iii) turn off if $\overline{V}$ surpasses 1m/s due to the droplet distortion/amalgamation caused by stronger air currents; and, (iv) turn off when solar radiation surpasses that of 300 W/m² beneath the misting mechanism due to the over-accelerated evaporative effect upon the micro-droplets, rendering the cooling sensation ineffective. Subsequently and when considering the results shown in Fig.4, all of these microclimatic thresholds are compatible with the average conditions presented in POI 5. (▪ See Appendix F.5)

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Appendix F. Solution datasheet II (Measure Specifications)

F.1	POI 2	POI 3	POI 4	POI 5
Vegetation	x	x		
Shelter Canopies	x		x	
Water / Spray System		x		x

F.2	Vegetation						
	#	PL	Species	Dimensions (*)		Foliation (*)	DeFol. (*)
POI 2	3	*LP*	*Tipuna Tipu*	*TH* : ≈ 12.5m	*CD* : ≈ 7m	Early May	Mid. March
POI 3	6	*GP*	*Tipuna Tipu*	*TH* : ≈ 12.5m	*CD* : ≈ 7m	Early May	Mid. March

F.3	Shelter Canopies		
	Material	Watts/m² below	Construction/Special Feature
POI 2	Nylon	75	Assembled with cables on tree branches in order to provide shade between tree crowns during the summer (JJA)
POI 4	Aluminium, Acrylic	150	Supported upon a central aluminium structure, seven acrylic flaps are adjustable through a pull-string mechanism which enables the pedestrians to choose to sit in the shade or in the sun in the centre of the square (JJA)

F.4	Water with surface wetting	LM : RH ≤ 70 % | SMD ≤ 500 μm			
		FP (JJA)	NH	Water Collection	SW Method
POI 3	10:00-11:00	OFF	0m	OFF	OFF
	11:00-12:00	2min + 2min interval		Every 30 minutes	Surfaces are wet for the specified period and then re-absorbed into the ground slabs
	12:00-13:00	3min + 2min interval			
	14:00-15:00	3min + 1min interval		Every 15 minutes	
	15:00-16:00	3min + 1min interval			
	16:00-17:00	4min + 1min interval			

F.5	Water without surface wetting	LM : RH ≤ 70 % | T_{amb} > 25 | $\overline{V}$ ≤ 1m/s | $\overline{G_{Rad}}$ < 300 W/m²			
		PP	NH	SMD	FP (JJA)
POI 5	10:00-11:00	OFF	3m	OFF	OFF
	11:00-12:00	5.0 Mpa		≈ 30 μm	1min + 2min interval
	12:00-13:00	5.5 Mpa		≈ 35 μm	2min + 3min interval
	14:00-15:00	5.5 Mpa		≈ 40 μm	3min + 2min interval
	15:00-16:00	6 Mpa		≈ 40 μm	3min + 2min interval
	16:00-17:00	6 Mpa		≈ 45 μm	3min + 1min interval

PL	Planting Layout	*TH*	Tree Height	LM	Limitation Mechanism	SW	Surface Wetting
LP	Linear Plantation	*CD*	Crown Dimension	FP	Functioning Period	PP	Pump Pressure
GP	Group Plantation	JJA	June, July, August	NH	Nozzle Height	SMD	Sauter mean diameter

Viñas, F., J. Solanich, X. Vilardaga and L. Montilo (1995). El Árbol en Jardinería y Paisajismo - Guía de aplicación para España y países de clima mediterráneo y templado. Barcelona, Spain, Ediciones Omega.

*Dimensions retreived from (Viñas, Solanich et al. 1995)

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Publication 7:

Confronting potential future augmentations of the physiologically equivalent temperature through public space design: The case of Rossio, Lisbon

A. Santos Nouri, A. Lopes, João Pedro Costa, A. Matzarakis

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Article Preamble

Based upon previously obtained results in Rossio, they are taken a step further in order to consider how a climatic worse-case-scenario by the end of the century could influence the existing conditions within Rossio given incorporation/lack of the proposed public space measures. As a result, a synoptic evaluation of how climate change conditions can aggravate existing thermal comfort conditions around the entire square through different analysed datasets is presented.

Article Symbol list

$\#K_X$	Variation of X variable	Q_H	Flux of sensible heat
‘*Csa*’	Hot-Mediterranean climate	T_{amb}	Ambient temperature
G_{rad}	Global radiation	T_{surf}	Surface temperature
$Q*$	Net of all-wave radiation	V	Wind Speed
Q_E	Flux of latent heat	ΔQ_A	Net heat advection
Q_F	Anthropogenic heat flux	ΔQ_S	Heat storage within urban fabric
T_{surf}	Surface temperature		

Article Acronym List

C	Cycle	PS	Physiological Stress
JJA	June July August	RH	Relative Humidity
PET	Physiologically Equivalent Temperature	TP	Thermal Perception
PETL	PET Load	UHI	Urban Heat Island
POI	Point of Interest		

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Confronting potential future augmentations of the physiologically equivalent temperature through public space design: The case of Rossio, Lisbon

A. Santos Nouri[a,*], A. Lopes[b], J. Pedro Costa[a], A. Matzarakis[c]

[a] Universidade de Lisboa, Faculdade de Arquitetura, CIAUD, Centro de Investigação em Arquitetura, Urbanismo e Design, Lisbon, Portugal
[b] Universidade de Lisboa, IGOT, Instituto de Geografia e Ordenamento do Território, Lisbon, Portugal
[c] Research Centre Human Biometeorology, Deutscher Wetterdienst Stefan-Meier-Str. 4, 79104 Freiburg, Germany

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ABSTRACT

When considering cities such as Lisbon, which due to their Köppen Geiger classification of '*Csa*', witness hot and dry summers, the translation of local bottom-up knowhow upon climatic guidelines has been a topic of considerable dissemination over recent years.

Depicting upon a concrete case study located in Lisbon's historical quarter, the results from a previous bioclimatic study undertaken by the authors were taken further in order to consider how worst-case-scenarios of climate change (A1FI/RCP8.5) could potentially impact the existing human thermal environment within the square. In addition to considering its existing layout, public space design interventions were also examined within different thermal/temporal scenarios through the use the Physiologically Equivalent Temperature (PET) and PET(Load) indices.

The results of the study revealed that within a climatic worse-case-scenario, and without any adaptive measures to address Physiological Stress (PS) levels, the majority of the square presented potential PS thresholds ranging between 'Extreme Heat Stress Lv.3/4', with PET values exceeding that of 51 °C and 56 °C. On the other hand, and particularly in regions prone to high levels of solar radiation, the thermal amelioration effects of the proposed public space design interventions presented reductions of PET values up to 16.6 °C.

1. Introduction

Recently, several agendas have presented themselves upon the contemporary and interdisciplinary practice of urban planning and design. Engrained within such agendas, lies the comprehension of how climate change adaptation can overcome issues of uncertainty and ambiguity until the end of the century. So far however, a considerable amount of research relating to 'locality' has been carried out through a top-down approach (Nouri, 2013). Such methods concentrate upon impact prediction through global models as a starting point to anticipate climate change scenarios. As a result, there has been a growing interest in bottom-up approaches that question how efforts at adaptation can be locally initiated and adopted (e.g., Wilbanks and Kates, 1999; Ali-Toudert and Mayer, 2007; Algeciras, Consuegra, & Matzarakis, 2016; Gómez, Cueva, Valcuende, & Matzarakis, 2013; Lin, Matzarakis, & Hwang, 2010; Mayer and Höppe, 1987; Nikolopoulou, 2007; Nouri and Costa, 2017a; Oliveira, Andrade, & Vaz, 2011; Shashua-Bar, Tsiros, & Hoffman, 2012).

In accordance with Global Circulation Models, it has been identified so far that global temperature will likely continue to rise throughout the 21st century, and that there shall be significant changes to air humidity, wind speed and cloud cover around the planet. Conversely, the reports of the Intergovernmental Panel on Climate Change have often described the effect of weather with a simple index based on amalgamations of air temperature and relative humidity. Although it is clear that such descriptions have substantially propelled the maturing top-down climate change adaptation agenda, when considering bottom-up approaches to climatic vulnerability, the exclusion of vital meteorological factors (i.e. radiation fluxes, wind speed and human thermophysiological factors) have arguably diminished the significance of such results for local design and decision making (Matzarakis and Amelung, 2008; Matzarakis and Endler, 2010).

Abbreviations: PET, Physiologically Equivalent Temperature; POI, Point of Interest; PS, Physiological Stress; SRES, Special Report on Emission Scenarios; RCP, Representative Concentration Pathways; C, Cycle; PET, Physiologically Equivalent Temperature Load

* Corresponding author.
E-mail addresses: andrenouri@fa.ulisboa.pt (A.S. Nouri), antonio.lopes@campus.ul.pt (A. Lopes), jpc@fa.ulisboa.pt (J.P. Costa), andreas.matzarakis@dwd.de (A. Matzarakis).

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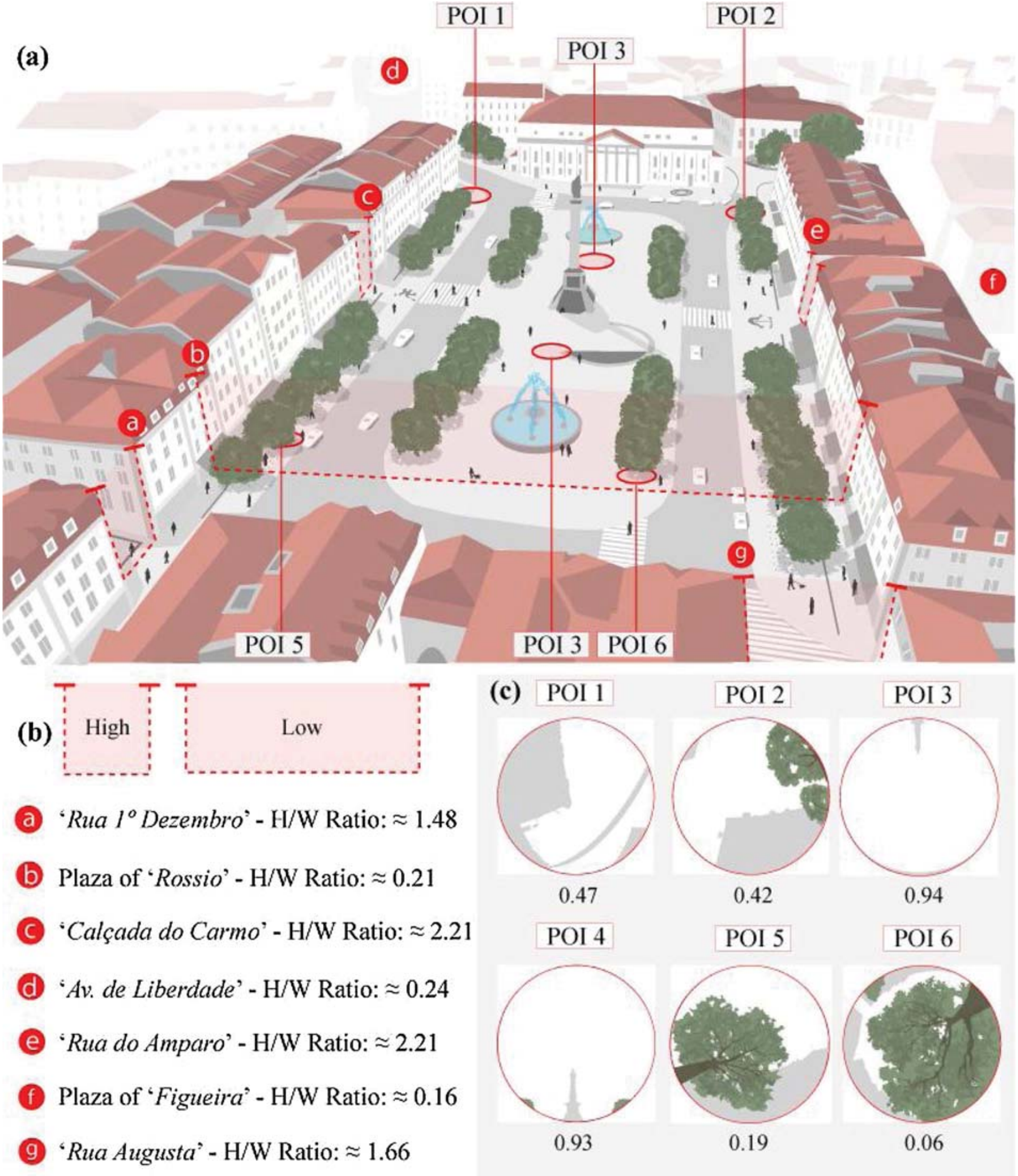


Fig. 1. (**a**) Southern perspective view of Rossio and location of each Point of Interest (POI) around the square | (**b**) Height-to-Width Ratios of Rossio, and surrounding canyons | (**c**) Polar diagrams for each POI, which were obtained through the use of a fish-eye lens camera and posteriorly simplified into vectorised before being processed by the Rayman.

The reason for such lapses can be attributed to the lack of climatic variables such as short and long wave radiation which are often not available in climate records. Nevertheless, and by referring to the methodology developed by Matzarakis and Amelung (2008), it is suggested that such gaps in climatic variables can be overcome. More specifically, and by referring to climatological and astronomical data to estimate short and long wave radiation fluxes, synoptic evaluations of climate change effects upon the thermal environment can be achieved. Thus, this approach enables existing biometeorological exemplary results to be explored within a future context, which in this article, focuses upon the potential bioclimatic environment by the end of the twenty-first century in Rossio.

Based upon this disclosed interest, this article further examines the results obtained from a previous climatic study by Nouri and Costa (2017b) that was undertaken in Rossio − Lisbon during the summer of 2015. In the initial study, the objectives were to: (i) identify the microclimatic risk factors within the different areas of the square; and, (ii) suggest conceptual solutions that could potentially improve outdoor thermal comfort during periods of annual accentuated climatological stress.

Considering the specific case of Lisbon, it has been identified that steps need to be taken to adapt to future climatic conditions that are already being felt within urban contexts (Alcoforado and Matzarakis, 2010; Alcoforado, Lopes, Alves, & Canário, 2014). Since the 1980′s, studies of Lisbon's urban climate have been disseminated in order to better inform the cohesion between the interdisciplinary spheres of urban planning/design with that of climatology and biometeorology. Thus far, such studies have focused upon general bioclimatic conditions within the public realm (e.g., Andrade, 2003; Oliveira and Andrade, 2007), effects and intensities of UHI's (e.g., Alcoforado and Andrade, 2006; Alcoforado et al., 2014; Lopes, Alves, Alcoforado, & Machete, 2013), wind studies (e.g., Alcoforado, Lopes, Andrade, Vasconcelos, & Vieira, 2006; Lopes, 2003), and, the integration with planning policy (e.g., Alcoforado, Lopes, Andrade, & Vasconcelos, 2005; Alcoforado and Matzarakis, 2010). Furthermore, and intrinsic to the developing climate change adaptation agenda, studies relating to potential future climate change impacts upon the urban realm have also been disseminated (e.g., Alcoforado, Andrade, & Oliveira, 2009; Costa, 2013; Costa, et al., 2013; Matos Silva, 2016; Matos Silva and Costa, 2017).

Invigorated by such studies, and although recognised that climate change and uncertainty go hand in hand, this article suggests that climate change adaptation should not be considered a 'vague concept' (Bourdin, 2010). Inversely, and as identified by Costa (2011), the concrete bond with specific localities is what substantiates such preciseness. As deliberated by Costa et al. (2013), it is here where the use of the 'What if?' agenda can provide means to: (i) estimate potential local climatic territorial impacts within a specific scenario; and just as importantly, (ii) anticipate potential resolutions and prospective alternatives as a response to the aforementioned assessments.

Within this study, and with the aim of considering opportunities for contemporary public space design, the following investigative question was launched: *If the A1FI (or RCP 8.5) scenario came to fruition, what impacts could this have upon the local biometeorological environment in Rossio?* In order to answer this question, and based upon use of the thermophysiological index, the Physiologically Equivalent Temperature (PET) (Höppe, 1999) was used to: (i) identify microclimatic risk factors that could be potentially aggravated by climate change impacts; and, (ii) scrutinise how the suggested conceptual solutions preform in attenuating such identified aggravations by the end of century.

2. Method

2.1. Site and existing bioclimatic conditions

The utilised biometeorological data within this study was obtained from a preceding assessment that was conducted by the authors within the historical quarter of downtown Lisbon, within the civic space of Rossio during the summer of 2015 (Nouri and Costa, 2017b). Through the use of Computational Fluid Dynamic and Shadow Behaviour Stimulation studies, six Points of Interest (POI) were established (Fig. 1**a**). The simulation of these two characteristics were based around establishing an initial understanding of wind patterns and radiation fluxes that has proven to be: (i) those most influenced by morphological and physical properties of the urban environment (Matzarakis, Fröhlich, & Gangwisch, 2016); (ii) proven to be the predominant parameters for thermal comfort studies (e.g., Algeciras et al., 2016; Lin, 2009; Lin et al., 2010; Walton, Dravitzki, & Donn, 2007); and, (iii) often disregarded in top-down climatic assessments (Matzarakis and Amelung, 2008). Such morphological considerations were particularly relevant, as within the historical district, most canyons present a relatively high H/W ratios (i.e., of ≈ 1.66), whereby in the case of Rossio, this ratio is considerably lower (i.e., of ≈ 0.21) (Fig. 1**b**), thus considerably raising its susceptibility to such microclimatic characteristics (Ketterer and Matzarakis, 2014).

The concept of establishing POI's was inspired by studies which analysed microclimatic patterns within pre-determined and concrete positions in an outdoor site/s (e.g., Alcoforado et al., 2014; Charalampopoulos, Tsiros, Chronopoulou-Sereli, & Matzarakis, 2016; Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007; Nikolopoulou and Lykoudis, 2006; Picot, 2004; Shashua-Bar and Hoffman, 2000; Tsiros, 2010; Takács, Kiss, Hof, Tanács, & Kántor, 2016).

Within the previous study, five different types of meteorological measurements were undertaken within the study: Wind speed (*V*), ambient temperature (T_{amb}), relative humidity (RH), global radiation (G_{rad}), and surface temperature (T_{surf}). Overall, a total of 6650 measurements were obtained amongst seven visits that were distributed out on every Monday and Friday in order to obtain an overall climatic assessment of July 2015 (■ see Appendix A). Furthermore, and in addition to the input of geographical coordinates and altitude, and similar to the methodology used in studies by (Alcoforado et al., 2005; Algeciras et al., 2016; Oliveira et al., 2011), polar diagrams were taken in each POI (Fig. 1**c**) in order to evaluate each respective Sky-View-Factor.

In order to determine the effects of the thermal environment upon pedestrians, the study referred to the energy balance of the human body within the urban environment. This enabled the analysis of how the human body perceived a combination of atmospheric elements through the use of a thermophysiological index, PET that was processed by the Rayman Pro model (Matzarakis and Rutz, 2006; Matzarakis, Rutz, & Mayer, 2007). Subsequently, and in order to establish the ranges of Physiological Stress (PS), the comparative chart by Matzarakis, Mayer, and Iziomon (1999) was utilised (Table1).

By correlating the mean processed PET values for All Days ($\overline{PET_{AD}}$) with the PS thresholds, the study demonstrated the diurnal amount of thermal stress upon the pedestrians at each location. As expected, it was revealed that $\overline{PET_{AD}}$ was higher in locations with less shade, as was the case of POI 3 and 4 during the hotter hours of the day. Based upon these results (■ see Appendix B), all locations which obtained at least a 'Strong' PS grade were selected to explore how public space design could attenuate such thermal stimuli in the hottest POIs (i.e., POI 2/3/4/5).

2.1.1. Solution proposals

Within the final section of the study, the authors identified conceptual solutions for each of the four hottest POIs in order to explore the attenuation of thermal comfort thresholds in each of the respective locations. Expressed as$\overline{PET_{D3}}$, and with the aim of considering the worst-case-scenario, the obtained PET from Day 3 (hottest day out of the seven site visits) was used in order to consider how potential public space design interventions could attenuate encircling microclimatic stimuli within each of the four hottest POIs. Thus, and based upon a bottom-up approach, the proposed solutions were based upon three types of measures, namely, vegetation, shelter canopies, and water/misting systems as presented in Fig. 2.

Such proposals follow the approaches used in similar bioclimate studies where the introduction of thermal sensitive interventions were also suggested and/or implemented in order to attenuate the amount of thermal stimuli upon pedestrians. Often, but not limited to, such

Table 1
Ranges of the thermal index Physiologically Equivalent Temperature (PET) for different grades of Thermal Perception and Physiological Stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to Matzarakis, 1997).
Source: (Adapted from, Matzarakis et al., 1999)

PET	Thermal Perception	Physiological Stress
4 °C	Very Cold	Extreme Cold Stress
	Cold	Strong Cold Stress
8 °C	Cool	Moderate Cold Stress
13 °C	Slightly Cool	Slight Cold Stress
18 °C	Comfortable	No Thermal Stress
23 °C	Slightly Warm	Slight Heat Stress
29 °C	Warm	Moderate Heat Stress
35 °C	Hot	Strong Heat Stress
> 41 °C	Very Hot	Extreme Heat Stress

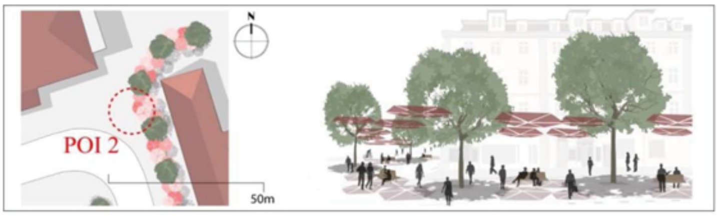
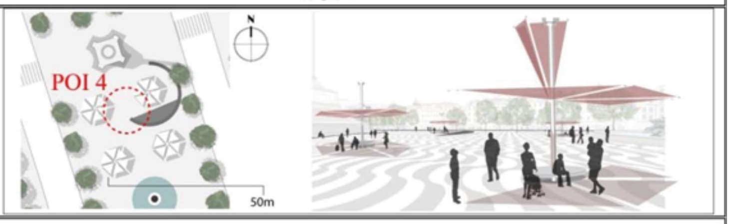
	POI 2
	
(*i*)	Existing linear plantation was extended by three trees (of the same species, i.e. *Tipuana Tipu*) in order to continue the vegetative shading upon the eastern sidewalk.
(*ii*)	Nylon canopies were suggested between the branches of the trees in order to induce a continuous shaded/seating area upon the middle of the pavement.
	POI 3
	
(*i*)	The introduction of a group plantation of six *Tipuana Tipu* trees was introduced in order to deflect accentuated amounts of radiation, and stronger wind currents.
(*ii*)	With a total area of 160m^2, a sheet of water would be sprayed through a micro nozzle system, which would subsequently be reabsorbed into the new paving slabs. To ensure that the desired RH levels were not exacerbated, the diurnal functioning period and water collection was fluctuated.
	POI 4
	
(*i*)	Based upon providing both seating and shading options for pedestrians. In order to augment perceived control between being cast in the sun or shade, four shelter canopies were suggested for the location which permitted each of the seven flaps to be independently.
	POI 5
	
(*i*)	Based upon a misting system which, unlike POI 2, would not allow surface wetting. The design of the system was based upon balancing T_{amb} and RH in order not to exacerbate atmospheric moisture content, and yet decrease air temperature. In order to quantify the balance between decreasing T_{amb} through the increase of RH levels, the ratio identified by Ishii, Tsujimoto et al. (2008) and Ishii, Tsujimoto et al. (2009) was used in order to propose an initial estimation on the correct amount of mist throughout the day.

Fig. 2. General descriptions of the conceptual public space design measures recommended for the hottest Points of Interest (POI) (Ishii et al. 2008, 2009).
Source: Author's figures (■ see Appendix C)

proposals occur in cities with '*Csa*' climates, which due to their hot and dry summers, particularly demand the presence of urban thermal sensitive interventions. With regards to vegetation, even at a meso/regional scale, Qiu et al. (2013) presented a summary of scientific studies that observed the cooling effects of green spaces 'in-situ' and within adjacent areas by up to 4.0K_{amb}. Within the scope of public space design, limited work has been carried out upon how such considerations function at a local/micro scale within the public realm (Tsiros, 2010).

Nevertheless, various authors have already analysed 'in-situ' tree characteristics to determine the impact of different vegetation species/layouts upon pedestrian thermal comfort levels (e.g., Almeida, 2006; Beckett, Freer-Smith, & Taylor, 2000; Erell et al., 2011; Fahmy and Sharples, 2011; Fahmy and Sharples, 2009; McPherson, 1984; Ochoa de la Torre, 1999; Picot, 2004; Taha et al., 1988; Shashua-Bar, et al., 2010; Shashua-Bar, Pearlmutter, & Erell, 2011). Moreover, and within the context of wholesome bioclimatic urban design projects, such know-how is already beginning to be applied (e.g., Coello and Philippe, 2015; Knuijt, 2013; TVK, 2013). In addition, more recent studies have also focused upon developing concrete urban design/planning priorities to attenuate urban microclimatic risk factors attributable to specific morphological composition (Norton et al., 2015), and concrete strategies to attenuate UHI effects (e.g., Akbari et al., 2016; Santamouris et al., 2016; Tan, Lau, & Ng, 2016; Wang, Berardi, & Akbari, 2016).

Of the measures suggested for Rossio, the alteration of paving material was not considered due to the presence of heritage decorated cobblestone paving within most the square. Nevertheless, such a design intervention still presents very promising microclimatic benefits in squares with low aspect ratios. In such urban spaces, and particularly within their central areas, there is an opportunity for public space design measures (such as paving materials) to address microclimatic exacerbations such diurnal G_{rad} intensity. When considering these effects upon other microclimatic variables, it becomes important to also counteract the effects of sensible heat loss from variables such as T_{surf} (and its potential influence upon T_{amb} values) when local albedo/emissivity values are low (Akbari et al., 2016; Georgakis and Santamouris, 2006; Santamouris, 2007; Stathopoulouet al., 2009; Santamouris et al., 2012; Santamouris, 2013). For this reason, further studies are required in Lisbon in order to reflect upon how such thermal sensitive measures can be explored in squares which are particularly vulnerable to diurnal G_{rad} intensities.

In the case the measures presented for Rossio, Table 2 illustrates the PET modifications that were calculated by the biometeorological model for each of the four locations. In the case of: (i) POI 2, once the location was cast in the sun after C3, $\Lambda T_{PET(2)}$ presented 'Moderate Heat Stress' as opposed to the previous 'Extreme Heat Stress'; (ii) POI 3, $\Lambda T_{PET(3)}$ fluctuated between 'Slight Heat Stress' and 'Moderate Heat Stress', which before ranged 'Extreme Heat Stress' after C3; (iii) POI 4, $\Lambda T_{PET(4)}$ fluctuated between 'Strong Heat Stress' and 'Moderate Heat Stress', which similarly to POI 3, previously ranged above 'Extreme Heat Stress' after C3; and lastly, (iv) POI 5, $\Lambda T_{PET(5)}$ presented a constant PS of 'Slight Heat Stress' after C3, which formerly obtained a PS of 'Moderate Heat Stress'.

The results of the study disclosed two fundamental aspects with regards to the interdisciplinary practice of local climate sensitive urban planning and design, namely the: (i) the identification of microclimatic risk factors within Mediterranean climates with hot and dry summers; and, (ii) exploration of conceptual public space design interventions that could potentially improve thermal comfort thresholds through pubic space design. Nevertheless, and given the projections of possible future climate change until the end of the century, such results were taken further in the subsequent section in order to consider how such meteorological aggravations can influence physiological comfort thresholds in the future.

2.2. The 'What if?' agenda

2.2.1. Future scenarios (SRES & RCP)

Future climatic projections provide a basis of quantifiable data, which in this case, relays to potential increases in temperature, amplified heatwaves, and augmented effects of UHI. Consequently, this raises the necessity to not only consider and generate adaptation measures, but to furthermore, correctly transpose such endeavours upon the built environment (Matos Silva and Costa, 2016; Nouri, 2015). In addition, such a transposition must always evaluate the bioclimatic performance of a site's configuration in order to obtain suitable, and integrated, outdoor urban design (Algeciras et al., 2016; Charalampopoulos et al., 2016; De Abreu-Harbich, Labaki, & Matzarakis, 2015; Krüger, Drach, Emmanuel, & Corbella, 2013; Lin et al., 2010; Matzarakis et al., 2016; Vanos, Warland, Gillespie, & Kenny, 2010). As a result, the practice of urban planning and design must thus undertake a flexible perspective which considers a wide range of future scenarios that are based upon scientific estimations of possible biometeorological and climatological outcomes until the end of the century.

Within this article, and in order to consider uncertainty whilst estimating potential climatic territorial impacts and anticipate potential resolutions, a range of socio-economic scenarios were used from the Special Report of Emission Scenarios (SRES) (IPCC, 2000). Among the four main SRES, the A1FI and A2A represent the cases with the fastest and most dramatic effects upon climate change predictions, while the B1A and B2A scenarios represent more attenuated levels of climatic variation. More recently, and within the fifth assessment report of the IPCC, these scenarios were replaced by the Representative Concentration Pathway (RCP) scenarios, namely: (i) RCP 8.5, based upon a future with no policy changes to reduce emissions − comparable to the SRES A1FI scenario; (ii) RCP 6, based upon the application of technologies and strategies for reducing GHG − comparable to the SRES B2 scenario; and, (iii) RCP 4.5, based upon ambitious reductions of global emissions − comparable to the SRES B1 scenario.

Focussing upon the worse-case scenario, and through the continued use of the disclosed thermo-physiological index, the 'What if?' agenda provided a means in which to launch the interrogation: *If the A1FI (or RCP 8.5) scenario came to fruition, what impacts could this have upon the local biometeorological environment in Rossio?*

2.2.2. Dataset modification and projected bioclimatic oscillations

In order to consider the impact of these scenarios upon projected PET values, Matzarakis and Amelung (2008) obtained all required variables from the Climatic Research Unit 1.0, and the HadCM3 datasets. As a result, and using the RayMan model, the PET and Mean Radiant Temperature (T_{mrt}) of each global grid were calculated based upon the following introduced parameters: T_{amb}, RH, V and cloud cover (manipulated from mean monthly sunshine fraction values). Also processed by the RayMan model, the historical period 1961–1990 served as bases for comparison in order to identify the respective deviation of PET until the end of the century. Dataset modification and projected bioclimatic oscillations

Based upon the previous, yet comparable version of the RCP 8.5 scenario (Rogelj, Meinshausen, & Knutti, 2012), the results of the A1FI SRES scenario illustrated drastic shifts towards warmer conditions around most of the world by 2100. With regards to the Mediterranean region, PET values revealed considerable increases in excess of 10 °C. Reflectively, these values were substantially higher than the estimated increase of up to 4.0 °C in air temperature by the end of the century (IPCC, 2014). Furthermore, and particularly within the Mediterranean area, the calculated PET could potentially surpass an increase of 15 °C. Such an increase, based upon the classification of Matzarakis and Rutz (2006) shown in Table 1, corresponds to three levels of increased physiological strain upon pedestrians. When considering the Iberian Peninsula, it was revealed that PET varied between +10 °C and +15 °C. More concretely, and in the case of Lisbon, an approximate variation of +10 °C and +12.5 °C was noted. In the case of the RCP 4.5 (or B1 SRES scenario), which corresponds to a considerably less grave scenario, projected modifications of bioclimatic conditions were more moderate. Within the Iberian Peninsula, and also for the JJA period, PET values ranged between +5.0 °C and +7.5 °C. Regardless, although a more attenuated oscillation from the previous scenario, still presents considerable aggravations of existing conditions. As a result, and established upon these variations for the Lisbon area, moderate PET increases of 10 °C and 6 °C were selected for the A1FI/RCP8.5 and B1/

Table 2
Existing mean PET values during day 3 and projected PET values after public space design interventions in each of the four POI.

	POI 2			POI 3		
	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$
10:00-11:00	21.2	0.0K	21.2	31.8	-7.7K	24.1
11:00-12:00	23.8	0.0K	23.8	36.6	-9.9K	26.7
12:00-13:00	30.2	-5.3K	24.9	37.5	-11.6K	25.9
14:00-15:00	39.3	-9.8K	29.5	45.0	-14.2K	30.8
15:00-16:00	43.0	-9.9K	33.1	46.9	-16.6K	30.3
16:00-17:00	44.5	-9.4K	35.1	44.0	-16.2K	27.8

	POI 4			POI 5		
	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$	$\overline{PET_{D3}}$	Δ	$\overline{PET\Delta_{D3}}$
10:00-11:00	32.9	-5.7K	27.2	30.5	0.0K	30.5
11:00-12:00	31.5	-5.9K	25.6	34.5	-0.9K	33.6
12:00-13:00	38.5	-6.3K	32.2	36.3	-1.9K	34.4
14:00-15:00	45.7	-10.5K	35.2	31.1	-4.7K	26.4
15:00-16:00	48.6	-12.3K	36.3	33.4	-3.9K	29.5
16:00-17:00	44.5	-10.9K	33.6	31.5	-3.6K	27.9

Key:	$\overline{PET_{D3}}$	PET values for Day 3	$\overline{PET\Delta_{D3}}$	Proj. PET values for Day 3 after suggested public space design interventions
	Colour coded based upon corresponding PS value represented in **Tbl.2**			

RCP4.5 scenarios, respectively.

2.3. Extension of physiological stress grades

Based on the investigative question launched within this study, and through the use of the 'What if?' agenda, a pilot analysis of the impacts upon the biometeorological conditions within Rossio could be approached. Constructed upon the modest oscillations of +10 °C and +6 °C upon the obtained PET values, the existing values presented in Table 1 required a significant adjustment. Based upon the increment of roughly 5 °C per physiological threshold within the existing grade system, three new grades were necessary beyond the initial 'Extreme Heat Stress' grade in order to articulately plot the projected PET results.

As shown in Table 3, the existing PS grades were expanded in order to include three additional categories beyond a PET value of 41 °C. Although further study is indispensible to determine the precise impact of such stress upon the human physiological system, this initial approach provides a basis of comparison with those obtained from existing measurements.

2.4. Dataset comparison

Based upon the disclosed increments of PET values upon the registered values during Day 3, within the four hottest POIs in the square, different sets of PET were thus cross-examined as presented in Table 4.

3. Results

As demonstrated in Fig. 3, when comparing the datasets, it was possible to verify: (i) a considerable oscillation of diurnal PET values between existing and future scenarios; and, (ii) the potential impact of the public space design interventions in each respective scenario.

In addition, when comparing the deviations between the B1A and the A1FI scenarios, it was noted that even in less severe climate change scenarios, the resulting projected bioclimatic environment still presented elevated 'Extreme' levels of physiological stress. Following this line of reasoning, this enforces the necessity for thermal sensitive public space design, which as indicated in Fig. 2, led to significant reductions in all assessed scenarios. Nevertheless, with the intention of identifying the most dramatic thermo-physiological implications upon the bioclimatic conditions in Rossio, the focus was turned to the A1FI scenario. As shown in Fig. 4 and as revealed by POI 3 and 4, the largest oscillations between the datasets were in locations that had elevated exposure to solar radiation. At these locations, and as shown by the $\overline{PET\Delta_{A1FI}}$ dataset, the microclimatic amelioration effects of the suggested public space design measures by the end of the century were significant. Between 15:00-16:00, and within POI 3, this was particularly evident when the $\overline{PET_{D3}}$ dataset surpassed that of $\overline{PET\Delta_{A1FI}}$ by almost 7.0K_{PET}.

As a result, and comparatively to existing thresholds, this inferred that the amount of PS upon pedestrians could be significantly lower by the end of the century with the presence of the suggested solutions. Although to a lesser extent, this occurrence was also witnessed in POI 4. In the case of POI 2, although the $\overline{PET\Delta_{A1FI}}$ dataset did not drop below$\overline{PET_{D3}}$, both were almost identical after 14:00. Such outcomes indicate that the existing thermal stress felt currently in the square could potentially be the same by the end of the century with the presence of the proposed public space design interventions. Generally, and

Table 3
Grade Extension of Physiological Stress on human beings to accompany increased values beyond the Physiologically Equivalent Temperature (PET) value of 41 °C in light of projected estimates (see Table 1).
Source: (Adapted from, Matzarakis et al., 1999)

PET	Physiological Stress Grade	
	Slight Cold Stress	Existing Grades
18ºC	No Thermal Stress	
23ºC	Slight Heat Stress	
29ºC	Moderate Heat Stress	
35ºC	Strong Heat Stress	
41ºC	Extreme Heat Stress (LV1)	
46ºC	Extreme Heat Stress (LV2)	New Required Grades
51ºC	Extreme Heat Stress (LV3)	
>56ºC	Extreme Heat Stress (LV4)	

in most POIs, the $\overline{PET_{A1FI}}$ dataset presented radical increases in physiological stress, especially in POIs located within the center of the square.

However, and in the case of POI 5 (identified as the coolest of the four hottest POIs), the projected thermal stress levels were less accentuated. Although attributed to the lower amount of received diurnal solar radiation, this still did not devalue that the projected increases in PS would correspond to those presently found in the center of the square.

3.1. Grid network

3.1.1. Postulation of physiological stress distribution

Based on the obtained PET oscillations to inform a projective distribution of physiological stress, a hypothetical 5m by 5m grid network was considered throughout the entire square. In order to preserve precision whilst assessing PS values around the square, the established grid enabled a more concise: (i) consideration of shade upon pedestrianized areas as a result of the street trees; (ii) contemplation of hotter surface temperatures around the square; and, (iii) definition of shade patterns cast by encircling structures such as building façades and square amenities (including those resultant of the proposed solutions).

Although this approach indicates just a synoptic and initial estimation of thermal comfort distribution around the entire square, the results obtained at each POI were used to inform how similar locations could influence pedestrian PS thresholds. More specifically, in liaison with previous simulations undertaken by the authors in the initial study, and considering the results from the RayMan model during the hottest diurnal hour, i.e. C5, between 15:00 and 16:00:

- POI 1 provided a reference for an area of the western sidewalk that was not shaded by vegetation, yet, that was cast in shade cast by the western façade of the square during the afternoon
- POI 2 provided a reference for an area of the eastern sidewalk that was not cast in the shade by a building façade, yet, was cast in the shade by an encircling vegetative crown in the afternoon

Table 4
Description of the Physiologically Equivalent Temperature (PET) datasets at each Point of Interest (POI) before and after interventions for existing and future A1FI/RCP8.5 and B1/RCP4.5 scenarios.

Existing Scenarios	
$\overline{PET_{D3}}$	Representing existing PET without public space design interventions
$\overline{PET\Delta_{D3}}$	Representing existing PET with public space design interventions
Projected Scenarios	
$\overline{PET_{B1A}}$	Representing projected PET without public space design interventions in a scenario with ambitious reductions of global emissions
$\overline{PET\Delta_{B1A}}$	Representing projected PET with public space design interventions in a scenario with ambitious reductions of global emissions
$\overline{PET_{A1FI}}$	Representing projected PET without public space design interventions in a scenario with no policy changes to reduce global emissions
$\overline{PET\Delta_{A1FI}}$	Representing projected PET with public space design interventions in a scenario with no policy changes to reduce global emissions
Specific diurnal period	
$\overline{PETX_{(C5)}}$	PET dataset *X* at C5 (i.e. between 15:00-16:00)

POI 2

	$\overline{PET}_{D3}$	$\overline{PET}_{B1A}$	$\overline{PET}_{A1FI}$	$\overline{PET\Delta}_{D3}$	$\overline{PET\Delta}_{B1A}$	$\overline{PET\Delta}_{A1FI}$
10:00-11:00	21.2	27.2	31.2	21.2	27.2	31.2
11:00-12:00	23.8	29.8	33.8	23.8	29.8	33.8
12:00-13:00	30.2	36.2	40.2	24.9	30.9	34.9
14:00-15:00	39.3	45.3	49.3	29.5	35.5	39.5
15:00-16:00	43.0	49.0	53.0	33.1	39.1	43.1
16:00-17:00	44.5	50.5	54.5	35.1	41.1	45.1

POI 3

	$\overline{PET}_{D3}$	$\overline{PET}_{B1A}$	$\overline{PET}_{A1FI}$	$\overline{PET\Delta}_{D3}$	$\overline{PET\Delta}_{B1A}$	$\overline{PET\Delta}_{A1FI}$
10:00-11:00	31.8	37.8	41.8	24.1	30.1	34.1
11:00-12:00	36.6	42.6	46.6	26.7	32.7	36.7
12:00-13:00	37.5	43.5	47.5	25.9	31.9	35.9
14:00-15:00	45.0	51.0	55.0	30.8	36.8	40.8
15:00-16:00	46.9	52.9	56.9	30.3	36.3	40.3
16:00-17:00	44.0	50.0	54.0	27.8	33.8	37.8

POI 4

	$\overline{PET}_{D3}$	$\overline{PET}_{B1A}$	$\overline{PET}_{A1FI}$	$\overline{PET\Delta}_{D3}$	$\overline{PET\Delta}_{B1A}$	$\overline{PET\Delta}_{A1FI}$
10:00-11:00	32.9	38.9	42.9	27.2	33.2	37.2
11:00-12:00	31.5	37.5	41.5	25.6	31.6	35.6
12:00-13:00	38.5	44.5	48.5	32.2	38.2	42.2
14:00-15:00	45.7	51.7	55.7	35.2	41.2	45.2
15:00-16:00	48.6	54.6	58.6	36.3	42.3	46.3
16:00-17:00	44.5	50.5	54.5	33.6	39.6	43.6

POI 5

	$\overline{PET}_{D3}$	$\overline{PET}_{B1A}$	$\overline{PET}_{A1FI}$	$\overline{PET\Delta}_{D3}$	$\overline{PET\Delta}_{B1A}$	$\overline{PET\Delta}_{A1FI}$
10:00-11:00	30.5	36.5	40.5	30.5	36.5	40.5
11:00-12:00	34.5	40.5	44.5	33.6	39.5	43.6
12:00-13:00	36.3	42.5	46.3	34.4	40.4	44.4
14:00-15:00	31.1	37.1	41.1	26.4	32.4	36.4
15:00-16:00	33.4	39.4	43.4	29.5	35.5	39.5
16:00-17:00	31.5	37.5	41.5	27.9	33.9	37.9

Without Interventions | With Interventions

PS: Slight Cold Stress | No Thermal Stress | Slight Heat Stress | Moderate Heat Stress | Strong Heat Stress | Ext. Heat Stress LV1 | Ext. Heat Stress LV2 | Ext. Heat Stress LV3 | Ext. H. Stress LV4

Fig. 3. Comparison of existing PET averages during Day 3 with future A1FI/RCP8.5 and B1/RCP4.5 scenarios until the end the century.

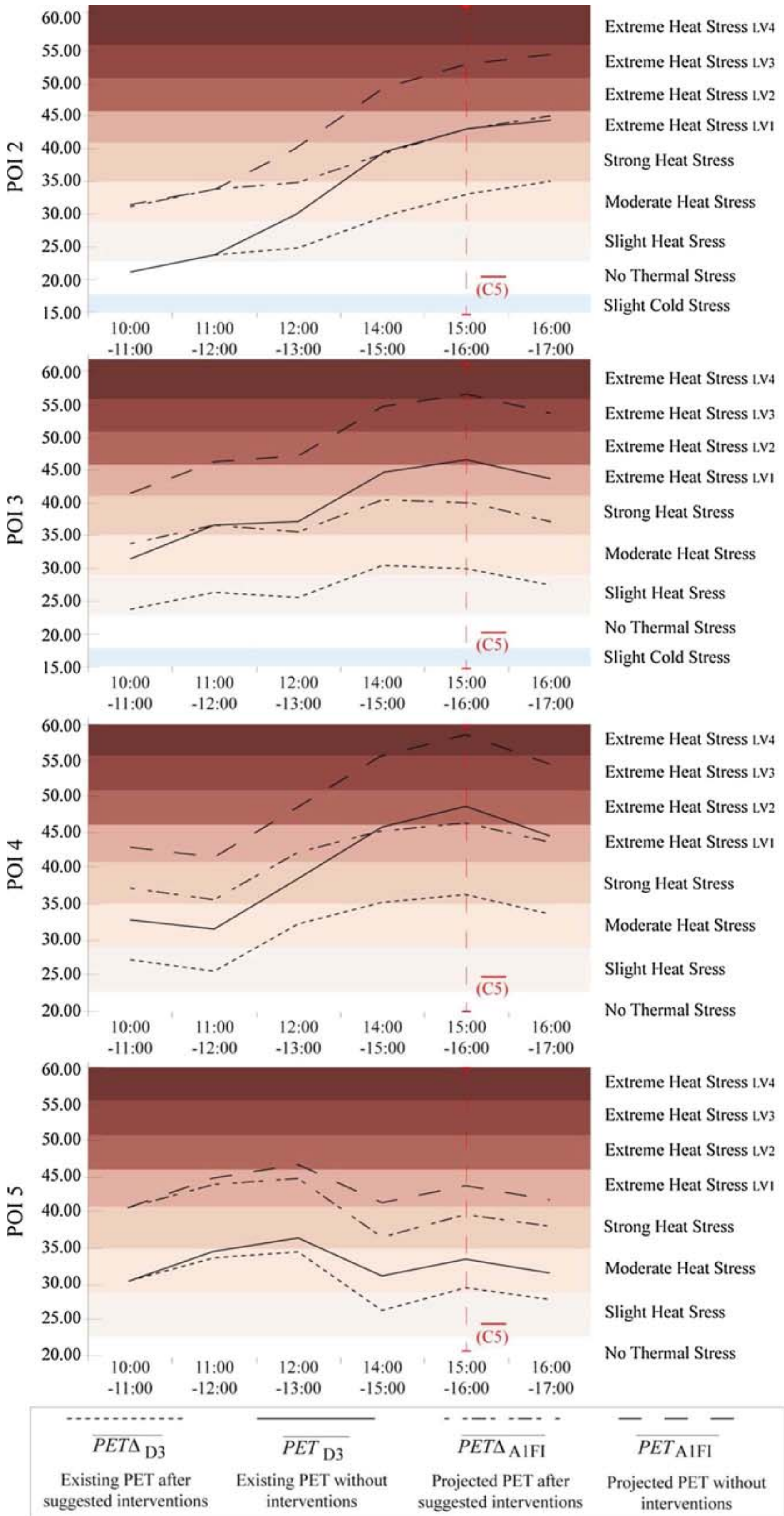


Fig. 4. Comparison of existing PET averages during Day 3 (before and after interventions) with future projections until the end the century, C5 emphasised by red line which identifies period where majority of POI's witnessed highest stress levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

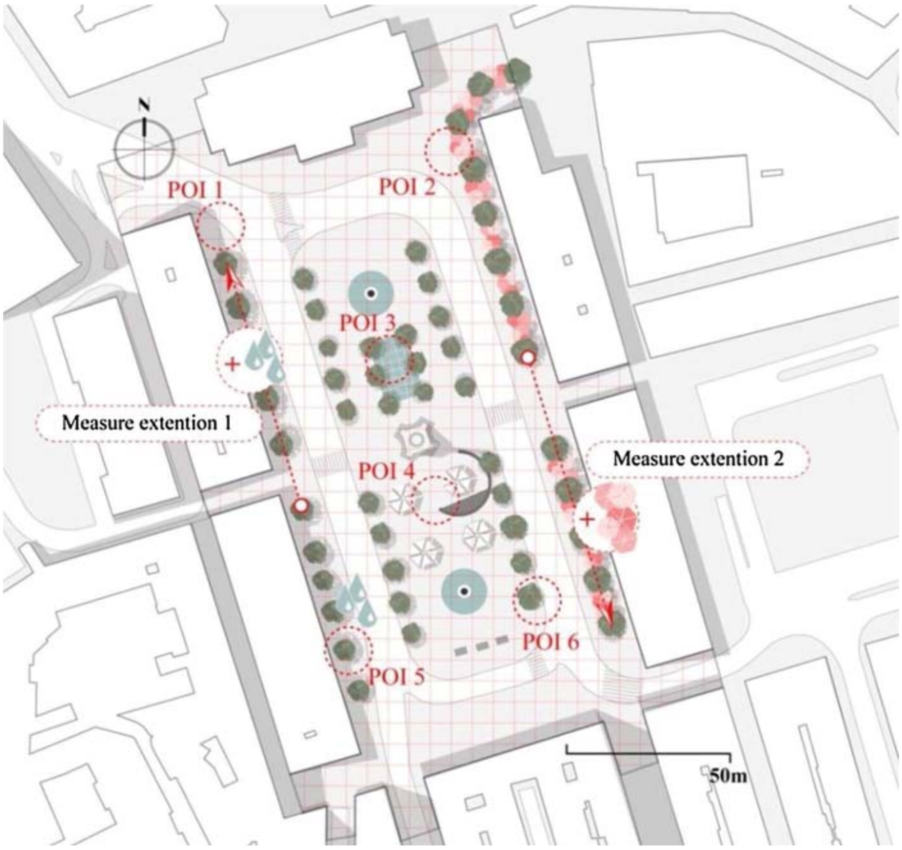


Fig. 5. Gridded layout of Rossio with proposed public space design interventions with extensions on western and eastern sidewalks.

- POI 3 provided a reference for the northern central area of the square that contained no source of shade
- POI 4 provided a reference for the southern central area of the square that also contained no trace of diurnal shade
- POI 5 provided a reference for an area of the western sidewalk that was both shaded by vegetation and cast by the western façade of the square
- POI 6 provided a reference for areas within the central square that were shaded by a vegetative crown

3.2. Measure extension

As the distribution of PS was considered around the entire square, it was also decided to expand two of the suggested public space design interventions in order to consider how thermal comfort could be modified throughout the entire western and eastern sidewalks. More concretely, and as shown Fig. 5, in the case of: (i) POI 1–considering the western sidewalk, the five trees between POI 1 and 5 were also considered to have the misting system within the branches of the tree crown; and, (ii) POI 5–considering the eastern sidewalk, the use of nylon canopies between the vegetation was extended to the remaining five trees to the south.

