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Article

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

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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.

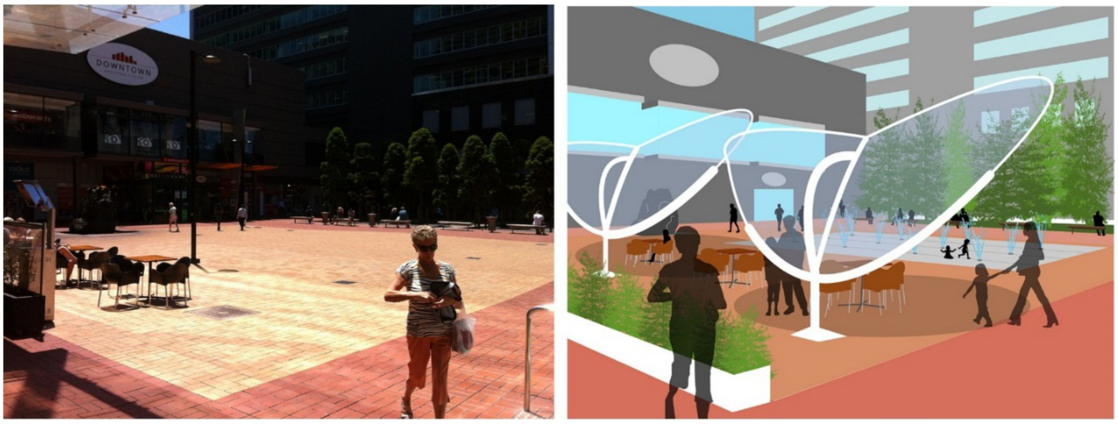
Another noteworthy and runner up entry was the submission of ABM Architects "Activity Tree" that, although it shall inevitably remain as a concept, offers, nevertheless, valuable precedents in terms of shelter canopies (Case #4). Established through an in-depth site analysis, the zones which would require 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.

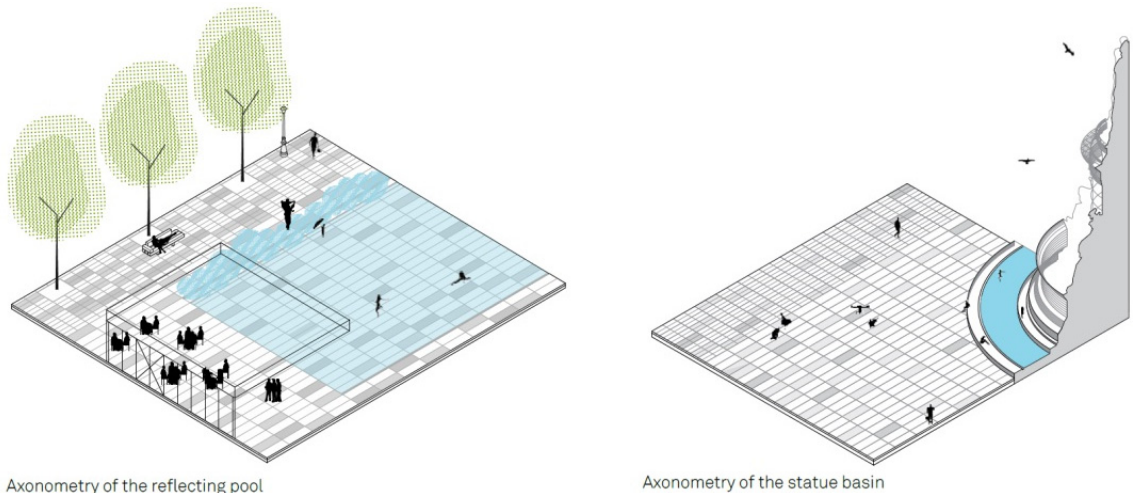


Figure 3. Axonometric of the (**a**) Reflecting pool; (**b**) Statue basin. Adapted with permission from Trévelo & Viger-Kohler [19].

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.