Also referring to the values obtained at each POI, and in order to consider how PS thresholds could be modified throughout the entire western and eastern sidewalks; the solutions proposed for POI 5 (water misting system), and POI 2 (nylon canopies), were extended as shown in Fig. 5 (■ See Appendix C). In the case of the western sidewalk (i.e. measure extension 1), the five trees between POI 1 and 5 were also considered to have the misting system within the branches of the tree crown. On the south-eastern sidewalk (i.e. measure extension 2), the use of nylon canopies between the vegetation was extended to the remaining five trees to the south.

As shown in Fig. 5, the overlapped grid network provided a base to determine the dimensional extents of both existing and new public space design implementations. Such dimensions are what provided a foundation to differentiate the PS attributed to each respective grid.

Although rudimentary, it provided a means to carry out a synoptic thermal evaluation of the entire square based on existing PET values in locations with similar characteristics. As a result, and considering the outcomes shown in Fig. 4, when analysing the physiological results with the use of the grid network, and as presented in Table 4, four different scenarios were subsequently applied.

4. Discussion

4.1. Intensity of physiological stress

4.1.1. Existing scenario

As expected, $\overline{PET\Delta_{D3(C5)}}$ revealed the lowest PS thresholds of all four datasets. In particular, there was a significant reduction of PS within the center of the square. Such descents resulted from the public space design interventions within POI 3/4 which lowered physiological strain by up to three levels.

Given the fact that the western side of the square was cast in the shade, the influences of the suggested public space design interventions were smaller in comparison to the results obtained within the eastern sidewalk. As revealed by $\overline{PET\Delta_{D3(C5)}}$ the nylon canopies reduced PS by up to two levels resultant of the shade cast upon the sidewalk, thus matching the PS expected on the western sidewalk (Fig. 6**a)**. The continuous shade upon the sidewalk enabled solar radiation to be reduced over a larger area, in comparison to the lesser and intermittent reduction demonstrated by$\overline{PET_{D3(C5)}}$.

As indicated in Fig. 6**b**, the$\overline{PET_{D3(C5)}}$ revealed that areas in the center of the square can already obtain a PS of 'Extreme Heat Stress Lv.2′. Thus, all grids that did not receive shade within the center of the square were attributed this PS level. In addition, and considering that the road surface obtained very high temperatures, road areas located around the center of the square were also attributed the same PS level. In the case

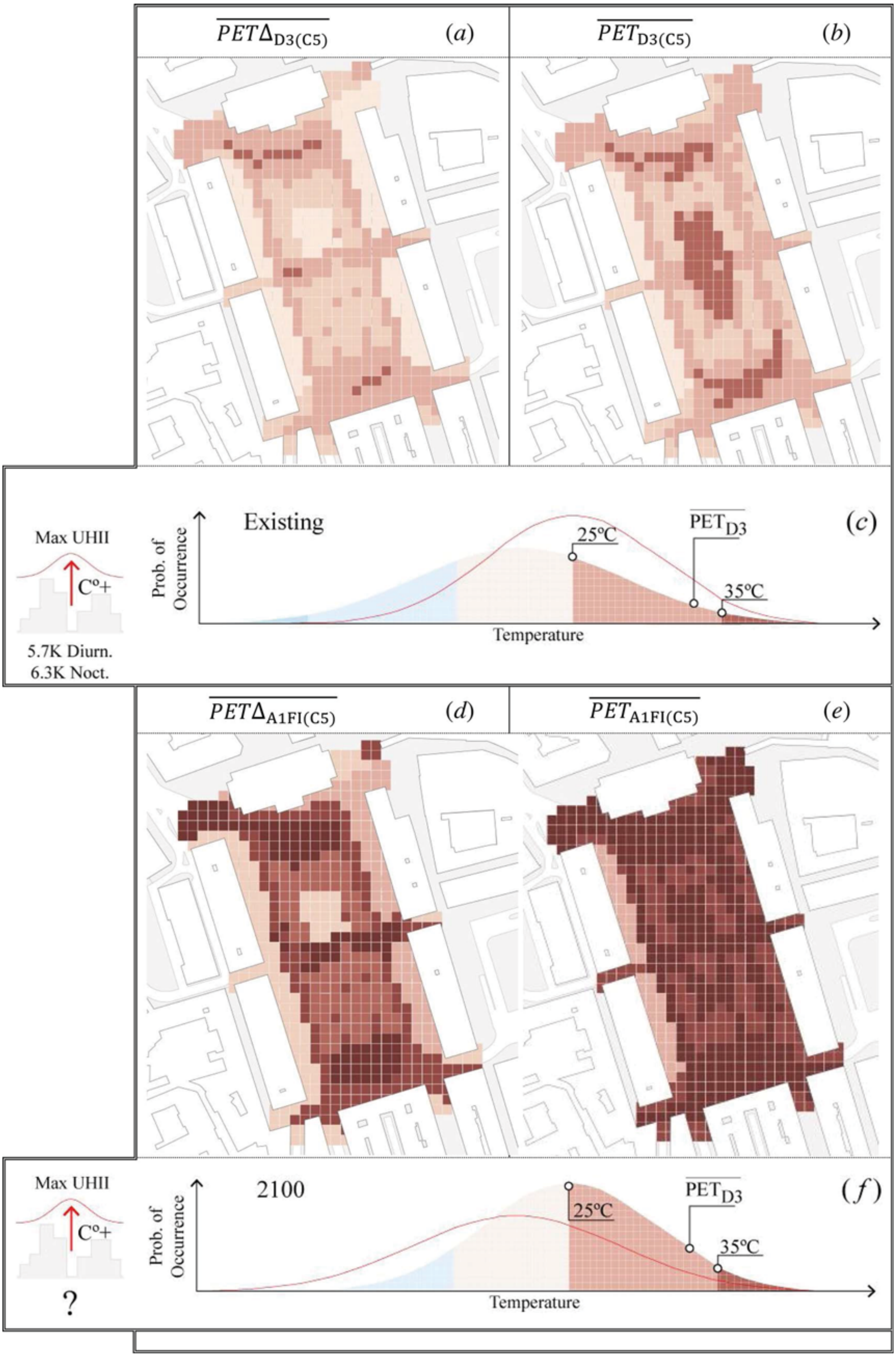


Fig. 6. Distribution of Physiological Stress around Rossio for existing and projected climate.

of $\overline{PET\Delta_{D3(C5)}}$, due to the lower PS thresholds obtained within the northern and southern extremities of the square's center, fewer grids were attributed such a PS grade.

4.1.2. Future scenario

When considering the datasets $\overline{PET\Delta_{A1FI(C5)}}$ and $\overline{PET_{A1FI(C5)}}$, the results demonstrated a dramatic increase of overall PS around the entire square. Founded upon the outcomes presented in Fig. 6, the modest increase of +10 °C in PET dramatically shifted PS thresholds, especially in the case of $\overline{PET}_{A1FI(C5)}$ where no solutions were introduced within the square. Even with the presence of vegetation/shade, wind currents, and building shade, most of the square presented either a PS of 'Extreme Heat Stress Lv.3′ or 'Extreme Heat Stress Lv.4′ resultant of PET values exceeding that of 51 °C or 56 °C, respectively. Even though not located in the center of the square, the eastern sidewalk also presented similar increases of physiological strain by up to three levels.

The coolest region in the square was the western sidewalk, which although cast in the shade, still obtained a PS of 'Extreme Heat Stress'. This grade was obtained by the addition of 10 °C in PET upon the existing PS of 'Moderate Heat Stress'. Such results thus imply that if no action is taken until the end of the century, the coolest sensation a pedestrian could feel in Rossio could be equivalent to what is currently felt in the center of the square today.

Comparatively, the $\overline{PET\Delta}_{A1FI(C5)}$ presented more attenuated PS thresholds as a result of the proposed solutions. Within the western sidewalk the combination of the shade cast by the building façade and the misting mechanism led to a PS threshold of 'Strong Heat Stress'. In the case of the eastern sidewalk, the combination of the added nylon canopies with the increased northern *Tipuana Tipu* tree-line also decreased PS by three levels comparatively to the $\overline{PET}_{A1FI(C5)}$ dataset. Within the center of the square, the proposed shelter canopies for POI 4 led to a reduction of two PS levels due to the attenuation of solar radiation. Nevertheless, it was still noted a substantial PS of 'Extreme Heat Stress Lv.2′, which corresponds to the physiological strain felt today with no attenuation measures. Still within the center of the square, the most drastic reduction however was identified in POI 3, which presented a vast reduction of four PS levels from 'Extreme Heat Stress Lv.4′ to 'Strong Heat Stress'.

4.2. Periodicity of physiological stress

Similarly to the intensity of physiological stress, the periodicity and duration of such thermal stimuli also required scrutiny. In order to undertake this analysis, both Control and Projected annual figures were required for the Lisbon area. This information was retrieved from the research project Climate Change in Portugal, Scenarios, Impacts and Adaptation Measures conducted by Santos and Miranda (2006) who utilised regional climate models to determine existing and potential future aggravations of extreme temperatures and heatwaves at a regional scale.

As indicated by Miranda (2006), when considering the occurrence of climatological occurrences such as 'Very Hot Days' ($T_{amb} > 35$ °C), 'Summer Days' ($T_{amb} > 25$ °C), and Heatwaves (Consecutive days where max $T_{amb} > 32$ °C), specifically for the Lisbon region, there will be a considerable increase between existing figures and those projected for the end of the century. Accordingly, and as indicated by existing literature, it is 'very likely' that heatwaves will occur more often and last longer by the end of the century (IPCC, 2014), including within the European and Mediterranean region (Kuglitsch, Toreti, Xoplaki, Della-Marta, & Zerefos, 2010). Furthermore, the IPCC also stipulated in their fifth assessment report that the influence of prospective climate change upon heatwaves shall be more significant than the impact upon global average temperatures (IPCC, 2013).

In the case of Western Europe in particular, and considering the heatwave of 2003, it was enforced that European countries, such as Portugal, required additional measures to warn, cope, and prevent the recurrence of such events (Kovats and Ebi, 2006; Matzarakis, 2016). More concretely, and within the district of Lisbon, between the 29th of July and the 13th of August 2003, it was identified by Nogueira et al. (2005) that: (i) 15 days had maximum temperatures above 32 °C; (ii) there was a noteworthy consecutive run of 10 days with temperatures superior to 32 °C; and finally, (iii) there was a 5 day period which consecutively experienced temperatures above 35 °C. When considering such impacts upon public health, an estimated mortality rate increase of 37.7% (i.e. corresponding to 1316 excess deaths) in comparison to what would be expected under normal conditions.

4.2.1. Existing scenario

Based upon Miranda (2006), the existing physiological results from the $\overline{PET}_{D3}$ dataset could be evaluated in terms of annual periodicity. Firstly, and obtained from the hottest day, the absolute maximum T_{amb} measured on site was of 32.9 °C, a value that was obtained at POI 2, during Cycle 6, measurement 5 (■ See Appendix A). This infers that although the dataset revealed 'Extreme Heat Stress' levels, and met the 'Summer Day' criteria, the maximum recorded T_{amb} was insufficient to fall under the 'Very Hot Day' classification as synoptically represented in Fig. 6**c**. The implication of this divergence suggests that under present conditions, there already is a possibility of 10–20 days rendering hotter ambient temperatures, albeit by a small margin.

4.2.2. Future scenario

Based upon SRES A2 projections for the end of the century, it was identified that within the A2 scenario, areas such as Lisbon could potentially witness a: (i) total of 50 days a year with diurnal temperatures surpassing that of 35 °C, i.e., labelled as a 'Very Hot Day'; (ii) doubling in duration of days that consecutively surpass temperatures of 35 °C, (implying a potential span of 20 uninterrupted days with such diurnal temperatures); (iii) radical upsurge of 'Tropical Nights' with elevated temperatures, raising from 20 to a potential 80 annual nights where the minimum T_{amb} surpasses that of 20 °C; and lastly, (iv) considerable increase of 'Summer Days' (potentially varying up to 180 days). This was represented in Fig. 6**f**, whereby half the year is attributed a classification of 'Summer Day' which implies reaching a diurnal T_{amb} of 25 °C.

More seriously however, A2 projections suggest that by the end of

Table 5
Physiologically Equivalent Temperature Load (PETL) for each assessed scenario.

	Set of Days		Single Day (Based upon Day 3)			
	Existing Scenario		Existing Scenario		Projected Scenario	
	$\overline{PETL}_{AD(C5)}$	$\overline{PETL}_{NC(C5)}$	$\overline{PETL\Delta}_{D3(C5)}$	$\overline{PETL}_{D3(C5)}$	$\overline{PETL\Delta}_{A1FI(C5)}$	$\overline{PETL}_{A1FI(C5)}$
POI 1	8.7	9.2	≈ 9 *1	≈ 9 *1	≈ 15 *2	≈ 20.5 *3
POI 2	13.2	16.4	10.1	20.0	20.1	30.0
POI 3	16.4	20.0	7.3	23.9	17.3	33.9
POI 4	15.2	19.2	13.3	25.6	23.3	35.6
POI 5	9.5	8.2	6.5	10.4	16.5	20.6
POI 6	10.9	12.9	≈ 15 *2	≈ 15 *2	≈ 25.5 *4	≈ 30.5 *5

*Based on subtraction of *A* (i.e., 23.0) from Mid-Range (MR) value of: 1 = Moderate Heat Stress; 2 = Strong Heat Stress; 3 = Extreme Heat Stress Lvl.1; 4 = Extreme Heat Stress Lvl.2; 5 = Extreme Heat Stress Lvl.3

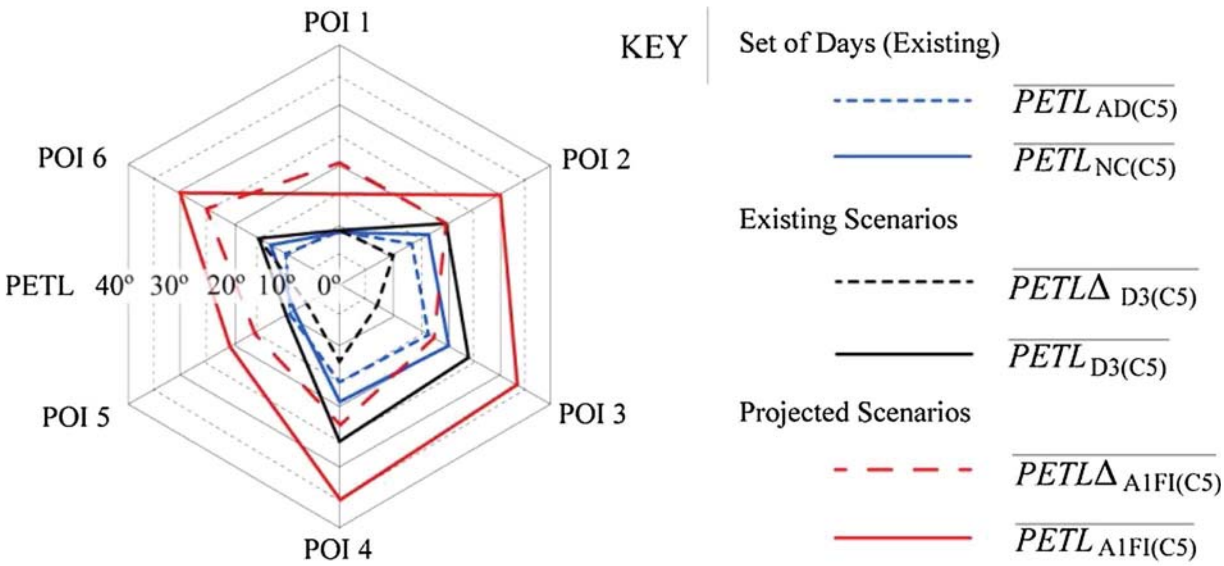


Fig. 7. Radar Chart of Distribution of Physiologically Equivalent Temperature Load (PETL) at C5 within the different assessed scenarios.

the century, there can potentially be up to 50 annual days with hotter diurnal temperatures. In addition, almost half of these days can potentially consecutively follow one another. Also represented in Fig. 6**f**, and based on the definition of Calheiros (2006), the occurrence of consecutive days with similar temperatures as those found in $\overline{PET}_{D3}$ (constituting a heatwave), can also dramatically increase by the end of the century.

For these reasons, and specifically considering Lisbon's existing and projected climatological trends, the duration of a thermal stimulus becomes just as important as its respective intensity. Accordingly, although the PET from Day 3 (hottest of all site visits) may currently represent a comparatively infrequent occurrence, future projections indicate that such conditions: (i) will very likely be the new standard, and resulting PS levels will become customary instead of intermittent; and, secondly (ii) can recurrently be exceeded by hotter days that further augment PS levels, i.e. where diurnal T_{amb} surpasses a value of 35 °C. In addition, and having in mind that the A2 projections are based upon a more attenuated SRES projection in comparison to the A1FI scenario, such deliberations should further refer to the heatwave in Lisbon during 2003, which had a dramatic impact upon urban public health and mortality rates.

4.3. Overall physiological stress & physiologically equivalent temperature load

In order to consider an overall comparison between the different presented thermal environments in Rossio, PET Load (PETL) was utilised to compare how the obtained PET results differ from the proposed optimal PET value. This parameter was developed by Charalampopoulos et al. (2016) in order to identify the discrepancy of the mean hourly PET value in comparison to the optimal established PET values in various locations.

$$\mathrm{PETL} = \mathrm{PET_h} - A$$

Whereby: $\mathrm{PET_h}$ → is the average hourly PET value; A → is representative of the PS grade of 'Comfortable'

Applying this parameter to the case study of Rossio, and since the analysis conducted in Fig. 6 is established upon C5 (i.e., between 15:00-16:00), $\mathrm{PET_h}$ was based upon the PET values obtained during this hour. Since the A factor can be calibrated depending on the specified PET ranges (Hwang, Lin, & Matzarakis, 2010; Charalampopoulos et al., 2016; Lin and Matzarakis, 2008; Lin, 2009), a PET value of 23.0 °C was selected as it represented the upper limit of the 'Comfortable' classification as illustrated in Tables 1–3.

The overall results for every examined dataset during C5 were presented in Table 5. On the left side of the table, both $\overline{PETL}_{AD(C5)}$ and $\overline{PETL}_{NC(C5)}$ are indicative of the PET obtained during C5 during all days, and days in which there were no clouds (i.e., days 1/2/3/5/7). On the right side of the table the results obtained from the four datasets obtained for day 3 were divided into existing and projected scenarios.

Fig. 7 presents the distribution of thermal load beyond what is considered 'comfortable' in PS terms within the different datasets and scenarios. Such results indicate: (i) the small yet clear deviation of PS between $\overline{PETL}_{AD(C5)}$ and $\overline{PETL}_{NC(C5)}$ datasets, due to extraction of days with no clouds from the general dataset, especially in POIs with limited shading (i.e. POI 2/3/4); (ii) the large disparity of PS between existing scenarios (i.e. $\overline{PETL\Delta}_{D3(C5)}$ and $\overline{PETL}_{D3(C5)}$) as a result of proposed public space design interventions within POI 2/4/5, and a particularly in POI 3; (iii) the comparatively dramatic increase of thermal load in the cases of $\overline{PETL\Delta}_{A1FI(C5)}$ and $\overline{PETL}_{A1FI(C5)}$, particularly within the middle of the square, such as in the case of POI 4 in the latter scenario which obtained a drastic PETL value of 35.6 °C above the established 'comfortable' stress grade; and lastly, (iv) the overlapping of datasets within the different scenarios, such as $\overline{PETL\Delta}_{A1FI(C5)}$ that integrates the public space design interventions by the end of the century, with those currently found on site today without any interventions as indicated by $\overline{PETL}_{D3(C5)}$ in POIs 2/3/4.

4.4. Urban heat island effects

Finally, the last considered factor within the study was the implications of UHI upon the PS levels found in Rossio. Although the section raised more questions than answers (particularly for future scenarios), when considering studies such as the one conducted by Alcoforado et al. (2014) that focused upon the case of Lisbon, it was suggested that: (i) thermal stress thresholds are considerably intensified due to the effects of UHI; (ii) steps ought to be taken to adapt to future climatic conditions which are already being felt within the city; and lastly, (iii) the UHI effect is stronger during the summer, obtaining a maximum hourly average of up to 6.3 °C. By comparatively counting the number of times a predetermined site was the hottest or coldest, it was identified that the site 'Restauradores' was the warmest location 64.9% of the time during the day, and 79.6% during the night. Opportunely, of the five measurement sites, this location was located just north of Rossio (located south of 'Avenida de Liberdade', indicated by point 'd' in Fig. 1**a**.

Such results verify the outcomes obtained by (Andrade, 2003; Alcoforado et al., 2005) who identified that stronger UHI intensities during the summer are normally found within the southern regions of the city. As indicated by studies conducted by Lopes (2002), it was suggested that the urban morphology, or urban 'roughness', can have a strong sheltering effect upon wind patterns, which can consequently influence UHI patterns. Within the same study, it was also identified that there is a potential of considerable future wind speed reductions within the city center as a result of augmented urban 'roughness' quantities further impeding northern winds to permeate southern regions of the city. However, this cause-and-effect relationship between these three characteristics has proven to be more complex than initially thought. As illustrated by Lopes et al. (2013), although it was verified that increases in wind speed led to a decrease of UHI intensities, the absence of wind (or prevailing atmospheric calm) did not lead to respective augmentations of the UHI.

As suggested by Oke (1976), the increase of UHI intensities is restricted to new urban structures requiring the demolishing of others once a certain amount of urban density is reached. This being said, when considering the urban energy balance as suggested by Oke (1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Whereby: Q^* → net of all-wave radiation; Q_F → anthropogenic heat flux; Q_H is the flux of sensible heat; Q_E → the flux of latent heat; ΔQ_S → heat stored within the urban fabric; ΔQ_A → net heat advection

It is vital to consider that the energy balance is transient given the dependency upon the constant fluctuation of urban radiation. For instance, when approaching the net of all wave radiation, changes in non-temperature factors such as short and long wave radiation produce direct repercussions upon outdoor comfort thresholds (Algeciras et al., 2016; Charalampopoulos et al., 2016; Matzarakis and Amelung, 2008). This being said, when considering the resulting modifications upon PS in Rossio, such repercussions were evident when considering the simple yet clearly divergent $\overline{PETL_{NC(C5)}}$ results obtained between $\overline{PETL_{AD(C5)}}$.

When considering future horizons, and due to the delicate equilibrium of the urban energy balance, it is here suggested that although downtown Lisbon may not increase in urban/structural density (or 'roughness'), current UHI intensity levels should not be considered stagnant during the twenty-first century. Instead, identified T_{amb} values such as 6.3 °C (Alcoforado et al., 2014), should be approached as a 'base value' which can be offset by modifications to the urban energy balance.

Beyond the results of this study, and exemplified by other prominent international studies, there already is evidence that local measures such as pavement/surface materials, vegetation, water features can considerably influence UHI intensities. As suggested by Santamouris et al. (2016) between the investigated 220 large scale projects that incorporated some form of local measure to reduce local thermal stress and UHI levels, the average peak T_{amb} drop was close to 2 °C. Similarly, within the city of Toronto, and through the combination of cool pavements/roofs, and vegetative shading, a T_{amb} reduction of up to almost 1 °C was identified (Wang et al., 2016). Moreover, and within Toronto's university campus, through the application of green roofs alone, potential reductions of average peak T_{amb} up to 0.4 °C were identified at pedestrian level (Berardi, 2016). Focusing upon vegetation at pedestrian level through the implementation of urban tree design approaches to combat UHI effects in Hong Kong, Tan et al. (2016) identified a potential T_{amb} reduction of 1.5 °C. Such results raise the opportunity for complementary future studies within Lisbon's public spaces, particularly in those presenting lower aspect ratios; not only due to their higher exposure to radiation levels, but more importantly, due to the opportunities to address such vulnerabilities through creative public space design.

For this reason, and considering Oke's energy balance specifically for the urban environment, the implementation of thermal sensitive public space design measures should premeditate upon the counteraction of: (i) the stress associated to the projected increase in the frequency, intensity and consecutiveness of annual summer/hot days by modifying the net/balance of all wave radiation, such as reducing the amount of incoming short-wave radiation upon pedestrians during such periods; (ii) the escalation of urban anthropogenic emissions associated to urban cooling energy requirements (such as air conditioning (Santamouris, 2016)) which as identified by Isaac and Vuuren (2009) can increase by up to 166% by 2100; (iii) the heat storage within the urban fabric of surface materials (such as pavements (Stathopoulou et al., 2009)); and, (iv) urban heat accumulation by insuring the permeability of wind currents in hotter regions of the city, which can have considerable influences upon thermal comfort levels, even in lower aspect ratios (Algeciras and Matzarakis, 2017).

For these reasons, and as expressed by '?' in Fig. 6**f** for future projections, the uncertainty of future UHI values/intensities thus becomes interlinked with action of Man, and his respective impacts upon the urban energy balance as suggest by Oke (1988). As described within this study, and as collaborated by other bioclimatic studies, attenuation of UHI intensities is possible, yet invariably, is only possible if local bottom-up action is undertaken within built environment. In the case of Lisbon, this is intrinsically concomitant with the decision to act in public spaces such as Rossio which are located in areas that are particularly vulnerable to UHI effects.

5. Conclusions

The use of the thermophysiological index PET enabled this study to compare various thermal scenarios that consider implications upon Rossio's existing and future biometeorological environments. Although based upon evaluations of future variations of radiation fluxes, (i.e., countenancing such assumptions of an increase of 10 °C in PET) such explorations allow for future climatic trends to be assessed. Even though the methods used in this bioclimatic study are still maturing, and thus require further study, it nevertheless marks a potential departure from more top-down orientated projections which do not include important meteorological factors (such as radiation fluxes). More specifically, simplistic reflections and/or projections of T_{amb} are continually proving to be insufficient for interdisciplinary practices such as public space design. As a result, the exploration and application of associated biometeorological studies are incessantly proving to be indispensable when addressing the existing, and future, bioclimatic environment of the urban public realm.

Within this study, and by considering existing and future PS thresholds through the application of the 'What if?' agenda, it was possible to explore what could happen within a public space that is already suffering from climatic aggravations. In order to do so, the existing PS grades were expanded beyond the initial > 41 °C threshold to plot the projected results for the end of the century given the A1FI/RCP8.5 scenario. Such a modification was seen to be synonymous with the necessity to question whether current approaches to thermal comfort require further contemplation based upon possible unprecedented aggravations of the urban climate within the public realm.

This being said, and as revealed by the distributive PS analysis around the square, existing diurnal and hourly PET datasets already revealed 'Extreme Heat Stress Lv1/2' within the center of the square. In addition, such PS thresholds were identified during a day which, although by a small margin, did not reach the delineated 'Very Hot Day' classification. More specifically, as the hottest registered T_{amb} value measured on site was a near 32.9 °C, this implied that such PS results can feasibly be more drastic during a day in which maximum T_{amb} values surpass the 35 °C threshold.

When approaching the augmentation of PET in the A1FI/RCP8.5 scenario, the comparative increase of PS levels was drastic. Such disparity was revealed by the dataset which presented the bioclimatic environment of Rossio with no proposed public space design interventions. Furthermore, regardless of the presence of vegetation/shade, wind currents, and building shade, most of the square presented a PS threshold ranging between 'Extreme Heat Stress Lv.3 and 4′, with PET values exceeding that of 51 °C and 56 °C. In parallel, and when considering both the datasets which incorporated public space design interventions, it was identified that the proposed solutions were able to substantially reduce PS levels, particularly in locations prone to high levels of solar radiation. During C5, such results were also confirmed by the PETL, when oscillations from the base 'Comfortable' physiological threshold reduced by −9.9 °C in POI 2, −16.6 °C in POI 3, and −12.3 °C for POI 4 with the presence of the public space design interventions.

Nevertheless, and although the public space design proposals presented promising reductions of existing physiological strain, when considering future horizons, such diminutions proved narrow. As illustrated by the study: (i) even with suggested public space design interventions, the lowest obtained PS grade was of 'Strong Heat Stress'; more seriously however, (ii) in the case where no action is taken until the end of the century within a A1FI/8.5 scenario, the lowest obtained PS grade was of 'Extreme Heat Stress', a threshold which corresponds to what would be felt today within the hottest regions of the square. For this reason, and when considering future augmentations of PET, this study argues that further action is required, whereby its urgency will systematically accompany the progression of potential climatic aggravations projected for the end of the century. To this end, there is an opportunity for a further study which focuses upon prior timeframes (such as 2040 and 2070) in order to identify the progression of these climatic aggravations before reaching the temporal slice discussed in this study.

This being said, and even at a more distant horizon, this study enforces that action is required both at an awareness level, and at a design level which is facilitated by an exploration which concedes the possibility that our cities may in fact have to deal with extreme scenarios by the end of the century. In this sense, such preparations require early and cautious design and planning efforts, that are firstly enabled by flexible examinations such as the 'What if?' agenda; and secondly, backed by projections which consider sufficient meteorological factors which can be used to evaluate the potential future bioclimate of our urban public realm.

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Appendix A. EQUIPMENT & MEASUREMENTS Adapted from (Nouri & Costa, 2017b).

	A.1	Equipment used during the field study			
	Equipment Name / Model #	Measurement	Value Output	Accuracy	Resolution
1	KESTREL 4600BT©	V	m/s	± 3% (of disp. reading)	0.1 m/s
		T_{amb}	Cº	± 0.5	0.1 Cº
		RH	%	± 3.0	0.1%
2	KKMOON SM206©	G_{Rad}	W/m^2	± 10	0.1 W/m^2
3	BENETECH GM550©	T_{surf}	Cº	1.5%	0.1 Cº

A.2	Meteorological measurement structure for the eight minutes at each Point of Interest (POI) during each of the six hourly analysis Cycles (C1-6) throughout each daily visit to the site in order to obtain eight recordings of each meteorological measurement					
	10:00-11:00 (C1)	11:00-12:00 (C2)	12:00-13:00 (C3)	14:00-15:00 (C4)	15:00-16:00 (C5)	16:00-17:00 (C6)
POI 1	10:00/08	11:00/08	12:00/08	14:00/08	15:00/08	16:00/08
POI 2	10:10/18	11:10/18	12:10/18	14:10/18	15:10/18	16:10/18
POI 3	10:20/28	11:20/28	12:20/28	14:20/28	15:20/28	16:20/28
POI 4	10:30/38	11:30/38	12:30/38	14:30/38	15:30/38	16:30/38
POI 5	10:40/48	11:40/48	12:40/48	14:40/48	15:40/48	16:40/48
POI 6	10:50/58	11:50/58	12:50/58	14:50/58	15:50/58	16:50/58

A.3	Notes
	In order to attain averages at each POI during each of the Cycles, a total of 8 min was spent at each point. This method allowed every POI to be assessed within one hour, with a 2 min breadth to set up the equipment at the subsequent location. At each point, wind speed, ambient temperature and RH values were measured at a height of 1.50m by the KESTEL 4600© every minute for eight minutes. This technique enabled for average values to be logged by the equipment, and also for the other required data to be obtained. Two other examinations were undertaken with the use of the KKMOON SM206© and the BENETECH GM550©. Firstly, and also at a height of 1.50m, global radiation was measured in order to determine the amount of radiation that was present at each location. Secondly, all paving surfaces were tested in order to define their surface temperature, both in the sun and in the shade.

Appendix B. Mean Physiologically Equivalent Temperature (PET) vs. Physiological Stress (PS) thresholds.

	POI 1		POI 2		POI 3	
	$\overline{PET}_{AD}$	PS	$\overline{PET}_{AD}$	PS	$\overline{PET}_{AD}$	PS
C1	30.0	Moderate Heat Stress	21.5	No Thermal Stress	28.6	Slight Heat Stress
C2	32.6	Moderate Heat Stress	24.0	Slight Heat Stress	32.6	Moderate Heat Stress
C3	34.6	Moderate Heat Stress	29.7	Moderate Heat Stress	33.8	Moderate Heat Stress
C4	30.7	Moderate Heat Stress	34.9	Moderate Heat Stress	37.8	Strong Heat Stress
C5	31.7	Moderate Heat Stress	36.2	Strong Heat Stress	39.4	Strong Heat Stress
C6	29.2	Moderate Heat Stress	37.7	Strong Heat Stress	39.2	Strong Heat Stress

	POI 4		POI 5		POI 6	
	$\overline{PET}_{AD}$	PS	$\overline{PET}_{AD}$	PS	$\overline{PET}_{AD}$	PS
C1	28.2	Slight Heat Stress	30.9	Moderate Heat Stress	26.2	Slight Heat Stress
C2	30.8	Moderate Heat Stress	34.3	Moderate Heat Stress	29.0	Slight Heat Stress
C3	33.8	Moderate Heat Stress	35.8	Strong Heat Stress	28.6	Slight Heat Stress
C4	37.1	Strong Heat Stress	33.0	Moderate Heat Stress	33.4	Moderate Heat Stress
C5	38.2	Strong Heat Stress	32.5	Moderate Heat Stress	33.9	Moderate Heat Stress
C6	37.5	Strong Heat Stress	30.6	Moderate Heat Stress	31.1	Moderate Heat Stress

Key:	$\overline{PET}_{AD}$	PET values for All Days	PS	Physiological Stress
	Colour coded based upon corresponding PS value represented in **Tbl.2**			

Appendix C. SOLUTION DATASHEET Adapted from (Nouri & Costa, 2017b).

C.1	POI 2	POI 3	POI 4	POI 5
Vegetation	x	x		
Shelter Canopies	x		x	
Water / Spray System		x		x

C.2	Vegetation						
	#	PL	Species	Dimensions (*)		Foliation (*)	DeFol. (*)
POI 2	3	LP	Tipuna Tipu	TH : ≈ 12.5m	CD : ≈ 7m	Early May	Mid. March
POI 3	6	GP	Tipuna Tipu	TH : ≈ 12.5m	CD : ≈ 7m	Early May	Mid. March

C.3	Shelter Canopies		
	Material	Watts/m² below	Construction/Special Feature
POI 2	Nylon	75	Assembled with cables on tree branches in order to provide shade between tree crowns during the summer (JJA)
POI 4	Aluminium, Acrylic	150	Supported upon a central aluminium structure, seven acrylic flaps are adjustable through a pull-string mechanism which enables the pedestrians to choose to sit in the shade or in the sun in the center of square (JJA)

C.4	Water with surface wetting	LM : RH ≤ 70 % | SMD ≤ 500 μm			
		FP (JJA)	NH	Water Collection	SW Method
POI 3	10:00-11:00	OFF	0m	OFF	OFF
	11:00-12:00	2min + 2min interval		Every 30 min	Surfaces are wet for the specified period and then re-absorbed into the ground slabs
	12:00-13:00	3min + 2min interval			
	14:00-15:00	3min + 1min interval		Every 15 min	
	15:00-16:00	3min + 1min interval			
	16:00-17:00	4min + 1min interval			

C.5	Water without surface wetting	LM : RH ≤ 70 % | T_{amb} > 25 | $\overline{V}$ ≤ 1m/s | $\overline{G_{Rad}}$ < 300 W/m²			
		PP	NH	SMD	FP (JJA)
POI 5	10:00–11:00	OFF	3 m	OFF	OFF
	11:00–12:00	5.0 Mpa		≈ 30 μm	1min + 2min interval
	12:00–13:00	5.5 Mpa		≈ 35 μm	2min + 3min interval
	14:00–15:00	5.5 Mpa		≈ 40 μm	3min + 2min interval
	15:00–16:00	6 Mpa		≈ 40 μm	3min + 2min interval
	16:00–17:00	6 Mpa		≈ 45 μm	3min + 1min interval

PL	Planting Layout	TH	Tree Height	LM	Limitation Mechanism	SW	Surface Wetting
LP	Linear Plantation	CD	Crown Dimension	FP	Functioning Period	PP	Pump Pressure
GP	Group Plantation	JJA	June, July, August	NH	Nozzle Height	SMD	Sauter mean diameter

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*Dimensions retreived from (Viñas et al. 1995).

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Section 4

Projecting thermal attenuation priorities and 'in-situ' impacts within idealised/default urban canyons

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Publication 8:

Examining default urban-aspect-ratios and sky-view-factors to identify priorities for thermal-sensitive public space design in hot-summer Mediterranean climates: The Lisbon Case

A. Santos Nouri, João Pedro Costa, A. Matzarakis

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Article Preamble

Lisbon's bioclimatic risk factors are evaluated and then translated into thermal attenuation priorities for public space design during periods of accentuated stimuli. The examination is structured into sequential stages in order to present how lack of meteorological information can be overcome to assess pedestrian comfort thresholds when pondering the application of local measures within different locations of various stipulated default urban canyons

Article Symbol list

T_{amb}	Ambient temperature	M_{Sun}	Minutes cast in sun
T_{dew}	Dewpoint temperature	WS	Wind speed
T_{surf}	Surface temperature	$WS_{1.1}$	Wind speed at 1.1m
G_{rad}	Global radiation		

Article Acronym List

AR	Aspect Ratio	Oktas	Total Cloud Oktas
BC	Background Conditions	PET	Physiologically Equivalent Temperature
cPETL	Cumulative PETL	PETL	PET Load
CTIS	Climate-Tourism/Transfer-Information-Scheme	PS	Physiological Stress
DJF	December January February	PSD	Public Space Design
HWE	Heat Wave Event	RH	Relative Humidity
JJA	June July August	SON	September October November
KG	Köppen Geiger	SVF	Sky-View-Factor
MEMI	Munich Energy balance Model for Individuals	TAP	Thermal Attenuation Priority
mPET	modified PET	UHI	Urban Heat Island
MR	Mid-Range value	WEO	West-to-East Orientation
MRT	Mean Radiant Temperature	WMO	World Meteorological Organisation
NSO	North-to-South Orientation	WS	Wind Speed

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Examining default urban-aspect-ratios and sky-view-factors to identify priorities for thermal-sensitive public space design in hot-summer Mediterranean climates: The Lisbon case

A. Santos Nouri[a,*], João Pedro Costa[a], A. Matzarakis[b]

[a] Universidade de Lisboa, Faculdade de Arquitetura, CIAUD, Centro de Investigação em Arquitetura, Urbanismo e Design, Lisboa, Portugal
[b] Research Centre Human Biometeorology, Deutscher Wetterdienst, Stefan-Meier-Str. 4, 79104 Freiburg, Germany

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Sky-view-factor

ABSTRACT

This study evaluates Lisbon's bioclimatic risk factors, and how such microclimatic considerations can be transferred into priorities for thermal sensitive Public Space Design (PSD) during periods of accentuated thermal stimuli. The examination was structured into three sequential stages to address how the often lack of meteorological information can be overcome to assess pedestrian thermal comfort thresholds within specific morphological configurations within the historical district of the city. Firstly, through the application of the human-biometeorological model RayMan, the monthly variations of diurnal Physiologically Equivalent Temperature (PET) and corresponding Physiological Stress (PS) fluctuations were examined to obtain an overall comprehension of annual thermal bioclimate conditions within Lisbon. Secondly, diurnal variations were analysed in more detail through hourly oscillations for July in order to obtain an understanding of how thermal comfort thresholds were influenced during one of the hottest months of the year. Thirdly, such results was subsequently cross examined within the constructed default urban Aspect Ratios (AR) and Sky-View-Factors (SVF) within the SkyHelios model to evaluate concrete hourly PSD priority for urban canyons with diverse morphological compositions.

Based upon the results obtained from the study, adaptations of the thermo-physiological index were tested/used, namely the modified PET (mPET), PET Load (PETL), and the cumulative PETL (cPETL) in order identify Thermal Attenuation Priorities (TAP) for PSD within concrete locations of the identified canyons during specific periods of the day.

1. Introduction

Since the early 1980s, examinations of Lisbon's urban climatic conditions have been undertaken in order to address the gap between the interdisciplinary spheres of urban planning/design with that of climatology and biometeorology. Commonly within southern Europe, many cities often present a significant lack of meteorological and climatological information that could otherwise inform design and decision making within the public realm. Considering the case of Portugal in particular, and as identified by Ref. [1], the analysis of 15 Master-plans of urban municipalities revealed that although climatic information was discussed in nearly all of them, the respective information often proved of limited use for local adaptation efforts. Such oversights have been suggested to be attributable to numerous reasons, namely to the fact that meteorological data from 'classical' stations used in the abovementioned municipal plans, were usually not applicable to meso, and microscales [2].

As a response from the scientific community, there has been a dissemination of studies that have made valuable contributions to comprehending the general bioclimatic conditions within the public realm (e.g., [3,4]), causalities of and intensities of Urban Heat Islands (UHI) (e.g., [5–7]), wind current studies (e.g., [8,9]), and, the combination

Abbreviations: UHI, Urban Heat Island; PSD, Public Space Design; AR, Aspect Ratio; SVF, Sky-View-Factor$_{(\#\ respective\ region)}$; TAP, Thermal Attenuation Priority; KG, Köppen Geiger; HWE, Heat Wave Event; WMO, World Meteorological Organisation; PET, Physiologically Equivalent Temperature; MRT, Mean Radiant Temperature; PS, Physiological Stress; Oktas, Total Cloud Oktas; T_{amb}, Ambient Temperature; RH, Relative Humidity; WS, Wind Speed; T_{dew}, Dewpoint Temperature; $WS_{1.1}$, Wind Speed at height of 1.1m; G_{rad}, Global Radiation; CTIS, Climate Tourism/Transfer Information Scheme; (MR), Mid-Range value; NSO, North-to-South Orientation; WEO, West-to-East Orientation; M_{Sun}, Minutes Cast in the Sun; T_{surf}, Surface Temperature; mPET, modified PET; PETL, PET Load; cPETL, Cumulative PETL; BC, Background Conditions; DJF, December January February; JJA, June July August; SON, September October November; MEMI, Munich Energy balance Model for Individuals

* Corresponding author.
E-mail addresses: andrenouri@fa.ulisboa.pt (A.S. Nouri), jpc@fa.ulisboa.pt (J.P. Costa), andreas.matzarakis@dwd.de (A. Matzarakis).

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with planning policy (e.g., [10,11]). In addition, and as a result of the maturing climate change adaptation agenda, studies pertaining to potential impacts upon Lisbon's climate have also been published (e.g., [12–16]). Adjacently, and prospectively further invigorated by bottom-up approaches to climate adaptation within the past decade, there continues to be a growing interest (and demand) for application-orientated perspectives at local scales [17]. It is here where the concept of 'locality' gives origin to creative and design driven practices such as Public Space Design (PSD) in confronting urban climatological aggravations associated to hot-summer climates (e.g., [4,18–23]).

Based upon contributing to this bottom-up approach, this study conducted an application-orientated analysis of Lisbon's bioclimatic environment to identify physiological risk factors within Lisbon's public spaces by: (i) examining Lisbon's annual climatic oscillations of diurnal thermal stress, with a recording interval of 3 h between 09:00 and 15:00; (ii) constructing an hourly evaluation of July's climatic conditions between the diurnal hours of 09:00 and 18:00, with a recording interval of 1 h; and, (iv) assessing how such conditions were affected by the different modelled default urban Aspect Ratios (AR) and Sky-View-Factors (SVF). Once identified, the obtained bioclimatic conditions within the different open spaces were assessed through the application of different thermo-physiological indices in order to build upon Thermal Attenuation Priorities (TAP) for the interdisciplinary and 'locality' based practice of PSD.

2. Methods

2.1. Site

Lisbon is located upon the western coast of Portugal at 38° 42′N and 9º08′W, with a climatic Köppen Geiger (KG) classification of '*Csa*', implying a Mediterranean climate with dry and hot summers [24]. As presented by Refs. [25] and [26], the city observes: (i) between 10 and 20 'very hot days' which are those that experience ambient temperatures (T_{amb}) above 35 °C; (ii) between 100 and 120 'summer days' where maximum T_{amb} surpass that of 25 °C; and lastly, (iii) frequent occurrences of Heat Wave Events (HWE), where T_{amb} sequentially surpass that of 32 °C during various days. With regards to wind patterns, N and NW wind directions are the most predominant during the year, particularly during the summer [2]. However, due to the proximity to the Tagus Estuary, estuary breezes reach adjacent urban areas on 30% of late mornings, and early afternoons during the summer [9]. Shown in Fig. 1, this study focuses mostly upon Lisbon's quarter around 'Baixa Chiado', which due to its morphological composition, often witnesses the highest intensities of UHI [3], and habitually the highest temperatures during the summer [10].

2.2. Data

In order to obtain the data required for this study, meteorological recordings were obtained from the World Meteorological Organisation (WMO) weather station with the Index Nº08535, located in Lisbon (at latitude of 38–43N longitude 009-09W, and an altitude of 77 m). Similar to existing studies (e.g., [2,27–32]), the extracted information from the station was subsequently processed through the RayMan Pro© model [33,34] in order to determine Physiologically Equivalent Temperature (PET) [35], Mean Radiant Temperature (MRT), and Physiological Stress (PS) levels. As presented by Ref. [36], PET is defined as the air temperature at which, in a typical indoor setting (i.e., without wind or solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. The reason for utilizing PET was twofold: (1) it is calibrated upon easily obtainable microclimatic characteristics; and, (2) it uses °C as the measuring unit to assess thermal comfort, it permits other professionals such as urban planners/designers to approach urban climatological aspects. Pertinent to the thermo-physiological assessments conducted in this study, the following microclimatic characteristics were initially introduced into the model: total cloud oktas (Oktas), T_{amb}, Relative Humidity (RH), and lastly, Wind Speed (WS).

With regards to the latter, once the values of WS were translated into ms^{-1}, a further adjustment was undertaken to account for the type of urban conditions discussed in this study. As suggested by Ref. [37], when considering speeds within beneath the Urban Canopy Layer (UCL), and within the streets themselves, modified WS values are often considerably lower than those presented by the meteorological station. As a result, and to determine the actual WS values upon the gravity centre of the human body as stipulated by Ref. [38], the obtained results from the station were adapted to a height of 1.1 m (henceforth expressed as $WS_{1.1}$). Similarly to the study conducted by Ref. [29], the formula presented in Refs. [38,39] was used (Eq. (1)):

$$WS_{1.1} = WS_h^* \left(\frac{1.1}{h}\right)^{\alpha} \qquad \alpha = 0.12^* z_0 + 0.18 \tag{1}$$

where: WS_h is the ms^{-1} at a height of h (10 m), α is an empirical exponent, depending upon urban surface roughness, and Z_0 is the corresponding roughness length.

Comparable to the morphological layout within the study of Ref. [29], Lisbon's denser downtown district with frequent open spaces also presented similar values of $z_0 = 1$ and $\alpha = 0.35$. In addition to these initial microclimatic variables obtained from the meteorological station, global radiation (G_{rad}) values were also introduced later in the study. Such data was retrieved from the authors through the use of the apparatus KKMOON SM206© with an accuracy of ± 10 and resolution

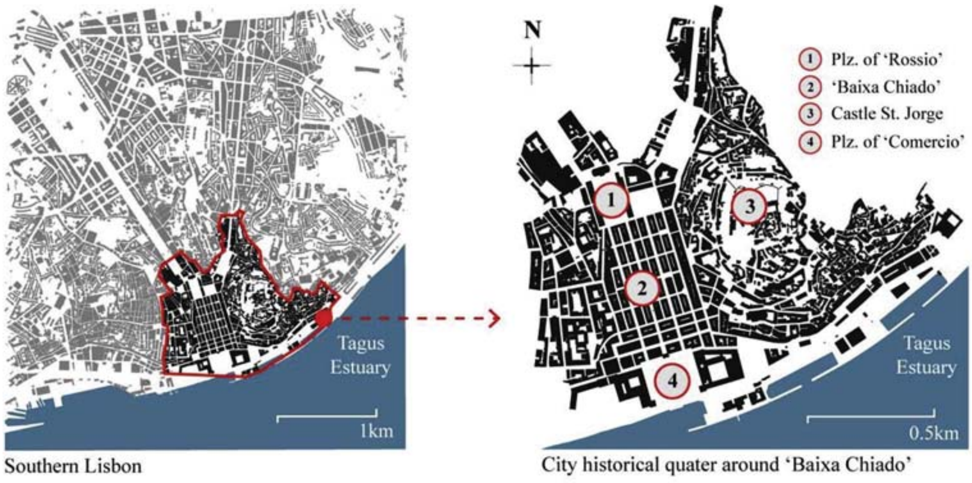

Fig. 1. Specific locations within Lisbon's historical quarter, surrounding context, and proximity to the Tagus.

of 0.1 W/m^2, which was used to obtain hourly oscillations of G_{rad} in canyons with different ARs located in Lisbon's historical centre (e.g., [22]). In conjunction to these climatological aspects, the calibration of the RayMan model was based upon the default standing 'standardised man', corresponding to: a height of 1.75 m, weight of 75 kg, aged 35, a heat transfer of clothing of 0.9 clo, and an internal heat production of 80w [35,36]. During the later stage of the study however, these default calibrations were explored further based upon an update of the RayMan software as discussed by Ref. [40]. As described in their research, the main modifications of mPET is the thermoregulation model (based upon a multiple-segment model), and the clothing model which presents a more accurate analysis of human bio-heat transfer mechanism. Such adjustments led to various dissimilarities between the results presented when examining the bioclimatic conditions of Freiburg during the summer, namely: (i) when considering PS grades, and unlike with PET, almost no 'Extreme' heat stress events were obtained from mPET; and, (ii) the probability of comfortable thermal conditions was higher through the application of the mPET index.

2.3. Applied methodology and structure

The study was undertaken in three sequential stages in order to evaluate Lisbon's bioclimatic risk factors and the resulting priorities for thermal sensitive PSD during periods of accentuated thermal stimuli. As a starting point, the monthly modifications of diurnal PET/PS fluctuations were analysed in order to obtain an overall comprehension of the most recent year (i.e., 2016), which served as reference point to identify periods of both cold and heat stress variations throughout the year. Secondly, based upon the annual analysis, diurnal variations were analysed in more detail through the hourly oscillations for July between 2012 and 2016 in order to obtain an understanding of such diurnal fluctuations over five years. Lastly, such data was subsequently cross examined within the different default AR to consider concrete hourly PSD implications for outdoor spaces with various morphological compositions.

2.3.1. Oscillations of diurnal PET/PS for 2016

Before addressing the summer period, the variations of diurnal PS was examined throughout the entire year. Such an approach enabled: (i) an overall understanding of Lisbon's annual bioclimatic conditions; and, (ii) later serve as an indicator to also recognise the implications for PSD during the colder months. Based upon the configuration of the meteorological station, three recordings were processed during each day at 09:00, 12:00, and 15:00. Such recordings aligned with the times in which the station registered the diurnal Oktas values, and were complemented with the introduced T_{amb}, RH, $WS_{1.1}$ recordings for every day of the year in 2016. The applied SVF at this stage in the study was configured at 1.00 (or 100%) which reproduced a total exposure to solar radiation due to a lack of urban obstacles or structures. Once the PET values were processed, the comparative chart developed by Ref. [41] was utilised in order to correlate the obtained values to a specific PS grade (Table 1).

In order to facilitate the representation of the monthly modifications of diurnal PET (and resulting PS), the results were processed with the Climate Tourism/Transfer Information Scheme (CTIS) [43]. Based upon the calibration of the desired thresholds and temporal period, this software facilitates the graphical representation of a specific climatic variable. In this way, fluctuations of the variable can be colour coded based upon lower and upper limits, thus facilitating the interpretation of the data. Such a method of representation has been used in similar climatic studies (e.g., [29,39,40,44,45]) to ease the understanding of bioclimatic data for non-experts in fields linked to climatology. To comply with the grades presented in Table 1, the colour gradient was configured to comply with the PET boundaries as stipulated by Ref. [41]. An additional classification of 'CAL' was created to account for days and/or hours in which PET values were unobtainable due to the calibration of the meteorological station.

Table 1
Ranges of the thermal index Physiologically Equivalent Temperature (PET) for different grades of Physiological Stress (PS) on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to Ref. [42]).
Source: (Adapted from, Ref. [41]).

PET	PS
	Extreme Cold Stress
4ºC	
	Strong Cold Stress
8ºC	
	Moderate Cold Stress
13ºC	
	Slight Cold Stress
18ºC	
	No Thermal Stress
23ºC	
	Slight Heat Stress
29ºC	
	Moderate Heat Stress
35ºC	
	Strong Heat Stress
> 41ºC	
	Extreme Heat Stress

2.3.2. Oscillations of diurnal PET/PS for July

Similar to the methods used to obtain results for the monthly modifications of diurnal PET/PS fluctuations for 2016, the diurnal oscillations for July were examined. As a means to obtain a more comprehensive understanding of July's bioclimate, PET values were processed at an hourly interval between 09:00 and 18:00. In addition, the assessment of July was undertaken during the years between 2012 and 2016, resulting in six data sets (i.e., $|Jul_{2012}|$, $|Jul_{2013}|$, $|Jul_{2014}|$, $|Jul_{2015}|$, $|Jul_{2016}|$, $|Jul_{Avg}|$). Such an examination enabled the appreciation of how previous years experienced dissimilarities in daily bioclimatic conditions based upon yearly variability.

The input parameters within the RayMan and CTIS model were identical to those used for the monthly oscillations of diurnal PET/PS in 2016. However, since Oktas values were only recorded by the meteorological station at 09:00, 12:00, and 15:00, it was necessary to approximate such values for the remaining hours. Such an approximation was accomplished by: (i) the identification of the Mid-Range (MR) values between the three daily recordings; and in conjunction, (ii) considering the qualitative meteorological descriptions presented by the station.

2.3.3. Configuring the default canyons

As shown in Table 2, through the geometric configurations built within the Obstacle plugin of RayMan, different canyons were modelled based upon the Height-to-Width (H/W) ratios of $H/W_{2.00}$, $H/W_{1.00}$, $H/W_{0.50}$, $H/W_{0.25}$, and that of $H/W_{0.17}$.

To modify the AR of the canyons, and similar to the categorisation presented by Ref. [46], each of the ARs were attributed a description varying from 'Very High' to 'Very Low'. Considering the general building heights in Lisbon's historical quarter, a canyon height of 20 m

Table 2
Description and categorisation of utilised Aspect Ratios (AR) and their respective Height, Width, and Ratio.

Aspect Ratio Description	Canyon Height	Canyon Width	H/W Ratio
'Very High'	20	10	2.00
'High'	20	20	1.00
'Medium'	20	40	0.50
'Low'	20	80	0.25
'Very Low'	20	120	0.17

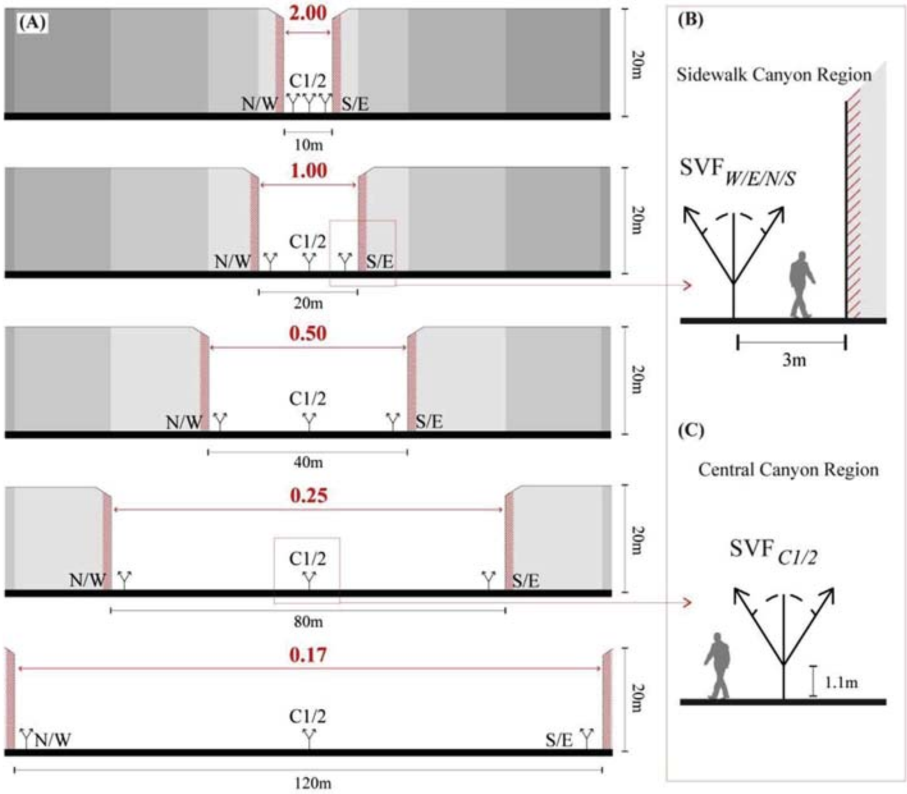

Fig. 2. Layout of the determined Sky-View-Factors (SVF) within the four stipulated Aspect Ratios (AR).

remained as the constant variable. On the other hand, and based upon the most common street/square widths, the width was varied between 10 m and 120 m.

Once defined, each canyon was then processed through the SkyHelios model [47] in order to determine SVF at a specific location within each canyon. Similar to the study conducted by Ref. [28] for the city of Cuba, although canyon length was not required to obtain the ARs, each canyon was attributed a length of 400 m in order to ensure that the 'edges' of the default canyon would not interfere with the obtained SVF within the SkyHelios model. In addition, for every AR, each canyon was categorised into a North-to-South Orientation (NSO) and a West-to-East Orientation (WEO) to evaluate the influence of the geo-referenced solar path upon their different morphological composition.

As discussed in the study conducted by Ref. [48] the estimation of SVF was based upon a classic single-point SVF (or SVF_{sp}) within specific locations to obtain a 'fisheye view' at a calibrated height of 1.1 m. As illustrated in Fig. 2A for both NSO and WEO, three SVFs were identified to examine the predominant variation of solar radiation within the canyons, whereby the: (1) NSO accommodates one central SVF located within the middle of the canyon (SVF_{C1}), and two lateral SVFs which were each located 3 m from the Western and Eastern canyon façade (SVF_W and SVF_E, respectively); and, (2) WEO accommodates another central SVF within the middle of the canyon (SVF_{C2}), and two additional lateral SVFs 3 m from the Northern and Southern canyon façade (SVF_N and SVF_S, respectively). As a result, the amount of solar radiation could be evaluated upon the different regions of the canyons, including upon sidewalk areas (Fig. 2B), and central regions of the canyon (Fig. 2C). Beyond determining the modelled SVF, it was also possible to determine the amount of diurnal Minutes cast in the Sun (M_{Sun}) at each specific location.

As previously described, the considered microclimatic parameters were based/adapted from values initially retrieved from the local weather station. When considering actual circumstances, it is highly likely that: (i) values such as T_{amb} and RH would not be identical at each single-point SVF; and, (ii) additional microclimatic factors such as surface temperatures (T_{surf}) and vehicular anthropogenic emissions could also influence thermal comfort conditions. Nevertheless, the emphasis of this study was to project how default canyon variables (i.e., width, height and orientation) would generate different bioclimatic conditions as a result of susceptibilities to microclimatic variables such as solar radiation. For this reason, the meteorological station values served as a means to construct a baseline of thermal conditions that would be altered when assessing the bioclimatic conditions within each of the ARs/SVFs. With regards to concrete variables such as T_{surf} and 'in-situ' anthropogenic emissions, since these factors are induced by specific local design factors (e.g., surface colour/material, road layout/typology), such considerations were not considered by this study. These deliberations should however be considered when approaching an actual site whereby PSD elements (e.g., pavement, vegetation, shelter canopies, and water features) can attenuate microclimatic risk factors. Based upon the default ARs presented in Fig. 2A, such risk factors were subsequently identified and discussed.

2.3.4. Assessing local bioclimatic conditions and priorities

Within the previous assessments, the SVF was calibrated to 1.00, thus leading to results which represented a total exposure to solar radiation. However, and resultant of the default ARs, it was subsequently possible to examine the influence of urban morphology upon the modelled bioclimatic environment. During this section of the study, the $|July_{2016}|$ data set was used by averaging the month's hourly recordings of T_{amb}, RH, and $WS_{1.1}$, which were then introduced into the RayMan model. In addition, to supplement output precision, hourly G_{rad} values were also specified. Accordingly, PET values for each of the AR, Orientation, and SVF were obtained for each hour between 09:00 and 18:00. Such outcomes were then compared against the new updated PET model for Western Europe developed by Ref. [40] to assess how the results were influenced by the new thermal index, modified PET (mPET). Based upon the more reliable output obtained by mPET, this index was selected to undertake the prioritisation analysis. Moreover, and referring to the methodology developed by Ref. [30], the PET Load

(PETL) and the cumulative diurnal PETL (cPETL) were also applied, where: (i) PETL refers to the outcome difference from optimum conditions, allowing thus for a value which specifically denotes the amount of physiological stain upon optimum thermal conditions; and, (ii) cPETL ascertains the cumulative sum of the PETL specifically during a fixed amount of hours. In this study, by adapting their equations to incorporate mPET, such methods permitted: (i) each hourly physiological stress load to be accounted for based upon the different morphological conditions and time of day based on (Eq. (2)); and, (ii) the cumulative sum of mPETL to be examined between the specific hours as presented in (Eq. (3)):

$$\text{mPETL} = \text{mPET}_\text{h} - BC \tag{2}$$

where: mPET_h is the average hourly mPET value (obtained in this study from the $|\text{July}_{2016}|$ data set), and *BC* (Background Conditions) in this study was set to denote the maximum PET for the PS grade of 'No thermal stress' (i.e., of 23 °C).

$$M\text{cmPETL} = \sum_{h=9}^{12} \text{PETL} \qquad A\text{cmPETL} = \sum_{h=13}^{18} \text{PETL} \qquad D\text{cmPETL} = \sum_{h=9}^{18} \text{PETL} \tag{3}$$

where: $M \triangleq$ Late Morning Period (09:00–12:00), $A \triangleq$ Afternoon Period (13:00–18:00), $D \triangleq$ Diurnal Period (09:00–18:00).

3. Results

3.1. Diurnal PET/PS results for 2016

The results shown in Fig. 3 show the annual climatic variation of Lisbon's '*Csa*' climate during the morning, midday and mid-afternoon. As expected, there was a considerable variation of PS throughout the year, especially between the winter and summer periods. By undertaking the analysis for every day of the year through the CTIS software, it was possible to concretely determine the progressive annual oscillations between the two periods, and moreover, how such bioclimatic fluctuations varied between the three stipulated diurnal recordings.

During the winter period (i.e. DJF), the lowest PS was of 'Extreme' cold Stress, where PET descended to as low as 1.5 °C at 09:00. During this morning measurement, and amongst the winter months, the most common PS varied between 'Strong' and 'Moderate' cold levels. For this reason, it became important to note that Lisbon's climate also witnessed some extent of cold PS during DJF, a factor which was subsequently considered when discussing PSD priorities for the summer later in the study. As presented by Fig. 3, the winter period also witnessed some periods of heat stress during particular periods the day. Particularly at 12:00, the obtained PET values led frequently to 'Slight' heat stress mid-to-late January, thus suggesting the susceptibility to physiological heat stress even during the colder months of the year. Opposingly, when considering the 09:00 measurements, such grades were not witnessed until late April. By this time of year, both the 12:00 and 15:00 measurements recorded PS grades ranging between 'Slight' and 'Moderate' heat stress. Until early October, both of these measurement times progressively reached 'Strong' and 'Extreme' heat stress levels. Furthermore, to plot PET values which considerably surpassed the 41 °C benchmark, an added 'Extreme' PS grade was added to the CTIS calibration. As a result, it was possible to plot PET values that reached 46 °C, which was particularly relevant for mid-July/August, and early September. Out of the entire JJA period, the month with the highest PS (albeit by a small margin) was July, a result that was also confirmed by the monthly MRT analysis.

As expected, the 09:00 measurements revealed the lowest frequency and intensity of annual heat stress, where for the exception for mid-to late July, PS values remained below 'Strong' heat stress. However, the differentiation between the duration and intensity of heat stress between the 12:00 and 15:00 measurements was more intricate. On the whole, and as demonstrated most effectively by the autumn months (SON), the higher PS levels were obtained by the 12:00 measurements. On the other hand, and as a relegation to this norm, the month of May demonstrated that the obtained measurements at 12:00 were cooler than those presented at 15:00.

Correspondingly, the presented monthly MRT averages in Table 3 corroborate such results, whereby: (i) 09:00 measurements constantly presented lower MRT throughout the entire year, particularly for the colder months with a $\overline{\Delta\text{MRT}}$ of up to +16.51 °C during December; (ii) 15:00 measurements were mostly lower then 12:00, with the exception for May with a $\overline{\Delta\text{MRT}}$ of +0.9 °C, and July and August which revealed minor variations of +0.27 °C.

3.2. Diurnal PET/PS results for July

Equating to the middle of the summer period, and in line with the study previously conducted by the authors in Ref. [22]; the month of July was selected in order to examine the month in which PS were at their highest in Lisbon. As shown in Fig. 4, it was possible to identify bioclimatic: (i) variations between the 5 datasets; (ii) events pertaining to a specific year; and, (iii) diurnal oscillation average between 2012 and 2016 through the inclusion of the $|\text{Jul}_\text{Avg}|$ dataset.

In addition, it was possible to identify that not all datasets reached the added second 'Extreme' heat stress grade, as demonstrated by $|\text{Jul}_{2014}|$ and $|\text{Jul}_{2015}|$. Out of the five datasets, $|\text{Jul}_{2014}|$ was the only exemplar to obtain any sign of cold stress during the month as presented between 10:00–11:00 and 18:00. Moreover, this dataset

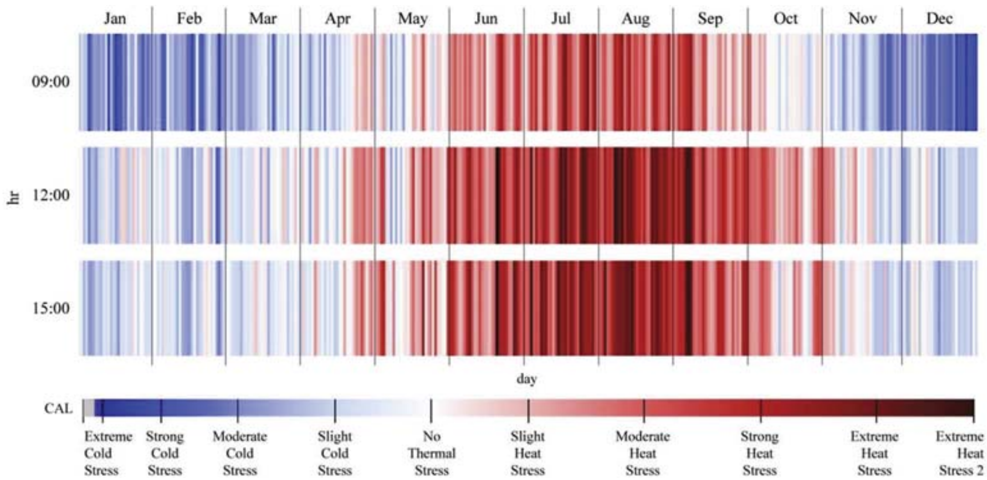

Fig. 3. Variations of diurnal Physiological Stress (PS) at 09:00, 12:00 and 15:00 for 2016.

Table 3
Average monthly Mean Radiant Temperature ($\overline{MRT}$) at each measurement time and variation for 2016.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
09:00	12.71	18.08	24.67	32.47	35.63	44.03	46.32	45.32	40.48	28.76	18.07	10.86
$\overline{\Delta MRT}$	15.43	11.86	11.74	9.25	7.05	5.26	6.05	7.17	8.98	13.16	14.91	16.51
12:00	28.14	29.94	36.41	41.72	42.68	49.29	52.37	52.49	49.46	41.92	32.98	27.37
$\overline{\Delta MRT}$	−3.5	−0.73	−2.59	−2.28	0.9	−0.14	0.27	0.03	−2.94	−6.16	−5.25	−3.09
15:00	24.64	29.21	33.81	39.44	43.58	49.15	52.64	52.52	46.52	35.76	27.73	24.28

presented the lowest amount of heat stress between all of the datasets with a considerable amount of days which varied between 'No thermal stress' and 'Slight' heat stress, particularly before the 9th of July. Although similar conditions were found in different datasets, such as $|Jul_{2012}|$ between the 5th and the 14th, such periods were followed by sequential days which witnessed the first and second PS grades of 'Extreme' heat stress. In particular, $|Jul_{2013}|$ revealed an extended period of such stress which, as defined by Ref. [25], revealed four sequential 'Very Hot Days' (i.e., where maximum T_{amb} surpass that of 35 °C). Such an increase took place between the 4th and 7th, where the last day presented a maximum diurnal T_{amb} of 38.5 °C at 15:00. Just as significantly, it was noted that during these days, the second 'Extreme' heat stress grade was obtained as early as 11:00 and as late as 17:00.

Undertaking a similar approach utilised by Ref. [49], who described a HWE as sequential set of days where maximum T_{amb} surpassed that of 32 °C, such an identification was incorporated into Fig. 4. Between the 5 datasets, $|Jul_{2016}|$ revealed the month with the highest frequency of 3 HWE, while $|Jul_{2013}|$ presented the longest HWE which lasted a total of 8 days. Such results equate to the importance of predicting and preventing such events particularly for Western Europe as seen by the considerable impact and consequences resultant of the 2003 HWE [50,51].

As revealed by Fig. 5, which undertook the same analysis that was carried out in Fig. 4, only based upon mPET outputs, it was noted that the adapted index presented very similar results to those identified by Ref. [40]. More concretely, this similarly relayed to 'Extreme' heat stress levels being less frequent, particularly with regards to the second PS level attributed to m/PET values exceeding 41 °C. Such values were only obtained by the $|Jul_{2013}|$ and $|Jul_{2016}|$ datasets and for much shorter periods of time than those presented by PET results in Fig. 4. Similarly, and using the $|Jul_{Avg}|$ dataset as an overall example, it was possible to verify that PS levels were generally lower over the 5 years, particularly during the middle of the day.

3.3. Canyon outcomes

As suggest by the research conducted by Ref. [52] in Freiburg, "… *thermal bioclimate conditions in urban areas can be affected strongly by the urban configuration* (…) *width, height and orientation of an urban canyon are all very important parameters for the evaluation of specific thermal bioclimatic conditions.*" (p.202). Resultant of their study outputs, it became clear that when approaching microclimatic characteristics such as radiation fluxes, simulations provide an important base for urban planning/design issues in addressing urban bioclimatic conditions of a specific 'locality'. Similar conclusions were reached by Ref. [28] who also considered variations of the urban bioclimate in different canyons with different AR and orientations in the city of Camagüey.

Correspondingly, and within the study conducted by Ref. [53], the correlations between urban canyons and thermal comfort conditions have also been discussed. Within their study, it was identified that "*outdoor stress in a hot-arid* [climate] *may be dramatically reduced by compact sectional proportions (H/W in the range of 1.00–2.00) when the street is orientated north-south* (…) *such a compact street geometry serves to protect pedestrians from thermal stress*" (p.2408). Although the assessment was carried out within the more arid climate within southern Israel, it was possible to identify relatable results (particularly within the $H/W_{1.00}$) to those projected for a Mediterranean climate, as shown in Fig. 6.

As shown, the implications of urban morphology upon thermal comfort conditions have already been discussed in numerous studies. Inclusively, there has also been an emerging subdivision of studies that have identified the impacts of asymmetrical canyons upon bioclimatic conditions at pedestrian level (e.g., [54,55]). Although this study is based upon a district in Lisbon with predominantly symmetrical canyons, future study entices the consideration of how asymmetrical canyons within other districts can lead to different thermal conditions and opportunities.

Processed through the RayMan and SkyHelios models, Fig. 6 demonstrates the results for each SVF in every AR and respective orientation. The solar path, represented by the red line, was geo-referenced, and calibrated to illustrate the solar path for the 15th of July, which provided adequate accuracy to examine the oscillations for the entire month. Naturally, the SVF and M_{Sun} generally increased as the AR decreased. However, such a cause-and-effect relationship proved to be more intricate between M_{Sun} and SVF. Such was exemplified by $2.00SVF_E$ presenting 180 M_{Sun} with a SVF of 0.16; whilst $0.17SVF_S$ also presented 180 M_{Sun} yet with a substantially higher SVF of 0.50. These early outcomes indicated how the specific location of the SVF within the canyon could lead to considerably different bioclimatic conditions within the same AR, and even reflect those of a completely different morphological configuration. From $H/W_{1.00}$ downwards, due to being located within the central region of the canyon, the two SVFs with the generally highest amount of M_{Sun} were SVF_{C1} and SVF_{C2}. Between the two, SVF_{C2} often obtained higher amounts of M_{Sun}, particularly in the case of $0.25SVF_{C2}$ and $0.17SVF_{C2}$ which obtained 600 M_{Sun}, an amount not obtained in canyons with a NSO.

3.4. Bioclimatic results and thermal attenuation priority

Although the $|Jul_{Avg}|$ dataset was initially considered for this section of the study, it was found that the hourly oscillations were rendered too indistinct. For this reason, and due to being one of the hottest datasets, and in line with the assessment undertaken in Fig. 3, the average diurnal variation obtained for $|Jul_{2016}|$ was used. In addition to the average hourly values of T_{amb}, RH, and $WS_{1.1}$ processed from the $|Jul_{2016}|$ dataset, the respective G_{rad} and SVF values were introduced into RayMan. Contiguous to this assessment of the bioclimatic conditions in each AR, the mPET was also tested alongside the PET outputs.

Revealed by the results presented in Fig. 7, it was possible to again verify that the mPET index behaved analogously with the results obtained by Ref. [40]. Although both indices presented mostly the same PS threshold, in circumstances of higher susceptibility to heat stress, PET generally revealed a higher PS grade. In effect, within all canyons, mPET never presented a PS of 'Extreme' heat stress even when PET values obtained such grades, as exemplified by $0.17SVF_{C1}$, $0.17SVF_{C2}$, $0.25SVF_{C1}$, and $0.25SVF_{C2}$. Regardless of the index, the largest impact upon PET and mPET was the amount of M_{Sun}, represented by a red circle next to each column resultant from the CTIS model.

As to be expected, there was a wide range of oscillation in bioclimatic conditions within each SVF, AR and orientation. Naturally, the

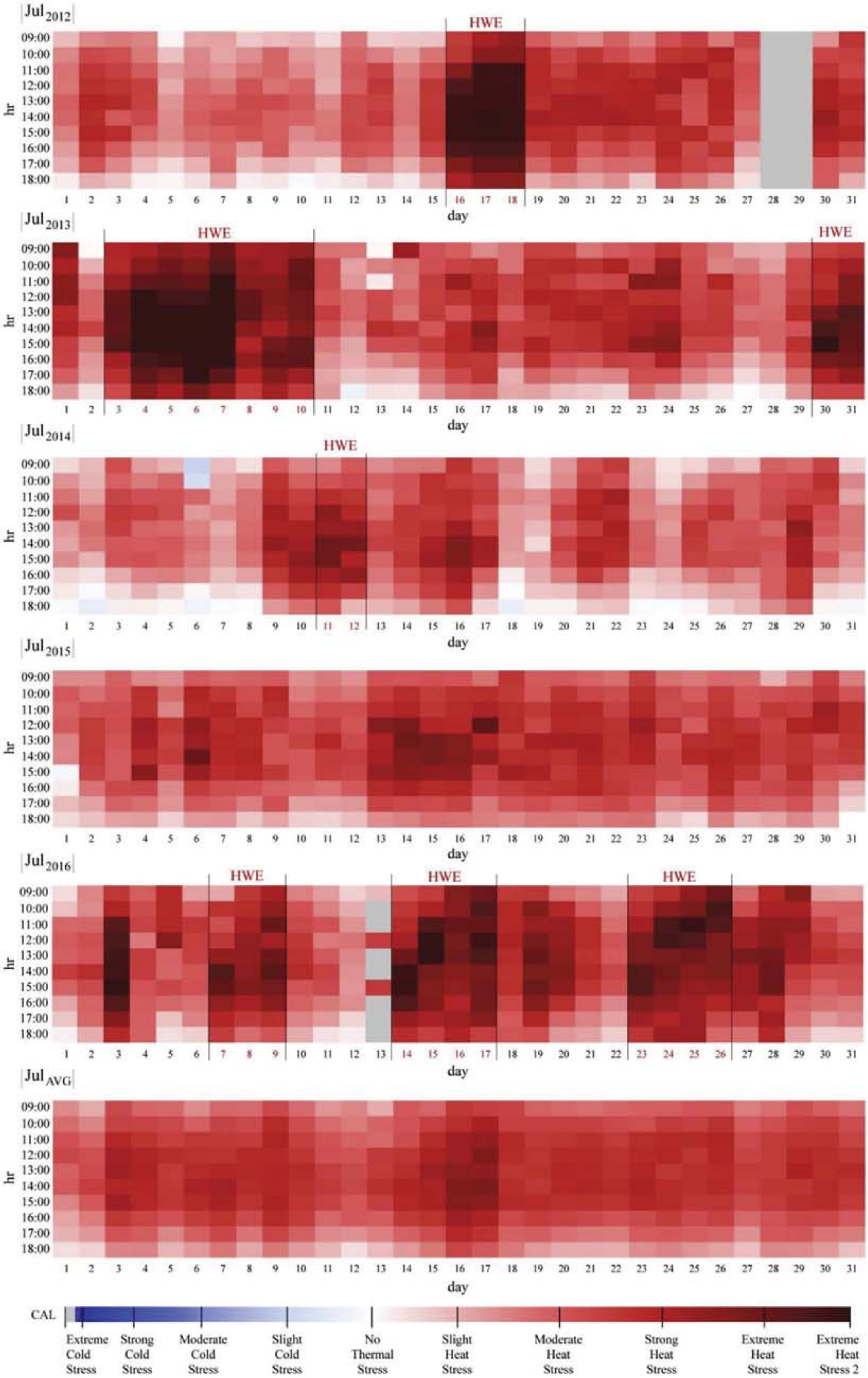

Fig. 4. Variations of diurnal Physiological Stress (PS) based upon Physiologically Equivalent Temperature (PET) at an hourly interval between 09:00 and 18:00 for 2012–2016 with identification of Heat Wave Event (HWE).

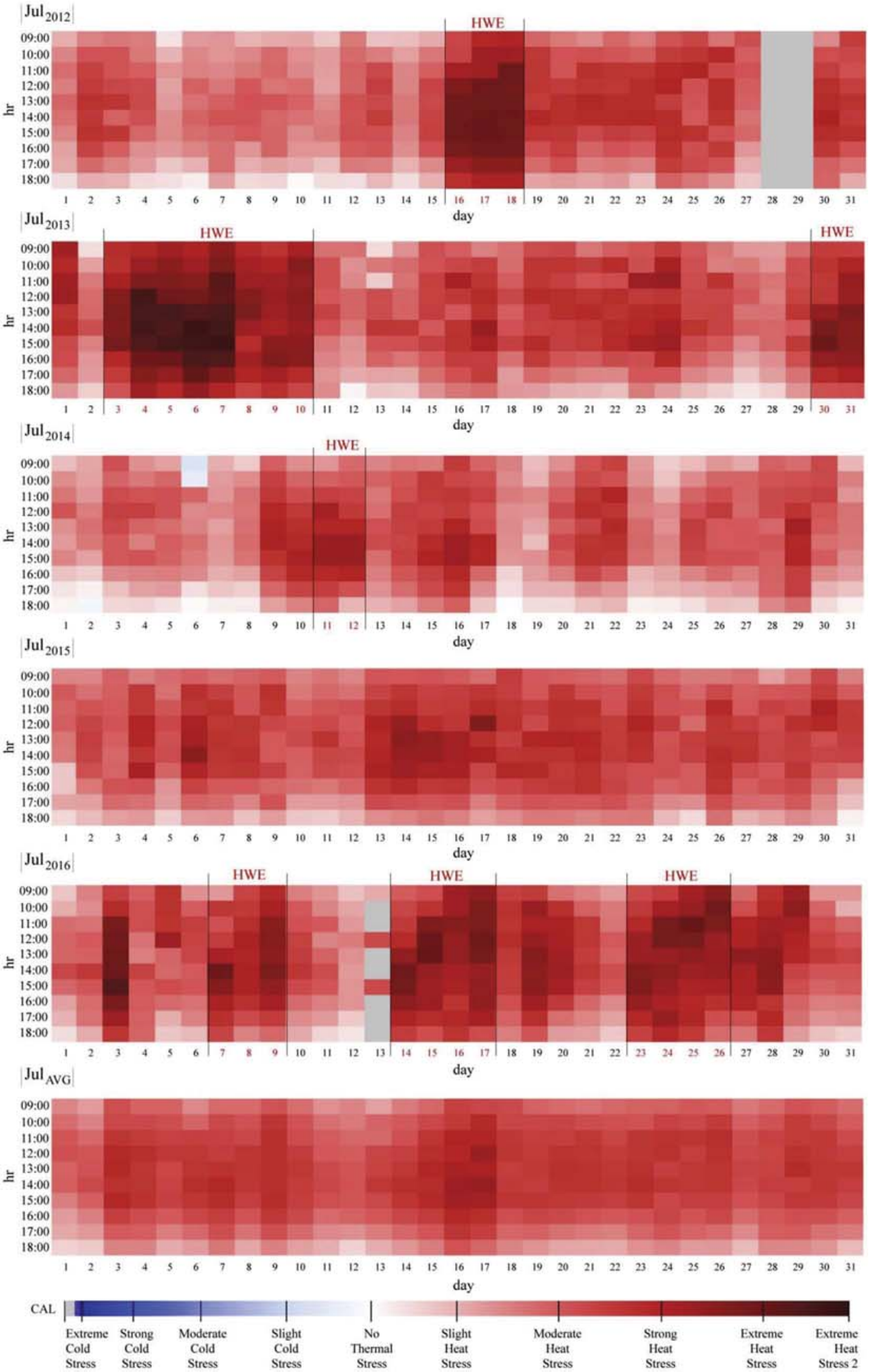

Fig. 5. Variations of diurnal Physiological Stress (PS) based upon modified Physiologically Equivalent Temperature (mPET) at an hourly interval between 09:00 and 18:00 for 2012–2016 with identification of Heat Wave Event (HWE).

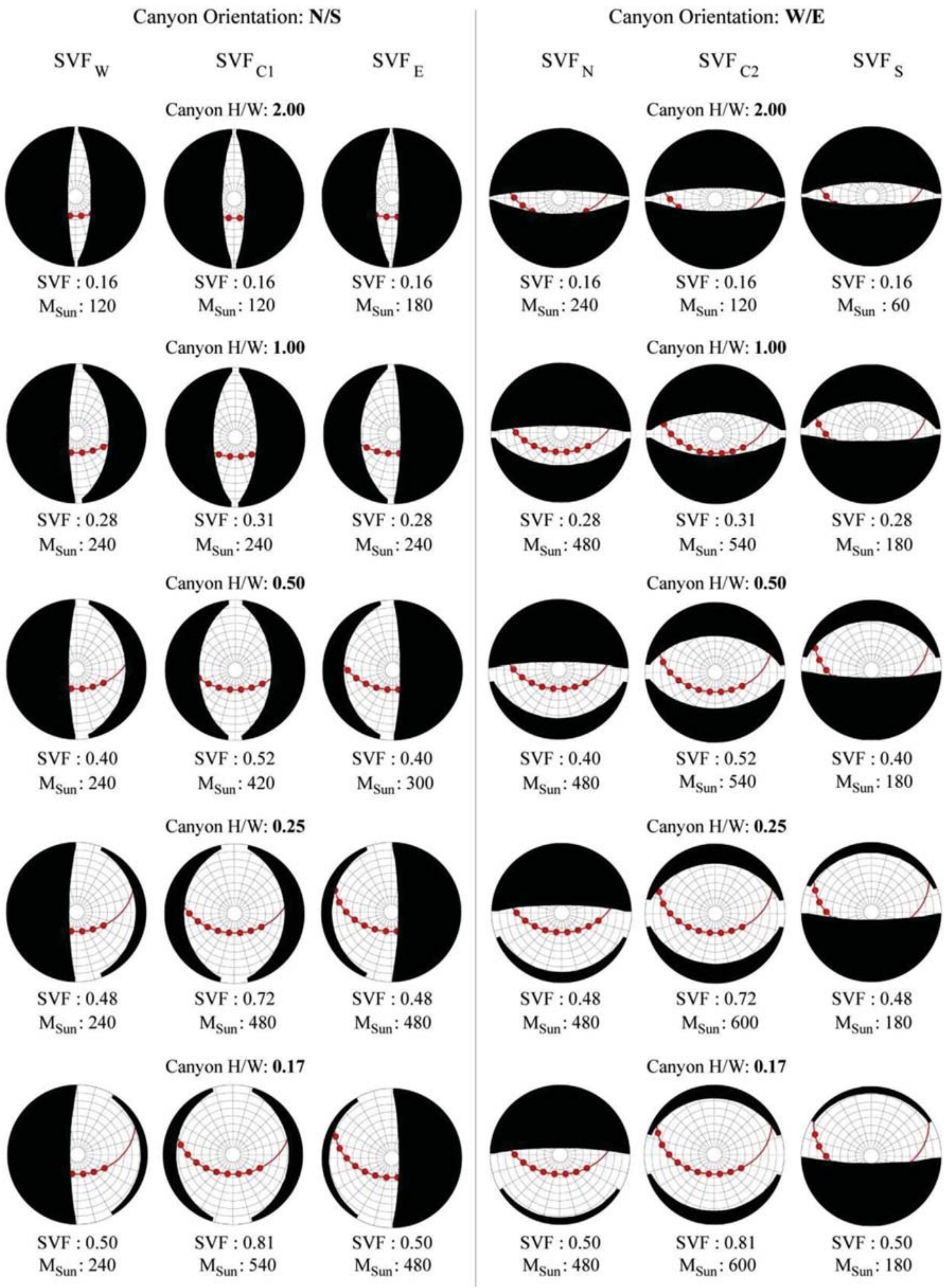

Fig. 6. Identification of Sky-View-Factor (SVF) and Minutes Cast in Sun (M_{Sun}) between 09:00–18:00 for each specific location with a solar path calibrated to the 15th of July.

AR with the least amount of heat stress was $H/W_{2.00}$, which due to its short width, presented little variation between the three SVFs in both NSO and WEO. Nevertheless, between the two orientations, since WEO was predominantly cast in the sun during mid-afternoon, the combination with lower diurnal T_{amb} temperatures led to lower PS levels. As the AR lowered, the higher exposure to radiation fluxes had different implications upon the two canyon orientations:

- In the case of the WEO, when the AR ranged between $H/W_{1.00}$ and $H/W_{0.17}$, SVF_N and SVF_{C2} presented the longest diurnal exposure to thermal stress which often fluctuated between 'Strong' and 'Extreme' heat stress. Opposingly, even in the lowest AR of $H/W_{0.17}$, SVF_S presented the lowest heat stress levels, often obtaining a maximum of 'Moderate' heat stress for most of the day until cast in the sun between 16:00 and 18:00.

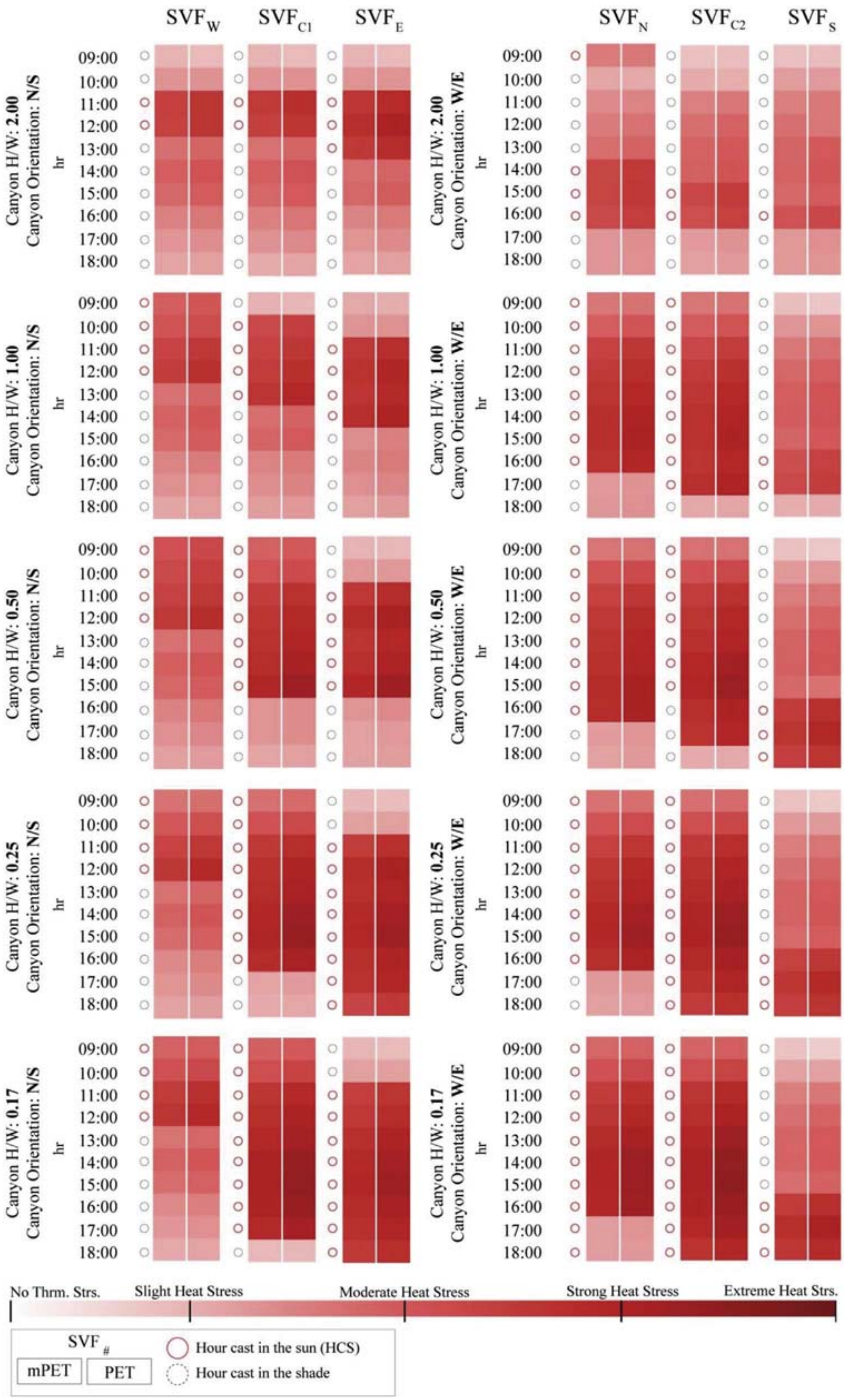

Fig. 7. Canyon variations of diurnal Physiological Stress (PS) resultant of hourly Physiologically Equivalent Temperature (PET) and modified PET (mPET) between 09:00 and 18:00 based upon climatic averages obtained for July 2016.

- With regards to the NSO, similar PS levels were identified, yet, and particularly in $H/W_{2.00}$, $H/W_{1.00}$, and $H/W_{0.50}$, the duration of such heat stress was shorter due to larger amount of shade cast by the canyon. Such distinctions were clear in the case of $2.00SVF_E$, $1.00SVF_E$, and $0.50SVF_E$ where PS grades oscillated considerably between 'Slight' to 'Strong' during the middle of the day. Such deviation changed in the $H/W_{0.25}$ and $H/W_{0.17}$, where the afternoon period was no longer cast in the shade, hence maintaining higher stress thresholds until 18:00. Similar to SVF_S within the WEO, SVF_W presented the lowest overall heat stress for NSO, including in low ARs attributable to the higher amount of diurnal shading hours.

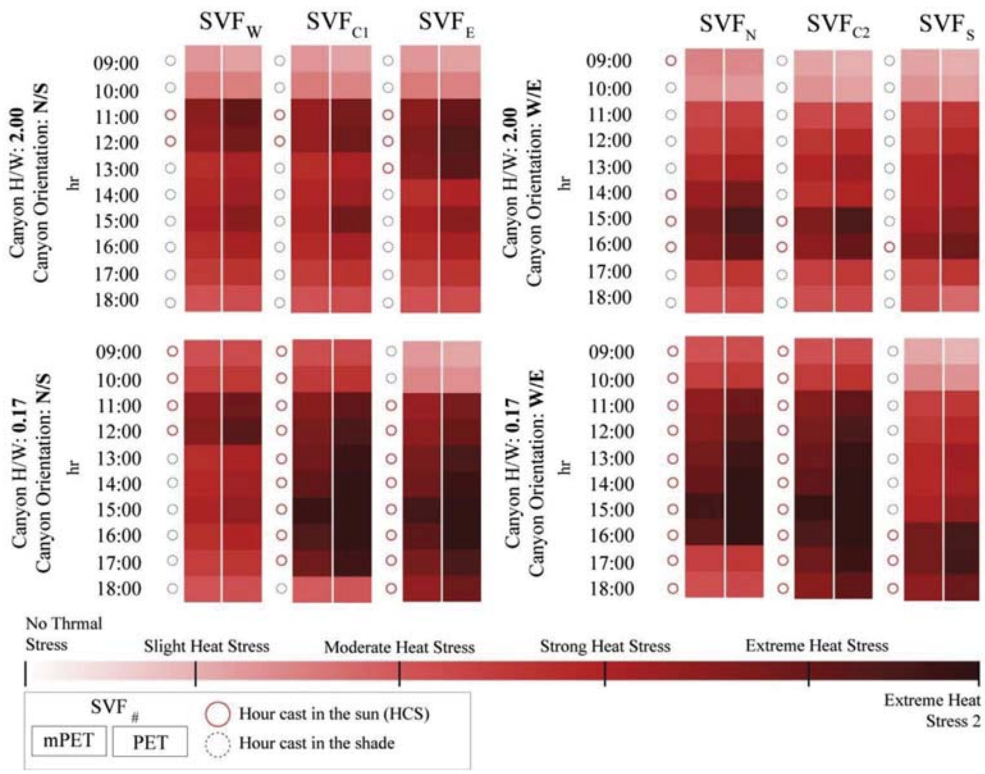

Fig. 8. Canyon variations of diurnal Physiological Stress (PS) resultant of hourly Physiologically Equivalent Temperature (PET) and modified PET (mPET) between 09:00 and 18:00 based upon climatic averages obtained for the 3rd of July 2016.

Based upon interrogative 'What if?' approach as conducted in Ref. [14], and having identified periods of high thermal stress for the month of July as identified in Fig. 4, the following query was thus launched: *If the assessment was based upon a particularly hot day, instead of the averages obtained for the $|Jul_{2016}|$ dataset, how would this influence the obtained bioclimatic results?*

To answer this question, the diurnal results obtained for the 3rd of July 2016 were used, as it was the hottest day of the month, and presented PS grades ranging up to the second 'Extreme' heat stress level. The results of this evaluation are illustrated in Fig. 8, which demonstrated significantly dissimilar outcomes to those obtained for the $|Jul_{2016}|$ dataset. As the intention was to sample the implications of a 'worse-case-scenario' upon the bioclimatic environment, only the highest and lowest ARs were examined. Two principal conclusions were extracted from this 'What if?' scenario.

Firstly, and more distinctively then in Fig. 7, it was possible further collaborate the results obtained by Ref. [40], given the increased disparity between PS grades between mPET and PET in scenarios of higher stress. It is worth noting that unlike in Fig. 7 and Fig. 8 included the second level of 'Extreme' heat stress due to the considerably higher thermal stimuli witnessed during the day. This being said, mPET values revealed generally lower PS grades, and very rarely did it go beyond 'Extreme' heat stress during the day as exemplified by $0.17SVF_{C1}$, $0.17SVF_E$, $0.17SVF_N$, and $0.17SVF_{C2}$. It was furthermore noted that in these examples, mPET always oscillated beyond 'Extreme' heat stress at 15:00, regardless of the canyon's orientation. Contrariwise, and in the case of $0.17SVF_{C1}$, $0.17SVF_{C1}$, and $0.17SVF_{C2}$ PET values frequently reached the second 'Extreme' PS grade, which lasted up to 6 h. These results revealed the considerable difference between the two thermal indices, particularly in events of higher stress levels, whereby "*in temperate regions, mPET rates the climate as not extremely hot thermal conditions, while PET overestimates the climates as extremely hot during the summer*" ([40], p.14). Such over estimations by far devalue the overall validity of the PET outcomes. Instead, these outcomes suggest circumstances in which the index may be complemented by new improvements to the original Munich Energy balance Model for Individuals (MEMI) model parameters.

The second conclusion in light of the outcomes shown in Fig. 8 refers to the cause-and-effect relationship between the frequency/duration of M_{Sun} and thermal stress. During events of extreme heat stress, although M_{Sun} generally leads to higher thermal stress, once individual climatic variables such as diurnal T_{amb}, RH, and $WS_{1.1}$ reach a certain level, bioclimatic conditions in the shade may still reveal elevated heat stress. On the 3rd of July, T_{amb} reached a notable maximum of 35.9 °C at 15:00, with a low RH of 32.6%, and a slow $WS_{1.1}$ of 1.0ms^{-1}. Such conditions clarify why even mPET values surpassed that of 'Extreme' heat stress at 15:00. For this reason, as revealed in most scenarios presented in Fig. 8, it was recognised that during periods of extreme thermal stimuli, even locations cast in the shade can present considerably high PS grades.

When approaching the general bioclimatic conditions identified for July, an overall TAP was constructed. Such a prioritisation was built upon translating the identified bioclimatic conditions into PETL and cPETL as described in the methods section. Illustrated in Fig. 9 the objective of the TAP was to establish the hourly physiological stress load within the different morphological composition (and specific locations) at a specific hour of the day. Such results were constructed upon mPET results rather than PET due the thermal index presenting more consistent outputs during periods of more accentuated thermal stimuli. The consequence of this choice was that if the regular PET index had been used, the TAP would present a slightly exaggerated priority, particularly between the hours of 12:00 and 15:00.

In order to construct the TAP, five different priority levels were established based upon the amount of variation from *BC* (i.e., equating to a PET of 23 °C which represents a PS of 'No thermal stress' as shown in Eq. (2)), whereby:

- Nil – 0 °C corresponding to no increase from 23 °C; (2) Low Priority – 4 °C corresponding to a mPETL of 27 °C; (3) Medium Priority – 8 °C corresponding to a mPETL of 31 °C; (4) High Priority – 12 °C corresponding to a mPETL of 35 °C; and, (4) Very High Priority – 16 °C corresponding to a mPETL of 39 °C.

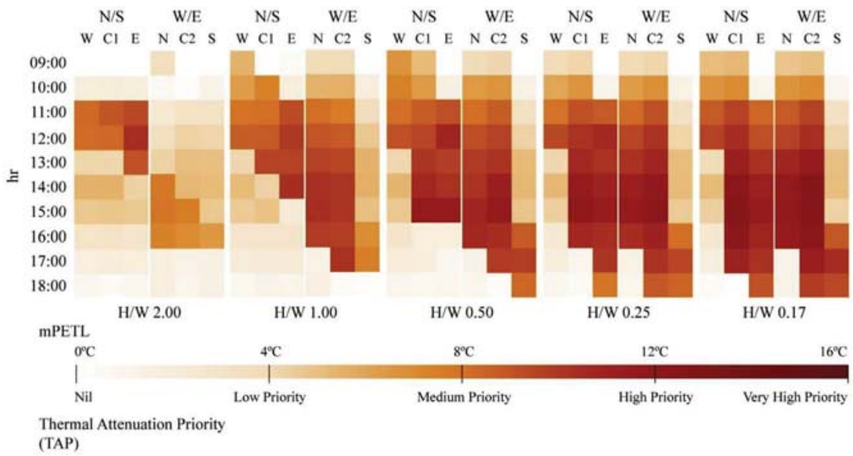

Fig. 9. Thermal Attenuation Priority (TAP) for the different canyons through the identification of modified Physiologically Equivalent Temperature Load (mPETL) between 09:00 and 18:00 based upon climatic averages obtained for July 2016.