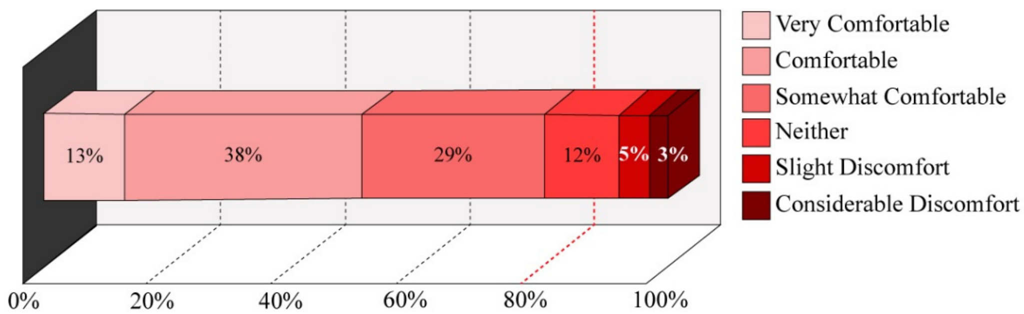


Figure 4. Results from thermal comfort questionnaire. Adapted with permission from CiNii [39].

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.

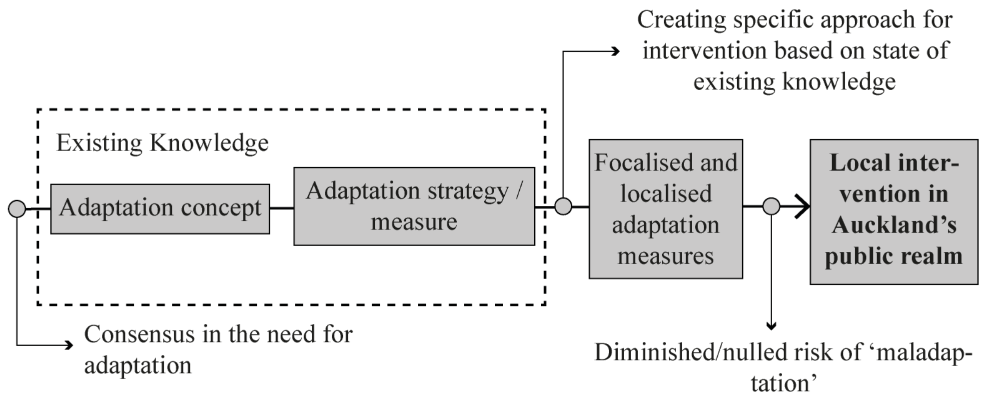


Figure 5. Proposing adaptation measures which focus upon Auckland's public realm and local risk factors. Adapted with permission from Taylor & Francis [45].

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.

References

1. Auckland Council. *The Proposed Auckland Unitary Plan (Notified 30 September 2013)*; Auckland Council: Auckland, New Zealand, 2013.
2. Peel, M.; Finlayson, B.; McMahon, T. Updated world map of the koppen-geiger climate classification. *J. Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644.
3. *Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand*; Ministry for the Environment: Wellington, New Zealand, 2008; p. 149.
4. Semadeni-Davies, A. *National-Climate-Centre: State of the Climate 2013*; National Institute of Water & Atmospheric Research (NIWA): Wellington, New Zealand, 2013; p. 109.