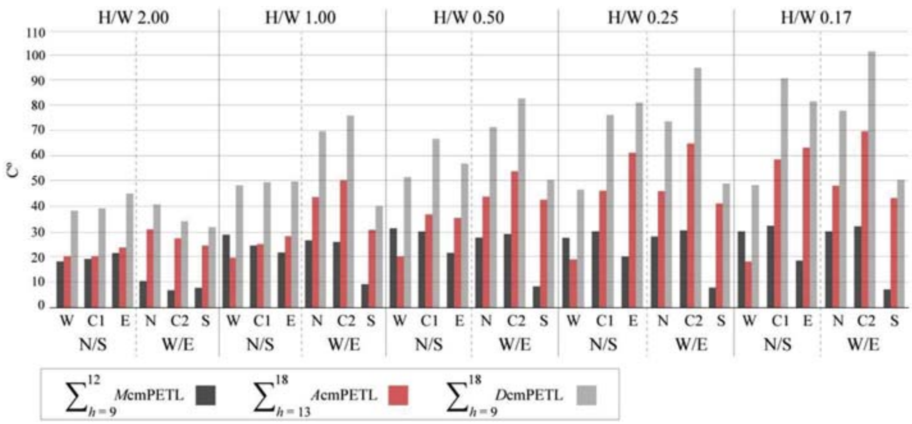

Fig. 10. Cumulative modified Physiologically Equivalent Temperature Load (cmPETL) for the Morning (*M*), Afternoon (*A*), and Diurnal (*D*) period for the different canyons between 09:00 and 18:00 based upon climatic averages obtained for July 2016.

Such incremental values were based upon establishing a constant variation of ± 4 °C, which allowed the mPET results to be evenly distributed with some correspondence to the grades of PS as stipulated by Ref. [42]. Nevertheless, such distribution and calibration presents the opportunity for future refinement and study. Such variations of physiological indices and their respective calibration against stress levels continue to be a constant item of revision (e.g., [30,44,56,57]). Furthermore, it is recognised that even in the case of mPET, future study is required to address its intrinsic relationship with that of thermal classifications [40].

As shown in Fig. 9, it was identified that attenuation priority varied significantly between the different canyons, and that all ARs presented at least a high priority at some point of the day. Within the NSO, as demonstrated by $2.00SVF_E$ (the most susceptible SVF from the $H/W_{2.00}$), attenuation priority ranged from medium to high between the hours of 11:00 and 13:00. Such results propose that during this short period of time, even in a high AR, thermal attenuation is recommended during the summer. When comparing such results with the WEO, priority levels were considerably lower. Out of all of the default canyons, this was the only circumstance in which the WEO priority levels were generally lower than those presented by the NSO.

Within the $H/W_{1.00}$, priority levels increased dramatically, especially for the WEO, as exemplified by $1.00SVF_N$ and $1.00SVF_{C2}$ ranging between a medium and high priority for most of the afternoon. Moreover, where $H/W_{2.00}$ presented between nil and low attenuation priority for the hours of 09:00 and 10:00, $H/W_{1.00}$ presented up to a medium priority for the morning period. Similarly to the $H/W_{2.00}$ and $H/W_{1.00}$, $H/W_{0.50}$ attenuation priority ranged between nil and low within the NSO during the latter part of the afternoon. However, in the case of $H/W_{0.50}$, such a period occurred directly after 15:00, that revealed an attenuation priority varying between high and very high in $0.50SVF_{C1}$ and $0.50SVF_E$. Similar levels were obtained for $0.50SVF_{C2}$ between 14:00 and 15:00, yet within the WEO, priorities remained elevated during the latter part of the day.

Between the lowest ARs of $H/W_{0.25}$ and $H/W_{0.17}$, there was little variation of priority levels with exception for the hours between 14:00 and 16:00 where $0.17SVF_{C1}$ and $0.17SVF_{C2}$ revealed a very high priority for thermal attenuation. In addition, and particularly in the case of $H/W_{0.17}$, there no longer was a period of reduced attenuation priority during the latter part of the day for the NSO. It was noted, however, that between 17:00–18:00 and 09:00–10:00 there still were periods with a nil or a low priority for thermal attenuation. Such outcomes result from a combination of early/late diurnal T_{amb} values, high RH levels, and the presence of shade in the specific locations as exemplified by $0.17SVF_W$ in the late afternoon, and $0.17SVF_E$ in the morning.

Finally, the latter results of the study complement the outcomes presented by the TAP within the default urban ARs and SVFs by considering the cumulative sum of the mPETL (see Eq. (3)) for the morning period (09:00–12:00), afternoon period (13:00–18:00), and for the diurnal period (09:00–18:00).

Fig. 10 presents the variation of thermal stress during the different periods through the use of cmPETL index. Such results complement the previous TAP outcomes by illustrating the cumulative oscillations within each default canyon and their respective SVFs. More concretely, it summarises that: (i) with exception for $H/W_{2.00}$, SVF_{C2} always represented the highest amount of cmPETL during the diurnal period; (ii) in all canyons, SVF_W and SVF_S consecutively revealed considerably lower amounts of cmPETL during the diurnal period; (iii) interlinked with the previous point, while SVF_W constantly presented the lowest cmPETL for the afternoon period, SVF_S almost always presented the lowest cmPETL for the morning period; (iv) the cmPETL of central regions of the canyons did not always present the highest values, including in lower ARs, as demonstrated by $0.25SVF_E$ for the diurnal period; and (v) interlinked with the previous point, it was noted that for both $H/W_{0.25}$ and $H/W_{0.17}$, the afternoon cmPETL obtained by SVF_E surpassed that of SVF_{C1}, particularly in the case of $H/W_{0.25}$.

When considering the differences between NSO and WEO, it was identified that within the mid-range ARs (i.e. $H/W_{1.00}$ and $H/W_{0.50}$), WEO generally presented a higher cmPETL for all three specified cumulative periods. In the case of $H/W_{0.25}$ and $H/W_{0.17}$, such a difference amongst the two orientations became much less distinguishable due to their already considerable canyon width.

4. Discussion and opportunities for PSD

When it comes to urban PSD, the crucial and well known humble vision of "*What attracts people most, it would appear, is other people*" ([58], p.19) is still, today, of key significance. Such an 'attraction' can be approached as an 'adaptive thermal comfort process' in which pedestrians go through when exposing themselves to a given outdoor environment. Such a process has been described by Ref. [59] to be divisible into three principal categories: physical, physiological, and psychological. As suggested by the early studies by Whyte, the presence of other people alone is representational of a psychological aspect which draws people to a given location. Nevertheless, in order for people to be there in the first place "*their first psychological attributes that are affected are the amount of time and environmental stimuli the pedestrian chooses to expose themselves to within the public space. Initially, these mental manifestations are those that are directly influenced by microclimatic occurrences in a given outdoor space* [whereby] *if pedestrians are exposed to too much thermal stress/stimuli, regardless of the built surroundings, they shall inevitably choose to leave* …" ([17], p.10). For this reason, while Whyte's vision is indubitable, it's validly is substantiated once the process is successful and presents itself as almost a cyclic rotation of the 'adaptive thermal comfort process'.

This study concentrated principally upon the category of physiological considerations, and building upon guidelines which can support PSD by identifying the priorities for thermal attenuation given the climatic risk factors associated to hot-summer Mediterranean climates in Lisbon. At a local design guideline level, Ref. [46] have already revealed important results with regards to the prioritisation of measures such as vegetation to cool elevated urban temperatures within different default canyons. Nevertheless, and although this study has presented concurring results with regards to canyons with lower ARs presenting the highest priority for interdisciplinary practices of PSD, such guidelines can be taken a step further. Such a step trails the approaches undertaken in different locations/climates such as Stuttgart [60], Barcelona [29], Freiburg [52], and Camagüey [28].

4.1. General thermal sensitive PSD priority

Overall, based upon Lisbon's hot-summer Mediterranean climate, and particularly within its historical centre which often witnesses the highest T_{amb} and UHI intensities within the city, thermal sensitive PSD is of very high priority. Such urgency is particularly applicable to the JJA period, and to some extent, for the afternoon periods during the SON period. These priorities are rapidly increased given the relatively frequent occurrences of HWE and 'Very Hot Days' (Fig. 4). Interlaced with this priority, relays the requirement to comprehend which are the localities most susceptible to excessive thermal stimuli upon pedestrians.

As shown in Fig. 3, it must be considered that Lisbon's climate also leads to some degree of cold stress during DJB period, particularly during the early mornings of December. For this reason, PSD proposals must consider their implications during periods in which solar radiation would otherwise be beneficial upon pedestrians, particularly when using: (i) permanent shelter canopies which are not short term, or an Ephemeral Thermal Comfort Solution [61]; and, (ii) vegetative species, which must be selected with caution in order to obtain the pertinent shading effects during the pertinent time of year [62,63], and during their different growth stages [64–66].

4.2. Location specific thermal sensitive PSD priority

As expected, when considering the most vulnerable default canyons, the lower ARs presented the highest susceptibility to thermal stimuli, regardless of their orientation. However, the specification of the various SVFs allowed for more concrete conclusions to be obtained. Even in higher ARs, and particularly in the case of northern and central regions of $H/W_{1.00}$ with a WEO, considerable PS was identified for most of the day. Such results reveal the importance of going beyond the AR, and consider how specific locations within the same canyon may present completely different thermal stress levels upon pedestrians. Still within the same AR, such results were further corroborated when considering that southern regions revealed dramatically lower PS levels, even when cast in the sun during the afternoon (Fig. 7).

When approaching high to medium ARs, canyon orientation became a far more significant influence upon thermal comfort conditions within space. Such outcomes are derivative of the way in which the solar path interacted with the morphological composition of the space. Unlike in $H/W_{0.17}$ and $H/W_{0.25}$, the lower canyon widths resulted in very dissimilar amounts of M_{Sun} between NSO and WEO, as shown Fig. 6. As a result, it was possible to establish that ARs down to $H/W_{0.50}$ presented a much higher susceptibility to thermal stimuli within WEO canyons. As demonstrated in Fig. 9, such implications led to the conclusion that PSD priority is generally higher in such circumstances, particularly in northern and central regions of $H/W_{1.00}$. Within the low default ARs, central SVFs generally presented a very high priority for PSD interventions. However, it was noted that lateral SVFs also presented a high necessity for thermal attenuation. During various occasions, lateral regions presented close to, or even surpass, PS thresholds as exemplified by eastern region of $H/W_{0.25}$ with a NSO in Fig. 10. Such results imply that central canyons regions do not always correspond to the location with the highest PS thresholds in low ARs. Moreover, these results serve as a reminder that lateral regions can also present similar or higher levels of thermal stress, and must thus be reflected through the locations PSD.

In almost all analysed conditions, it was identified that the canyon locations with the generally lowest priority for PSD was western regions within the NSO, and southern regions within the WEO. Regardless, there were specific times in which PSD would present important contributions in addressing pedestrian thermal comfort levels. It was here where the time of day became an equally critical variant to help decide upon the application of PSD measures within a respective outdoor space.

4.3. Hourly thermal sensitive PSD priority

The hourly recordings enabled the study to identify times of the day in which higher and lower PS led to different priority levels for PSD. Generally, the hours which presented the highest priority for thermal attenuation ranged between the hours of 12:00 and 15:00. Yet such a generalisation was somewhat limitative given the variations presented by the analysed default ARs. In the case of $H/W_{2.00}$, particularly in the NSO which presented considerably higher PS levels (exemplified by eastern region of the canyon), the hours between 11:00–13:00 presented a medium to high priority for thermal attenuation through PSD. In the case of $H/W_{1.00}$ the amount of hours presenting such priorities increased drastically between 10:00–17:00, particularly in the WEO. The increase of the priority periods between $H/W_{1.00}$ and $H/W_{0.50}$ was small. On the other hand, the actual priority levels between the two ARs increased considerably, particularly between 14:00 and 15:00. Within the $H/W_{0.25}$, a considerable increase of priority periods was noted, particularly within the central and eastern regions between the hours of 16:00–18:00. Lastly, and within the lowest AR of $H/W_{0.17}$, although the priority periods varied only slightly from $H/W_{0.25}$, overall priority levels increased considerably, particularly between 13:00–16:00.

5. Concluding remarks

Based upon the results discussed in this study, PSD is approached as an interdisciplinary approach which can present creative design solutions to address the physiological aggravations of Lisbon's urban bioclimate. Here, the bottom-up concept of 'locality' was embraced by using local morphological characteristics to inform, and refine, climatic data into urban planning/design considerations. As suggested by the results obtained in this study, when approaching PSD solutions, whether it is through the use of materiality, water/misting features, vegetation or shelter canopies, their overall bioclimatic success depends upon their introduction within the correct locations, and with the correct temporal duration. In summary, this study has demonstrated that:

- The lack of meteorological information that can aid local decision making and design at microscales can be overcome by the gathering of climatic data available from local weather stations, and easily accessible/usable meteorological apparatus. Once obtained, such data can be adapted and calibrated into thermo-physiological indices through the use of easy to use software in order to assess pedestrian thermal comfort thresholds in a specific location within the urban environment.
- Through the application of the thermo-physiological indices, it was possible to assess annual, monthly and diurnal oscillations of thermal stress, which moreover, ascertained the results from other studies that applied similar methods to those used within this study.
- At a microscale, it was possible verify bioclimatic conditions of different ARs, and furthermore, identify how such conditions oscillate within the different regions of the canyons based upon their morphological composition. As a result it was possible to identify TAP for PSD in specific locations, and during specific periods of the day.
- Given particular meteorological events such as HWE and 'Very hot days' in Lisbon, the average assessment of the bioclimatic conditions within a particular scenario must be reassessed. More specifically, during such periods, it was important to note that even in scenarios where G_{rad} levels were low, other individual climatic variables such as diurnal T_{amb}, RH, and $WS_{1.1}$ can also lead to considerable thermal discomfort once they surpass a certain threshold.
- There are various opportunities to take the results of this study further such as: (i) refine the relationship between mPETL and the priority classifications; (ii) mapping the AR within Lisbon's historical quarter in order to present a map of TAP for PSD; and, (iii) investigate and/or estimate how actual PSD solutions could lower the identified bioclimatic conditions within the different disclosed default ARs in this study.

Overall, and within a city which witnesses the thermal exacerbations associated to Mediterranean climates with hot and dry summers, this study has identified the importance of approaching such urban climatic obstacles as opportunities for PSD. Such an approach represents that of an interdisciplinary practice which is argued to ascertain the safety, presence, activity threads, and comfort levels of pedestrians within Lisbon's urban fabric within a century expected to witness considerable aggravations of the global climate system.

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Publication 9:

The Impact of *Tipuana tipu* Species on Local Human Thermal Comfort Thresholds in Different Urban Canyon Cases in Mediterranean Climates: Lisbon Portugal

A. Santos Nouri, Dominik Fröhlich, Maria Matos Silva, A. Matzarakis

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Article Preamble

Study examines the 'in-situ' effects of vegetation upon pedestrian thermal comfort levels. Being one of Lisbon's most common shading tree species, the influences of the *Tipuana tipu* is selected in order to evaluate its influences upon thermal stress within different locations within various canyons with dissimilar morphological compositions. Such an examination is conducted both during the winter and summer to present such 'in-situ' influences resultant of the presence/absence of the *Tipuana tipu* tree.

Article Symbol list

$\#K_X$	Temperature difference of X variable	M_{Sum}	Minutes cast in sun during summer
'*Aw*'	Tropical Savannah with dry winter climate	M_{Win}	Minutes cast in sun during winter
'*Bwh*'	Desert climate	Okt	Oktas
'*Cfa*'	Humid subtropical climate	r	Vegetative crown radius
'*Csa*'	Hot-Mediterranean climate	T_{amb}	Ambient temperature
'*Cwa*'	Temperate dry winter and hot summer	T_{mrt}	Mean radiant temperature
d	Trunk diameter	V	Wind speed
G_{rad}	Global radiation	$V_{1.1}$	Wind speed at 1.1m
h	Tree height	V_{10}	Wind speed at 10m
l	Trunk length		

Article Acronym List

CTIS	Climate-Tourism/Transfer-Information-Scheme	SVF	Sky View Factor
HW	Height-to-Width Ratios	TTSim	Simulations with Tipuana Tipu
KG	Köppen Geiger	UCC	Urban Canyon Cases
mPET	modified Physiologically Equivalent Temperature	UHI	Urban Heat Island
NSO	North-to-South Orientation	UHW	Urban Heat Wave
NVSim	No Vegetation Simulation	UTCI	Universal Thermal Comfort Index
PET	Physiologically Equivalent Temperature	VCR	Vegetative Coverage Ratio
PS	Physiological Stress	VHD	Very Hot Day
RP	Reference Point	WEO	West-to-East Orientation

atmosphere

MDPI

Article

The Impact of *Tipuana tipu* Species on Local Human Thermal Comfort Thresholds in Different Urban Canyon Cases in Mediterranean Climates: Lisbon, Portugal

Andre Santos Nouri [1,*], Dominik Fröhlich [2], Maria Matos Silva [1] and Andreas Matzarakis [2,3]

[1] University of Lisbon, Faculty of Architecture, CIAUD—Research Centre for Architecture, Urbanism and Design, Rua Sá Nogueira, Pólo Universitário do Alto da Ajuda, Lisbon 1349-063, Portugal; m.matosilva@fa.ulisboa.pt

[2] Research Center Human Biometeorology, German Meteorological Service, D-79104 Freiburg, Germany; Dominik.Froehlich@dwd.de (D.F.); Andreas.Matzarakis@dwd.de (A.M.)

[3] Environmental Meteorology, Faculty of Environment and Natural Resources, Albert-Ludwigs-University, D-79085 Freiburg, Germany

* Correspondence: andrenouri@fa.ulisboa.pt; Tel.: +351-919-247-292

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Abstract: Based upon the case of Lisbon, this article examined the in-situ effects of vegetation upon pedestrian thermal comfort levels. Focussing specifically upon the historic quarter that often witnesses the highest T_{amb} values and Urban Heat Island (UHI) intensities during the summer, the most common urban canyon cases (UCCs) were modelled, along with one of the most commonly used vegetative semi-deciduous species found in the city, *Tipuana tipu*. Based upon a reference point (RP) system, the assessments were undertaken through the use of a new version of the SkyHelios model, local obtained G_{rad} values, and the modified physiologically equivalent temperature (mPET) index calculated through the human-biometeorological model RayMan. The study identified the in-situ thermo-physiological influences of *Tipuana tipu* during different periods of the year: (1) during the summer, which revealed considerable reductions of PET/mPET of up to 15.6 °C/11.6 °C during a very hot day (where daily maximum T_{amb} surpassed 35 °C); and (2) during the winter, which revealed the risks of oversharing as a result of the species keeping its foliage during the winter with reductions of PET/mPET of up to 2.7 °C/2.6 °C. Furthermore, the study utilised the climate tourism/transfer information scheme (CTIS) to categorise and facilitate the interpretation of the results.

Keywords: public space design; physiologically equivalent temperature; urban canyon cases; thermal comfort; Mediterranean climate; *Tipuana tipu*

1. Introduction

Currently, and within existing cities, particularly those concomitant to Mediterranean climates with hot–dry summers and classified with a Köppen Geiger (KG) of '*Csa*', the importance of local human thermo-physiological thresholds is gaining new weight for local urban design and planning. Still, and often within southern Europe, many cities habitually present a noteworthy absence of climatological data/know-how that could prove useful for local decision making and design within the urban public realm [1].

As a result, and within the context of Lisbon, there have been a substantial amount of studies that have provided valuable contributions towards the comprehension of the overall bioclimatic conditions within its public realm [2,3], UHI intensities [4,5], and integration with planning policy [6,7]. Moreover, and given the progress of the climate change adaptation agenda, studies specifically pertaining to impacts within Lisbon have also been undertaken [8–10].

Within the international arena, including within other cities located in other KG classifications, the influences of urban vegetation have already been debated within existing review studies [11,12–14]. Within such studies, the benefits of vegetation upon the urban public realm were reviewed, including their capacity to regulate urban ambient temperature (T_{amb}), and UHI effects. In addition, the scientific community has also endeavoured to expand upon the known in-situ effects of vegetation, including their respective thermo-physiological influences upon pedestrians. Within this line of study, the particular influences of tree species have also been identified within different urban conditions [15,16–20]. It is also worth noting that, within studies which identified bioclimatic conditions/opportunities within different default urban canyon cases (UCCs) (both symmetrical and asymmetrical), the thermo-physiological benefits from vegetation were also mentioned, namely by (i) Ali-Toudert and Mayer [21] in Ghardaia, Algeria (with KG of '*Bwh*'); (ii) Ketterer and Matzarakis [22] in Stuttgart, Germany (with KG of '*Cfa*'); Qaid and Ossen [23] in Putrajaya, Malaysia (with KG of '*Af*'); (iii) Morakinyo and Lam [24] in Hong Kong (with KG of '*Cwa*'); (iv) Algeciras, Consuegra [25] and Algeciras, Tablada [26] in Camagüey, Cuba (with KG of '*Aw*'); and lastly, (v) Nouri, Costa [27] in Lisbon, Portugal (with KG of '*Csa*').

Notwithstanding, and as suggested by Kong, Lau, et al. [28] within the scientific community, there are still a greater amount of studies which have focussed upon T_{amb} variations rather than thermo-physiological impacts as a result of local vegetation. Concomitant with this perspective, this article is centred upon the importance of going beyond sole climatic characteristics, and aims to add to the existing studies which identify the significance of considering 'in-situ' thermo-physiological influences resultant of urban vegetation.

In line with this objective, this study (i) utilises a new version of the SkyHelios model [29,30] as a new means to address microclimatic characteristics (namely Wind (V) speed); and, (ii) examines and applies new modified thermo-physiological indices [31] to conduct more accurate evaluations of thermal comfort conditions during different periods of the year. Such methods are applied to the case of Lisbon to identify how one of the most commonly-found shading trees within the city (i.e., *Tipuana tipu*) can influence the in-situ bioclimate conditions within symmetrical urban UCCs which are typically located within the city's historical district. The results of the study indicate (1) how simulations can be united with field measurements to compare and adapt climatic data from the local meteorological station; (2) the in-situ thermo-physiological effects that a common shading tree can have upon pedestrians during the summer and winter periods in areas prone to higher thermal stimuli, particularly during the summer; and lastly, (3) how such outcomes can ease the transition and 'shared language' [1] between the fields of urban climatology and local urban design/planning.

2. Experiments

2.1. Site

Located on the western coast of Portugal at 38°42′ N and 9°8′ W, Lisbon has a KG classification of '*Csa*', which constitutes a Mediterranean climate with dry and hot summers [32]. Accordingly, and as identified by studies conducted by Miranda [33] and Calheiros [34], the urban microclimatic conditions present annual periods in which outdoor thermal comfort thresholds can be strained as a result of numerous of climatic occurrences, namely (i) between 10 and 20 days where daily maximum T_{amb} surpasses 35 °C; (ii) an occurrence of between 100 and 120 'summer days' where daily maximum T_{amb} exceeds 25 °C; and additionally (iii) frequent occurrences of heat waves, where daily maximum T_{amb} exceeds that of 32 °C for various periods of successive days.

As identified in the study conducted by Alcoforado, Andrade [1], both North and Northwest wind directions are the most common throughout the year, particularly during the summer. This being said, due to the proximity to the Tagus, Lopes [35] identified that estuarine breezes reach adjacent urban areas on 30% of the late mornings and early afternoons during the summer. This study focuses predominantly upon the historical quarter of 'Baixa Chiado', which due to its general morphological composition has been identified to frequently witness the highest UHI intensities [2] and highest temperatures during the summer [6].

2.2. Data

To retrieve the base climatic data for the study, meteorological recordings were attained from the World Meteorological Organisation weather station with the Index N°08535, located within Lisbon with the latitude of 38°43′ N, 9°9′ W, and an altitude of 77 m. As with similar existing studies [1,19,25,31,36–39], the extracted data was converted into a variation of the thermo-physiological index, physiologically equivalent temperature (PET) [40–42]. The respective index was used due to the (i) feasibility of being calibrated upon easily obtainable microclimatic parameters; and (ii) base measuring unit being °C, which facilitates its comprehension by professionals such as urban planners and designers when approaching climatological facets.

Before considering the influences of UCCs and vegetation, an initial analysis was established to determine general diurnal thermal conditions during different climatological circumstances, i.e., during the summer and winter within the city (Table 1). Such an approach enabled a 'base understanding' of Lisbon's thermo-physiological conditions as presented by the weather station.

Table 1. Average and diurnal (3rd of July and 16th of December) climatic data obtained from weather station (Index N°08535; Okt: oktas).

Time	$\overline{July}$				3rd July				$\overline{December}$				16th December			
	T_{amb}	RH	$V_{1.1}$	Okt	T_{amb}	RH	$V_{1.1}$	Okt	T_{amb}	RH	$V_{1.1}$	Okt	T_{amb}	RH	$V_{1.1}$	Okt
	C°	%	m/s		C°	%	m/s		C°	%	m/s		C°	%	m/s	
09:00	24.5	56.7	1.8	2.0	26.4	54.2	2.1	0.0	10.5	86.0	1.7	3.7	10.0	79.9	2.1	7.0
10:00	25.9	51.9	1.8	1.7	26.9	58.6	1.6	0.0	11.6	82.2	2.0	3.6	8.9	89.1	3.6	7.0
11:00	27.6	46.7	1.9	1.2	31.7	44.4	1.0	0.0	12.7	76.6	1.9	3.5	9.2	87.3	3.6	7.0
12:00	28.8	43.7	1.9	1.1	33.0	39.5	1.0	0.0	13.9	72.9	1.7	3.5	10.2	77.8	3.0	6.0
13:00	29.4	41.4	2.3	1.1	35.0	35.1	1.6	0.0	14.7	69.6	1.7	3.5	9.8	81.6	4.1	6.0
14:00	29.7	41.4	2.5	1.1	34.7	35.7	1.6	0.0	15.1	68.3	1.7	3.7	12.2	72.5	3.6	6.0
15:00	29.4	41.6	2.8	1.1	35.9	32.5	1.0	0.0	14.8	70.5	1.6	3.8	11.5	75.4	3.1	7.0
16:00	27.9	46.1	2.9	0.9	34.3	37.4	2.0	0.0	14.7	71.3	1.5	3.7	12.4	72.0	3.6	7.0
17:00	27.3	47.4	2.9	0.9	32.9	39.9	2.6	0.0	14.3	73.6	1.5	3.6	12.0	68.1	4.1	7.0
18:00	26.5	48.6	2.7	0.9	31.2	40.7	2.6	0.0	13.7	76.7	1.5	3.6	11.6	68.9	4.2	7.0

In order to carry out this initial assessment, the RayMan Pro© model [43,44] was used to process the following retrieved parameters: T_{amb}, relative humidity (RH), total cloud oktas (Okt), and V_{10}. In addition to these climatological aspects, the calibration of the RayMan model was constructed upon the default standing 'standardised man'; i.e., a height of 1.75 m, weight of 75 kg, aged 35, with a clothing 0.9 clo, and an internal heat production of 80 w [40,41]. In order to account for the deceleration effect of 'urban roughness' upon wind speeds obtained from the meteorological station [45], the values were adapted to permit the estimation of V values upon the gravity centre of the human body. As a result, V_{10} values were interpreted to a height of 1.1 m (henceforth expressed as $V_{1.1}$) by using the formula presented by Kuttler [46] (Equation 1). Given Lisbon's denser downtown district with frequent open spaces, and similar to the morphological layout/compositions examined within comparable bioclimatic studies in Barcelona [38] and within the historical district of Lisbon [27], the study applied the following calibrations to the formula: z_0 = 1.00 m, and α = 0.35.

$$V_{1.1} = V_h \times \left(\frac{1.1}{h}\right)^{\alpha} \quad \alpha = 0.12 \times z_0 + 0.18 \tag{1}$$

where V_h is the m/s at a height of h (10 m), α is an empirical exponent, depending upon urban surface roughness, and z_0 is the corresponding roughness length.

At a later stage in the study, another variable tuning was considered when addressing the 'in-situ' effects of vegetation upon pedestrian comfort as a result of evapotranspiration. As identified by the early studies of Oke [47], McPherson [48], and Brown and Gillespie [49], T_{amb} and RH are usually not meaningfully modified by landscape elements such as trees since the encircling atmosphere quickly dissipates any such in-situ oscillations. Such results were also obtained by later studies [19,50,51–53] who identified such limitations resulting from evapotranspiration effects, particularly from single trees. Moreover, such outcomes were also obtained by a recent study conducted within one of the widest public spaces located in Lisbon's historical centre. Carried out in July 2015, and as shown in Figure 1 the limited effects of evapotranspiration beneath the crown were also verified.

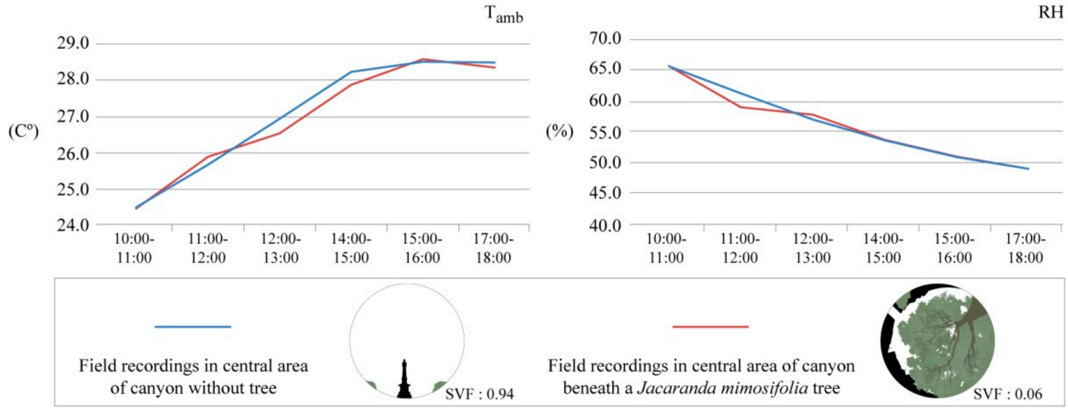


Figure 1. Comparison of monthly averages of T_{amb} and relative humidity (RH) field recordings obtained without the presence of a shading tree against those obtained directly beneath a vegetative crown in the central area of a low urban canyon case (UCC) in Lisbon's historical district | Source: Adapted from [54].

As a result, the lower impact that evapotranspiration could generate upon comfort conditions at pedestrian height was not considered in this particularly study. Instead, the assessments were predominantly based upon evaluating the in-sit' impacts of a specific tree species beneath its crown, or in other words "the cool feeling people experience as a result of a reduction in radiation" [15]. Although such information has grown in recent years (as exemplified by numerous studies mentioned in this study), the authors argue that there is still a need to build upon estimations of radiation modifications as a result of vegetative deflection as suggested by Brown and Cherkezoff [55]. As a result, such outputs should continue to build upon the growing comprehension of vegetation influences upon microclimatic characteristics at the pedestrian level [56].

Therefore, supplementary data modifications/calibrations were applied to assess the specific thermo-physiological in-situ effects of *Tipuana tipu* upon pedestrian comfort levels. In addition to the preliminary climatic variables, global radiation (G_{rad}) retrieved by the authors were used to supplement the radiation flux assessments. These values were obtained through field surveys through the use of the handheld apparatus KKMOON SM206, with an accuracy of ±10 and a resolution of 0.1 W/m^2. Similar to the approach carried out by Nouri and Costa [54], such measurements were established to obtain hourly oscillations of G_{rad} (i) in specific locations of different UCCs; and (ii) beneath vegetative canopies to identify the amount radiation that was diluted by the vegetative crown mass. Such an approach enabled solar attenuation radiation levels to be determined specifically beneath the tree crowns, and later introduced within the biometeorological model.

2.3. Applied Methodology and Structure

The modelling, refinement, and representation of the UCC assessments were processed through a three-step approach. Firstly, a new version of the SkyHelios model(i) [29] was used in order to assess the microclimatic conditions and implications upon the introduced parameters with respect to the urban morphologies. As presented by Fröhlich [30], the model has been developed to analyse the spatial dimension of a specific microclimate. The short runtime and wide range of support input formats, as well as the capability of dealing with different projected coordinate systems permit the applicability of the model to evaluate the comparison of different UCCs, tree compositions and their effect on thermal biometeorology. In processing terms, the new SkyHelios model essentially follows a similar approach to that of the Rayman model, but it has the additional feature of also considering the spatial dimension of the parameters. As a result, SkyHelios makes use of the graphic processor for computing the sky view factor (SVF) [29]. Based upon the SVF, the radiation fluxes can be determined for any location within the respective model area, and summarised as mean radiant temperature (T_{mrt}). As defined by Oke [47], the SVF is the fraction of the visible sky seen from a specified point. Within the software module, the first operation is the rendering of a fisheye image for that stipulated location, and secondly, the SVF is determined by distinguishing transparent and coloured pixels within the generated image. Similar to real environments, the fisheye image is a half-sphere, and not all of the pixels should have the same influence upon SVF. Therefore, a dimensionless weighting factor represented as $\omega proj$ (Equation 2) is utilised to consider the projections that adjusts the impact of a pixel by the sine of the zenith angle φ (°).

$$\omega proj = \sin(\varphi) \times \left(\frac{\varphi}{90°}\right)^{-1} \quad (2)$$

This results in a spherical SVF, whereby if a planner SVF is desired, another correction by ωplanar (again dimensionless) needs to be performed (Equation 3). Such a modification increases the impact of objects close to the ground by the cosine of the azimuth angle (counted from the ground to the top).

$$\omega planar = \omega proj \times \cos(\varphi) \quad (3)$$

Furthermore, a three-dimensional diagnostic wind model was integrated within the updated version in order to provide estimations of 'in-situ' V measurements, which as discussed can differ significantly from those presented by the meteorological station. Such a model was based upon the approach conducted by Röckle [57], but, and as discussed by Fröhlich [30], with updated parameterizations, namely (i) an improved upwind cavity as discussed in Bagal, Pardyjak [58]; and (ii) an improved description of street canyon vortices as described in Singh, Hansen [59]. As a result, the SkyHelios model enables the identification of spatially-resolved V and associated direction. The wind field calculated by the given functions most likely contains a certain degree of divergence. Assuming incompressible air, such a divergence has to be minimized in order to get a valid wind field. In mathematical terms, this is performed by minimizing the functional for the scalar H (Equation 4).

$$\mathrm{H}(u,v,w) = \iiint \left(b_{\mathrm{h}}^2 (u-u^0)^2 + b_{\mathrm{h}}^2 (v-v^0)^2 + b_{\mathrm{v}}^2 (w-w^0)^2\right) dxdydz \quad (4)$$

As shown in Equation 4 b_h and b_v are horizontal stability factors in s/m; u, v and w are the stream components in m/s, u^0, v^0 and w^0 are representative of the initial stream components in m/s while dx, dy and dz are the grid spacing in metres. Due to this integration, the model is capable of estimating thermal indices Perceived Temperature (PT) [60], Universal Thermal Comfort Index (UTCI) [61], and PET that are spatially resolved at high resolutions (e.g., 1 × 1 m).

The second step was orientated at processing the results through the updated version of the RayMan model(ii) in order to interpret them into the modified physiologically equivalent temperature (mPET) as discussed in Chen and Matzarakis [31]. As presented in their study, the predominant differences of the mPET index are the integrated thermoregulation model (based upon a multiple-segment model), and the clothing model which relays a more accurate analysis of the human bio-heat transfer mechanism. For this reason, the initial examination of the diurnal conditions both during the summer and winter conditions were thus presented in both PET and mPET; to firstly examine such differences identified by Chen and Matzarakis [31], and secondly, present more accurate evaluations of the human thermal comfort conditions examined later in the study.

The third step of the study was to ensure that the study outputs were communicated in a way to facilitate their comprehension by non-experts in the subjects linked to climatology. As a result, the obtained results were processed with the climate tourism/transfer information scheme(iii) (CTIS) [62]. Such means of communication have been growing within the scientific community in similar climatic studies [31,38,63–65].

2.3.1. Identification of Bioclimatic Conditions During Summer/Winter Periods

As discussed, the first stage was to identify the general bioclimatic conditions (i.e., PET and mPET values) retrieved from the specified weather station. As a result of this exercise, not only was it possible to identify how physiological stress (PS) grades vary during different times of the year, but moreover to identify the days on which the simulations would be based. Based upon the configuration of the meteorological station, since the total Okt values were only recorded at 09:00, 12:00, and 15:00, it was necessary to approximate values for the remaining hours between 09:00 and 18:00. Such an approximation was undertaken by (i) the delineation of the mid-range values between the three daily recordings; and, in addition, (ii) taking into account the qualitative meteorological descriptions provided by the station. Such inputs were accompanied by the introduced T_{amb}, RH, and $V_{1.1}$ diurnal recordings for the months of July and December, each representative of the hottest and coldest annual conditions for 2016 found in Lisbon (Table 1). Furthermore, and at this stage of the study, the applied SVF value was calibrated at 1.00 (or 100%) which would reproduce an assessment with total exposure to solar radiation. Once the PET and mPET values were processed, the comparative chart presented by Matzarakis, Mayer [42] was used in order to categorise the obtained temperature values into specific PS levels, shown in Table 2.

Table 2. Ranges of the thermal index physiologically equivalent temperature (PET) for different grades of physiological stress (PS) on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo according to [66] | Source: Adapted from, [42].

PET	PS
<4 °C	Extreme Cold Stress
4–8	Strong Cold Stress
8–13	Moderate Cold Stress
13–18	Slight Cold Stress
18–23	No Thermal Stress
23–29	Slight Heat Stress
29–35	Moderate Heat Stress
35–41	Strong Heat Stress
>41	Extreme Heat Stress

Once the boundaries for each temperature range were stipulated, it was possible to input such margins into CTIS to facilitate the representation of the diurnal modifications of PS during the months of July and December. Such methods of representation have already been used in similar bioclimatic studies [31,38,63–65] which also aimed at facilitating the comprehension of the obtained thermo-physiological results.

2.3.2. Defining *Tipuana tipu* Characteristics and Layout

The *Tipuana tipu* species originates from the region adjacent to the Tipuani River in Bolivia, and is also known for its lineages from both Brazil and Argentina. Given the right conditions, the species can reach considerable sizes, and presents a dark trunk, twisted branches, and a densely vegetated round crown. Resulting from the '*Csa*' climate, the equally ornamental and rustic species are particularly compatible with Lisbon's climate. Consequently, they are one of the most commonly used deciduous species [67], with approximately 1900 examples within the city [68,69]. In a few locations, a particular few have been listed as 'public interest' due to their considerable age and size as exemplified in 'Cais Sodré', 'São Bento' Plaza, and the 'Nove de Abril' Park, registering ages of 100, 80, and 128, respectively. Recognised as an effective urban shading tree specifically within Mediterranean climates [17,54,67,69–71] it is also frequently mixed with other species within Lisbon. Such circumstances can be exemplified by a mixture with other identified 'shading trees' such as *Jacaranda mimosifolia* within the urban garden of 'Santos' and the public plaza of 'Rossio' within the historical quarter.

The example of the latter is illustrated in Figure 2A, which shows a lined sidewalk seating area beneath the vegetative crowns of a linear plantation of *Tipuana tipu* with a parallel row of *Jacaranda mimosifolia* on the edge of the sidewalk. Common to sidewalk plantation typologies as identified by Torre [70], the linear plantation configuration has been identified to effectively attenuate (i) radiation, especially when the tree lines are parallel/close to a building frontage [48,49,73,74]; and (ii) wind patterns that take place perpendicularly to the tree line [70,72,75].

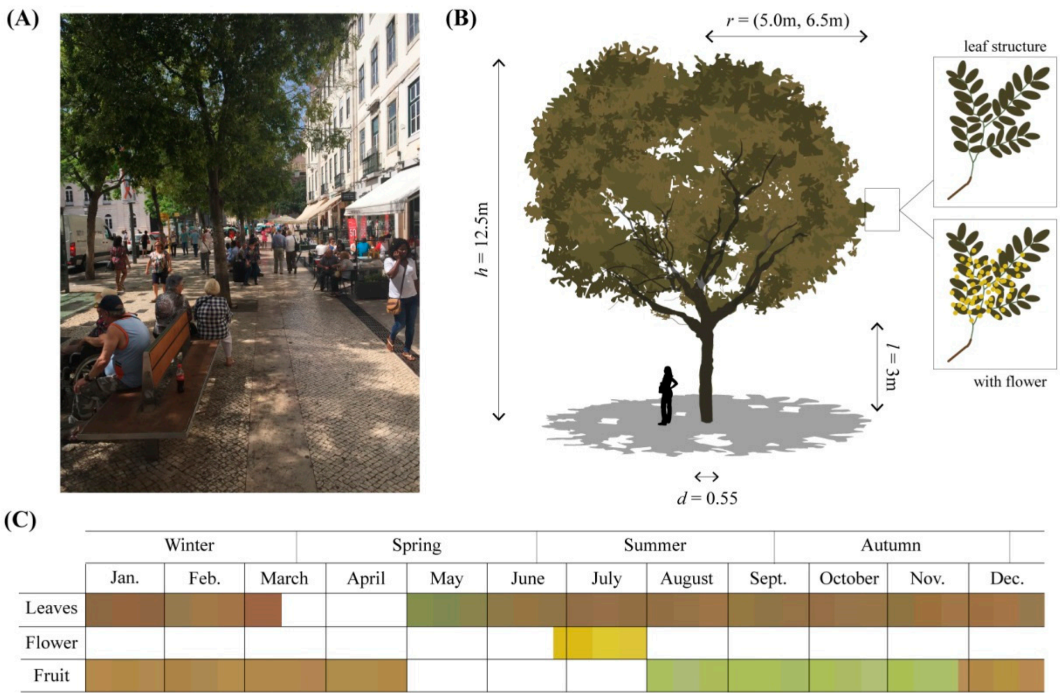


Figure 2. Representation of the *Tipuana tipu* species | (**A**) Example of linear planation of species within the eastern lateral sidewalk in Rossio during the afternoon | (**B**) Dimensions of tree of which were later used in simulations | (**C**) Annual foliation and coloration of vegetative crown - adapted from Viñas, Solanich [72].

Within urban pavements, the species often present smaller sizes [17,67,72,76] which is often due to inferior soil conditions and embedding methods. Illustrated in Figure 2B, and based upon the aforementioned studies, the dimension of the trees used within the study were calibrated with a height (h) of 12.5 m, vegetative crown radius (r) of 5.0/6.5 m, trunk length (l) of 3 m, and a trunk diameter (d) of 0.55 m. Furthermore, since G_{rad} values were measured beneath the crowns, parameters such as leaf area index and leaf angle distribution were not required to determine the vegetative density/transmissivity of the tree crown.

Beyond being one of the most commonly used 'shading' tree species, and unlike most deciduous species, it also has the particularity of maintaining its foliation both during the summer and winter period. As demonstrated in Figure 2C, and as identified by Viñas, Solanich [72] within the Iberian Peninsula, the only period in which the *Tipuana tipu* loses its leaves is during the early spring. Accordingly, and given the permanency of its vegetative crown during the winter, it was also possible to assess how the vegetative crown would influence 'in-situ' thermal conditions during colder conditions. As identified by early studies [15,49,55,77], it was possible to examine the consequences of reductions of radiation fluxes during the winter; a known essential microclimatic variable with both physiological and psychological connotations to counteract colder conditions during the winter in outdoor urban public spaces [78].

2.3.2. Application and Construction of the SkyHelios Simulations

Within the 'Obstacle' plugin associated with both the RayMan and the SkyHelios models, various morphological compositions were constructed. Based upon modifying one of the characteristics of the canyons, it was possible to obtain dissimilar height-to-width (HW) ratios which were the most commonly found within Lisbon's historical district. Accordingly, the canyon height was maintained at 20 m (equating roughly to a building of five stories), and the canyon widths fluctuated between 10, 20, 40, and 120 metres to obtain 'very high', 'high', 'medium', and 'very low' UCCs, respectively. Although focused upon a larger scale, a similar approach was applied by Norton, Coutts [79], who categorised broad priority requirements for green infrastructure within different urban canyons. Previously, an UCC with a description of 'low' was also initially considered for the study. Such a canyon presented a canyon width of 80 m, and a HW ratio of 0.25, yet based upon a previous study conducted by the authors, it was identified that it presented almost identical thermal conditions to the 0.17 ratio. As the latter presented greater dissimilarities to the higher 0.50 ratio, it was decided to focus upon the four identified UCCs within this specific study as presented in Table 3.

Table 3. Description and categorisation of utilised urban canyon cases (UCCs) and their respective height, width, and height-to-width (HW) ratio.

UCC Description	Canyon Height	Canyon Width	HW Ratio
'Very High'	20	10	2.00
'High'	20	20	1.00
'Medium'	20	40	0.50
'Very Low'	20	120	0.17

In accordance with the proportional and rigid morphological composition succeeding the reconstruction of Lisbon's historical district following the great earthquake of 1755, all modelled canyons were symmetrically configured. Although such an approach is frequently 'presumed' when approaching H/W ratios, recent microscale bioclimatic studies [23,26] have also produced important results in asymmetrical canyons whilst also addressing urban thermal comfort conditions.

Through the use of the SkyHelios model, the $HW_{2.00}$, $HW_{1.00}$, $HW_{0.50}$, and $HW_{0.17}$ were processed under two conditions: (i) without the presence of vegetation; and (ii) with the presence of vegetation. In addition, each canyon was aligned into a north-to-south orientation (NSO) and a west-to-east orientation (WEO) in order to assess the influence of the geo-referenced summer/winter sun path upon the two alignments. The layout of the NSO simulations with the presence of the *Tipuana tipu* is represented in

Figure 3 indicates how, depending upon the UCCs, the tree layouts were structured within each undertaken assessment. Such an adjustment was based upon maintaining a similar amount of vegetative coverage ratio (VCR) throughout the width of each UCC. Within this study, such an indicative value was obtained by applying the straightforward formula as shown in Equation 5.

$$\mathrm{VCR} = \frac{(100 \times CS)}{W} \quad CS = n \times r \times 2 \tag{5}$$

where W is the width of the aspect ratio, CS is the crown spread, n is the number of trees, and r is the radius (5, 6.5).

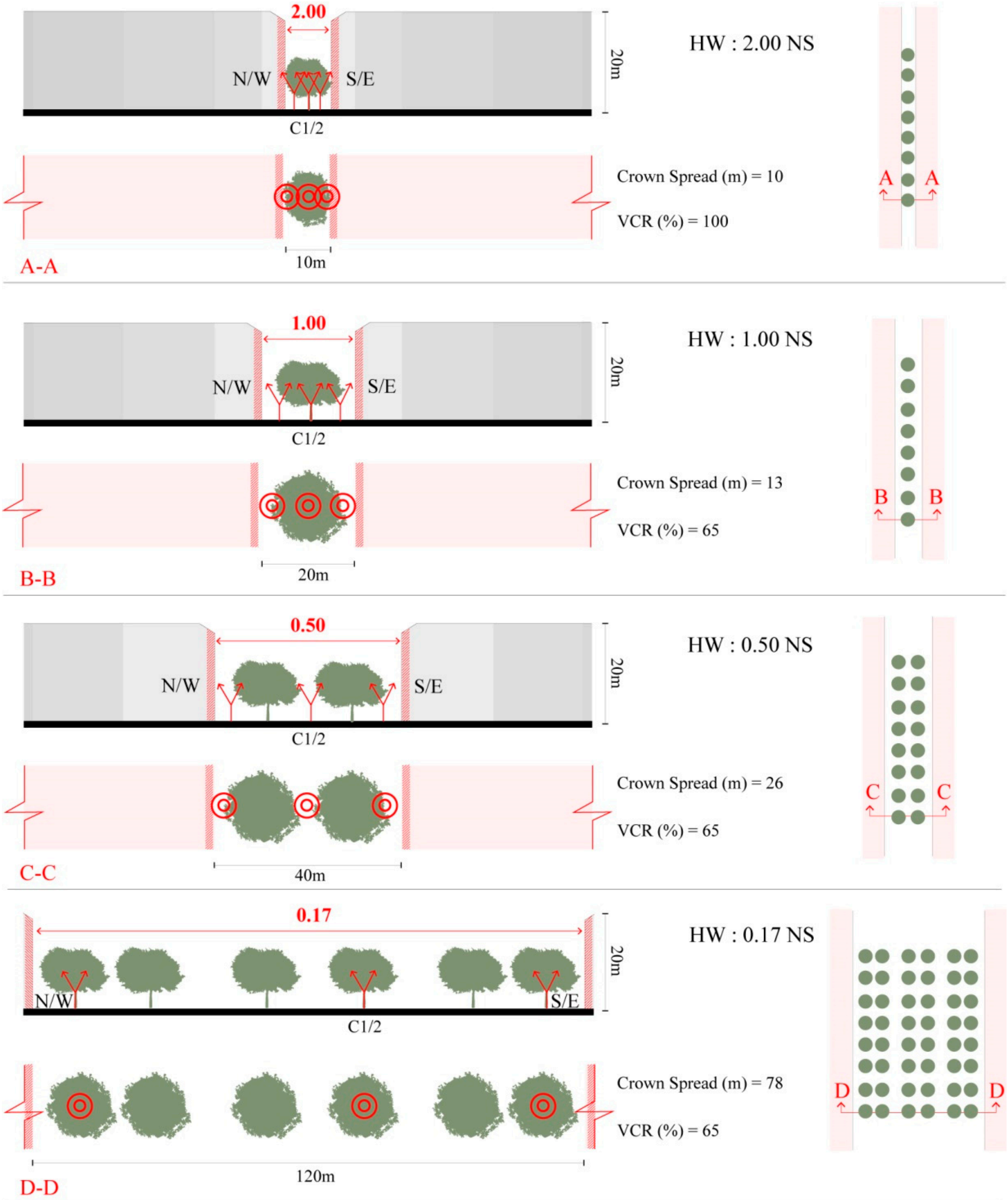


Figure 3. North-to-south orientation (NSO) layout of the determined urban canyon cases (UCCs) and the central/lateral reference points (RPs) with specified crown spreads and vegetative coverage ratios (VCR); A-A cross-section in $HW_{2.00}$, B-B cross-section in $HW_{1.00}$, C-C cross-section in $HW_{0.50}$, D-D cross-section in $HW_{0.17}$

Although the VCR was based upon determining the amount of vegetation against the width of the canyons, comparable ratios were also utilised within similar studies [17,56,80] who quantified the amount of vegetative biomass within an entire outdoor area. Based upon the discussed parameters in Figure 2B, the dimensions of the introduced trees were calibrated with a diameter of

13 m, with the exception for $HW_{2.00}$, which accommodated trees with a lower diameter of 10 m. Such a reduction was undertaken to account for the shorter width of the street, whilst respecting the smaller, yet feasible dimensions of the *Tipuana tipu*.

As presented within the study conducted by Lin, Tsai [81], the calculation of SVF within this study was based upon the classic single-point SVF within a specific location in the canyon to obtain a fisheye image at a calibrated height of 1.1 m. Similar to an approach applied by Algeciras, Consuegra [25] both the NSO and WEO accommodated three specific reference points (RPs) which were established to identify the diurnal oscillations of solar radiation. As shown in Table 4, the RPs were attributed a specific location within the different UCCs, and their respective coordinates within the SkyHelios model are presented and discussed in Table 5. Additionally, and even though canyon length was un-associated to the HW ratio, each was attributed a length of 200 m in order ensure that 'edges' of the default canyon would not meaningfully affect the obtained SVF values obtained by the SkyHelios.

Table 4. Stipulation of reference points (RPs) within each of the assessed urban canyon cases (UCCs) based upon single-point sky view factors (SVFs).

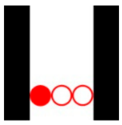
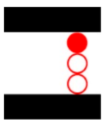
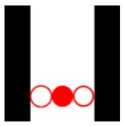
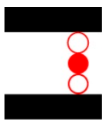
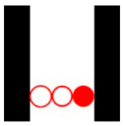
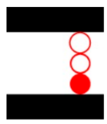
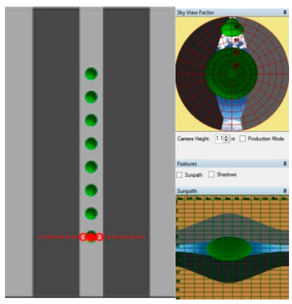
	SkyHelios RP Stipulation					
Region	Lateral 1		Central		Lateral 2	
Orientation	NS	WE	NS	WE	NS	WE
Location						
Reference Point	(RP_W)	(RP_N)	(RP_{C1})	(RP_{C2})	(RP_E)	(RP_S)

Table 5. Input coordinates and description of reference points (RPs) within each assessed canyon, each with a total length of 200 m.

		SkyHelios Coordinate Input Values								**SkyHelios 1.00 Screenshot**
UCC°	RP	**2.00**		**1.00**		**0.50**		**0.17**		
		X	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	
N/S	**W**	47.2	−49.6	42.4	−53.6	34.2	−50.6	46.8	−54.6	
	C1	49.9	−49.6	50.1	−53.6	50.1	−51.6	110.5	−54.6	
	E	52.9	−49.6	57.3	−53.6	66	−51.6	152.6	−54.6	
W/E	**N**	200.6	−52.8	197.1	−57.1	198.4	−65.8	195.9	−151.7	
	C2	200.6	−49.7	197.1	−49.4	198.4	−50.1	195.9	−89.7	
	S	200.6	−46.9	197.1	−42.3	198.4	−33.8	195.9	−47.5	

HW	Description of RP placement
2.00	Central and lateral RPs were varied little due to the limited width of the canyon
1.00	Central RPs were placed beneath tree crown, while the lateral RPs were situated amid the edge of the tree crown and the lateral façades of the canyon
0.50	Central RPs were placed between the edges of two tree crowns, and the lateral RPs placed between the edge of the tree crown and the lateral façades of the canyon

0.17	Central RPs were slightly offset to be directly beneath a tree crown, and lateral RPs which were also placed beneath the trees located adjacent to the façades of the canyon

Based upon the calibration of a three-dimensional diagnostic wind model integrated within the program, the last of the eight-tree line was selected to permit the identification of the influence of preceding trees in UCCs (Figure 3). As a result, it was possible to determine how such obstacles within each canyon would influence $V_{1.1}$ once it reached each of the designated RPs. Configured within the diagnostic tool within SkyHelios (Table 6), the initial $V_{1.1}$ values obtained through Equation 1 could be recalibrated.

Table 6. Specific configurations of SkyHelios wind diagnostic tool.

Calculation Variables	Input	Details
'Instrument Height'	10 m	Accounting for the meteorological station at a height of 10m
'Vertical Output Height'	1.1 m	Accounting for gravity centre of the human body which was identical to the stipulated SVF 'Camera height' (i.e., target analysis height) of 1.1 m
'Vertical Displacement Height'	6.6 m	Accounting for the configured structure of the 2.00,1.00,0.50,0.17 UCCs
'Resolution Output'	1.0 m	To provide sufficiently detailed outputs based upon pretended results, especially for vegetation simulations
'Wind Direction'	340°	Accounting for the predominant wind patterns predominantly between North and Northwest within the historical quarter of the city [1,54]
Vegetation offset in simulated canyons	50 m	Accounting for possible interference of the wind vortices at the entrance/exit of the examined canyons

3. Results

3.1. General Bioclimatic Conditions during Summer/Winter Periods

3.1.1. Disparities between July and December Bioclimatic Conditions

Demonstrated in Figure 4, the processed microclimatic parameters of T_{amb}, RH, $V_{1.1}$, and Okt obtained from the meteorological station were translated into PS levels for both July and December. As expected, between these two months, there was a large variation of diurnal thermal stress.

During July 2016, PS grades predominantly varied between 'slight heat stress' and 'extreme Heat stress'. In addition, and due to the thermo-physiological indices reaching values which considerably surpassed that of 41 °C, an 'extreme' PS grade was added ('extreme heat stress 2') to the CTIS calibration to effectively present results which reached 46 °C. Consequently, such an adjustment also relays back to the possibility for expanding the existing ranges of PS upon human beings as presented in Table 2. Such PS stress levels were obtained during days with particularly elevated T_{amb} values. More precisely, the occurrence of 'extreme heat stress 2' took place under two extreme heat events: (1) during a sequential set of days where maximum diurnal T_{amb} values surpass that of 32 °C—described as an 'urban heat wave' by Calheiros [34]; and (2) during a specific day where maximum diurnal T_{amb} values surpass that of 35 °C—described as a 'very hot day' by Miranda [33]. As revealed in Figure 4, July 2016 witnessed three urban heat waves and very hot days, whereby most extreme events were interlinked with one another, with the exception of the 3rd of July. During this specific day, recorded T_{amb} values almost constantly remained at 35 °C with low $V_{1.1}$ values ranging between 1.0 m/s and 2.0 m/s between 12:00 and 16:00 (Table 1).

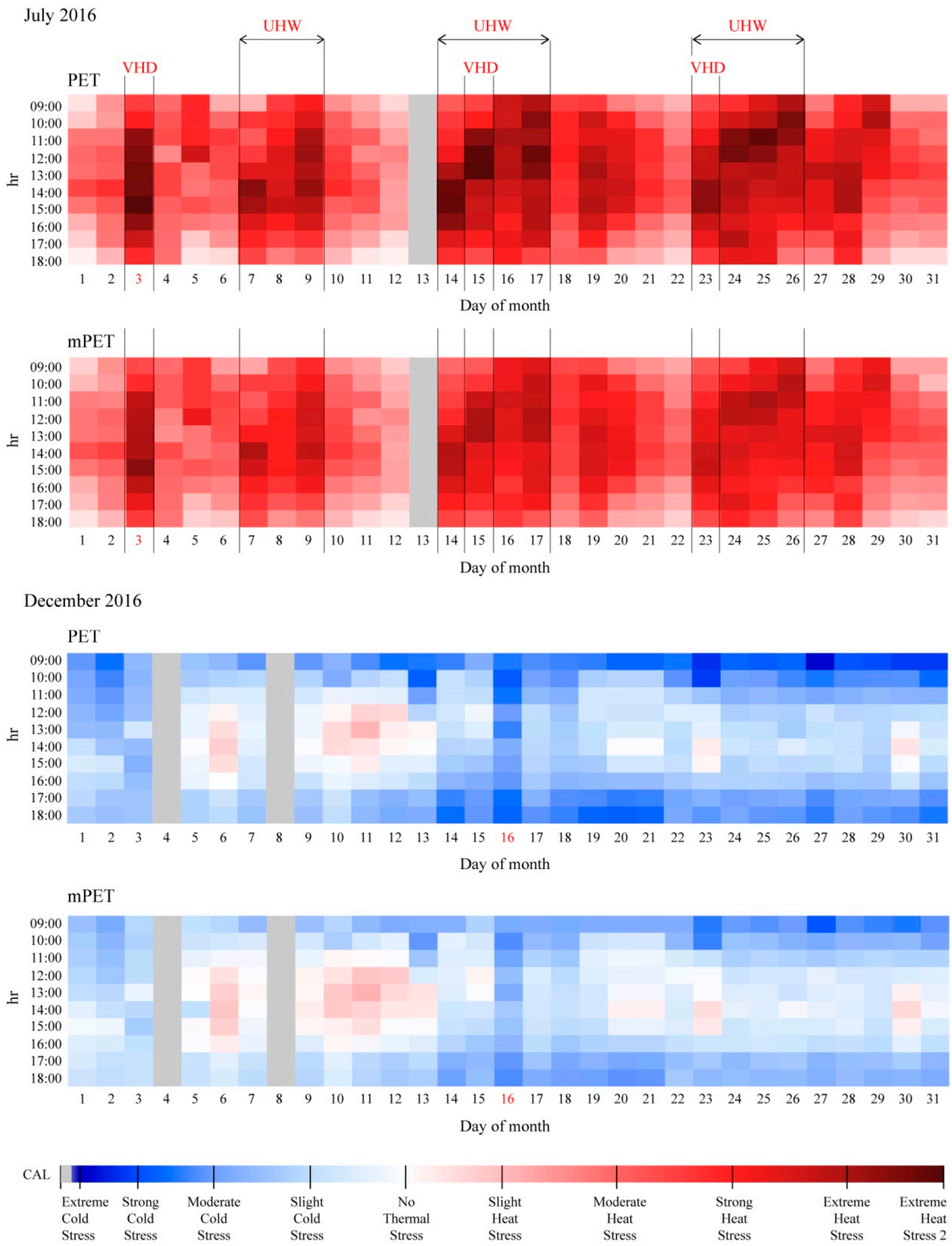


Figure 4. Variations of diurnal physiological stress (PS) based upon physiologically equivalent temperature (PET) and modified PET (mPET) at an hourly interval between 09:00 and 18:00 for July and December 2016 with identification of urban heat waves (UHW) and very hot days (VHD).

When considering the results for December 2016, it was evident that the PS thresholds varied differently than those observed for the summer period. More concretely, although only heat stress was observed during July, December revealed both types of thermal stress, particularly during the first half of the month. Such results imply that, whilst Mediterranean climates do witness rare occasions of considerable cold stress (as exemplified during the mornings of the 23rd and 27th), the majority of PS tends to vary between 'moderate cold stress' and 'no thermal stress'. Nonetheless, it was also noted that, particularly between the hours of 12:00 and 15:00, there were also periods surpassing 'slight heat stress', as exemplified by the 6th and 10th–12th of December. These outcomes indicate that Lisbon's thermo-physiological conditions during the winter fluctuate considerably less from thermal comfortable conditions than those obtained during the summer. Regardless it was noted the occurrence of days where, even between 12:00 and 15:00, PS grades still presented 'Moderate Cold Stress' as was the case during the 16th of December. Such conditions took place due to a combination of microclimatic characteristics, such as lower diurnal T_{amb} values (i.e., oscillating between 8.9 °C and 12.4 °C), and higher $V_{1.1}$ values (i.e., oscillating between 2.0 m/s and 4.1 m/s) (Table 1).

3.1.2. Comparisons between PET and mPET Indices

The inclusion of both thermo-physiological indices permitted (i) the comparison of PET results against those obtained by a newly adapted mPET index; and (ii) the scrutiny of whether the application of mPET in this study would also collaborate with the general the results obtained by Chen and Matzarakis [31] for western European climates. When cross-examining the outcomes of the two indices for July and December in Figure 4, two major distinctions were acknowledged.

Firstly, in the case of July, it was possible to verify that mPET values very rarely reached a PS of 'extreme heat stress'. In the sporadic case when mPET did reach such a PS threshold (such as 15:00 during the 3rd of July), it was associated to an extreme heat event (a very hot day). Yet, even under such conditions, and unlike the results obtained by the PET index, the adapted index was distant from 'extreme heat stress 2'. Concordant with these results, and as discussed within the original study, "almost no extreme hot events were given by the estimation of mPET and only moderate heat stress occurred […] on the contrary, PET [led to] the occurrence of extreme heat stress in Freiburg during the summer" ([31], p. 7).

Secondly, and focusing upon the month of December, it was demonstrated that overall PS values were closer to the PS grade of 'no thermal stress' with the use of the mPET index, as opposed to the PS levels obtained by the PET index. Again, such outcomes were also obtained within the original study in Freiburg. Similar to the divergence between the indices for the 3rd of July, colder days such as the 16th of December revealed also lower stress levels through the estimations obtained by mPET.

For these reasons, and based upon the more accurate analysis of the human bio-heat transfer system when exposed to thermal stimuli, the mPET index was used throughout the rest of the study. Such a decision by far devalued the use of the PET index in such studies; rather, it proposed settings in which the preceding index may be complemented b: (i) new improvements to the original Munich energy balance model for individuals model parameters; and (ii) an adjustment of the existing ranges of PS upon human beings.

3.1.3. Day Selection for simulations

Based upon the outputs obtained for both July and December 2016, it was possible to identify the days in which to undertake the simulations within the SkyHelios model. Beyond providing the daily input variables for the particular days, this approach also enabled specific Summer/Winter sun paths to be calibrated into the model. As the intention was to examine the influence of the *Tipuana tipu* species during annual extreme conditions during the different times of year, both the hottest and coldest days were selected for the simulation of the UCCs. Based upon the identification of the monthly variations of diurnal PS, the 3rd of July and the 16th of December were chosen to represent extreme summer and winter conditions, respectively.

3.2. Canyon RP Outcomes

As identified by existing studies, thermal comfort within urban contexts is strongly affected by urban configurations, whereby morphological elements such as width, height and orientation of a specific canyon are imperative to evaluate precise microclimatic conditions [25,30,82,83–85]. Additionally, and through SVF assessments, the impact of vegetation has also been identified as exemplified by Charalampopoulos, Tsiros [86], who determined that, particularly with low SVF values, the presence of vegetation presented positive influences upon thermal comfort conditions. Analogous results obtained by Shashua-Bar, Potchter [17] also indicated such an intrinsic relationship between the thermal effect of trees, with that of urban street geometry.

Undertaking a similar approach to the aforementioned studies, and processed by the SkyHelios model, Figure 5 and Figure 6 present the obtained SVF values for the UCCs. Moreover, based upon the stipulation of the summer paths, it was possible to ascertain the amount of time that each RP was exposed to the sun between 09:00 and 18:00. Such variables were expressed as M_{Sum} and M_{Win} to portray the number of minutes each RP was cast in the sun, during the summer and winter, respectively. As expected, M_{Sum} at each RP was higher given the absence of vegetation. M_{Win} did not follow this tendency due to its lower winter sun path with the exception for 0.17 RP_N which revealed a reduction in M_{Win} of 270.

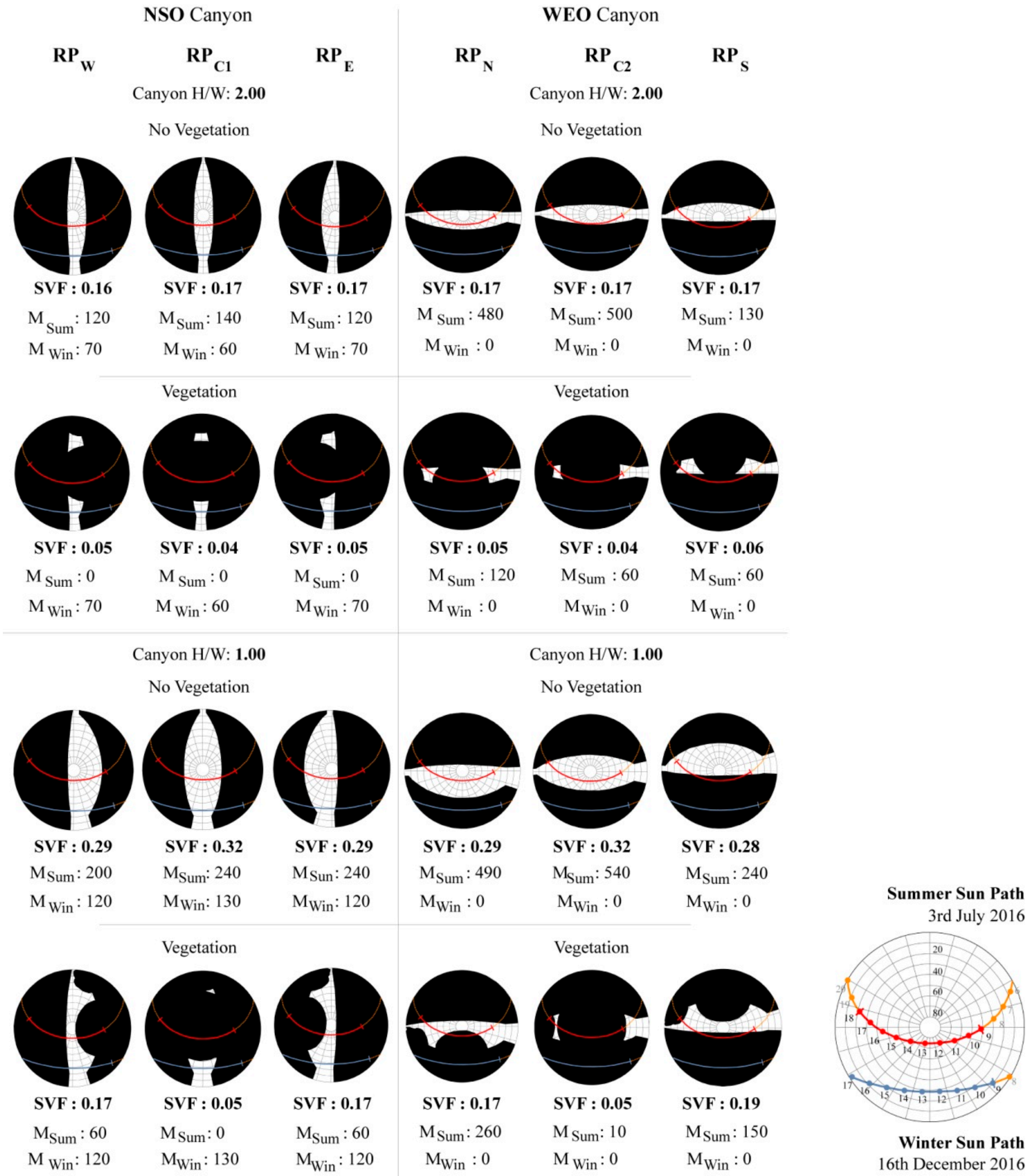


Figure 5. Identification of SVF and minutes cast in the sun during the summer/winter (M_{Sum}/M_{Win}) between 09:00–18:00 for each RP for $HW_{2.00}$ and $HW_{1.00}$.

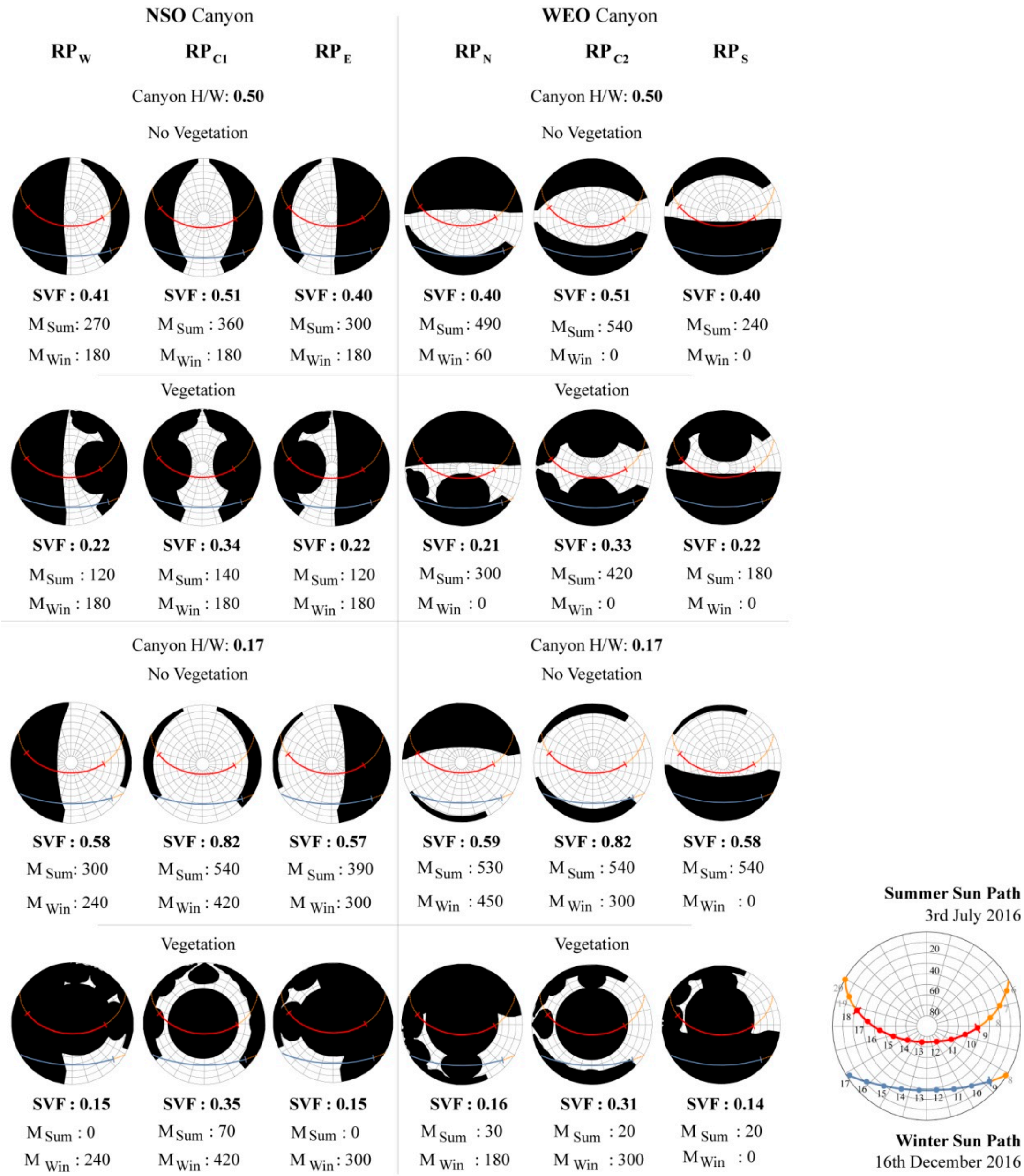


Figure 6. Identification of SVF and minutes cast in the sun during the summer/winter (MSum/MWin) between 09:00–18:00 for each R for HW0.50 and HW0.17.

Between the two UCCs orientations, WEO generally resulted in higher durations of solar exposure. Yet, such durations varied between the RPs within the specific canyons. As exemplified by the WEO, considerable differences in M_{Sum} were identified, as exemplified by 2.00 RP_S obtaining the M_{Sum} of 130, when 2.00 RP_{C2} and 2.00 RP_N revealed higher M_{Sum} values of 500 and 480, respectively. In the case of $HW_{0.50}$, which was the only UCCs in which the central RPs were not placed directly beneath a tree crown, 0.50 RP_{C1} and 0.50 RP_{C2} still revealed considerable reductions in M_{Sum}, particularly 0.50 RP_{C1}. Nevertheless, the highest reductions of M_{Sum} were obtained in $HW_{0.17}$, within all RPs, with a maximum reduction witnessed at 0.17 RP_{C1} where M_{Sum} was reduced by 470.

3.3. Canyon mPET Outcomes

Within this section, the results obtained from SkyHelios and subsequently processed by RayMan to obtain mPET values, and respective PS grades, were demonstrated for each of the four UCCs (Figure 7/Figure 8). In order to facilitate the comprehension of the results, the CTIS program was used to present the (i) differences obtained between the simulations with no vegetation (NV_{Sim}), against simulations with the presence of the *Tipuana tipu* species (TT_{Sim}); and, (ii) identified disparities from the results as initially obtained from the meteorological station. As anticipated, the UCCs with the least amount of thermal stress were $HW_{2.00}$ and $HW_{1.00}$ which generally presented both lower periods and quantities of thermo-physiological stress. Such was predominantly recognised within the NV_{Sim}. More precisely, and with regards to the $HW_{2.00}$ canyon, it was established that during the

- 3rd of July within the NSO, the presence of the tree crowns was able to reduce PS levels between 12:00–14:00 by one whole stress grade with a maximum mPET reduction of 6.8 °C (obtained at 14:00 in RPE). Such a decrease represented the capacity of the tree crown to decrease the vulnerability at pedestrian height during the few hours in which the canyon became exposed to direct solar radiation;
- 3rd of July within the WEO, the TT_{Sim} presented much more prolonged reductions of PS thresholds, especially in RP_N and RP_{C2} which were cast in the shade of the vegetative crown between 10:00–15:00 and 10:00–16:00, respectively. During these hours, and in the case of RP_{C2}, the reduced mPET values ranged between 29.1 °C–37.7 °C, instead of 34.6 °C–42.9 °C as obtained in the NV_{Sim};
- 16th December for both the NSO and WEO, it was possible to identify that the absence/presence of vegetation led to no significant differences between the NV_{Sim} and the TT_{Sim}. In the case of the NSO, the very subtle variations of PS such as those presented at 12:00 and 16:00 were a result of $V_{1.1}$ values oscillating by 0.1 m/s. Within the WEO such distinctions were even less significant, yet as a result of generally higher $V_{1.1}$ values (i.e., between 0.2 m/s and 0.7 m/s), all RPs presented slightly colder PS levels.

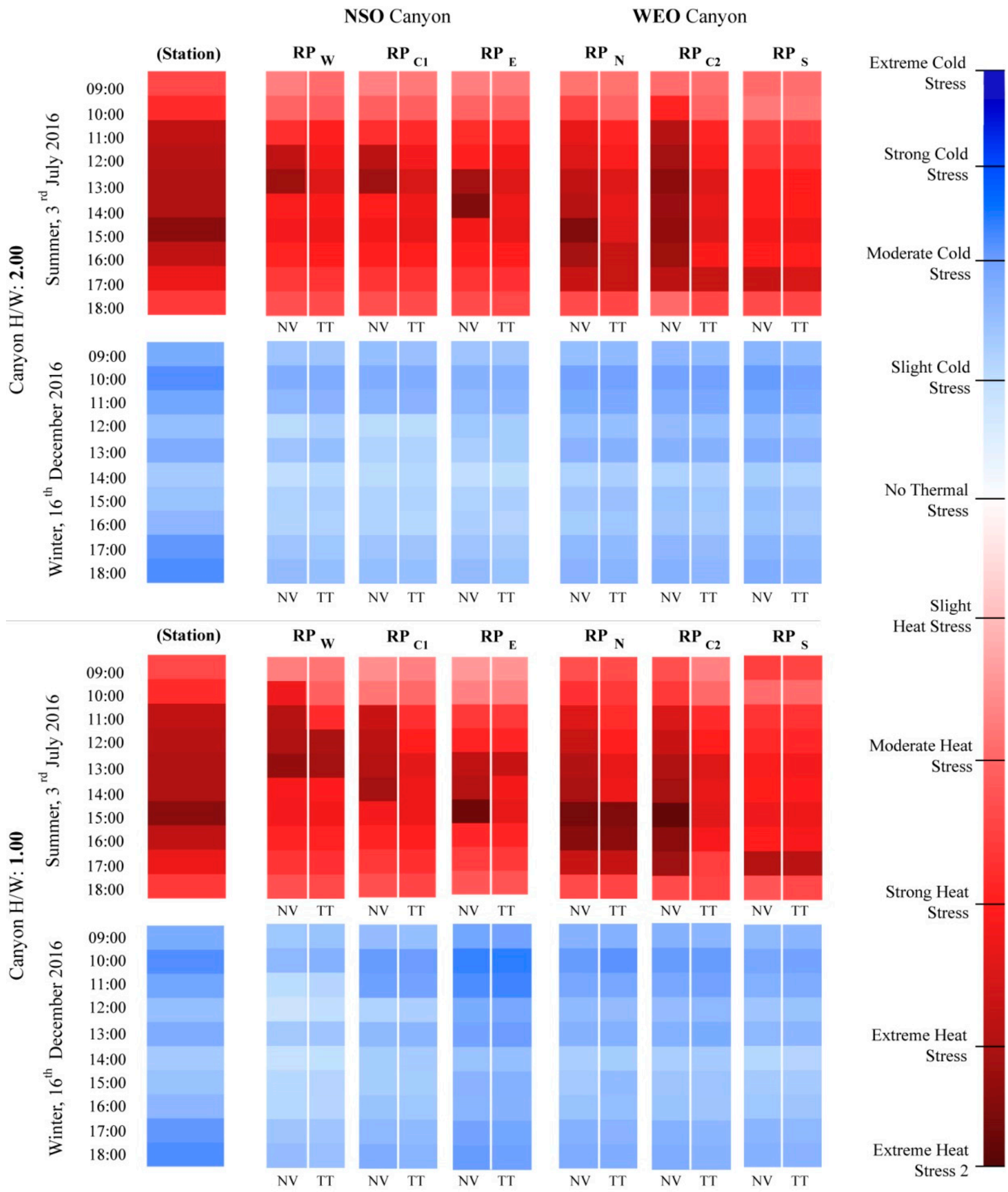


Figure 7. Canyon variations of diurnal PS resultant of hourly mPET between canyon simulations with no vegetation (NV) vs. with the *Tipuana tipu* (TT) and those originally presented by the meteorological station for $HW_{2.00}$ and $HW_{1.00}$.

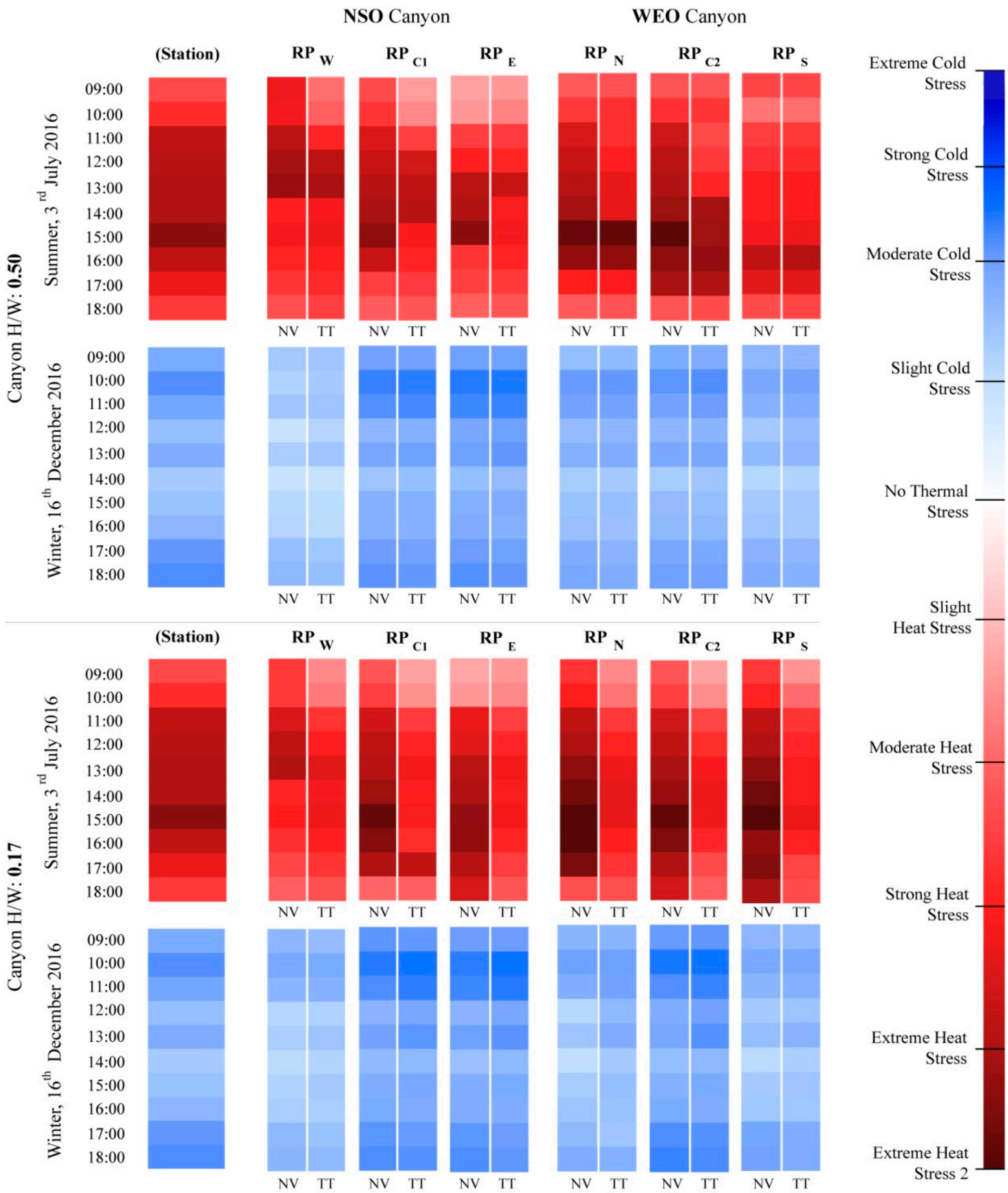


Figure 8. Canyon variations of diurnal PS resultant of hourly mPET between canyon simulations with NV vs. with the *Tipuana tipu* (TT) and those originally presented by the meteorological station for $HW_{0.50}$ and $HW_{0.17}$.

Within the $HW_{1.00}$ canyon, it was determined that during the:

- 3rd of July within the NSO, results were not excessively dissimilar from those obtained in $HW_{2.00}$. However, within this UCC, PS levels increased both in stress intensity and duration. Both lateral RPs revealed periods of 'extreme heat stress' even in the TT_{Sim} as exemplified between 12:00–13:00 for RP_W, and at 13:00 for RP_E. Both of these circumstances took place when the sun path crossed the gap between the crown and that of the western/eastern canyon facades. Nevertheless, the diurnal mPET results obtained in the NV_{Sim} presented much higher PS grades when the canyon was directly exposed to radiation fluxes. Also obtained at RP_E, a maximum reduction in mPET of 7.7 °C was identified when the PS in the NV_{Sim} almost reached 'extreme heat stress 2';
- 3rd of July within the WEO, the results obtained in RP_N show the influence that the vegetative shade could present within the RP until 15:00. At this specific time, both mPET values for the

NV_{Sim} and TT_{Sim} reached 43.6 °C and 44.1 °C, respectively, thus leading to equally extreme PS grades, which gradually subsided by 18:00;

- 16th December for both the NSO and WEO, and similar to the $HW_{2.00}$ canyon, there were very limited variations of thermal conditions between the NV_{Sim} and TT_{Sim}. Nevertheless, it was noted that the WEO presented much more stable PS grades between in $RP_{N/C2/S}$ in comparison to those within the NSO. The justification for this was attributed to the considerable variations of $V_{1.1}$ conditions in the entire canyon which were later presented in Figure 9.

When considering the results for the $HW_{0.50}$ and $HW_{0.17}$, it was verified that overall PS levels increased, and the TT_{Sim} presented even stronger attenuation results during the summer. Within the $HW_{0.50}$ canyon, during the

- 3rd of July within the NSO, due to the increased width of the canyon, the susceptibility to solar radiation was augmented in both the NV_{Sim} and the TT_{Sim}. Within the NV_{Sim}, elevated PS levels increased in duration in comparison to $HW_{1.00}$, especially during the morning in RP_W, and the afternoon in RP_{C1}. Given the placement of the RP_{C1} between the edges of two tree crowns within the TT_{Sim}, it witnessed similar PS grades between 12:00–14:00 to those obtained in the NV_{Sim};
- 3rd of July within the WEO, RP_N and RP_{C2} presented similar occurrences within the TT_{Sim}. Whilst cast in the shade within the middle of the canyon, mPET values decreased by up to 6.3 °C as illustrated at 13:00 in RP_{C2}. When not cast in the shade, however, even the TT_{Sim} presented PS thresholds reaching 'extreme heat stress 2' with mPET values reaching 45.2 °C. Such a value actually exceeded slightly the mPET value of 44.9 °C obtained in NV_{Sim} as a result of a slightly higher $V_{1.1}$ value (+0.2 m/s);
- 16th December for both the NSO and WEO, there still were no clear variations between PS grades between the NV_{Sim} and the TT_{Sim}. It was however noted that, between all RPs, the PS grades within RP_{C1} and RP_E revealed higher cold stress as a result of higher diurnal $V_{1.1}$ values within these two locations (Figure 9).

Lastly, and within the $HW_{0.17}$ canyon, it was determined that during the:

- 3rd of July, PS values often reached 'Extreme Heat Stress 2' within the NV_{Sim}. In contrast, within all locations, the highest PS obtained by the TT_{Sim} was just below the 'extreme heat stress' grade as revealed at 17:00 in RP_{C1} with a mPET value of 39.6 °C. When comparing the general mPET results between the NV_{Sim} and the TT_{Sim}, it was identified that the largest variation between PS thresholds took between 16:00–17:00. As summarised in Table 7, the highest variations took place within the WEO, whereby a maximum reduction of mPET of 11.6 °C (equating to a PET of 15.6 °C) was observed at 16:00 in RP_N;
- 16th of December, the obtained PS levels revealed, for the first time, noteworthy variations between the NV_{Sim} and the TT_{Sim}. Such was witnessed particularly within RP_N and RP_{C2} between the hours of 12:00 and 15:00, where the TT_{SIM} presented comparatively colder PS levels as a result of the shade cast by the tree crown. Between the two, RP_N revealed the highest mPET reduction of 2.6 °C (equating to a PET of 2.7 °C) at 12:00. As result, such outcomes suggest the potential of vegetation to induce colder conditions due to obstructing radiation fluxes during the winter.

Figure 9. Diurnal wind speed ($V_{1.1}$) variations between the RPs within all NSO canyons for the 16th of December.

Table 7. Maximum reductions (K) in thermo-physiological indices between simulations with no vegetation (NV_{Sim}) vs. with the *Tipuana tipu* (TT_{Sim}) at each specific location within $HW_{0.17}$.

0.17 RP#	**Hour**	**NV_{Sim}**		**TT_{Sim}**		***K***	
		PET °C	mPET °C	PET °C	mPET °C	PET °C	mPET °C
N	16:00	52.3	46.3	36.7	34.7	−15.6	−11.6
C2	16:00	47.9	43.5	35.7	34.1	−12.2	−9.4
S	17:00	48.4	43.5	33.1	31.8	−15.3	−11.6

Analogous to existing studies [1,25,30], the disparity of thermal conditions between those presented from the meteorological station and those obtained from the in-situ assessments were substantial, even in the case of the NV_{Sim}. Therefore, such outcomes continue to infer the risk of solely considering station values for microscale and studies/projects. On the other hand, these studies also present the methodical means in which to adapt such results into useful data that can be much more valuable for local/microscale thermal sensitive urban design and planning.

Regardless of the considerable differences, there were however associations between the results obtained from the station and those from the 'in-situ' assessments. For example, within most of the UCCs it was possible to identify the influence of the accentuated climatic circumstances as initially identified by the station, namely: (i) the elevated T_{amb} (35.9 °C) and simultaneously low V_{10} (2.0 m/s) obtained at 15:00 during the 3rd of July 2016; and also, (ii) the low T_{amb} (9.8 °C) and simultaneously high V_{10} (8.0 m/s) obtained at 13:00 during the 16th of December 2016.

3.3.1. Wind Influences

As expected, the lower the UCC, the higher the variation of $V_{1.1}$ between the different RPs within the canyons. Such variations are presented in Figure 9, which summarises the NSO canyon results obtained through the use of the three-dimensional tool integrated within SkyHelios during the winter period. When considering the modifications of mPET/PS during December, it was possible to make direct associations between the thermal comfort conditions and the $V_{1.1}$ results.

When considering the NSO canyons in December, the variations of PS between the RPs (shown in Figure 7 and Figure 8) can be directly linked to the variations of $V_{1.1}$ shown in Figure 9. More specifically, to the: (1) $HW_{2.00}$ canyon presenting almost identical values at each RP; (2) $HW_{1.00}$ canyon revealing the highest values in RP_E, in-between values in RP_{C1}, and the lowest in RP_W; (3) $HW_{0.50}$ revealing equally higher values in RP_E and RP_{C2}, with lowest values in RP_W; and lastly, (4) $HW_{0.17}$ again revealing greater values in RP_E and RP_{C2}, and RP_W once again revealing the lowest values amongst the three. Thus, it was possible to identify why almost all RP_W PS levels were slightly closer to 'comfortable conditions' in comparison to the other two locations in the canyon.

Finally, when considering the vacillation of $V_{1.1}$ values between the NV_{Sim} and the TT_{Sim}, it was identified that the estimated effects upon wind currents at pedestrian height were fairly inconsequential. Such a result can be attributed to the output of the wind simulations being set at a height of 1.1 m, which fell well beneath the calibrated trunk height (*l*) of 3 m. Nevertheless, such a result calls for a future study into the effects of vegetation when they are configured closer to one another (i.e., in a cluster) rather than spaced at a considerable distance as calibrated in the TT_{Sim}. Such a study would also certainly render very different results upon the radiation fluxes at pedestrian height as well.

3.3.2. Tmrt Influences

Contrasting the $V_{1.1}$ results, the NV_{Sim} and the TT_{Sim} demonstrated very clear deviations of T_{mrt} in all canyons. As a result of the tree crowns, the casted shade within the RPs led to considerable reductions of radiation fluxes at the pedestrian level.

More specifically, Figure 10 exemplifies such variations of T_{mrt} within the northern area of the different WEO canyons, whereby (i) even in the case of $HW_{2.00}$ (with a canyon width of only 10 m) the crown of the *Tipuana tipu* was able to reduce T_{mrt} by 15.6 °C; (ii) in both $HW_{1.00}$ and $HW_{0.50}$ which presented a similar SVF value, similar T_{mrt} reductions were of 13.1 °C and 13.3 °C, respectively; and lastly, (iii) the largest difference between the four locations was $HW_{0.17}$ which presented a dramatic T_{mrt} decrease of 29.5 °C. Subsequently, and when referring to the obtained mPET differences between the NV_{Sim} and the TT_{Sim}, it was possible to identify the strong correlation with these T_{mrt} results in each specific RP.

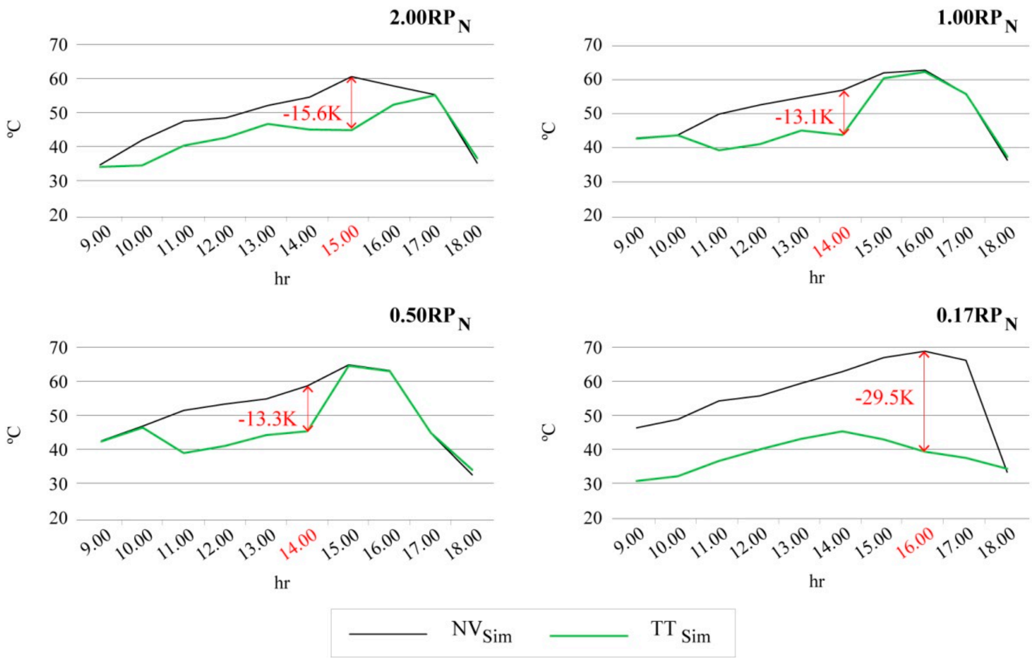


Figure 10. Mean radiant temperature (T_{mrt}) differences during the summer at selected RPs between simulations with No Vegetation (NV_{Sim}) vs. with the *Tipuana tipu* (TT_{Sim}) during the 3rd of July.

When observing the T_{mrt} deviations during the winter between the two simulations, smaller, yet important differences were also acknowledged. As shown in Figure 11, due to the *Tipuana tipu* species maintaining its foliation during the winter, the vegetative crown also reduced radiation fluxes at pedestrian level during December. As a result, in some circumstances (particularly in lower UCCs) this led to the TT_{Sim} presenting lower comfort conditions. Within the $HW_{0.17}$ canyon, and principally in RP_N and RP_{C2}, it was possible to verify direct results at 13:00 upon the obtained PS grades, even with small reductions of 5.5 °C and 4.6 °C, respectively.

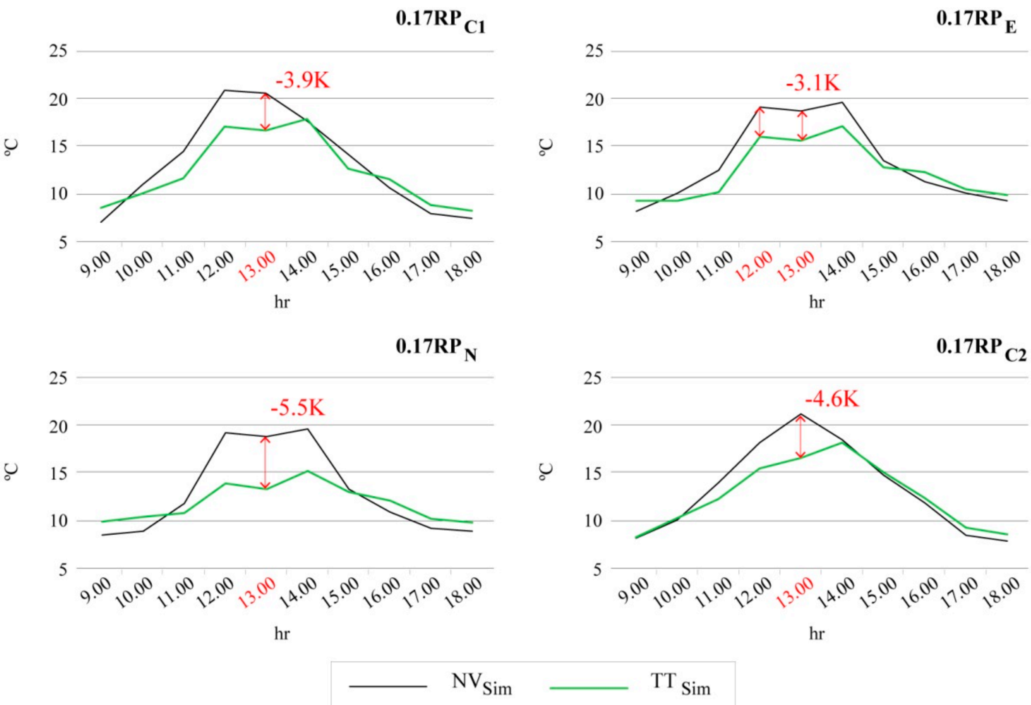


Figure 11. Mean radiant temperature (T_{mrt}) differences during the summer at selected RPs between simulations with no vegetation (NV_{Sim}) vs. with the *Tipuana tipu* (TT_{Sim}) during the 16th of December.

4. Discussion

When considering the results obtained by this study, it became clear that the use of the updated SkyHelios version provided an effective tool to (i) downscale results obtained from Lisbon's meteorological station and render more accurate outputs for the microclimatic examinations as exemplified by this investigation; and (ii) estimate the in-sit' effects of the *Tipuana tipu* species by considering a multitude of climatic variables. Such an examination was complemented with the use of onsite measurements of G_{rad} in order to attribute more precision to the results obtained by the simulations within each UCC.

Naturally, the results obtained from the model should be approached as estimations of what would take place within actual conditions, particularly with regards to the $V_{1.1}$ presented by the new integrated wind analysis tool. As a result, this raises the opportunity to undertake further field studies to further elaborate the results presented by this article. Nevertheless, it was noted that the output speeds during July within the lower UCCs were very similar to those obtained by the field measurements obtained by Nouri and Costa [54] during the summer of 2015 in Lisbon's historical quarter. In addition, the variation of different speeds within the different regions of the canyon were also analogous, whereby (i) the western regions of the NSO canyon also revealed the lowest wind speeds; and (ii) the central and eastern regions respectively revealed the highest values. Furthermore, and when considering the relationship of all outputs from the NV_{Sim} and the TT_{Sim}, it was possible to see clear associations between the different microclimatic variables, namely between the (i) quantity of M_{Sum}/M_{Win} values associated to each RP, and the general diurnal thermal conditions within that location; (ii) variations of thermal conditions suggested by the meteorological station, and those obtained within each assessed canyon/location; and, (iii) the impact of climatic variables such as T_{amb} and $V_{10/1.1}$ upon the overall thermo-physiological projections.

The application of the new mPET index within this study also provided the opportunity to both compare and apply a newer PET version based upon an improved thermoregulation model. The results obtained in this study were concomitant with those revealed by Chen and Matzarakis [31], whereby the initial identification of bioclimatic conditions (PET and mPET variables) during the month of July and December did not reveal PS values exceeding that of 'Extreme Heat Stress'. Although later in the study the mPET results did in fact lead to higher PS grades within the NV_{Sim} and the TT_{Sim}, such exacerbations were attributed to the identification of dramatic 'in-situ' microclimatic occurrences such as when G_{rad} values exceeded that of 900 W/m^2, and other climatic variables such as T_{amb} were particularly high (such as at 15:00 during the 3rd of July). Such extreme heat conditions, as a result, point to the need to improve the prediction and prevention of such events particularly for the context of Western Europe [87,88].

Within this study, numerous opportunities for future study were identified, namely (1) how mPET/PET entirely based upon variables obtained from the field surveys could differ and/or complement those obtained in this study, especially V values as identified in Nouri and Costa [54]; (2) the opportunity to consider how a group/cluster of trees would present different results, including possible oscillations of V between the NV_{Sim} and the TT_{Sim} [76]; (3) the expansion and of PS thresholds to situate mPET/PET results beyond existing levels (e.g., that of 41 °C) as discussed in Nouri, Lopes [10]; (3) following from the previous point, to moreover investigate how mPET outputs may need a general recalibration of existing PS boundaries as already indicated by Chen and Matzarakis [31]; and, lastly (iii) consider how other types of public space design measures, such as misting systems, can be incorporated within vegetative crowns to further augment thermal comfort through the effects of evaporative cooling [89,90].

As stipulated, the 3rd of July and the 16th of December were selected due to their particularly high estimated diurnal stress levels in order to evaluate the potential 'in-situ' attenuation effects from the *Tipuana tipu*. Both days revealed important results, whereby: (i) the summer simulation revealed considerable reductions of PET/mPET of up to 15.6 °C/11.6 °C during a very hot day where diurnal T_{amb} surpassed that of 35 °C; and, (ii) the winter simulations revealed the risk of over shading within certain conditions, which in turn, led to a reduction of PET/mPET of up to 2.7 °C/2.6 °C. Such results relate directly to the significance of considering year-round implications of shading patterns within outdoor spaces, especially due to their identified dynamic and occasionally dramatic effect upon comfort conditions year round.

5. Concluding Remarks

- Today, in most cases, the urban fabric is already consolidated. As a result, the interdisciplinary practices of urban design and climatology must frequently seek resolutions to address thermal comfort factors in existing UCCs. Consequently, this results in the need for these two disciplines to symbiotically collaborate with one another. This originates the need for practices such public space design to (i) identify existing thermal risk factors; and just as importantly, (ii) produce creative solutions to generate better thermal environments for pedestrians in an era moreover prone to climate aggravations. The types of solutions are numerous, yet this study has focussed upon the use of urban vegetation to obtain such outcomes.
- The study has sought to evaluate how an updated simulation tool and a newly updated thermo-physiological index can contribute to existing studies which recognise the importance of evaluating the in-situ influences of urban vegetation within different urban morphological compositions.
- Focused upon the case of Lisbon, the study identified the in-situ influences of one of the most common shading trees in UCCs which are commonly found within the city's historical district; one which is known to particularly suffer from high T_{amb} values and UHI effects during the summer. Notwithstanding, the study also examined the possible negative 'in-situ' thermo-physiological impacts that the *Tipuana tipu* species can have during the winter due to the permanency of its foliage during the colder periods of the year. As a result, the presence of vegetation in different UCCs was approached as an urban element which can both improve and decrease pedestrian thermal comfort during different periods of the year.
- Beyond presenting bioclimatic results (which deliberates upon both singular climatic variables and thermo-physiological stress thresholds), the study suggests the importance of facilitating the transversal comprehension of the outcomes for non-climatic experts to easily interpret such outcomes discussed in the study. As an example, through the use of the CTIS software, the data from the meteorological station and the attained G_{rad} were translated into easily interpretable figures which are constructed upon the common measuring unit of °C. Even when considering elements such as urban tourism (which is particularly elevated within Lisbon's historical centre during the summer), such a facilitation can also prove important when safeguarding other urban socio-economic aspects which are also intrinsically dependent upon a thermally comfortable public realm.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Online Materials: Software package retrievable (upon request) from:

(i) http://www.urbanclimate.net/skyhelios/
(ii) http://www.urbanclimate.net/rayman/
(iii) http://www.urbanclimate.net/climtour/mainframe_tools_ctis.htm

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Conclusions

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People love to spend time outside – strolling, interacting with nature, gossiping with friends, visiting shops, lingering over a cappuccino in an outdoor café. Landscape architects and urban designers strive to design places that encourage these kinds of activities, places where people will want to spend their time. However, their designs often focus on such elements as physical attractiveness, functionality, and composition. These are all important, of course, but without one invisible, intriguing component of the landscape they are doomed to failure. Unless people are thermally comfortable in the space, they simply won't use it. Although few people are even aware of the effects that design can have on the sun, wind, humidity, and air temperature in a space, a thermally comfortable microclimate is the very foundation of well-loved and well-used outdoor places" [I]

Discussion and Hypothesis Validation

For decades now, the scientific community has identified the necessity to consider the influences of urban climatology upon the thermal comfort, liveability, quality, and safety of the urban public realm. Beyond the already delicate, and dynamic, nature of the existing urban energy balance as stipulated by Oke (1988); the knowledge of the climate change adaptation agenda has propagated the need to deliberate upon the future modifications, and equilibrium, of such an energy balance. In addition, and within the global community itself, while different and separate disciplines have made extraordinary breakthroughs, there is nevertheless the need for further interdisciplinary collaboration between these often segregated disciplines. Such an emergence, is by its own right, believed to be a breakthrough, as it epitomises the: (i) sufficiency and ability of scientific know-how to be transferred upon another discipline; (ii) modest recognition that the integration with other disciplines can benefit both the original and added arenas in addressing a specific problem; and, (iii) necessity of scientists to work and collaborate with other fields of practice, which in turn, raises the constant reminder that their breakthroughs can be understood, utilised, and adapted by others. It is here where the importance of interdisciplinarity gains its equitable weight in science.

So far, top-down assessments of climate change have provided an excellent foundation to inform how the global climate system can lead to potential impacts during the unravelling of the 21st century. Yet, and in parallel to such a consensus amongst the global community, particularly in recent years, it has also been recognised that adaptation efforts to such identified ‘risk factors’, shall ultimately, be undertaken within local scales.

When considering the majority of top-down assessments, two predominant limitations are particularly tangible, i.e., their: (i) lack of local specificity; and, (ii) predominant focus upon the exposure of cities to hazards that have an enormous impact, yet low frequency – and yet little emphasis upon high-frequency microscale phenomena within the urban environment. As suggested by the quote by (Brown 2010, p.1-2) [I], such high frequency microclimatic characteristics are of key importance for an active public realm. As a result, and considering the already existing urban climatic ‘risk factors’, which can be further exacerbated by the effects of climate change, local scale efforts on behalf of numerous professions are faced with overcoming issues of climatic uncertainty, and applicative knowhow.

In this light, this doctoral thesis tested the validity of the hypothesis that:

> The interdisciplinary union between the distinct fields of urban climatology and public space design can be strengthened to improve local pedestrian thermal comfort levels while confronting existing and projected microclimatic aggravations associated to climate change

In order to undertake this assessment, the thesis was divided into four sequential stages which examined the different aspects associated to the hypothesis, whereby each section was concomitant to the stipulated specific research objectives, i.e., to:

(1) Inspect implications of the emerging climate change agenda upon the importance of bottom-up approaches to local scale adaptation

(2) Identify existing measures and both quantitative/qualitative approaches to thermal sensitive public space design

(3) Examine how public space design can identify/improve existing/future human thermal comfort risk factors within a specific site

(4) Consider how thermal attenuation priorities can be identified and met through public space design in various urban morphological settings

Section 1

The first section of the research focused predominantly upon the emergence of the climate change adaptation agenda, and how impact prediction can correspondingly be undertaken through bottom-up urban planning approaches. Such an approach was progressively downscaled within the section, from global climate models to the approach of human thermal comfort factors.

When considering imperative tools such as Global Circulation Models and Regional Climate Models their applicability for local scale adaptation efforts is limited. Such a statement directly relays back to issues of scientific objectivity, and purposefulness. Due to the factual limitation of computational processing power to assess such vast amounts of data, both Global Circulation Models and Regional Climate Models cannot be confused with means to directly assess urban climatic implications. Even in the case of Regional Climate Models, when considering local action within the built environment, climatic effects “*cannot be downscaled from a regional climate model, they are complex and require local observation and understanding*” (Hebbert and Webb 2007, p.125). It is this ‘local observation and understanding’ which is the very foundation of bottom-up approaches, whereby the concrete bond with specific localities substantiates analytical preciseness.

Evidently, and as discussed within Publication 2, top-down assessments have drastically propelled Mans understanding of the global climatic system. More concretely, global disseminations from the Intergovernmental Panel on Climate Change (IPCC) (since their initial First Assessment Report, and their emission scenario exercises in 1990) were critical for numerous reasons. Firstly, such disseminations marked a departure from singular mitigation attitudes, thus opening a period that was more synonymous with global scientific collaboration, rather than that of solely regulatory enforcement as previously overseen by the Kyoto Protocol. Secondly, institutions such as the IPCC are continually revealing information which serves the scientific community (i.e., with regards to sea level rise, increases of global surface temperatures, occurrences of draught/flooding risks, and changes in precipitation and temperature extremes). Instigated by such scientific knowledge, Publication 2 identified how the emergence of National Adaptation Strategies have provided means for numerous ‘front-runner’ countries to already consider both adaptation strategies, and even measures. Often, such approaches served as foundations for other countries to develop their own responses to their own potential localised impacts.

As a result, the climate change adaptation agenda, and independent of inherent political attrition, has been able to instigate global cooperation through the sharing of scientific know-how and partnership. This being said, and invariably associated to individual National Adaptation Strategies, although contributions from global scientific entities have propelled such international agendas, there is now, more than ever, the requirement for further bottom-up and localised action – including for disciplines such as urban planning and design.

As already mentioned, when considering local scales, information obtained solely from Global Circulation Models and Regional Climate Models often do not (nor should they be expected to) present sufficient information to address nor undertake local scale adaption. Resultantly, this relates to the argument presented by Wilbanks and Kates (1999), who early on, identified the crucial need for interactionism between global and local scale analysis.

When approaching local scales, and moreover that of human thermal comfort within the public realm, local understanding of climatic variables becomes paramount. Associated to such a comprehension, is the recognition of how the urban climate is invariably further modified by local characteristics, a consequence which conveys directly back to the urban energy balance defined by Oke (1988). As identified by the numerous studies and discussed in Publication 3, the biometeorological influence and significance of such variables can be identified through various approaches. As suggested by Olgyay (1963), the thermal 'comfort zone' within outdoor environments is the result of numerous aggregating variables such as ambient temperature (T_{amb}), Relative Humidity (RH), Wind speed (*V*), and radiation fluxes.

Consequentially, and still in biometeorological terms, this implies that such a 'comfort zone' is resultant of a combination of thermo-physiological stimuli, and not just one (such as T_{amb}). To approach such a balance, the human energy budget as defined by the Munich Energy-balance Model for Individuals (Höppe 1984, Höppe 1993) can be utilised. Based upon such a budget, the Physiologically Equivalent Temperature (PET) index (Mayer and Höppe 1987) has been utilised in climatic and biometeorological studies to examine pedestrian thermo-physiological stress levels. In addition, and based upon the established grades identified within (Matzarakis 1997, Matzarakis, Mayer et al. 1999), PET values can be moreover be plotted against grades of Thermal Perception and Physiological Stress (PS). Furthermore, and considering issues of climatic uncertainty within future horizons, Publication 3 moreover discussed the potentiality of the strategic '*What if?*' agenda (Costa 2011, Coelho, Costa et al. 2012) to project, and consider a set of given conditions/scenarios. As a result, efforts at anticipation of future aggravations of existing conditions are feasible through a flexible and exploratory approach.

When considering the hypothesis of the research, within Section 1 'The emergence of the climate change adaptation agenda and the growing role of bottom-up approaches to local scales' – it was correspondingly identified that:

- Further instigated by the emergence of the climate change adaptation agenda, and in amalgamation with the maturing global National Adaptation Strategies, the necessity for bottom-up approaches to local scale risk factors shall continue to grow

- Although top-down approaches and disseminations have presented an imperative emerging international co-operative understanding of the existing and future global climatic system, such outcomes are rarely capable (nor intended) to provide guidance at local scales

- In collaboration with top-down assessments, disciplines such as urban planning and design must undertake bottom-up assessments in order to concretely identify local risk factors, including that of human thermal comfort within the urban public realm

- Approaches to human thermal comfort within the disciplines of urban climatology and biometeorology have already been present within the scientific arena long before the emergence of climate change adaptation agenda. Similarly, the general influence of microclimatic characteristics upon the use of outdoor public spaces has also been well documented prior to the agenda. As a result, although segregated within respective disciplines, critical know-how with regards to addressing local microclimatic risk factors such as human thermal comfort at local scales already exists

- In continuation from the previous point, and based upon examining the importance and role of local scales – interdisciplinarity becomes fundamental when evaluating means to approach thermal risk factors through bottom-up planning and design. It is here where the interdisciplinary practice of urban public space design can play a fundamental role in local scale adaptation; where existing knowledge from different disciplines can be united to inform means to evaluate, and improve, existing/future concrete local human thermal comfort levels

Section 2

This section investigated general existing measures and approaches to thermal sensitive public space design. Such a section was required to establish an overall understanding of existing measures, and both quantitative/qualitative approaches to thermal sensitive public space design. As a result, Section 2 was divided into two predominant sections, the: (1) first scrutinised initial means in which public space design measures could improve general human thermal comfort levels within a specific climate; and, (2) second examined how existing generic analytical approaches to public space design could be further developed to address existing and future pedestrian comfort thresholds in more detail.

Within Publication 4, an open ended framework of built and conceptual precedents revealed how different typologies of public space design measures could potentially be considered to reduce existing and future thermal stress within a specific city/climate. Centred upon the case of Auckland, it was moreover possible to identify how the established measures could also be integrated within its regulatory Unitary Plan, and non-regulatory 'Auckland Design Manual'.

Based upon the figures presented by the National Institute of Water and Atmosphere, New Zealand does not have a broad temperature range, and it lacks extreme values commonly found in most continental climates. Nevertheless, and as identified by MfE (2008) and Gluckman (2013), the potential increases of urban temperatures, frequency of elevated temperatures, and of annual 'hot days' (by up to 200%), catalysed the requirement to ensure the resilience of Auckland's public realm, particularly given its 'Quality urban growth objective' as stipulated by the Unitary Plan. Such objectives were also associated to the projected increase of Auckland's urban population, density and CO_2 emissions by 2040. As a result, and based upon the referral to locations with similar Köppen Geiger classifications, Publication 4 presented 17 bioclimatic case studies that ranged from already built projects to scientific studies. Correspondingly, the practical experience from actual construction, convergent thinking through conceptual exploration, and the empirical outcomes of scientific methodologies could be presented within the open ended framework. Amongst the 17 case studies, four predominant categories were established in order to facilitate their typological division, these being: Trees and Vegetation, Shelter Canopies, Materiality, and Water/Misting Mechanisms.

Once constructed, the study subsequently presented how the framework could be potentially integrated within the Unitary Plan and 'Auckland Design Manual' to provide more concrete guidelines on how Auckland's public spaces could be more responsive to increased hot days, heatwaves, and managing UHI effects. More specifically, when considering the concrete 'Section 4 – Design for Comfort and Safety', the presented framework launched existing applicable bioclimatic solutions that could be made applicable for Auckland's Central Business District. Such was suggested within an extension of Section 4, explicitly orientated towards 'Dealing with Thermal Comfort & Climate Change', to: (1) avoid issues of maladaptation, and present recommendations for local thermal sensitive design and decision making through the introduction of the section 'General Guidelines for Microclimatic Assessment'; and, (2) present means in which to tackle the increase of annual hot days, heatwaves and UHI in correlation with the different approaches and options presented in the framework. Still regards to the latter, it was aimed that such an addition to local guidelines would provide an aid in: (i) exploiting the effects of local evapotranspiration in locations increasingly prone to UHI; (ii) effectually reducing/enabling solar and wind patterns within correct locations; (iii) designing suitable annual availability of choice between exposed, semi-shaded, and shaded areas; (iv) supporting pedestrian activity threads through passive strategies, evaporative cooling systems and vegetation; (v) reducing surface temperatures (T_{surf}) through the implementation of cool materials; and, (vi) implementing water/misting systems that could (through different means) attenuate local thermal comfort levels.

Such a section of 'Dealing with Thermal Comfort & Climate Change' was presented to the 'Built Environment Team' within the Auckland council to discuss how the city's public spaces could develop their own: (i) passive strategies and/or vegetation layout to attenuate the effects caused by the increase of annual hot days; (ii) overcoming of difficulties presented by high RH levels when cooling the public realm; and, (iii) decreasing urban surface temperatures by reconsidering the predominant use of dark pavements used within areas such as the Central Business District.

Although Publication 4 considered how existing measures and practices could present local 'benchmarks' within a specific city and climate, a specific outdoor space was not evaluated in terms of 'in-situ' thermal risk factors, nor how such measures could address such factors. Before this exercise could be undertaken, Publication 5 further explored the existing quantitative and qualitative aspects of the interdisciplinary concept of 'Place making'.

Within this publication, and with the interest of also expanding upon current generic approaches and tools to evaluate the 'success' of a given public space; well-known interrogations such as 'What makes a great place?' was also dissected. Such an inspection was divided into the: (1) discussion of the existing diagram from the Project for Public Spaces; (2) establishing of new qualitative/quantitative criteria; and, (3) ensuing restructuring of the diagram.

Since its establishment in 1975, their "*approach to place making is based on* [their] *belief that it is not enough to simply develop design ideas and elements to improve or develop a public space* (…) *improvements need to reflect community values and needs*" (PPS 2003, p.3). For this reason, and after evaluating thousands of public spaces worldwide, the Project for Public Spaces created an evaluation centred upon four principal urban qualities: (1) Sociability; (2) Uses and Activities; (3) Access and Linkages; and, (4) Comfort and Image. As described by the PPS (2003), the diagram: (i) establishes these four qualities which are associated to intangible (i.e., qualitative aspects), and measurable (i.e., quantitative aspects) criteria; and (ii) is a generalist approach to considering the qualities of a public space – thus the intention is not to lead to concrete answers, but instead, to aid local designers and decision makers in considering general factors which are encapsulated by a 'successful' public space.

Resultantly, the aspect of 'Comfort' within the 'Place Diagram' was expanded to consider pedestrian thermal comfort aspects, including those concomitant to potential climate change; this 'new approach' thus consisted of looking to the future functioning/roles of public spaces, and moreover, beyond that of past and current functionality, or 'success'. When establishing the qualitative/quantitative criteria for the expanded 'Comfort' criterion, two predominant investigations were launched, the: (i) analysis of new qualitative criteria which considered the processes which pedestrians undergo to improve the fit between the environment and their thermal requirements; and, (ii) the assessment of quantitative criteria which raised deliberations upon local characteristics that require consideration/modification to address human thermal comfort.

When evaluating the qualitative criteria, it was acknowledged that there was a very strong association with the psychological and sociological perception of Humans to their surroundings. Although there exists a considerable lack of knowledge on how to approach such a subjective area of study, the concept of thermal acceptability was nevertheless identified as a crucial element for urban planning and design. In the scope of human thermal comfort in public space design, this may involve all process which people go through to improve the fit between the environment and their preferential requirements. For this reason, the six psychological factors disclosed by Nikolopoulou and Steemers (2003) were addressed, these being: (1) naturalness; (2) expectations; (3) past experience; (4) time of exposure; (5) perceived control; and, (6) environmental stimulation. In order to consider these factors in design terms, the six psychological factors were cross examined against the three sets of potential preferences defined by Erell, Pearlmutter et al. (2011) as the: Climatic Environment, Built Environment, and Human Environment. In practical terms for public space design, the result of this cross-examination was a three step process which identified how qualitative criteria could be influenced through a design-orientated approach. To test the validity of the three step approach in defining the qualitative criteria, the three layers were analysed against existing empirical studies that examined pedestrian behaviour and thermal comfort thresholds.

The result of this analysis was a simplification of the complex relationship between climatic dynamics, built form, and that of human perception. As an example, and in summary of the empirical studies, while referring to the built environment layer, one psychological aspect was the most common in influencing pedestrian behaviour. This aspect was perceived control, which permitted pedestrians to personify their stay within a given outdoor space. Also associated to the criterion of expectations, such a personification ranged from being able to choose where to sit, or simply whether to be located in the shade or sun. When addressing perceived control, there was also a direct impact upon the aspect of time of exposure within numerous identified case studies. Furthermore, the empirical studies also revealed that when the environments were considered to contain a certain degree of naturalness, thermal comfort thresholds also augmented. Such was particularly true given the presence of public space features such as vegetation and/or water bodies.

Within the human layer, the desired amount of environmental stimulation was very variable across all identified case studies as pedestrians: (i) demonstrate a high adaptability to their surroundings; and, (ii) accept conditions that would normally appear to lie outside of their Physiological Comfort Zone. Such results indicated that pedestrians are comfortable in a wide range of environments as they respond to various situations which lead them to have higher thermal comfort thresholds. Such a tendency was attributed to 'the adaptive approach' as initially described by Humphreys, Nicol et al. (2007).

This being said, and in order to successfully introduce interventions/measures within the built environment (or the 'Human Made Phase' according to the three step approach), quantitative aspects was also extrapolated. Six criteria were examined, these being: (1) local microclimatic data; (2) urban morphology; (3) greenery and amenities; (4) availability of choice; (5) surrounding context; and, (6) future climatic risk. In summary, it was identified that each of the six criteria could be assessed and/or measured by different means through bottom-up local field studies. Each of the factors was presented within a three tier system of characteristics which directly, or indirectly, influenced human thermal comfort, where: (1) Tier One – illustrated the respective six quantitative criteria; (2) Tier Two – showed the specific characteristics of each of the factors; and lastly, (3) Tier Three – demonstrated how such characteristics could be broken down further into exact measurable quantities/extents.

Resultant of such an integration of new qualitative and quantitative criteria when addressing ‘Comfort’ in public spaces, Publication 5 identified that existing approaches such as ‘Place Diagram’ must be modified in light of the opportunities presented in an era where the importance of climatic adaptation shall likely continue to propagate. Thus, the associated requirement of developing thermal sensitive recommendations at a design guideline level is one which shall accompany such an expansion. Invariably, and considering approaches such as the generic ‘Place Diagram’, although a ‘present’ public space may currently demonstrate ‘successful’ characteristics, without addressing human thermal comfort, such characteristics in the future may no longer be sufficient in sustaining public life and activity.

When considering the hypothesis of the research, within Section 2 ‘Examining existing measures and approaches to thermal sensitive public space design’ – it was correspondingly identified that:

- Similar to the global co-operative nature and the emergence of National Adaptation Strategies as described within Section 1, the same type of co-operation can also be directly beneficial for local design and decision making. Although situated in different locations, the identification of both existing measures and quantitative/qualitative approaches presented an excellent foundation in addressing how such lessons could be adapted into other locations

- Within Publication 4, and focused upon examining international case studies which addressed similar microclimatic constraints as those presented in Auckland, it was feasible to suggest more concrete local guidelines on how to tackle microclimatic issues. As a result, the practical experience from actual construction, convergent thinking through conceptual exploration, and outcomes of scientific methodologies could be presented within an online platform that could be accessed by local decision makers and designers. In addition, and to also avoid issues of ‘maladaptation’, a complementary section of ‘General Guidelines for Microclimatic Assessment’ was also recommended for the Auckland Design Manual

- In continuation from the previous point, previous local design guidelines such as the Auckland Design Manual had a very limited amount of case studies, which only partially discussed factors such as human thermal comfort. The invitation and reception of the ‘Built Environment Team’ within the Auckland council was promising evidence that regulatory bodies (and their associated non-regulatory entities) welcome a stronger union between urban climatology and that of public space design. Even if ‘just’ based upon an open ended framework of existing international ‘benchmarks’, in the eyes of non-climatic experts, it proved very useful in witnessing how the gap between theory and practice was already undertaken by others; and in addition, how others concretely overcame similar microclimatic risk factors through creative public space design

- The approach to thermal sensitive public space design should take into account both quantitative and qualitative factors. Such a relationship between these factors must be correctly balanced to effectively understand, and modify, human thermal comfort through public space design. Initially identified within Publication 4 as ‘the availability of choice’, before approaching a specific site study, a better grasp of such psychological aspects was also sought in Publication 5

- By expanding upon the aspect of ‘Comfort’ within the Project for Public Space’s ‘Place Diagram’, it was possible to deliberate how it could be modified to more effectively consider human thermal comfort aspects. In this way, it was possible to better ascertain: (i) the psychological (and in part sociological) processes pedestrians undergo to improve their integration within the built environment based upon their thermal requirements; and, (ii) the local characteristics (including their measurable quantities/extents) that necessitate consideration/modification to address local human thermal comfort thresholds

Section 3

Turning to the case of Lisbon, and within Section 3, both Publication 6 and Publication 7 examined how existing and future thermal comfort thresholds within a specific site could be approached through a bottom-up approach. It was at this stage of the thesis where concrete empirical results were generated from the union between urban climatological factors with that of public space design. Moreover and also guided by the outputs from the previous publications, this section was entirely based upon site visits and local meteorological measurements. Such results immediately, although in part, already presented promising indications of the validity of the research hypothesis.

More concretely, and within the case of Publication 6, the combination of considering thermo-physiological thresholds and psychological aspects permitted the wholesome comprehension of the site's meteorological risk factors, and how they could be potentially improved through public space design. Such an approach enabled bioclimatic public space recommendations to be established to address human thermal comfort levels, both at quantitative and qualitative levels. Such results were obtained by establishing two fundamental interrogations during the study: (1) What are the principal microclimatic risk factors within the square that can affect pedestrian thermal comfort thresholds?; and, (2) How can the identified risk factors be translated into opportunities for public space design?

Resultantly, and referring back to the identified need for further bottom-up and localised action for urban design and planning as initially discussed in Publication 2, the more encompassing objective of the study was to determine: (1) the lessons that could be extracted from a site which witnesses some of the highest T_{amb} values and UHI intensities within Lisbon; and, (2) how accessible and easy-to-use meteorological equipment and models/software could be subsequently utilised by urban design and planning professionals in similar subsequent studies and approaches.

As revealed within Publication 6, the utilisation of the Point of Interest (POI) enabled PET values to be obtained from average recorded measurements of V, T_{amb}, RH, G_{rad} and, T_{surf}. In addition, Pedestrian Based Response interviews were also undertaken to approach psychological (or quantitative/intangible) human thermal comfort aspects. Such identification of variables was based upon the outputs obtained from Publication 3 (where biometeorological approaches were identified), and Publication 5 (where both quantitative/qualitative aspects were identified). The placement of the POIs was based upon preliminary computer simulations (i.e., Computational Fluid Dynamic and Shadow Behaviour Simulation studies) to: (i) identify areas that were more prone to microclimatic risk factors; and, (ii) validate the simulation results against subsequent onsite measurements.

With regards to the Pedestrian Based Response results, it was discovered that the idiosyncrasy correlated to the human psyche of 'choice making', as previously deliberated within Publication 5, could be better comprehended, and moreover associated to the physical characteristics in and around the square. In addition, the second section of the Pedestrian Based Response also revealed robust correlations between physiological and psychological decision making, especially with regards to the pursuit of environmental stimulation and time of stay. Through the use of cognitive mapping, it was possible to identify that (and significantly dissimilar to the results obtained from singular climatic recordings of T_{amb}) pedestrians: (1) found the middle of the square to be the hottest area, and (2) considered the western region of the square to be one of the coolest regions.

When considering average PET from all site visits undertaken in July, when compared against the PS grades, it was identified that the hottest times of the day was predominantly around 15:00, resulting in 'Strong Heat Stress' predominantly in POIs with high Sky View Factor (SVF) values. Such locations were located within the centre of the square – namely in POI 3 and 4. Very interestingly, and even though recorded T_{amb} values in these locations were the lowest amongst all POIs, both PET and Pedestrian Based Response results revealed that these locations were the hottest in the square. Correspondingly, POI 1 and 5 which were located in the cooler zones, as identified by the Pedestrian Based Response, also revealed considerably lower PET values in all six POIs. Such outcomes revealed two paramount factors the: (1) effectiveness of the RayMan model, and its thermo-physiological PET/PS outputs: and, (2) notable capacity and sensitivity of pedestrians to evaluate the encircling microclimatic environment around them.

Finally, such a comprehension of local risk factors allowed the consideration of how public space interventions could attenuate the encircling microclimate in each of the identified four hottest POIs in the square. Such interventions were based upon some of the identified measures which were identified previously Publication 4, again suggesting the importance of learning, yet adapting, lessons taught by others. Between the four POIs, the following types of measure typologies were utilised: vegetation, shelter canopies, and water/misting systems. Each measure was carefully examined to obtain informed reduction estimations of thermo-physiological stress within each location through the use of RayMan model. It was at this stage of the thesis where creative public space design solutions could be directly unionised with climatic and biometeorological know-how to tackle local human thermal risk factors. Between the different measures, and particularly within the centre of the square, dramatic reductions of $16.6K_{PET}$ and $12.3K_{PET}$ were obtained in POI 3 and 4, respectively. Correspondingly, such reductions in PET led to reductions of 3 entire PS grades within areas that were initially the most susceptible to human thermal discomfort.

Encircling the approach that was initially discussed in Publication 3/5, the '*What if?*' agenda was utilised in Publication 7 to establish a pilot examination of how climate change scenarios could influence the site measurements undertaken in within Rossio in Publication 6. Focused upon predominantly a worse-case-scenario, the study identified potential risks upon human thermal comfort conditions within the square by the end of the century. Using the results obtained by Matzarakis and Amelung (2008) which was based upon variables obtained from the Climatic Research Unit 1.0 and the

HadCM3 datasets, the aggravations of existing thermo-physiological conditions (both with and without suggested public space interventions) were synoptically projected.

Focusing upon the $SRES_{A1FI}$ (or $RCP_{8.5}$) scenario, POI 3 and 4 revealed the largest oscillations in human thermal conditions due to their higher exposure to solar radiation. Within these two locations, the $\overline{PET\Delta_{\mathrm{A1FI}}}$ dataset revealed that the amelioration effects of the suggested public space design measures by the end of the century were significant. In fact, between 15:00-16:00, and within POI 3, this was particularly palpable when the $\overline{PET_{\mathrm{D3}}}$ dataset referring to current conditions (and without proposed public space design measures) actually surpassed $\overline{PET\Delta_{\mathrm{A1FI}}}$ by $7.0K_{PET}$. With regards to the $\overline{PET_{\mathrm{A1FI}}}$ dataset, which referred to conditions by the end of the century without public space design interventions, there was an alarmingly drastic increase of thermo-physiological stress levels. Such an increase was, again particularly associated to the centre of the square, which revealed potential PET values surpassing that of 56 ºC.

Moreover, and even when considering the coolest of the four hottest POIs identified in Publication 6, located on the western sidewalk and under the crown of a *Tipuana tipu*, the projected human thermal stress for the year 2100 in POI 5 was notably lower. Nevertheless, it was important to note that although witnessing much lower thermal stimuli then those found in the centre of the square, POI 5 within the $\overline{PET_{\mathrm{A1FI}}}$ dataset nevertheless revealed similar conditions to those found today within the centre of Rossio.

In order to go beyond identifying such results at each of the six initial POI, a hypothetical 5m x 5m grid network enabled PET and PS oscillations to be considered for the entire square. Furthermore, to aid projection precision, the grid facilitated a more concise: (i) consideration of shade cast upon pedestrianized zones as a result of street trees; (ii) contemplation of hotter T_{surf} around the square; and, (iii) definition of shade patterns cast by encircling structures, including those of urban amenities and building façades. In addition, and in liaison with the results from Publication 6, although rudimentary, such an approach allowed for a first synoptic thermal evaluation of the entire square under different scenarios; each grounded upon the local microclimatic lessons learnt from locations with similar characteristics. Within Publication 7, in order to approach PET values which considerably surpassed that of 41 ºC, and based upon a general increment of 5 ºC per threshold, the initial 'Extreme Heat Stress' was expanded by another three levels, until 'Extreme Heat Stress Lv.4' (PET > 56 ºC). Such an exercise was fundamental when considering the 2100 datasets which revealed dramatic augmentations of overall PS around the entire square.

Finally, the issue of periodicity was also very important when approaching human thermal comfort in the square. More specifically, and similarly in Publication 6, the datasets regarding current conditions (both with and without public space design interventions) were based upon the results from the hottest day of all site visits, i.e., Day 3 (D3). This being said, it was noted that although it was the hottest day, the maximum diurnal T_{amb} value was 32.9 ºC, which according to Miranda (2006) suggests that it fell just short of a 'Very Hot Day' (T_{amb} > 35 ºC), and remained within the respective 'Summer Day' classification (T_{amb} < 25 ºC).

Such an outcome suggested that: (i) the amount of thermal stimuli upon pedestrians can already be higher than those discussed in both Publication 6 and 7; but more seriously, (ii) even within a less grave $SRES_{A2}$ scenario, by 2100, days such as D3 could potentially increase up to 180 days a year. Regarding the latter point, it was thus fundamental to note that a $SRES_{A1FI}$/$RCP_{8.5}$ could not only lead to a higher amount of such days, but moreover, to the vulnerability of increased 'Very Hot Days' – further jeopardising the already concerning results and projections for Lisbon discussed in Section 3.

When considering the hypothesis of the research, within Section 3 'Addressing existing and future thermal comfort thresholds within the square of Rossio' – it was correspondingly identified that:

- When approaching a specific site, bottom-up approaches are not only able to identify human thermal comfort risk factors, but also, able to aid the generation of attenuation solutions for such risk factors through public space design. Such an exercise can, moreover, be undertaken through easy-to-use meteorological equipment, and moreover, with limited personnel. Based upon indicative initial site assessments POIs can be thereafter established in order to undertake local hourly cyclic evaluations of singular climatic variables

- The use of thermo-physiological indices such as PET is imperative to effectively quantify human thermal comfort levels through straight forward software models such as RayMan (Matzarakis and Rutz 2006, Matzarakis, Rutz et al. 2007, Matzarakis, Rutz et al. 2010) as it considers the human energy balance; and identifies the crucial influence of non-temperature variables such as radiation fluxes upon pedestrian thermo-physiology. On the other hand, and as identified by both PET and Pedestrian Based Response outputs, the sole reliance upon singular variables such as T_{amb} as an indicator of human thermal comfort can be extremely deceptive

- When addressing the Physiological Comfort Zone, it should be noted that although it provides an effective method to quantify thermo-physiological stress, it should also be considered that pedestrians avert microclimatic monotony. As a result, design solutions should also deliver a base of 'choice' that enables a range of thermal stimuli exposure

- Psychological aspects of thermal comfort can become a potent tool to aid design decisions. Elements such as delivering a base of 'choice' can be facilitated by also evaluating pedestrian cognitive mapping, evaluations of individual climatic stimuli, and registering basic information of their time of stay, activity and recent thermal history

- Within low Aspect Ratios, when considering design options for the centre of a canyon, the continuous susceptibility of elevated G_{rad} must be tackled due to reduced shading hours, which results in dramatic increases in other variables such as PET, T_{mrt}, and T_{surf}. On the other hand, when considering design options for the lateral areas of the canyon, addressing variations of G_{rad} is equally essential

- Resultant of the higher susceptibility to PS, and since canyons with lower Aspect Ratios often present higher activity threads in the lateral areas of the canyon, when accounting for central areas, public space design measures should therefore reinforce 'choice' both in terms of activity threads (such as seating), and of 'thermal personification' (such as provision of shaded and non-shaded areas)

- When reflecting upon vegetative shading, it should be noted that even at full maturity, individual trees do not lead to reductions of T_{amb}, nor to sequential increases of RH at pedestrian height. On the other hand, shading species such as *Tipuana tipu* provide sufficient biomass density to decrease SVF, attenuate G_{rad}, and ultimately reduce both T_{mrt} and PET. However, it is equally fundamental to approach shading as a means to increase 'choice' of climatic stimuli, and not to render a monotonous conditioned environment

- Following on from the previous point, the use of shelter canopies must also always consider annual variations of the canyon's thermal conditions, particularly in the case of permanent canopies. Nevertheless, at a design level, such ameliorations should always reinforce pedestrian thermal 'choice', again, both in terms of activity, and 'thermal personification', which are often lacking within the centre of canyons that present a low Aspect Ratio

- The application of water/misting systems within public space design for climates with hot and dry summers must be based upon the decision on whether Surface Wetting is desired or not. In addition, to avoid exacerbating atmospheric water content, numerous limitation mechanisms should be established, such as period of functionality, interval frequency, and activation during the correct encircling microclimatic conditions

- In <u>Publication 7</u>, both the importance, and limitations, of top-down approaches for urban planning and design were clearly acknowledged. On the one hand, and based upon the outputs of Global Circulation Models, it was possible to obtain indicative future estimations of PET until the end of the century. On the other hand, such outputs were only ascertained by complementing such top-down outputs with lacking information with variables such as short and long wave radiation which are often not present in climate records. As a result, this led to disconcerting discrepancies that are particularly relevant for human thermal comfort assessments

- Based upon the flexible '*What if?'* agenda it was possible to identify the implications that a PET increase of 10 ºC in Lisbon could have upon thermal comfort thresholds, both with and without the public space design interventions initially presented in <u>Publication 6</u> by the end of the century

- As revealed by the distributive PS analysis around the square, even existing diurnal and hourly PET datasets already revealed 'Extreme Heat Stress Lv.1/2' within certain areas of the square, hence indicating that existing thermal conditions already present significant risk during the summer. Moreover. such PS grades were identified during a day which, albeit by a small margin, did not reach the 'Very Hot Day' classification – thus it is very likely that PS upon pedestrians could be even higher in squares such as Rossio

- The augmentation of PET in the $SRES_{A1FI}/RCP_{8.5}$ scenario led to drastic increases in PS around the entire square. Particularly in the scenario where no public space design action was undertaken, most of the square presented a PS grade of 'Extreme Heat Stress Lv.3/4', resultant of PET values respectively reaching 51 ºC and 56 ºC

- Although public space design presented clear reductions of PS at the end of the century, they were still generally insufficient. Even with the suggested interventions, the lowest obtained PS grade was of 'Strong Heat Stress'. Such an outcome reveals that while the public space design solutions presented in Publication 6 may currently present very effective attenuations of current thermal risk factors, they should not, by any means, be considered adequate in ensuring a pleasant and comfortable environment under such a scenario by the end of the century

Section 4

Still enrooted within the case of Lisbon, and based upon the outputs from the previous sections, the final section of the research identified: (1) how climatic data from Lisbon's meteorological station could be utilised to inform 'in-situ' 'Thermal Attenuation Priorities' for thermal-sensitive public space design within Lisbon's historical quarter; and, (2) how a specific public space design measure could influence 'in-situ' human thermal comfort levels, both during the summer and winter. Opposingly to Section 3 which was based solely upon on-site measurements, both Publication 8 and 9 identified how data extracted from the meteorological station could also be used to approach local human thermal comfort thresholds. Furthermore, within the final section of the research, such an approach was undertaken within numerous default/idealised canyons with differing Aspect Ratios. Lastly, with the interest of testing/comparing new and improved indices/tools to assess thermo-physiological conditions, Section 4 also verified: (i) the greater accuracy of the modified PET (mPET) developed by Chen and Matzarakis (2017) in presenting enhanced estimations of thermal comfort conditions during periods of increased stimuli; and, (ii) the capacity of the updated SkyHelios model (Matzarakis and Matuschek 2011, Fröhlich 2017) to also address microclimatic variables such as *V*, resultant of the integration of a new three-dimensional diagnostic tool.

In Publication 8, and in order to evaluate Lisbon's bioclimatic risk factors and the resulting priorities for public space design, the study was divided into three segments, the: (1) monthly modifications of diurnal PET/PS fluctuations to obtain an overall comprehension of 2016, which served as a base to identify annual periods of cold and heat stress; (2) hourly oscillations for July between 2012 and 2016 to assess diurnal fluctuations over five years; and, (3) cross examination of such data against different default Aspect Ratios to consider concrete hourly 'Thermal Attenuation Priorities' for public space design within various morphological compositions. Within all segments, and with the interest of illustrating how such information could be easily communicated, and interpreted, the Climate-Tourism/Transfer-Information-Scheme (CTIS) (Matzarakis 2014) was utilised.

Within the first segment, and by determining PS/PET at 09:00, 12:00 and 15:00 from the meteorological station for every day of the year in 2016 through the use of the RayMan model, the annual progressive oscillation of thermal conditions in Lisbon was identified. In addition, monthly T_{mrt} averages corroborated such results, whereby: (i) 09:00 measurements constantly presented lower values throughout the entire year, particularly during December; and, (ii) although by a small margin, 15:00 measurements frequently presented lower values then at 12:00, with exception for the months of May, July and August.

In the second segment, and based upon the month of July, it was possible to evaluate: (i) bioclimatic variations of thermo-physiological conditions of each year between 2012-2016 based upon the hourly measurements; (ii) climatic events within each of the five years; and, (iii) averages of diurnal oscillation between 2012-2016. Through this exercise, it was also possible to ascertain numerous extreme heat events such as the occurrences of 'Very Hot Days', which took place extensively within the $|Jul_{2013}|$ dataset. Furthermore, the identification of 'Heat Waves Events' (a sequential set of days where maximum T_{amb} surpassed that of 32 ºC (Nogueira, Falcão et al. 2005)) it was possible to also assess such events during the five years. Between the 5 datasets, $|Jul_{2016}|$ revealed the highest frequency (equating to 3 events), and $|Jul_{2013}|$ revealed the longest event (lasting a total of 8 days).

Still within the second segment, using the PET results as a base for comparison, the analysis undertaken for the July datasets were repeated to examine if the mPET index would render the same type of results as those presented by Chen and Matzarakis (2017). Correspondingly, such an exercise permitted the study to verify that the modified index presented a more precise estimation of human thermal comfort, particularly during periods more accentuated stimuli. Such was evident by 'Extreme' heat stress levels being less frequent, particularly with regards to the second level of 'Extreme Heat Stress'. This surpassing was only obtained in the $|Jul_{2013}|$ and $|Jul_{2016}|$ datasets, yet for much shorter periods.

Within the third segment, and through the use of the Obstacle plugin within the RayMan model, based upon the Aspect Ratios most commonly found within Lisbon's historical quarter, different canyons were modelled stipulated upon the Height-to-Width (H/W) ratios of $H/W_{2.00}$, $H/W_{1.00}$, $H/W_{0.50}$, $H/W_{0.25}$ and $H/W_{0.17}$. Subsequently, each canyon was then processed through the SkyHelios model in order to determine the SVF at a specific location. In addition, for every Aspect Ratio, each canyon was categorised into a North-to-South-Orientation and a West-to-East-Orientation to evaluate the influence of the geo-referenced solar path upon their morphological composition. Finally, for both North-to-South-Orientation and West-to-East-Orientation, three single point SVFs were established to evaluate the amount and influence of solar radiation upon the lateral and central regions of the canyons. Focused upon the $|Jul_{2016}|$ dataset, and at this stage of the study, in addition to the climatic variables obtained from Lisbon's meteorological station, hourly G_{rad} values obtained from site measurements were also introduced into the RayMan model, along with the respective calculated SVF values. The results in this segment revealed that there was a wide range of oscillation in bioclimatic conditions within each SVF, Aspect Ratio, and orientation.

In addition to such identifications obtained for the West-to-East-Orientation and North-to-South-Orientation, and once again applying the flexible '*What if?*' agenda in Publication 7, a short parallel examination was undertaken to examine how such PS grades could vary if they were based upon hotter conditions. Thus far in the third segment of the study, the bioclimatic analysis of the different canyons was based upon averages obtained for the $|Jul_{2016}|$; for this reason, it was questioned how the identified thermal comfort conditions would vary if they were based upon the values retrieved from a particularly hot day in July. As a result, the diurnal results obtained for the 3rd of July were used. Moreover, and as the intention was to only sample the magnitudes of a worse-case-scenario, only the highest and lowest Aspect Ratios were examined. Two principal conclusions were extracted from this '*What if?*' exploration.

Firstly, it was possible to further corroborate the results of Chen and Matzarakis (2017) given the more evident disparity between PS grades between mPET and PET in circumstances of increased thermal stimuli. More concretely, and as a result of its more accurate human thermoregulation and clothing model, the mPET index revealed generally lower PS grades, and that it very rarely exceeded the 'Extreme Heat Stress' grade. On the other hand, and particularly in the case of central/eastern regions of the North-to-South-Orientation, and the northern/central regions of West-to-East-Orientation, PET values frequently reached the second level of 'Extreme Heat Stress' for up to six hours.

Secondly, the cause-and-effect relationship between the frequency/duration of 'Minutes in the Sun' and human thermal stress could be further understood. More precisely, during extreme heat events, even though 'Minutes in the Sun' generally led to higher thermal stress, once individual climatic variables reached a certain level, pedestrian thermal comfort even within the shade, may still be subjected to extreme PS. In the case of the 3rd of July, T_{amb} reached a notable maximum of 35.9 ºC (rendering it a 'Very Hot Day') at 15:00, with a low RH of 32.6% and *V* of 1.0 m/s. Such conditions clarify why even the mPET surpassed that of 'Extreme Heat Stress' at 15:00.

Within the final stage of the third segment of Publication 8, the 'Thermal Attenuation Priority' for public space design within the analysed canyons was constructed. Such a prioritisation was assembled upon translating the identified bioclimatic conditions into adaptations of the parameters developed by Charalampopoulos, Tsiros et al. (2016), i.e., the : (i) PET Load (PETL) which accounted for the quantitative amount of thermal stress beyond that of the stipulated 'comfortable' (m)PET value of 23.0 ºC; and, (ii) cumulative PETL (cPETL) which ascertained the cumulative sum of PETL during a stipulated period. The objective of the 'Thermal Attenuation Priority' was to establish the hourly PS load within the different morphological compositions, and the specific regions within them. As a result, five different priority levels were established based upon the amount of variation from the (m)PET value of 23 ºC which represented a PS of 'No Thermal Stress'. The increments were based upon establishing a constant variation of ± 4 ºC, allowing for the mPET results to be evenly distributed with some correspondence to the grades of PS as initially presented by Matzarakis (1997).

As revealed by the 'Thermal Attenuation Priority' analysis, it was verified that attenuation priorities for public space design varied significantly between the different canyons, and that all Aspect Ratios presented at least a high priority at some point of the day. Within the North-to-South-Orientation, as demonstrated by eastern region of the $H/W_{2.00}$, attenuation priority ranged from medium to high between the hours of 11:00 and 13:00. Such results indicate that even within high Aspect Ratios, thermal attenuation is still required. When considering the West-to-East-Orientation, priority levels were considerably lower, whereby out of all the default canyons, this was the only circumstance in which the West-to-East-Orientation priority levels were generally lower than those presented by the North-to-South-Orientation. This being said, within the $H/W_{1.00}$, priority levels increased dramatically, especially for the West-to-East-Orientation, where the central and northern regions revealed a medium to high 'Thermal Attenuation Priority' for most of the afternoon.

Between the lowest Aspect Ratios of $H/W_{0.25}$ and $H/W_{0.17}$, there was little variation of priority levels. However, and particularly in the case of the $H/W_{0.17}$, there were no periods of reduced 'Thermal Attenuation Priority' during the latter part of the day within the North-to-South-Orientation. It was however noted that between 17:00-18:00 and 09:00-10:00, there still were periods with a nil or low priority for thermal attenuation. Such a result can be attributed to the combination of early/late diurnal T_{amb} values, high RH levels, and the presence of shade as exemplified by the western and eastern regions of the North-to-South-Orientation canyons in the late afternoon and morning, respectively.

Within Publication 9, and in correlation with Publication 8, one specific type of public space design measure was examined to assess its 'in-situ' influence upon human thermal comfort thresholds within various default canyons. Based also upon climatic data obtained from the meteorological station, the influences of one of the most common species of shading tree in Lisbon (the *Tipuana tipu*) was assessed both during the summer and winter. As already stipulated, such an assessment included the use of the mPET index, and moreover, an updated version of the SkyHelios model. The decision to utilise such tools was not only to further test their validity, but moreover demonstrate their application within bottom-up approaches to local thermo-physiological thresholds.

As a result, and based upon the previously identified Aspect Ratios (or Urban-Canyon-Cases as referred to in Publication 9), each default Urban-Canyon-Case was assessed under two conditions: (i) without the presence of vegetation; and, (ii) with the presence of the *Tipuana tipu*. Once more, and within each Urban-Canyon-Case, three reference SVF points were stipulated in order to determine concrete variations between the central and lateral areas. Furthermore, both of these assessments were both undertaken during the winter and summer to identify how such 'in-situ' effects could render different effects upon pedestrians. In addition, and unlike in Publication 8 where *V* was 'assumed' to be a constant in each location; the new three-dimensional diagnostic wind model integrated within the updated SkyHelios model also permitted 'in-situ' estimations of *V* values to be obtained.

Once more, in addition to the climatic data retrieved from the station, G_{rad} values from site measurements were used to supplement the radiation flux assessments. Such an approach enabled hourly oscillation of G_{rad}: (i) in specific locations of the different Urban-Canyon-Cases; and, (ii) beneath vegetative canopies to identify the amount of radiation that was diluted by the vegetative crown biomass. Before this stage, and similar to the previous study, general bioclimatic conditions for the summer and winter periods were scrutinised based solely upon climatic data retrieved from the station (i.e., T_{amb}, RH, *V*, and Okt). Again through the use of RayMan model and CTIS software, such an assessment was undertaken for the months of July and December 2016. Once again, the 3rd of July was identified as the hottest day during examined summer period. For the winter month of December, the coldest identified day was the 16th.

Accordingly, for the canyon studies, both the 3rd of July and the 16th of December were selected to represent the hottest and coldest diurnal conditions. At this stage, and based upon the disclosed sources in the study, and within the 'Obstacle' plugin of the RayMan/SkyHelios models, it was possible to input the typical dimension of the *Tipuana tipu* (i.e., height, crown radius, trunk length, and trunk diameter), and then subsequently plot them into a linear configuration whilst ensuring a constant 'Vegetative Coverage Ratio' for the different canyons (i.e., $H/W_{2.00}$, $H/W_{1.00}$, $H/W_{0.50}$, and $H/W_{0.17}$). Finally the wind diagnostic tool was also calibrated so that original *V* values from the station could be processed entirely within SkyHelios for each location, and thus, rendering different values.

Once more, the CTIS software was used to communicate the results between the simulations with no vegetation (NV_{Sim}) against the simulations with the *Tipuana tipu* (TT_{Sim}). As anticipated, and similar to Publication 8, the Urban-Canyon-Cases with the least amount of thermal stress were $H/W_{2.00}$ and $H/W_{1.00}$ which both generally presented decreased periods/quantities of thermo-physiological stress.

With regards to the $H/W_{2.00}$ canyon, and during the 3rd of July: (1) within the North-to-South-Orientation – the presence of vegetation was able to reduce PS levels between 12:00-14:00 with a maximum mPET reduction at 14:00 of 6.8 ºC (obtained within the eastern point of the canyon); and, (2) within the West-to-East-Orientation – the presence of vegetation presented much more evident reductions of PS.

Considering the $H/W_{1.00}$ canyon and during the 3rd of July: (1) within the North-to-South-Orientation – PS levels increased both in stress intensity and duration, yet diurnal mPET results from the NV_{Sim} presented much higher PS grades; and, (2) within the West-to-East-Orientation – results obtained within the northern and central points of the canyon revealed the substantial influence of vegetative shade.

When considering the results for the $H/W_{0.50}$, and due to the increased width of the canyon, the higher susceptibility to solar radiation in both NV_{Sim} and TT_{Sim} lead to overall higher PS levels. During the 3rd of July: (1) within the North-to-South-Orientation – given the placement of the central point between the edges of two tree crowns within the TT_{Sim}, it witnessed similar PS grades between 12:00-14:00 to those obtained within the NV_{Sim}; and, (2) within the West-to-East-Orientation – similarly in the central point, while cast in the shade mPET values decreased by up 6.3 ºC as illustrated at 13:00.

The last Urban-Canyon-Case of $H/W_{0.17}$ revealed that within the NV_{Sim}, PS values often reached the second level of 'Extreme Heat Stress'. On the other hand, within all locations, the highest PS obtained by the TT_{Sim} was just below the 'Extreme Heat Stress' grade. When comparing the overall mPET results between the NV_{Sim} and TT_{Sim}, it was identified that the largest variation between PS took place between 16:00-17:00. During this hour, the highest variations took place within the West-to-East-Orientation, whereby a maximum mPET reduction of 11.6 ºC (corresponding to a PET of 15.6) was identified within the northern point of the canyon. During the 16^{th} of December, for the first time, PS levels revealed a noteworthy variation between the two assessments. Such was verified within the West-to-East-Orientation at the northern and central points between the hours of 12:00 and 15:00, where TT_{Sim} presented considerably lower PS as a result of the shade cast by the *Tipuana tipu* crown. Amongst the two, the northern point revealed the highest mPET reduction of 2.6 ºC (corresponding to a PET of 2.7 ºC). Such a result indicates the potential of vegetation to induce colder conditions due to obstruction of radiation fluxes during the winter.

Although Publication 9 also discussed concrete T_{mrt} results within the Urban-Canyon-Cases, an emphasis will be here made to the resulting *V* values obtained from the added three-dimensional wind tool within the new version of SkyHelios model. When considering the modifications of mPET/PS during December, it was possible to make direct associations between human thermal comfort conditions and the *V* values. When considering the North-to-South-Orientation canyons during December, the variations of PS between the reference points could be directly linked to the diurnal *V* variations between the different Urban-Canyon-Cases. Thus, it was possible to determine why almost all western points had PS slightly closer to 'comfortable conditions'. Furthermore, when considering the vacillation of *V* values between the NV_{Sim} and TT_{Sim}, it was identified that the estimated effects upon wind currents at pedestrian height were fairly insignificant. Such an outcome can be attributed to the output of wind simulations being set at a height of 1.1 m, falling well beneath the calibrated trunk height of 3.0 m.

When considering the hypothesis of the research, within Section 4 'Projecting thermal attenuation priorities and 'in-situ' impacts within idealised/default urban canyons' – it was correspondingly identified that:

- Overall, and based upon Lisbon's hot-summer Mediterranean climate, and particularly within its historical quarter which often witnesses the highest T_{amb} and UHI intensities in the city, thermal sensitive public space design is of very high priority. This urgency is particularly applicable to the summer period, where 'Thermal Attenuation Priority' can rapidly increase given the relatively frequent occurrences of 'Heat Wave Events' and 'Very Hot Days'

- Public space design must also consider that Lisbon's climate also leads to some degree of cold stress during winter, particularly during the morning period. For this reason, such proposals must consider their implications upon thermal comfort during periods in which microclimatic elements such as solar radiation

- The specification of various SVF reference points within the canyons themselves enabled a more wholesome understanding of local thermal comfort thresholds, and the associated priority for public space design interventions

- Even within higher Aspect Ratios such as $H/W_{1.00}$, considerable PS was identified for most of the day within the northern and central regions – while the southern regions revealed considerably lower PS when cast in the shade in the afternoon. Within medium Aspect Ratios, canyon orientation became a far more significant factor upon thermal stress. Moreover, it was established that Aspect Ratios down to $H/W_{0.50}$ presented a much higher 'Thermal Attenuation Priority' for public space design within West-to-East-Orientation canyons

- Within low Aspect Ratios, central regions presented a very high 'Thermal Attenuation Priority' for public space design, however, lateral regions also presented a high necessity for thermal attenuation. During various occasions, it was identified that such lateral regions presented close to, or even surpassed the stress thresholds found within central regions

- In nearly all analysed conditions, canyon locations with the generally lowest priority for thermal sensitive public space design were the western regions within the North-to-South-Orientation, and southern regions within the West-to-East-Orientation. Nevertheless, there still were specific times in which design measures would present significant attenuations of pedestrian thermal stress

- Generally, the hours which presented highest 'Thermal Attenuation Priority' ranged between the hours of 12:00-15:00. However, and based upon the stipulation of actual locations and Aspect Ratios, such priorities varied as a result of the relationships of the solar path with the morphological composition of the different canyons

- Within Publication 9, and following the 'Thermal Attenuation Priority' study, the potential 'in-situ' thermo-physiological influences of the *Tipuana tipu* species were examined within the various Aspect Ratios/'Urban-Canyon-Cases'. As well as examining the positive influences during the summer, the negative impacts during the winter were also obtained due to the particular species maintaining its foliage during the colder months of the year. Furthermore, such influences could be directly attributed to specific Aspect Ratios/'Urban-Canyon-Cases', concrete locations, and during specific hours of the day

- Within both Publication 8 and 9, the disparity of thermal conditions between those presented by the meteorological station, and those obtained from the 'in-situ' assessments within each of the Aspect Ratios/'Urban-Canyon-Cases' were substantial. On the other hand, both publications presented a methodical means in which to adapt such results into more useful know-how for local thermal sensitive public space design

- When addressing such a translation of information for local public space design, it was also possible to test, and verify, how new adaptations of the existing PET index and the SkyHelios model can render further useful/precise outputs for local design and decision making. Likewise, and again in both publications, beyond presenting bioclimatic results, the facilitation of the transversal comprehension of such outcomes for non-climatic experts was equally important. For this reason, and through the use of the CTIS software, the data from the meteorological station and obtained G_{rad} values could be translated into easily interpretable figures, which moreover, were based upon the common measuring unit of ºC

- In continuation from the previous points, the bottom-up concept of 'locality' was embraced by using local morphological characteristics to inform, and refine, climatic data into urban design and planning considerations. As suggested by the results in Publication 8 and 9, when approaching public space design solutions, their overall bioclimatic success depends upon their correct implementation, which inarguably, includes their insertion within the correct locations of a specified canyon

Concluding Overview

Instituted by the established research hypothesis, and based upon the outputs/data presented by the publications enclosed in this thesis – condensed in bullet-points, each respective publication validated that:

1. Within the state-of-the-art, there still needs to be a better integration of thermo-physiological indices to guide more wholesome local interdisciplinary climatic evaluations of public space design

2. Although top-down approaches present an imperative understanding of the existing/future global climatic system, urban planning and design shall continually depend more upon bottom-up assessments to accurately identify local risk factors

3. Serving as a catalyst, the emergence of the climate change adaptation agenda has enforced the presence of existing know-how and the importance in strengthening the relationship between public space design with that of urban climatology

4. Open ended frameworks of existing 'benchmarks' to similar climatic conditions proved to be very useful in the eyes of local non-climatic experts in facilitating the launch of their own respective strategies and measures to similar thermal risk factors

5. Approaching human comfort thresholds through public space design must take into account both quantitative and qualitative aspects when evaluating its long-term success in an era moreover vulnerable to future aggravations of the global climatic system

6. It was possible to both identify human thermal comfort risk factors in Rossio-Lisbon, and in addition, aid the generation of attenuation solutions through public space design through on-site assessments undertaken with easy-to-use equipment/software

7. Through the use of the '*What if?*' agenda, it was possible to test the implications of numerous climatic scenarios within Rossio-Lisbon by the end of the century, although synoptic, it provided an important insight into potential future thermo-physiological conditions

8. Based mostly upon Lisbon's meteorological station data, 'Thermal Attenuation Priorities' for public space design could be constructed to determine 'in-situ' physiological stress within common default canyons, and their interior regions, during specific hours

9. Using data from the meteorological station, the potential 'in-situ' influences of the common *Tipuana tipu* shading tree, which thrives upon the climatic conditions found in Lisbon, were identified within the default canyons, and their interior regions during both the summer and winter

Future Work

Instigated by the ensuing theme of this thesis, beyond those identified within the corresponding publications, further research could also be undertaken to:

- Consider how public space design can attenuate human thermal comfort thresholds in colder climates, where physiological cold stress levels are investigated in more depth

- Develop the intrinsic association between quantitative and qualitative aspects of human thermal comfort within public spaces

- Mature the scientific equilibrium between that of simulation and measurement of climatic variables, and in addition, their associated validation procedures[1]

- Evaluate how warning systems of extreme climatic events during periods of higher annual stress can be further integrated within public spaces design

[1] With regards to this bullet point - Please refer to Appendix of the document to consult an additional accepted Publication beyond the discussed scope of the doctoral thesis

Acronym List

CPETL	cumulative PETL	POI	Point of Interest
CTIS	Climate-Tourism/Transfer-Information-Scheme	PS	Physiological Stress
H/W	Height-to-Width Ratio	RCP	Representative Concentration Pathways
IPCC	Intergovernmental Panel on Climate Change	RH	Relative Humidity
mPET	modified PET	SRES	Special Report on Emission Scenarios
NV_{Sim}	No Vegetation Simulation	SVF	Sky View Factor
PET	Physiologically Equivalent Temperature	TT_{Sim}	Tipuana tipu Simulation
PETL	PET Load		

Symbol List

G_{rad}	Global radiation	T_{surf}	Surface temperature
T_{amb}	Ambient temperature	V	Wind Speed
T_{mrt}	Mean radiant temperature	$XK_{\#}$	Temperature difference of X variable

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Appendix

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Beyond singular climatic variables – Identifying the dynamics of wholesome thermo-physiological factors for existing/future human thermal comfort during hot dry Mediterranean summers

A. Santos Nouri, Ioannis Charalampopoulos, A. Matzarakis

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Article

Beyond Singular Climatic Variables—Identifying the Dynamics of Wholesome Thermo-Physiological Factors for Existing/Future Human Thermal Comfort during Hot Dry Mediterranean Summers

Andre Santos Nouri [1,*], Ioannis Charalampopoulos [2] and Andreas Matzarakis [3,4]

1 University of Lisbon, Faculty of Architecture, CIAUD—Research Centre for Architecture, Urbanism and Design, Rua Sá Nogeuira, Pólo Universitário do Alto da Ajuda, 1349-063 Lisbon, Portugal
2 Laboratory of General and Agricultural Meteorology, Agricultural University of Athens, 118 55 Athens, Greece; icharalamp@aua.gr
3 Research Centre Human Biometeorology, German Meteorological Service, D-79104 Freiburg, Germany; Andreas.Matzarakis@dwd.de
4 Chair of Environmental Meteorology, Faculty of Environment and Natural Resources, Albert-Ludwigs-University, D-79085 Freiburg, Germany
* Correspondence: andrenouri@fa.ulisboa.pt; Tel.: +351-919-247-292

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Abstract: Centered on hot dry Mediterranean summer climates, this study assesses the climatic data that was extracted from Lisbon's meteorological station between the years of 2012 and 2016. Focused on the summer period, existing outdoor human thermal comfort levels that are already prone to extreme heat stress thresholds were evaluated. Such an assessment was rooted around identifying the relationship and discrepancies between singular climatic variables (e.g., air Temperature (T_a)); and adapted thermos-physiological indices (e.g., the modified physiologically equivalent temperature (mPET)), which also consider the influence of radiation fluxes over the human body. In addition, default urban canyon case studies (UCCs) were utilized to supplement how both differ and influence one another, especially under extreme weather conditions including heat waves events (HWE), and very hot days (VHD). Through the use of wholesome thermo-physiological indices, the study revealed that while human health and thermal comfort is already prone to extreme physiological stress (PS) grades during one of the hottest months of the year, the current extremes could be drastically surpassed by the end of the century. Within the examined UCCs, it was identified that the projected PET could reach values of 58.3 °C under a projected climate change RCP8.5/SRES A1FI scenario. Similarly, and in terms of thermo-physiological stress loads, the following could happen: (i) a future "cooler summer day" could present similar conditions to those currently found during a 'typical summer day; (ii) a future 'typical summer day' could present hourly physiological equivalent temperature load (PETL) that recurrently surpassed those currently found during a "very hot day"; and, (iii) a future "very hot day" could reveal severe hourly PETL values that reached 35.1 units beyond the established "no thermal stress" class.

Keywords: human thermal comfort; physiologically equivalent temperature; urban canyon cases; climate change; Mediterranean climate

1. Introduction

Within the international arena, the effects of climate change are continually becoming a pressing issue for human health and comfort within consolidated urban environments. During 2018, the occurrence of copious extreme climatic events within the Northern hemisphere was accompanied by topical research suggesting that these climatic manifestations would both continue, and increase, during the next four years [1]. Similarly, the recorded global average air temperature for 2017 rendered it the third warmest year in the National Oceanic and Atmospheric Administration's 138-year climate record, behind 2016 and 2015 successively [2]. Furthermore, it was argued that for 2017, (i) there was clear evidence of human influence on summer air temperature, both in the overall recordings, and in the heatwave labelled as "Lucifer"; and, (ii) the effects of climate change made the summer of 2017 at least ten times more likely in comparison to the early 1900's effects [3].

Previously in 2003, and in the case of Western Europe, it became clear that European countries, including Portugal, required additional measures to caution, manage, and diminish recurrences of these events [4–7]. More specifically for the case of Lisbon, between 29 July and 13 August 2003, the following was identified by Nogueira et al. [8]: (i) 15 days had a maximum recorded air temperature (T_a) above 32 °C; (ii) there was a noteworthy consecutive run of 10 ten days with a maximum recorded T_a above 32 °C; (iii) there was a five day period that consecutively recorded T_a values above 35 °C. In association, the research also identified that, as a result of this particular summer period, there was a serious impact on public health, whereby the estimated mortality rate increased by 37.7% (i.e., corresponding to 1316 excess deaths) in comparison to standard/expected figures.

Based on the risk factors associated with human thermo-physiological conditions, interdisciplinary practices including that of urban climatology and biometeorology are also striving to understand how local bottom-up assessments of outdoor environments can lead to a comprehension of both existing and future threats to human thermal comfort thresholds [9–22]. Considering these thresholds, and as reinforced by numerous recent studies [7,23–25], the human thermo-physiological perception of thermal conditions exceeds that of solely T_a, and conglomerates with numerous other imperative climatic variables. Within these studies, it was demonstrated that to effectively evaluate the influence of the thermal environment on individuals, it was necessary to use thermal indices centered on the energy balance of the human body [26]. Of the numerous existing indices, the physiologically equivalent temperature (PET) [9,27] (based on the Munich energy-balance model for individuals (MEMI) [28,29]) is one of the most widely used steady-state models in bioclimatic studies [30].

Regardless of frequent political attritions and future uncertainty, which are concomitant with the topic of climate change, outputs from climatic top-down assessments have thus far identified that global T_a will likely continue to increase throughout the 21st century, and that there will moreover be changes in global humidity, wind speed, and cloud cover. Nevertheless, scientific dissemination like the reports presented by the Intergovernmental Panel on Climate Change have frequently described the effect of weather with a simpler index based on amalgamations of T_a and relative humidity (RH). Although it is inarguable that those disseminations have significantly propelled the maturing top-down climate change adaptation agenda, when considering bottom-up approaches to climatic vulnerability, the exclusion of vital meteorological factors (i.e., radiation fluxes, wind speed (henceforth expressed as V), and human thermo-physiological factors) have arguably diminished the relevance and applicability of the results for local action and decision making [31,32].

Subsequently, the assessments of human thermal comfort conditions need to accompany the growing responsibility for local scales also to tackle the "the high-frequency and microscale climatic phenomena created within the anthropogenic environment of the city" [33] (p. 126). Nevertheless, and as identified by numerous studies [22,24,34,35], the scientific community has already recognized a weakness in the studies that examine local approaches to human thermal comfort thresholds within Mediterranean climates. Similarly, the number of studies that consider the important effects (and possible mitigation efforts) of urban heat islands (UHI) upon local thermal conditions (including for Mediterranean climates) have also grown within the international scientific community (e.g., [36–46]).

To this end, and based on contributing towards methodical means to assess local human health and thermal comfort conditions in climates with hot dry Mediterranean summers, this study examined the following: (i) the relationship between singular climatic variables and thermo-physiological indices;

(ii) impact of selected urban morphological compositions on local thermo-physiological indices to identify the crucial role of radiation fluxes, which are intrinsic to the urban energy balance [47]; (iii) synoptic aggravations of current local human thermal risk factors given the occurrence of a potential worst-case-scenario of climate change; and lastly, (iv) intensity and periodicity between current conditions and those projected for the end of the century were cross-examined.

2. Materials and Methods

2.1. Site

Located on the western coast of Portugal at 38°42′ N and 9°08′ W, the capital city of Lisbon witnesses a climatic Köppen Geiger (KG) classification of '*Csa*' (hot-mediterranean climate), entailing its vulnerability to hot dry Mediterranean summers [48]. As described by Miranda [49] and Calheiros [50], Lisbon presents the following: (i) between 10 and 20 "very hot days" (VHD), where the maximum recorded T_a surpass 35 °C; (ii) a range between 100 and 120 "typical summer days", where the maximum recorded T_a surpassed that of 25 °C; and finally, (iii) repeated heat wave events (HWE), where T_a consecutively surpass that of 32 °C throughout numerous days. In addition to these factors, the study is based on Lisbon's historical quarter "Baixa Chiado", which, due to its morphological composition, often experiences the highest UHI intensities [51] and temperatures during the summer [52].

2.2. Data

To acquire the data required for the study, meteorological recordings were obtained from the World Meteorological Organization (WMO) weather station located in Lisbon, with the index N°08535. Similar to numerous studies [17,32,35,53–56], the retrieved information was then processed through the RayMan Pro© model (RayMan Pro, Research Center Human Biometeorology; Freiburg, Germany; http://www.urbanclimate.net/rayman/) [57–59] to determine the PET index [9], and the recently modified PET (mPET) index [60].

Based on the MEMI model [28,29], the decision for utilizing PET was because of the following: (i) calibration on easily obtainable microclimatic characteristics; and (ii) usage of °C as the measuring unit to assess thermal comfort, which in turn, facilitates other professionals to more effectively comprehend and approach urban climatological aspects. In addition, and according to the study conducted by Matzarakis [17], the outputs could subsequently be compared to different grades of human thermal perception and physiological stress (PS), as shown in Table 1.

Table 1. Ranges of the physiologically equivalent temperature (PET) for different grades of thermal perception and physiological stress (PS) on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo, according to the authors of [10] (source: adapted from the authors of [61]).

PET	Thermal Perception	Physiological Stress
<4 °C	Very Cold	Extreme Cold
4~8	Cold	Strong Cold
8~13	Cool	Moderate Cold
13~18	Slightly Cool	Slight Cold
18~23	Comfortable	No Thermal Stress
23~29	Slightly Warm	Slight Heat
29~35	Warm	Moderate Heat
35~41	Hot	Strong Heat
>41	Very Hot	Extreme Heat

With regards to the mPET index, and in accordance with Chen and Matzarakis [60], the major differences from the original index are the following: (1) an integrated multiple-segment thermoregulation model; and (2) a clothing model that provides a more accurate analysis of the human bio-heat transfer mechanism. Accordingly, and in comparison to the simpler two-node body model of the PET index, the body model of the mPET index can more efficiently identify heat transfer between the inner body and outer body. Within the specified study that considered bioclimatic conditions in Freiburg during the summer period, the following was verified: (i) when comparing the results against the PS grades, unlike PET outcomes, almost no "extreme heat stress" periods were presented; and, (ii) overall, the probability of comfortable thermal conditions (i.e., of "no thermal stress") was higher with the application of the mPET index. In line with these outputs, analogous results were also obtained by the authors of [22,23,62], particularly during periods of more accentuated thermal stimuli.

With regards to singular climatic variables, the following hourly data was collected between the hours of 09:00 and 18:00 from the specified meteorological station: total cloud octas, T_a, RH, and lastly, V. When approaching the latter, once the values of V were translated into m/s, a further modification was undertaken to account for the type of urban typology discussed by the study. As presented by Oliveira, Andrade, and Vaz [41], when approaching speeds beneath the urban canopy layer, and within the streets themselves, V values are considerably slower than those presented by the meteorological station. Consequently, to determine the actual V, which directly influence the gravity center of the human body, as specified by Kuttler [63]; the results from the meteorological station were adapted to a height of 1.1 m (henceforth expressed as $V_{1.1}$). Similarly to the studies conducted by the authors of [19,22,23], the formula presented in the literature [63,64] was used (Equation (1)), as follows:

$$V_{1.1} = V_h^* \left(\frac{1.1}{h}\right)^{\alpha} \qquad \alpha = 0.12^* z_0 + 0.18 \tag{1}$$

where V_h is the m/s at the height of h (10 m); α is an empirical exponent, depending on urban surface roughness; and Z_0 (m) is the corresponding roughness length.

Comparable to the morphological layout within the study of Algeciras and Matzarakis [19] in Barcelona, and moreover, identical to Nouri, Costa, and Matzarakis [22], and Nouri, Fröhlich, Silva, and Matzarakis [23] who also undertook their study in Lisbon's historical center, the variables of Z_0 and α were calibrated to 1.0 and 0.35, respectively. In addition to these climatological aspects, the calibration of the RayMan model was based on the default standing "standardized man" (equating to a height of 1.75 m, a weight of 75 kg, the age of 35, a heat transfer of clothing (clo) of 0.90, and an internal heat production of 80 watts) [9,27].

2.3. Applied Methodology and Structure

The undertaken study was divided into four sequential stages to evaluate the relationship between the singular climatic variables and the thermo-physiological factors of human comfort in an era of potential climate change. Throughout the majority of the study, and in order to facilitate the reading and interpretation of the data, (i) heatmaps were prepared through the use of R language scripts, enabling the climatic data to be displayed through the combination of raster and contour maps assembled by the ggplot2 R language package (ggplot2, Houston, TX, USA, https://ggplot2.tidyverse.org/) [65], and, (ii) the climate tourism/transfer information scheme (CTIS) model (Research Center Human Biometeorology; Freiburg, Germany; http://www.urbanclimate.net/climtour/mainframe_tools_ctis.htm) [66,67] used in similar climatic studies [16,22,54,55,68–70].

- Within the first section, and launching the study, the four singular climatic variables for the month of July were assessed. The analysis was carried out between the years 2012 and 2016, to determine the yearly trends and hourly oscillations during the mid-summer period. Once undertaken, the RayMan model was subsequently utilized to obtain both the PET and mPET values, thus enabling the identification of PS thresholds (Table 1).
- Considering the data obtained for 2016, the second section of the study examined three different days during July, based on their overall diurnal climatic conditions. The data was then translated

into urban canyon cases (UCCs) to evaluate how existing climatic conditions could vary amongst the different selected urban morphological compositions and their interior regions.

- Within the third section, referring to the data obtained for each UCC, and considering the worst-case-scenarios of climate change, the synoptic projections of human thermal conditions for the end of the century were evaluated. Although indicative, the exercise permitted the study to obtain an initial reflection on how current conditions within different UCCs could modify until the end of the century.
- Lastly, through an optimal benchmark of human thermal comfort, additional adaptations of the base PET index were utilized to compare both the intensity and periodicity of the thermal stress. As a result, both the present and synoptic projections of future thermal environments could be evaluated against one another.

2.3.1. Variable Oscillation for July

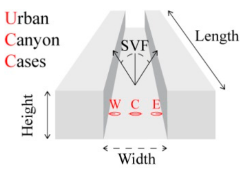
In this section, the four singular variables (Octas, T_a, RH, and $V_{1.1}$), which were retrieved from Lisbon's meteorological station for the month of July were collected, investigated, and presented through the ggplot2 R language package and CTIS model. With the interest of attaining a more comprehensive understanding of July's climatic conditions, and to moreover account for annual variations, a total of five datasets were processed (i.e., $|Jul_{2012}|$, $|Jul_{2013}|$, $|Jul_{2014}|$, $|Jul_{2015}|$, $|Jul_{2016}|$) for each variable. In the case of T_a, and referring to the specifications of Miranda [49] and Calheiros [50], it was possible to identify the occurrence of extreme weather occurrences, including VHDs and HWEs, and moreover, inspect how the other three variables interplayed during the events. In addition, as each variable was recorded every hour between 09:00 and 18:00, the outputs presented gradual or abrupt diurnal oscillations, which revealed the hours where certain variables tended to be higher or lower.

To obtain the PET and mPET indices, the four singular variables were processed through RayMan for each dataset. Within ggplot2 and CTIS, the grades illustrated in Table 1 were used to associate each specific value to a PS classification, as stipulated by Matzarakis, Mayer, and Iziomon [61]. Moreover, as with the presentation of the singular variables, the periods in which the meteorological station underwent calibration (CAL.) were also acknowledged.

2.3.2. Configuring the UCC Assessments

Considering the general morphological composition within Lisbon's historical quarter, known for its accentuated susceptibility to thermal stimuli during the summer, namely to UHI [51] and elevated T_a [52], a canyon height of 20 m remained as the constant physical variable. Contrariwise, and centered on some of the most common street/canyon widths [22], this variable was set to vary between 10, 20, and 80 m. Finally, and although the canyon length is unrelated to the height-to-width (H/W) ratio, each canyon was configured to a length of 200 m, to ensure that the "edges" of the canyon would not influence the obtained results. Consequently, and through "Obstacle Plugin" within the RayMan model, three UCCs were configured with varying height-to-width (H/W) ratios (Table 2).

Table 2. Representation and description of utilized default canyons and their respective height (H), width (W), and length (L). UCC—urban canyon cases.



H/W Ratio	Canyon Height (m)	Canyon Width (m)	Canyon Length (m)	Description (UCC)
2.00	20	10	200	$UCC_{2.00}$
1.00	20	20	200	$UCC_{1.00}$
0.25	20	80	200	$UCC_{0.25}$

At this point in the study, the applied sky-view-factor (SVF) was set equal to 1.00 (or 100%), which correlated to a total absence of urban obstacles or structures. Referring to the earlier study of Lin, et al. [71], the calculation of SVF was based on a classic single-point SVF (or SVF_{SP}) within a fixed point, so as to obtain a "fisheye view", with a calibrated height of 1.1m (which is complacent with the gravity centre of the human body as described by Kuttler [63]). As shown in Figure 1, each fixed point (henceforth reference point (RP)) within the UCCs was tested within the SkyHelios model (Research Center Human Biometeorology; Freiburg, Germany; http://www.urbanclimate.net/skyhelios/) [72,73], to identify the SVF_{SP} at each RP. Such a methodology was already utilized by numerous other studies ([23,54,69] for symmetrical canyons, and [55,74] for asymmetrical canyons). Within this study, and referring to the predominant symmetry that is characteristic of Lisbon's historical quarter, all of the modelled UCCs were symmetrically constructed. In addition, only the north-to-south orientation was modelled, as this was sufficient to assess how urban structures could lead to different human thermal comfort conditions by evaluating the influence of the geo-referenced sun path upon the morphological composition of each UCC.

As illustrated in Table 2 and Figure 1A, three SVF_{SP} were distributed throughout each canyon, in order to identify the thermo-physiological conditions within their different areas (i.e., Western RP (RP_W), Central RP (RP_C), and Eastern RP (RP_E)). Within the lateral points, $RP_{W/E}$ was adjusted 3 m away from the building façade to typify a pedestrian sidewalk area within the UCCs (Figure 1B). In the case of the central regions, RP_C was centered precisely within the middle of the UCCs (Figure 1C).

Through the application of the RayMan and SkyHelios models, Figure 1D represents the geo-referenced sun paths of three selected days (Table 3), these being the following: (1) 3 July, which was identified as a VHD because of the maximum registered T_a surpassing 35.0 °C, with generally low $V_{1.1}$ and Octas; (2) 8 July, which was identified as a "typical summer day", with T_a averaging at 29.4 °C, in addition to typical RH, $V_{1.1}$ and Octas values for the summer period; lastly, (3) 12 July, which represented a "cooler summer day", where the maximum T_a did not reach the 'typical summer day' threshold (25.0 °C), and $V_{1.1}$ was particularly elevated throughout the day, with a mean of 4.1 m/s. As to be expected, as these three days were not far apart from another, their sun paths did not vary much from one another.

Table 3. Maximum, mean, and minimum values for singular climatic variables retrieved from Lisbon's meteorological station (N°08535) for 3, 8, and 12 July 2016. RH—relative humidity.

Day	T_a			RH			$V_{1.1}$			Total Clo. Cover		
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
		(°C)			(%)			(m/s)			(Octas)	
3 July 2016	35.9	32.0	26.4	58.6	41.8	32.6	2.6	1.7	1.6	0.0	0.0	0.0
8 July 2016	32.1	29.4	25.9	41.7	29.3	21.4	3.6	2.6	1.6	1.0	0.4	0.0
12 July 2016	24.5	23.2	24.5	50.8	42.0	37.0	5.2	4.1	3.1	1.0	1.0	1.0

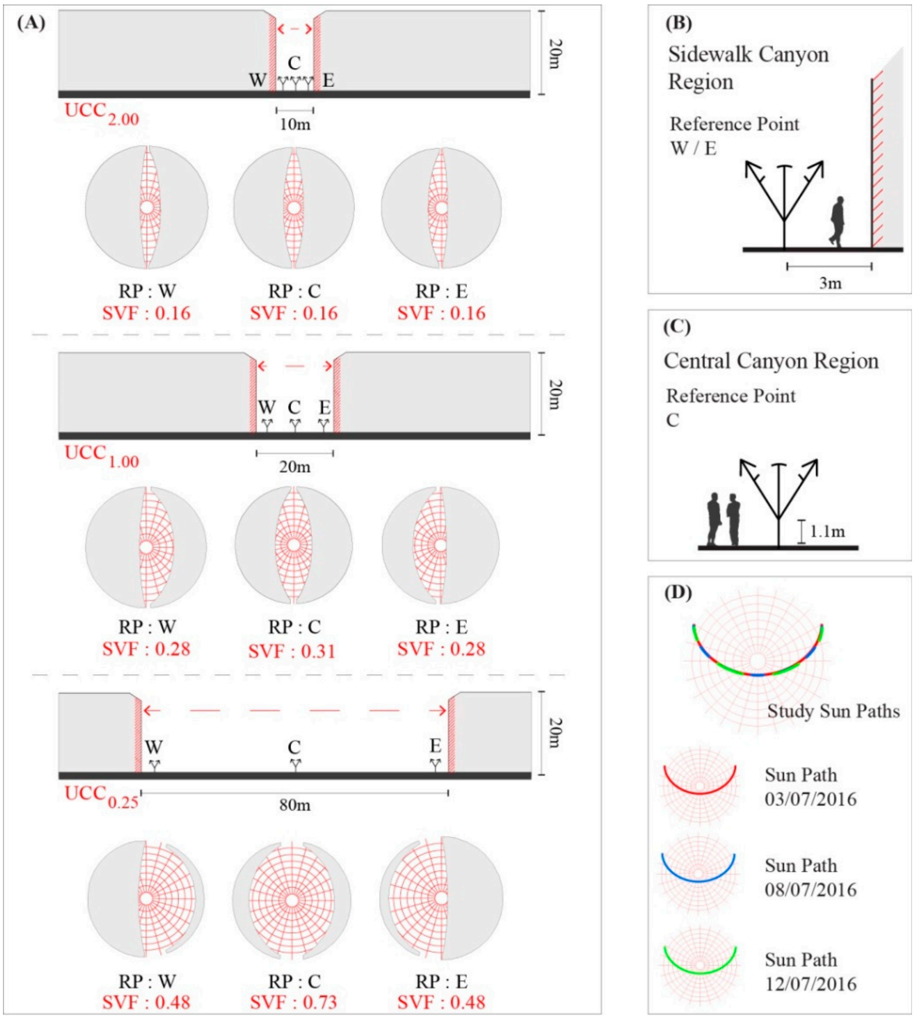


Figure 1. (**A**) The layout of the sky-view-factor (SVF) in each reference point (RP) within the three configured urban canyon cases (UCC). (**B**) Illustration of West or East RP in each UCC. (**C**) Illustration of Central RP in each UCC. (**D**) Illustration of Sun Paths for 3, 8, and 12 July 2016.

2.3.3. Establishing Synoptic Climate Change Aggravations

In order to construct a synoptic evaluation of how the identified climatological and bioclimatic conditions could be aggravated until the end of the century, the thermo-physiological projections specified by Matzarakis and Amelung [31] were applied. The projections were based on singular climatic variables (T_a, RH, V, and mean monthly sunshine fraction values) obtained from the Climatic Research Unit 1.0 and the HadCM3 datasets. Once obtained, the variables were processed within the RayMan model to obtain the PET and mean radiant temperature (T_{mrt}) values for each specific grid. Lastly, this process was also undertaken for the historical period 1961–1990, to establish the respective deviation of PET/T_{mrt} for the end of the century (i.e., CNTRL (or Control) period). The analysis was undertaken by referring to the Special Report of Emission Scenario (SRES) [75] of A1FI, which equated to the fastest and most dramatic effects of global climate change. More recently, this scenario would now equate to the Representative Concentration Pathway (RCP) [76] of 8.5, now comparable to the previous worst-case-scenario of A1FI [77].

Under the examined scenario, Matzarakis and Amelung [31] identified that specifically for the Mediterranean region, the PET values revealed considerable increases (including excesses of 15.0 °C) by the end of the century. These values sharply diverged from the estimated increase of up to 4.0 °C, under the same worst-case-scenario by the Intergovernmental Panel on Climate Change [78]. More concretely for the case of Lisbon, the projected augmentation of PET varied approximately between +10 °C and +12.5 °C. Based on these values and referring to the "what if?" approach discussed/applied by the authors of [22,25,79,80], a synoptic estimation of potential local climatic and bioclimatic territorial impacts on human health and comfort was thus permitted.

Centered on the augmentation of +10 °C in PET by the end of the century to establish a pilot estimation of future thermo-physiological conditions, it was also required to consider the extension of the original PS grades as delineated by Matzarakis and Rutz [57] (Table 1).

As shown in Table 4, three additional 'Extreme Heat Stress' grades were added based on an incremental PET increase of 5 °C beyond the value of 41 °C. Naturally, this extension raises the opportunity for future study and refinement, including how the related levels of stress could more concretely strain the human biometeorological system. This being said, the variation and distribution of thermo-physiological indices, and their respective calibration against stress levels have already been launched within numerous studies [14,16,20,22,25,56,81,82].

Table 4. Applied grade extension of physiological stress (PS) on human beings to accompany increased physiologically equivalent temperature (PET) values beyond 41 °C for RCP 8.5/SRES A1FI scenario until the end of the century (See Table 1). Adapted from the authors of [61]. *—additional grade.

PET	Physiological Stress	PS Acronym
...	...	-
8~13	Moderate Cold	MCS
13~18	Slight Cold	SCS
18~23	No Thermal Stress	NTS
23~29	Slight Heat	SHS
29~35	Moderate Heat	MHS
35~41	Strong Heat	SHS
41~46	Extreme Heat Lv.1	EHS1
46~51	Extreme Heat Lv.2 *	EHS2
51~56	Extreme Heat Lv.3 *	EHS3
56~61	Extreme Heat Lv.4 *	EHS4

2.3.4. Identifying Overall Thermo-Physiological Loads and Cumulative Stress

Estimating the average thermal stimuli per hour using different thermal indices has become the standard method to present thermal comfort conditions within a specific place and time, yet, as argued by Charalampopoulos, Tsiros, Chronopoulou-Sereli, and Matzarakis [20], "there is a need, however, to consider the total thermal load caused by the attendance of a person in an open space during a specific time period (...) More specifically, to approach the real effect of the environmental configuration of an open urban space on human health and comfort, the cumulative heat stress caused by each open space configuration should be considered" (p. 1). Guided by their methodology, the PET load (PETL) and the cumulative PETL (cPETL) were applied to the results obtained from the previous sections in this study, whereby (i) PETL refers to the outcome difference from the optimum thermal conditions, permitting the identification of a concrete value, which denotes explicitly the amount of thermal strain on "optimum thermal conditions" (Equation (2)); and, (ii) cPETL accounts for the cumulative sum of the PETL specifically during a predetermined set of hours (Equation (3)). Similarly adapted by Nouri, Costa, and Matzarakis [22], the following equations were utilised for this section:

$$\mathrm{PETL} = \mathrm{PET}h - BC \tag{2}$$

where PETh is the average hourly PET value, and BC (i.e., background conditions) in this section was set to denote the maximum PET for the PS grade of "no thermal stress" (i.e., a PET of 23 °C).

$$M\mathrm{cPETL} = \sum_{h=9}^{12} \mathrm{PETL} \qquad A\mathrm{cPETL} = \sum_{h=13}^{18} \mathrm{PETL} \qquad D\mathrm{cPETL} = \sum_{h=9}^{18} \mathrm{PETL} \tag{3}$$

where $M \triangleq$ is the morning period (09:00–12:00), $A \triangleq$ is the afternoon period (13:00–18:00), and $D \triangleq$ is the diurnal period (09:00–18:00).

Considering the thermal comfort conditions presented within one of the UCCs, PETL was utilized to summarize conditions within a specific urban morphological setting for the three different types of days extracted from the $|Jul_{2016}|$ dataset. In addition, and through the "what if?" approach, the assessment was compared against the results in light of the potential increase in PET values in light of the RCP 8.5/SRES A1FI scenario by the end of the century. Lastly, and returning to the thermal comfort conditions processed directly from the meteorological station, cPETL was considered for the entire $|Jul_{2016}|$ data set in order to obtain an overall comprehension of both the intensity and periodicity of thermo-physiological stress loads for both existing and projected future conditions.

3. Results and Discussion

3.1. July Datasets

3.1.1. Singular Variable Heatmaps

When considering the singular climatic results obtained from the meteorological station for the $|Jul_{2012}|$, $|Jul_{2013}|$, $|Jul_{2014}|$, $|Jul_{2015}|$, and $|Jul_{2016}|$ datasets, it was possible to identify the following: (i) the overall monthly variance of the different climatic variables for the month of July for 2012 through to 2016; (ii) the diurnal oscillation of variables throughout the month, permitting the identification of climatic events, including HWE and VHD; and (iii) the hourly oscillation of the variables between the hours of 09:00 and 18:00.

As shown in Figure 2, when reviewing the T_a results, it was possible to identify substantial differences between the datasets. Comparatively between the five, $|Jul_{2014}|$ and $|Jul_{2015}|$ were the datasets with generally lower T_a values. On the other hand, $|Jul_{2013}|$ and $|Jul_{2016}|$ were the datasets with the highest values, with frequent extreme climate events, including an eight-day HWE, which was also accompanied by a sequential four VHD in $|Jul_{2013}|$. In the case of $|Jul_{2016}|$, although shorter, three separate HWE were identified throughout the month, accompanied by four VHD. Moreover, as the values were recorded hourly, it was possible also to ascertain that even within the "cooler" datasets, the hours between 12:00 and 15:00 still witnessed elevated T_a values, namely during the short HWE during 11 and 12 July in the $|Jul_{2014}|$ dataset.

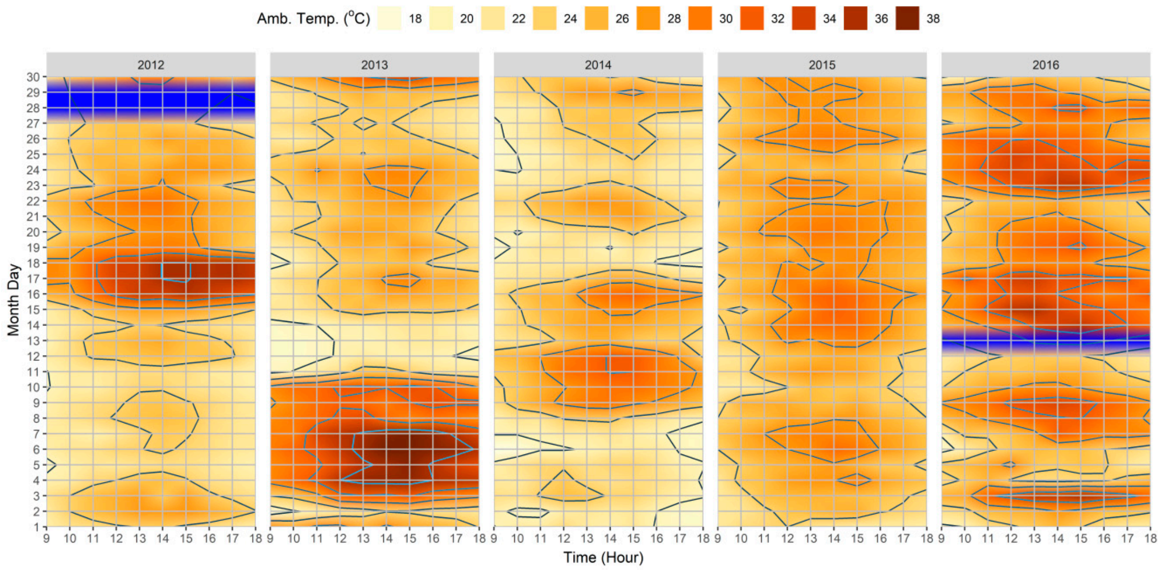


Figure 2. Heatmap of hourly variations of air temperature (T_a) between 09:00–18:00 for 2012–2016 extracted from Lisbon's meteorological station (N°08535). The blue color corresponds to the station calibration (CAL.) periods.

Unlike the T_a results, and as shown in Figure 3, $V_{1.1}$ tended to indicate stronger hourly oscillations because of its intrinsic higher rate of fluctuation [83]. That being said, it was possible to identify general trends amongst the datasets. Particularly in the case of ∣Jul_{2013}∣ and ∣Jul_{2014}∣, where diurnal $V_{1.1}$ was generally lower, the morning period tended to reveal lower speeds in comparison to those registered for the later part of afternoon period. With regards to higher $V_{1.1}$ values, both the beginning of the ∣Jul_{2012}∣ dataset and end of the ∣Jul_{2015}∣ dataset presented the longest periods of higher speeds. Nevertheless, it was identified amongst the datasets that there were also short periods (i.e., frequently between two and three days), which revealed higher $V_{1.1}$ values. To a certain degree, during these short periods, it was possible to verify the corresponding decreases in T_a as exemplified by the following: (i) 17th–19th and 23rd–24th in the ∣Jul_{2014}∣ dataset; and (ii) 1st–2nd, 10th–12th, and the 21st–22nd in the ∣Jul_{2012}∣ dataset. On the other hand, the days/hours with particularly high T_a values often presented lower $V_{1.1}$ values as exemplified by the following: (i) 16th–18th in the ∣Jul_{2012}∣ dataset; (ii) 30th–31st in the ∣Jul_{2013}∣ dataset; and (iii) 13th–15th in the ∣Jul_{2015}∣ dataset. It was noted however that the correlation between the two variables did not always take place, as exemplified by higher $V_{1.1}$ values during the afternoon period during the identified VHD/HWE in the ∣Jul_{2013}∣ dataset.

When considering the outcomes shown in Figures 4 and 5, it was possible to identify correlations between Octas and RH, and moreover, with the other variables. In general, when higher Octas values were registered by the meteorological station, the RH tended to be correspondingly higher, as exemplified by the following: (i) 3rd–4th in the ∣Jul_{2012}∣ dataset; (ii) 11th–14th in the ∣Jul_{2013}∣ dataset; (iii) 6th/18th/31st in the ∣Jul_{2014}∣ dataset; (iv) 1st/4th/9th/24th in the ∣Jul_{2015}∣ dataset; and (iv) 4th–7th in the ∣Jul_{2016}∣ dataset. Furthermore, and considering relationships with other variables such as T_a, and as exemplified by the VHD/HWE in the ∣Jul_{2013}∣ dataset, the higher air temperature was complemented with the days with low Octas/RH. Similarly, and still within the same dataset, just after these days with a very high air temperature a drop in T_a between the 11th–14th of the month was accompanied by increases of both Octas and RH; correspondingly, and although for shorter periods, similar correlations were also particularly discernable throughout the ∣Jul_{2016}∣ dataset.

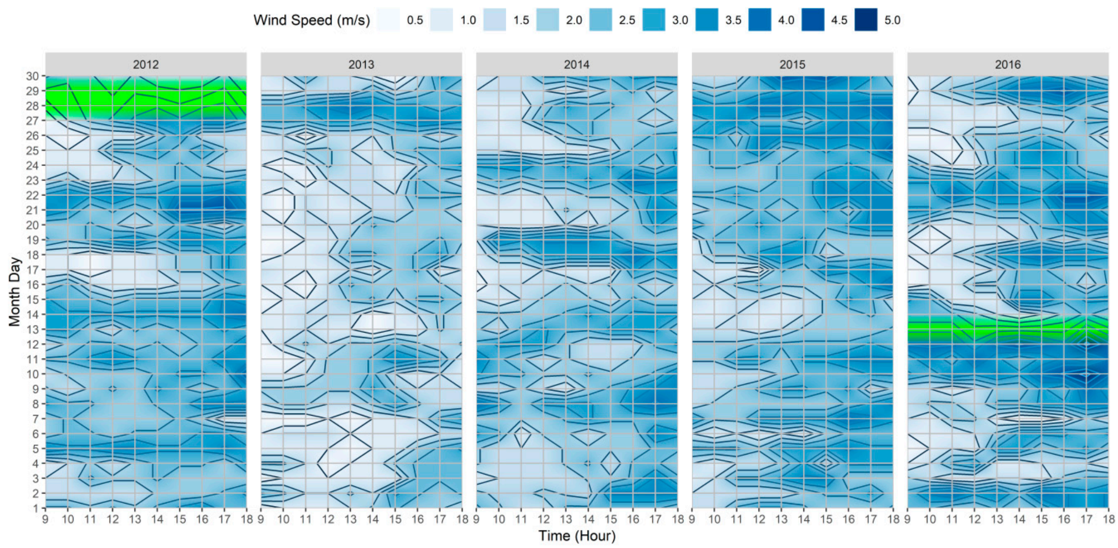


Figure 3. Heatmap of hourly variations of $V_{1.1}$ between 09:00–18:00 for 2012–2016 extracted from Lisbon's meteorological station (N°08535). The green color corresponds to the station CAL. periods.

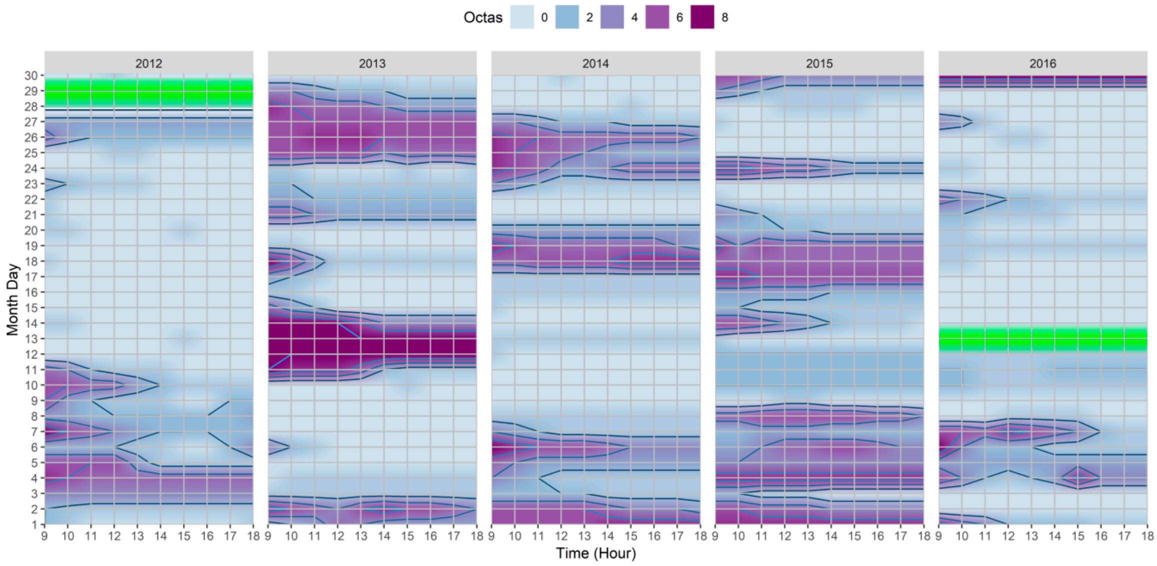


Figure 4. Heatmap of hourly variations of Octas between 09:00–18:00 for 2012–2016 extracted from Lisbon's meteorological station (N°08535). The green color corresponds to the station CAL. periods.

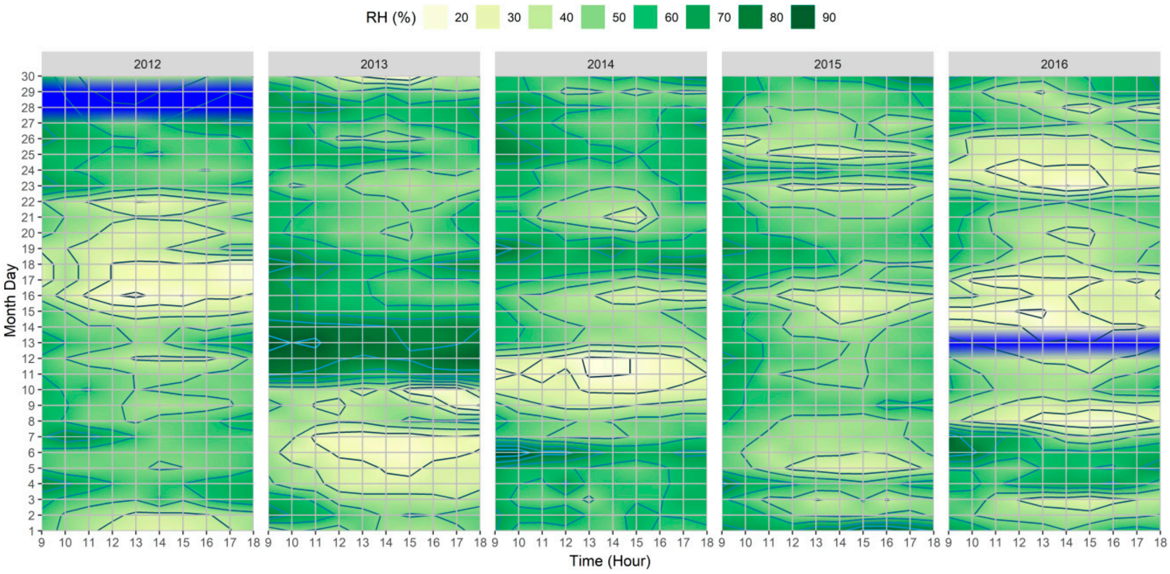


Figure 5. Heatmap of hourly variations of relative humidity (RH) between 09:00–18:00 for 2012–2016 extracted from Lisbon's meteorological station (N°08535). The blue color corresponds to the station CAL. periods.

3.1.2. Thermo-Physiological Heatmaps

Often within the previous section, it was possible to identify correlations between the singular variables within the different datasets. However, it was also identified that these correlations were not always clear, and usually took place when a specific variable was particularly high, including high T_a values during VHD/HWE. As a result, when approaching the human thermal comfort thresholds, a single unit that considers the interactions of all of the singular variables becomes essential. Consequently, the thermo-physiological indices of PET and mPET were processed in this section so as to obtain a wholesome understanding of how the amalgamation of variables could influence the human thermal comfort thresholds.

As presented in Figure 6, the PET results illustrate how a wholesome understanding can be obtained through the combination of all of the variables through the use of the RayMan model. As already stated, the reason for using PET was because of its calibration being dependent on easily accessible data, and moreover, it's measuring unit being based on °C. As demonstrated throughout the datasets, the utilization of PET permitted a more straightforward assessment of thermal comfort conditions. In addition, and by reviewing the PS grades as presented in Tables 1 and 4, it was possible to determine the hourly thermal stress grades on the human biometeorological system.

Between all of the individual climatic variables, the T_a results presented the most significant similarity to the thermo-physiological indices. Nevertheless, as the influence of other variables was not reflected, T_a alone was far less efficient to provide a complete evaluation of human thermal comfort conditions, as exemplified by the following: (1) continuation of higher thermal stress when T_a values decreased after the VHD/HWE in the $|Jul_{2012}|$ dataset, likely attributable to the permanency of low Octas values until the 26th; (2) high PET values during the VHD/HWE in the $|Jul_{2013}|$ dataset, which beyond high T_a values, can be also attributed to low $V_{1.1}$, Octas, and RH values between the 3rd–8th; (3) the lower PET values between the 11th–14th in the $|Jul_{2013}|$ dataset, which beyond lower T_a values, can also be interlinked to particularly high Octas and RH values for those days; (4) occurrence of some mild cold stress (i.e., PET < 22 °C) in the morning and late afternoon as demonstrated within the $|Jul_{2014}|$ dataset which can be associated to lower T_a and higher RH and $V_{1.1}$ values; and (5) resulting influences of days with both lower T_a and higher $V_{1.1}$ values on thermal comfort conditions which were particularly salient within the $|Jul_{2016}|$ dataset.

When considering the results presented in Figure 7, it was possible to identify that the adapted index presented similar outcomes to those presented by (i) the original study conducted by Chen and Matzarakis [60] for the city of Freiburg; (ii) the study undertaken by Lin, Yang, Chen, and Matzarakis [62] for the hot and humid conditions in Taiwan; and, (iii) the study elaborated by Nouri, Costa, and Matzarakis [22], which was also undertaken for the downtown district of Lisbon. More specifically, and particularly during the periods of higher thermal stimuli on the human body, it was verified that mPET revealed no periods that surpassed the "extreme heat stress" grade. The identified difference was particularly noteworthy between 12:00–16:00 on the 4th–7th within the $|Jul_{2013}|$ dataset, where the maximum presented PS grade was of "extreme heat stress", unlike PET, which reached the second level of "extreme heat stress" for the same period. In addition, it was also possible to determine that the mPET index also revealed a higher tendency to present values within the "No thermal stress" grade, both in the circumstances of cold stress (e.g., during the morning and late afternoon of the $|Jul_{2013}|$ and $|Jul_{2014}|$ datasets) and heat stress (e.g., during the afternoon in all datasets).

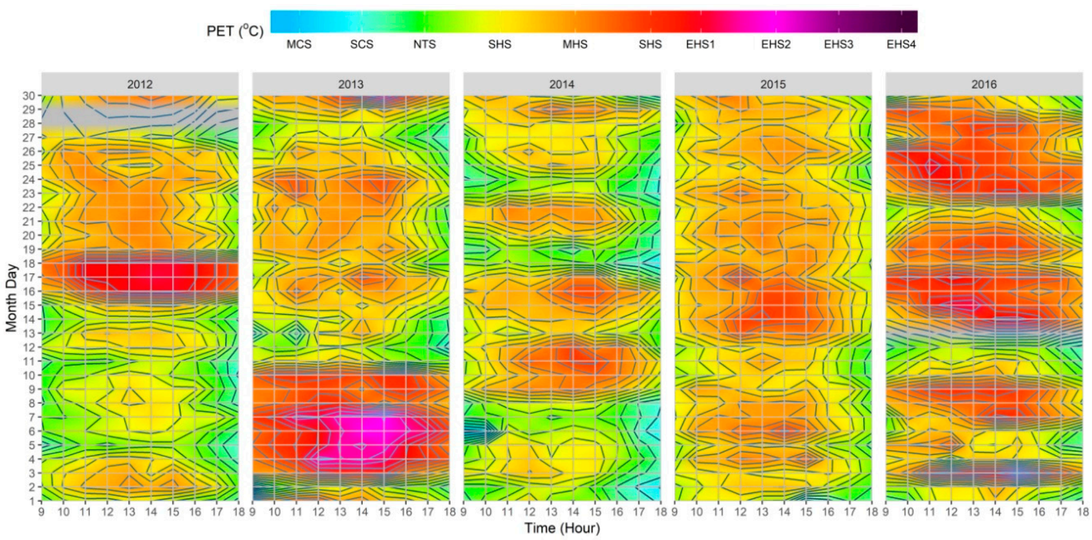


Figure 6. Heatmap of hourly variations of physiological stress (PS) grades based on physiologically equivalent temperature (PET) values between 09:00–18:00 for 2012–2016, based on the fusion of singular climatic variables extracted from Lisbon's meteorological station (N°08535). The grey color corresponds to the station CAL. Periods.

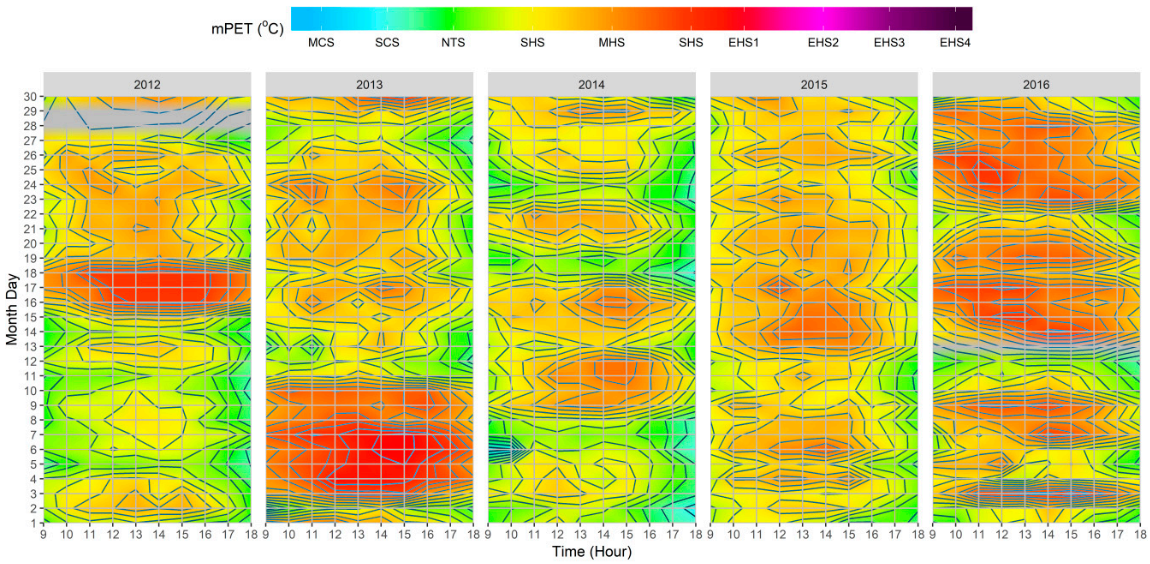


Figure 7. Heatmap of hourly variations of physiological stress (PS) grades based on modified physiologically equivalent temperature (mPET) values between 09:00–18:00 for 2012–2016, based on the fusion of singular climatic variables extracted from Lisbon's meteorological station (N°08535). The grey color corresponds to the station CAL. periods.

3.2. Urban Canyon Case Datasets

So far, within the existing literature, the crucial role of urban morphology (i.e., the width, height, and orientation of urban canyons) on thermal comfort conditions within the built environment has been well documented [22,23,54,55,69,70,74,84,85]. Therefore, and within this section, the UCCs were utilized to identify how different morphological compositions present different thermal comfort conditions from those presented by the meteorological station during three different types of days retrieved from the ∣Jul_{2016}∣ dataset. Analogously, both the PET and mPET results were also presented for comparative purposes within the three RPs for each UCC.

3.2.1. "Cooler Summer Day"—12 July

When considering the results for 12 July, which was a comparatively cooler day due to the comparatively elevated diurnal $V_{1.1}$ (with a mean of 4.1 m/s) and lower T_a (with a mean of 23.2 °C) (Table 3), it was possible to identify that the PS levels ranged predominantly between "slight cold stress" and "slight heat stress" (Figure 8). As expected, between the three UCCs, the case that presented the lowest amount of PS was $UCC_{2.00}$, because of its lower canyon width that reduced its exposure to radiation fluxes. On the other hand, $UCC_{0.25}$ revealed slightly higher PS levels as a result of its higher susceptibility to radiation fluxes, given its higher SVF_{SP}, which ranged between 0.48 and 0.78 (Figure 1) for the lateral and central RPs. Furthermore, it was also noted that in each UCCs, all of the three RPs within the canyons presented different PS grades to those presented by the meteorological station, particularly at 09:00 and 17:00–18:00, where PS were slightly lower than those identified by the station. In contrast, and with an exception of RP_E, all of the other RPs within the three UCCs presented either a continuation or amplification of PS grades obtained by the meteorological station at 12:00.

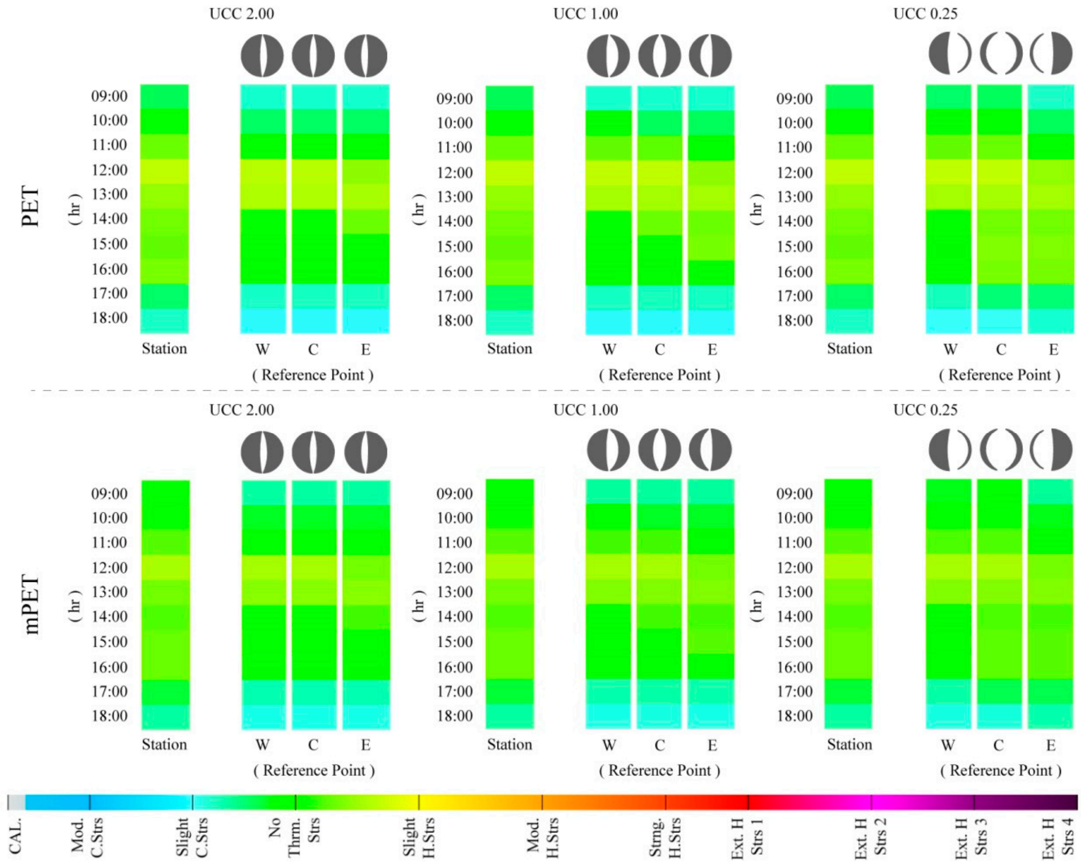


Figure 8. Hourly variations of physiological stress (PS) grades based on physiologically equivalent temperature (PET) and modified physiologically equivalent temperature (mPET) values between 09:00–18:00 for 12 July 2016 within the urban canyons cases (UCCs).

When comparing the mPET results for 12 July, it was identified that the modified index did not present significant divergences from PET. Nonetheless, it was again possible to verify that the mPET index tended to remain closer to the "no thermal stress" grade, particularly when the PET index tended to either oscillate to either "slight cold stress" or "slight heat stress".

3.2.2. "Typical Summer Day"—8 July

Centered on the classification of a "typical summer day", the results for 8 July presented fairly different results to those obtained for 12 July. As demonstrated in Figure 9, it was possible to identify that in the case of PET, the PS levels frequently reached "strong heat stress" during the afternoon. Furthermore, unlike the previous assessment, 12 July led to greater disparities between the PS results presented by the meteorological station and those within the UCCs. The divergence was particularly perceptible within $UCC_{2.00}$ and $UCC_{1.00}$ during the morning period (i.e., between 09:00 and 11:00), where PS tended to vary an entire grade (equating to PET variance of ~6.0 °C). Generally, the hours between 12:00 and 15:00 were the hours with the highest PS grades, which, in the case of the PET index, reached "strong heat stress". Conversely, in the case of $UCC_{0.25}RP_W$ and $UCC_{0.25}RP_C$, the PS grades were more similar with those presented by the meteorological station, where the morning stress grades were closer to the "moderate heat stress" grade. The reason for this can be attributed to the increased width of the $UCC_{0.25}$, thus presenting a greater vulnerability to radiation fluxes, with the exception of $UCC_{0.25}RP_E$, which was cast in the shade during the morning period. It was additionally identified that, similar to 12 July, the PS grades within the UCCs were almost always lower than those presented by the meteorological station. This variance ultimately relays to the attenuating influence of urban morphology on local human thermal comfort conditions.

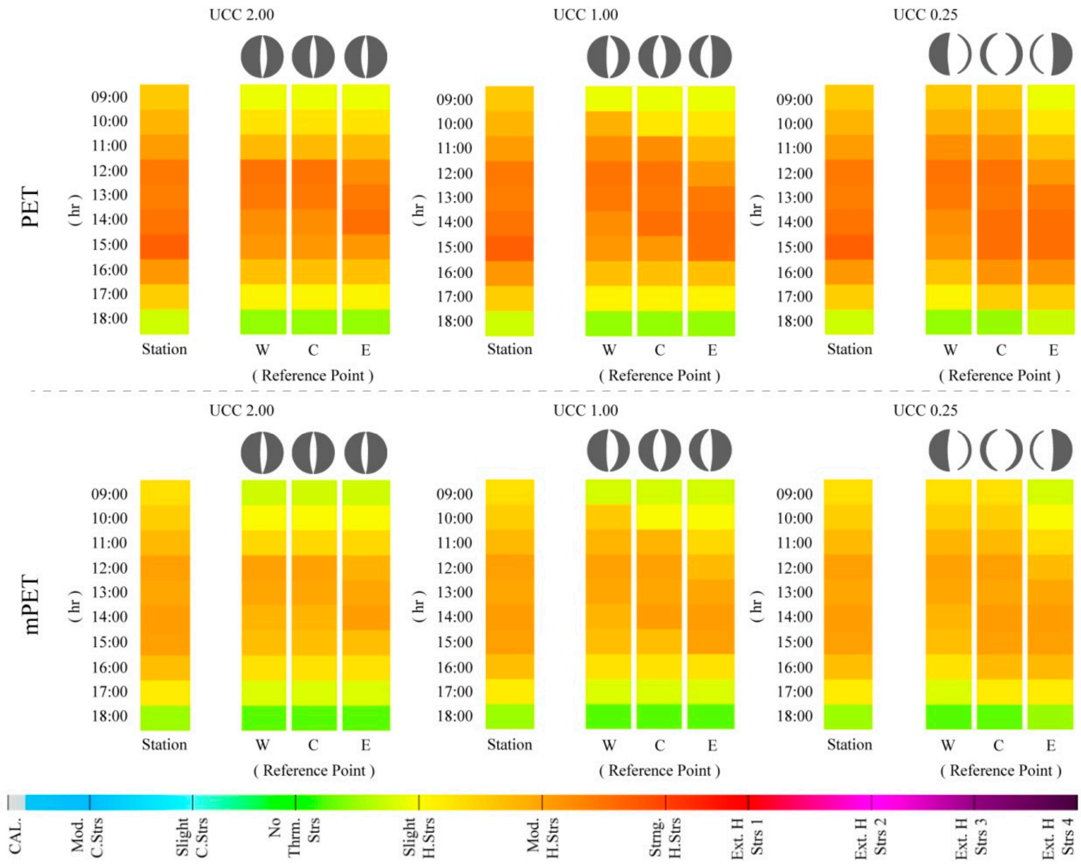


Figure 9. Hourly variations of physiological stress (PS) grades based on physiologically equivalent temperature (PET) and modified physiologically equivalent temperature (mPET) values between 09:00–18:00 for 8 July 2016 within the urban canyons cases (UCCs).

With regards to the mPET index, a greater variation from the PET results was manifested, especially during the afternoon, where PET reached a PS grade of "strong heat stress". During this period, mPET frequently revealed a PS of "moderate heat stress". At 09:00, mPET also revealed PS grades that were closer to "no thermal stress" in comparison to those revealed by PET.

3.2.3. "Very Hot Summer Day" (VHD)—3 July

In the case of the hottest day (i.e., a VHD) within the $|Jul_{2013}|$ dataset, 3 July revealed the strongest variations between the results obtained for the UCCs, and those from the meteorological station (Figure 10). In addition, it was the first circumstance in which the UCCs presented a higher PS grade to those presented by the station, as exemplified at 15:00 in $UCC_{1.00}RP_E$, $UCC_{0.25}RP_C$, and $UCC_{0.25}RP_E$. These variations did not only take place within wider UCCs, where canyon widths permitted the RPs to obtain higher SVF_{SP} values, as shown in Figure 1. Similar divergences were also observed in $UCC_{2.00}RP_W$ and $UCC_{2.00}RP_C$ at 12:00, where the PS grades surpassed the first grade of "extreme heat stress". During 12:00 and 13:00, both of these locations were exposed to the sun before being cast in the shade at 14:00, which led to a slight reduction of PS. At 15:00, and although still cast in the shade, climatic conditions (RH = 32.6%, $V_{1.1}$ = 1.0 m/s, Octas = 0.00, and T_a = 35.9 °C) led the PS grades to increase once more. Although also illustrated on 8 July, the results for 3 July presented larger alterations in the PS grades between the different RPs in each UCC. More specifically, and between 11:00 and 15:00, the PS grades frequently varied by up to one entire grade, which can be attributed to the variation of radiation exposure within the assessed canyons. As the processed climatic variables were identical for the UCCs, the RPs and meteorological station, the influence of non-temperature variables such as radiation fluxes proved to be a critical factor for assessing the in situ human thermal comfort conditions.

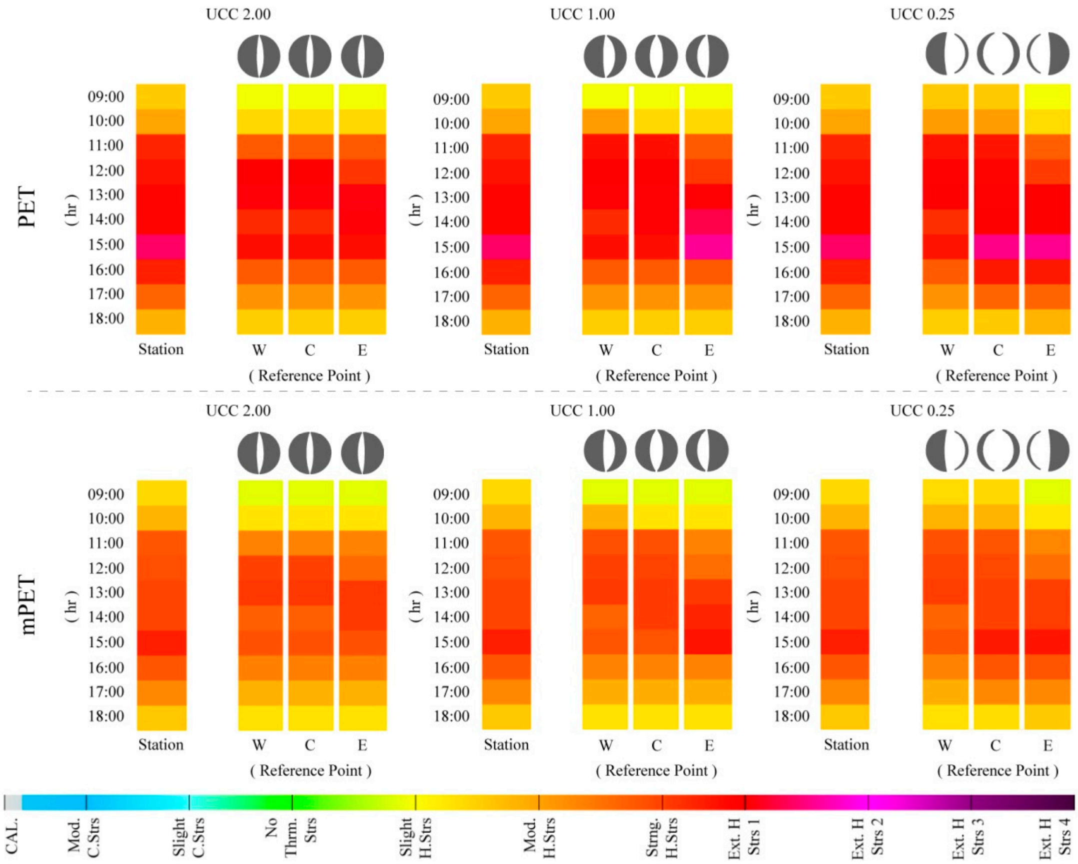


Figure 10. Hourly variations of physiological stress (PS) grades based on physiologically equivalent temperature (PET) and modified physiologically equivalent temperature (mPET) values between 09:00–18:00 for 3 July 2016 within the urban canyons cases (UCCs).

In comparison with the two previous days, the mPET values also led to higher PS grades. However, these grades were still significantly lower than those presented by the PET index. Even at 15:00, and as exemplified by $UCC_{1.00}RP_E$, $UCC_{0.25}RP_C$, and $UCC_{0.25}RP_E$, mPET did not surpass the first grade of "extreme heat stress". This drop of PS grades obtained by the mPET index was also generally evident between 11:00 and 15:00 for all of the UCCs.

3.3. Synoptic Projections of Thermal Conditions for the Urban Canyon Cases by 2100

"What if?" Projections Extrapolated from the 8 and 3 July Outputs

Constructed on the utilization of the exploratory "what if?" approach, the values obtained for 8 and 3 July were modified to synoptically consider how existing human thermal comfort conditions could be theoretically aggravated as a result of potential climate change impacts by the end of the century. As discussed in the methods section, the projections identified by Matzarakis and Amelung [31] were utilized to consider a PET increase of +10 °C on the current values given the occurrence of a global RCP8.5/SRES A1FI scenario. Consequently, as further study is required to consider these augmentations on the mPET index, only the PET values were utilized for the final sections of the study.

As illustrated within Figure 11A and given a worst-case-scenario of climate change until the end of the century, local human thermal conditions presented very different values to those observed for 8 July, representing a "typical summer day". Although the morning period continued to present lower

PS conditions to those presented by the meteorological station, it could not be overlooked that as early as 09:00, the PS values were already at "strong heat stress" and "extreme heat stress" within $UCC_{0.25}RP_W$ and $UCC_{0.25}RP_C$. Successively, and for most of the afternoon period, while the UCC values were lower, the PS values still ranged from the first and second level of "extreme heat stress". These results indicate that while the existing human thermal results are already alarming, they can be considerably aggravated given a typical hot dry Mediterranean summer. Furthermore, it was additionally acknowledged that the heightened thermal stimuli took place in all UCCs, and moreover, within all of their respective RPs.

Within Figure 11B the results from the estimated aggravation of thermo-physiological conditions obtained for 3 July (i.e., a VHD) are presented. In comparison to the previous synoptic projections that were grounded on a "typical summer day", the results based on a VHD presented dramatic thermal stress levels, reaching a maximum PET value of 58.3 °C in $UCC_{0.25}RP_E$, and 58.3 °C in $UCC_{1.00}RP_E$ at 15:00. These PET outcomes resulted in PS levels ranging up to the fourth level of "extreme heat stress", thus raising alarming implications for human thermal comfort conditions. Comparatively between the different UCCs, only the $UCC_{2.00}$ did not reach the utmost level of "extreme heat stress", nevertheless in all of the RPs; there was still a two-hour period in which the PS levels reached the third level of "extreme heat stress". The obtained results imply that within the worst-case-scenarios associated to climate change by the end of the century, regardless of urban morphology, human thermal comfort conditions within the built environment can potentially reach very high levels of thermo-physiological strain.

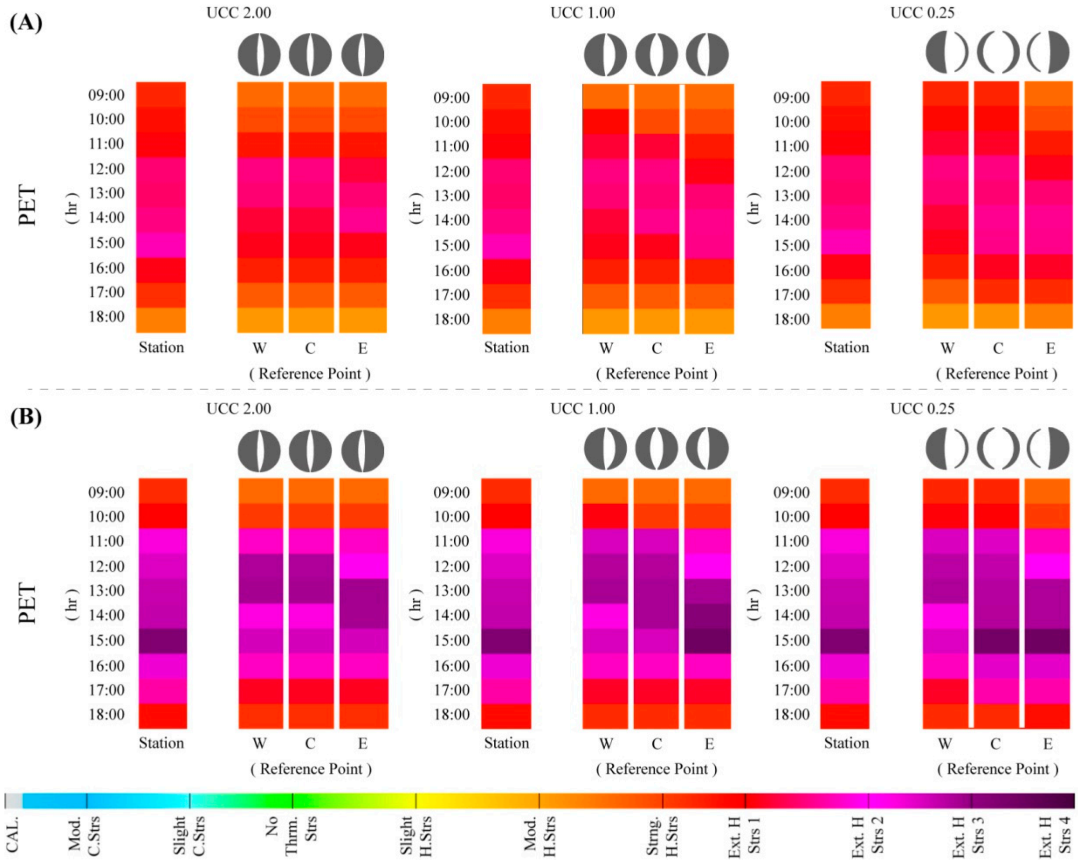


Figure 11. Hourly variations of physiological stress (PS) grades based on physiologically equivalent temperature (PET) and modified physiologically equivalent temperature (mPET) values between 09:00–18:00, based on 8 (**A**) and 3 (**B**) July 2016, with projected climate change augmentations (RCP8.5/SRES A1FI scenario) within the urban canyons cases (UCCs).

3.4. Present and Future Thermo-Physiological Loads and Cumulative Stress

3.4.1. The Intensity of Thermo-Physiological Loads beyond Comfortable Conditions

Established on a value that was representative of "optimum thermal conditions", the thermal load on the human body could be established through the adapted PET index, PETL. This assessment was carried out for the $UCC_{0.25}RP_C$ because of its greater susceptibility to higher thermal stimuli. As presented in Figure 12, based on considering any PET value above 23 °C as an additional thermal load beyond the grade of "no thermal stress" (or BC as presented within Equation (2)), it was possible to ascertain estimates of thermal stress loads for both existing, and projected future conditions.

As already discussed, out of the three days used for the UCC investigations, 12 July presented the lowest PS grades because of a combination of both lower diurnal mean T_a values and higher $V_{1.1}$ speeds. For this reason, and during the morning period, PETL revealed values below 0.0 °C, namely at 09:00 and 18:00, where PETL values reached −2.1 °C and −4.9 °C, respectively. Both in the case of the hotter days in July, the PETL values varied between: (i) 2.9 °C (at 18:00) and 15.3 °C (at 15:00) for 8 July; and (ii) 19.5 °C (at 09:00) and 35.1 °C (at 15:00) for 3 July. These values once again indicate that the existing conditions already present considerable thermal stimulus on the human body; particularly at 15:00, which in accordance with results in the previous section, was revealed to be the period with the highest amount of thermal stimulus. For this reason, and given that Mediterranean climates with hot and dry summers already present significant thermal "risk factors" during VHD/HWE events, approaches to attenuating thermal comfort conditions at local scales already play an imperative role for the welfare of outdoor comfort in consolidated urban environments.

When considering future bioclimatic conditions within the UCCs, and analogous to the outcomes presented in Figure 11, the results of Figure 12 reveal how potential climate change impacts could lead to dramatic increases of urban thermo-physiological stress loads on pedestrians. In the case of 12 July, its hourly PETL values were comparable to those presented by an existing "typical summer day". This similarity theoretically inferred that the thermal loads expected during a future "cooler summer day" could be concomitant with those found within what is now considered a "typical summer day". When considering the results for 8 July within a future scenario, hourly PETL intensities increased dramatically, whereby between 11:00 and 15:00, the PETL values ranged from 23.0 °C to 25.3 °C. In terms of thermal comfort thresholds, these results imply a drastic divergence from "no thermal stress" conditions for a future "typical summer day", where, moreover, the PETL values frequently surpassed those obtained for an existing VHD. Lastly, and in the case of the projected thermal effects obtained for 3 July, the PETL values were severe for the majority of the day, with values constantly remaining between that of 30.4 °C and 35.1 °C from 11:00 until 16:00. For this reason, while existing extreme events such as VHD already present alarming conditions for human health and comfort, the potential aggravating effects associated to the climate change RCP8.5/SRES A1FI scenarios can possibly reveal far more extreme thermo-physiological stress.

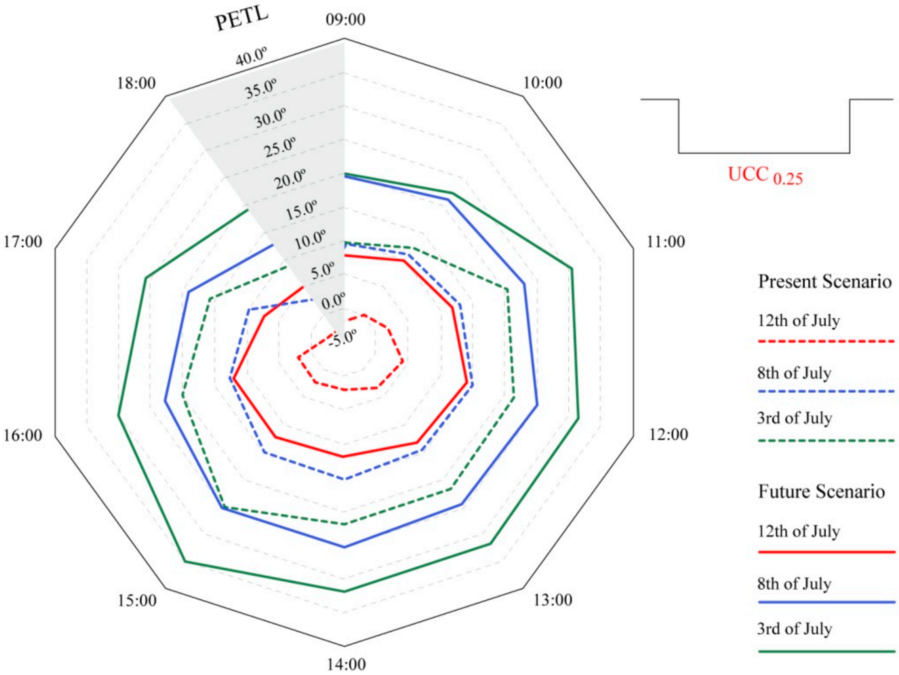


Figure 12. Radar chart of distribution for existing and projected diurnal physiologically equivalent temperature load (PETL) values within urban canyons case 0.25 ($UCC_{0.25}$) for 3, 8, and 12 July.

3.4.2. The Periodicity of Cumulative Thermo-Physiological Stress Load

Adjacently to the intensity of thermo-physiological stress, considering that the periodicity of the thermal stimuli is just as significant, as the exposure to outdoor conditions can last for various hours. As a result, and as suggested by the work elaborated by Charalampopoulos, Tsiros, Chronopoulou-Sereli, and Matzarakis [20], cumulative assessments are also required to obtain an estimation of the thermal stress resultant of remaining under set conditions for a given amount of time. As specified by Equation (3), within the methodology section, the values for *M*cPETL, *A*cPETL, and *D*cPETL from the $|Jul_{2016}|$ dataset were utilized to obtain an overall comprehension of cumulative thermal stress for each of the 31 days of the month.

As revealed in Figure 13, *M*cPETL, *A*cPETL, and *D*cPETL presented different bell curves resultant of the different susceptibilities to cumulative thermal stress. *M*cPETL revealed that the morning period presented the lowest quantity of cumulative stress load; whereby if a person were to remain outdoors for the morning period between the hours of 09:00 and 12:00 during July 2016, they would be susceptible to an estimated mean cPETL of 42.1. On the other hand, in the case of *A*cPETL, the afternoon period revealed a higher mean cPETL of 60.0, because of the exposure of hours that frequently presented the highest thermal stimuli. In the case of *D*cPETL, which equated to the combination of both the morning and afternoon periods, a person that remained outdoors for the entire day would be exposed to an estimated mean cPETL of 102.1. Amongst the thirty-one days of July, the location 3, 8, and 12 July were highlighted within the bell curve to demonstrate their particular rate of probability (Figures 13 and 14). Naturally, due to the notably colder/hotter conditions during both 12 and 3 July, these days were situated at opposite ends of the bell curve, implying considerably divergent amounts of cPETL within all of the stipulated timeframes. In contrast, 8 July, representing a "typical summer day", had the highest probability of the three days, with cPETL values not oscillating far from obtained mean values.

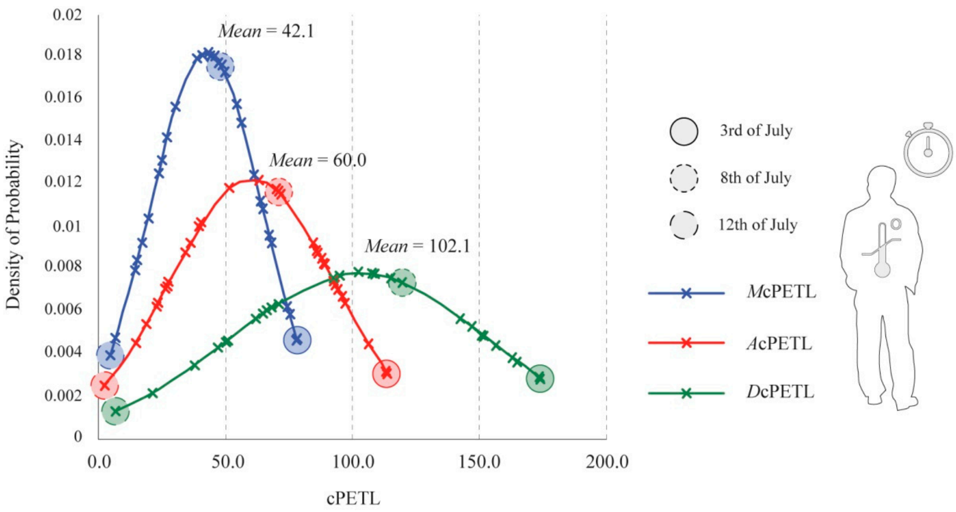


Figure 13. Bell curve comparison for existing morning, afternoon, and diurnal cumulative physiologically equivalent temperature loads (cPETL) for July 2016.

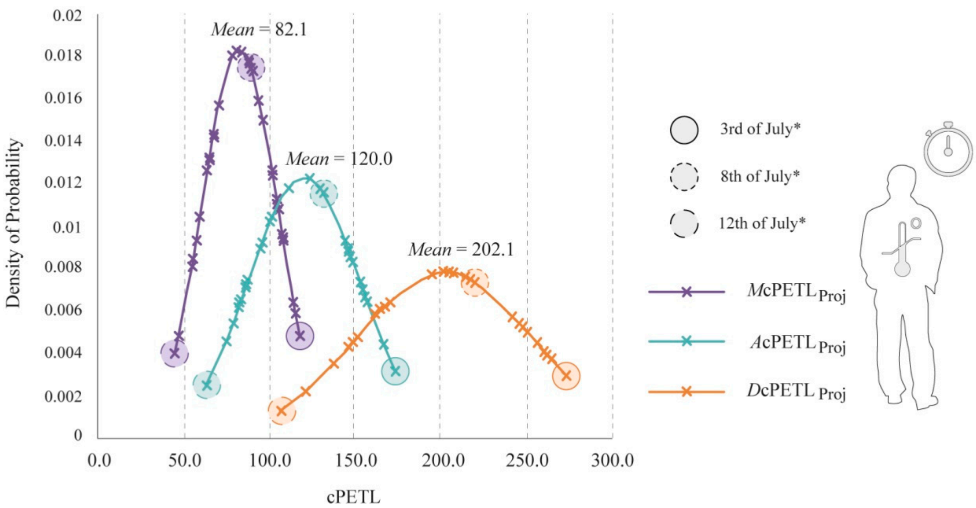


Figure 14. Bell curve comparison for projected morning, afternoon, and diurnal cumulative physiologically equivalent temperature loads (cPETL) for July 2016, with projected climate change aggravations * (RCP8.5/SRES A1FI scenario).

In comparison to the cPETL values presented for the existing thermal conditions, potential future augmentations of thermo-physiological stress led to considerably different bell curves, as revealed in Figure 14. Generally, there was almost a two-fold-increase in the cPETL values for all of the temporal periods, leading to significantly higher mean values for $M\text{cPETL}_{\text{Proj}}$, $A\text{cPETL}_{\text{Proj}}$, and $D\text{cPETL}_{\text{Proj}}$. Moreover, even in the case of $M\text{cPETL}_{\text{Proj}}$ during the corresponding coolest day of the month, cPETL was of 44.2, which was higher than the mean value for the existing *M*cPETL. Similarly, for $A\text{cPETL}_{\text{Proj}}$, the coolest day presented a cPETL of 62.3, which surpassed the mean value for an existing "typical summer day". Respectively, the modified estimated mean for $A\text{cPETL}_{\text{Proj}}$ severely amplified to 120.0, which was significantly higher than the acquired mean of 102.1 for the *D*cPETL presented in Figure 13. With regards to $D\text{cPETL}_{\text{Proj}}$, all of the cPETL values were very high, whereby its (i) mean cPETL was well beyond what would be expected during a current VHD; (ii) the lowest cPETL was of 106.5, which surpassed the mean value obtained for *D*cPETL; and lastly, (iii) the highest estimated cPETL ranged up to 274.8, a value that invariably implied the reduced feasibility of long-term pedestrian permanency in outdoor contexts under the disclosed climate change scenario.

Such outcomes again refer to the two interrelated rationales that exist within Mediterranean climates with hot and dry summers, namely: (1) existing thermal comfort thresholds are already prone to significant thermo-physiological stress intensity and periodicity during the hotter months of the year; and, in addition, that (2) vulnerabilities to such stimuli can dramatically increase by the end of the century in light of worst-case-scenarios associated to climate change within consolidated urban environments.

4. Concluding Remarks for Human Health and Thermal Comfort

With the objective of approaching human thermal comfort in climates with hot-dry Mediterranean summers, this article examined the following: (i) relationship between singular climatic variables and thermo-physiological indices; (ii) impact of selected urban morphological compositions upon local thermo-physiological indices to identify the crucial role of radiation fluxes; (iii) synoptic aggravations of current local human thermal risk factors, given the occurrence of a potential worst-case-scenario of climate change; and (iv) intensity and periodicity between current conditions and those projected for the end of the century.

- To a certain degree, it was possible to identify correlational "cause-and-effect" relationships between the individual variables, especially during the periods of higher climatic stimuli. However, and as directly revealed by the constructed heatmaps, these relationships were not always straightforward, nor did they provide an overall reflection of human thermal comfort conditions. This result was also pertinent to T_a as well. Although this specific variable presented the highest similarity to the thermo-physiological results, as the influences of other variables upon the human body were not reflected, T_a was insufficient to present a wholesome evaluation of thermal comfort conditions.
- In continuation from the previous point, the exercise of transposing meteorological station data into urban canyon cases further confirmed these results within Lisbon's historical district. More specifically, by identifying the central and lateral sky-view-factors, it was possible to undertake precise estimations of global radiation, which rendered clear differences in in situ thermal comfort thresholds. As a result, although the introduced individual variables (including T_a) retrieved from the station remained constant across the stipulated reference points, the thermo-physiological variables varied drastically (with PET variations of up to ~6.0 °C within the different regions of the canyons).
- Currently, human health and thermal comfort are already prone to extreme physiological stress levels during one of the hottest months of the year in Lisbon. Nevertheless, current extremes could potentially be alarmingly surpassed by the end of the century. In the case of synoptically estimating climate change aggravations on a current "typical summer day", even in the morning, the projected physiological stress already ranged between "strong heat stress" and "extreme heat stress". During the afternoon period, the physiological stress values ranged between the first and second level of "extreme heat stress" (representing PET values between 41 °C and 51 °C). Likewise, when considering the aggravations for a current 'very hot day', the projected PET values reached a maximum of 58.5 °C.
- As identified within the study, while the existing conditions extracted from the July 2016 dataset already presented high vulnerability rates during the morning, afternoon, and overall diurnal period—the synoptic projected cumulative thermo-physiological stress load values revealed drastic increases by almost 100%. As a result, this indicated that, regardless of the thermal risk factors already existing in Lisbon during the summer period, these conditions could drastically deteriorate. This deterioration would moreover lead to acute impacts upon urban mortality rates, outdoor activity threads, and overall urban well-being by the end of the century.

While it is inarguable that disseminations from entities such as the Intergovernmental Panel on Climate Change have been indispensable for the maturing climate change agenda, when approaching human thermal conditions at local scales, the use of simpler indexes that do not consider critical non-temperature characteristics (e.g., radiation fluxes patterns) shall always likely prove insufficient for concrete local adaptation efforts. For this reason, the use of climate models (e.g., RayMan and SkyHelios) play a fundamental role in approaching local human thermal comfort, because of their capacity to further specify the influences of local morphological characteristics within consolidated urban contexts. Within this study, and focused upon a bottom-up perspective, various methodologies were combined to demonstrate the relationship between singular climatic variables and that of thermo-physiological indices. This assessment was moreover undertaken to demonstrate how both existing and future human thermal conditions could be approached by non-climatic experts (including urban planners, urban designers, and landscape architects) to undertake adaptation initiatives in an era susceptible to further climatic aggravations and uncertainty.

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Nomenclature

'*Csa*'	hot-mediterranean climate (-)
*A*cPETL	afternoon cumulative physiologically equivalent temperature load (-)
BC	background conditions
CAL.	calibration period (-)
cPETL	cumulative physiologically equivalent temperature load (-)
CTIS	climate tourism/transfer information scheme (-)
*D*cPETL	diurnal cumulative physiologically equivalent temperature load (-)
H/W	height-to-width (-)
HWE	heat wave events (-)
KG	Köppen Geiger (-)
*M*cPETL	morning cumulative physiologically equivalent temperature load (-)
MEMI	Munich energy-balance model for individuals (-)
mPET	modified physiologically equivalent temperature (°C)
PET	physiologically equivalent temperature (°C)
PETL	physiologically equivalent temperature load (°C)
PS	physiological stress (-) *
RH	relative humidity (%)
RP_X	*X* reference point (-) (W—Western, C—Central, E—Eastern)
SVF	sky-view-factor (-)
SVF_{SP}	single point sky-view-factor (-)
T_a	air temperature (°C)
T_{mrt}	mean radiant temperature (°C)
UCCs	urban canyon case studies (-)
UCC_X	*X* H/W Urban Canyon Case (-)
$UCC_X RP_X$	*X* reference point in *X* urban canyon case (-)
UHI	urban heat island (-)
V	wind speed (m/s)
$V_{1.1}$	wind speed adapted to height of 1.1 m (m/s)
VHD	very hot day (-)

WMO	World Meteorological Organisation (-)
$XcPETL_{Proj}$	projected future values of X cumulative physiologically equivalent temperature load (-)
Z_0	urban roughness length (m)
α	urban surface roughness (-)

* Physiological stress acronyms from Tables 1 and 4 excluded

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