5. Mackintosh, L. *Mean Relative Humidity for Selected Locations through New Zealand, by Month—1981–2010 (Dataset)*; National Institute of Water and Atmospheric Research (NIWA): Auckland, New Zealand, 2013.
6. Mackintosh, L. *Climate Summaries—Annual Rain, Temperature, Sunshine, Frost, and Wind Data for Selected Locations through New Zealand—1981–2010 (Dataset)*; National Institute of Water and Atmospheric Research (NIWA): Auckland, New Zealand, 2013.
7. Gluckman, P. *New Zealand's Changing Climate and Oceans: The Impact of Human Activity and Implication for the Future*; Office of the Prime Minister's Science Advisory Committee (PMCSA): Auckland, New Zealand, 2013; p. 22.
8. Oliveira, S.; Andrade, H. An initial assessment of the bioclimatic comfort in an outdoor public space in lisbon. *Int. J. Biometeorol.* **2007**, *52*, 69–84.
9. Katzschner, L. *Microclimatic Thermal Comfort Analysis in Cities for Urban Planning and Open Space Design*; Network for Comfort and Energy Use in Buildings (NCUB): London, UK, 2006.
10. Nouri, A.S. A Bottom-up Perspective upon Climate Change—Approaches towards the Local Scale and Microclimatic Assessment. In *Green Design, Materials and Manufacturing Processes*; Bártolo, H., Ed.; Taylor & Francis: Lisbon, Portugal, 2013; pp. 119–124.
11. Olgyay, V. *Design with Climate, Bioclimatic Approach to Architectural Regionalism*; Princeton University Press: Princeton, NJ, USA, 1963.
12. Costa, J.P. "*Climate Proof Cities*". *Urbanismo e a Adaptação às Alterações Climáticas. As Frentes de Água*; Universidade Técnica de Lisboa: Lisboa, Portugal, 2011; p. 218. (In Portuguese)
13. Nikolopoulou, M. Designing Open Spaces in the Urban Environment: A Biocliamtic Approach. Available online: http://www.cres.gr/kape/education/1.design_guidelines_en.pdf (accessed on 4 March 2015).
14. Erell, E.; Pearlmutter, D.; Williamson, T. *Urban Microclimate—Designing the Spaces between Buildings*; Earthscan: London, UK, 2011.
15. Almeida, A.L.B. *O valor das Árvores: Árvores e Floresta Urbana de Lisboa*; Instituto Superior de Agronomia: Lisbon, Portugal, 2006. (In Portuguese)
16. Tsiros, I. Assessment and energy implications of street air temperature cooling by shade trees in Athens (Greece) under extremely hot weather conditions. *J. Renew. Energy* **2010**, *35*, 1866–1869.
17. Picot, X. Thermal comfort in urban spaces: Impact of vegetation growth. Case study: Piazza della scienza, milan italy. *Energy Build.* **2004**, *36*, 329–334.
18. Shashua-Bar, L.; Tsiros, I.X.; Hoffman, M. Passive cooling design options to ameliorate thermal comfort in urban streets of a mediterranean climate (Athens) under hot summer conditions. *Build. Environ.* **2012**, *57*, 110–119.
19. Trevelo & Viger-Kohler Architectes Urbanistes (TVK). *Place de la Republique*; TVK: Paris, France, 2013; p. 7.
20. Auckland Regional Public Health Service (ARPHS). *Feedback to the Draft*; ARPHS: Auckland, New Zealand, 2013; p. 78.
21. Whyte, W.H. *The Social Life of Small Urban Spaces*; Project for Public Spaces Inc.: New York, NY, USA, 1980.
22. Knuijt, M. One Step Beyond. Open Space 2013. Available online: http://www.okra.nl/wp-content/uploads/2014/07/2014_OKRA_Topos-85_-Knuijt.pdf (accessed on 6 March 2015).

23. Santamouris, M.; Gaitani, N.; Spanou, A.; Salirai, M.; Giannopoulou, K.; Vasilakopoulou, K.; Kardomateas, T. Using cool paving materials to improve microclimate of urban areas—Design realization and results of the flisvos project. *J. Build. Environ.* **2012**, *53*, 128–136.
24. Gustavsson, T.; Bogren, J.; Green, C. Road climate in cities: A study of the stockholm area, south-east sweden. *J. Meteorol. Appl.* **2001**, *8*, 481–489.
25. Santamouris, M. Using cool pavements as a mitigation strategy to fight urban heat islands—A review of the actual developments. *J. Renew. Sustain. Energy Rev.* **2013**, *26*, 224–240.
26. Doulos, L.; Santamouris, M.; Livada, I. Passive cooling of outdoor urban spaces. The role of materials. *J. Sol. Energy* **2004**, *77*, 231–249.
27. Synnefa, A.; Santamouris, M.; Livada, I. A study of the thermal performance of reflective coatings for the urban environment. *J. Sol. Energy* **2006**, *80*, 968–981.
28. Georgakis, C.; Santamouris, M. Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. *J. Energy Build.* **2006**, *38*, 367–376.
29. Stathopoulou, M.; Synnefa, A.; Cartalis, C.; Santamouris, M.; Karlessi, T.; Akbari, H. A surface heat island study of athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials. *J. Sustain. Energy* **2009**, *28*, 59–76.
30. Santamouris, M.; Xirafi, F.; Gaitani, N.; Saliari, M.; Vassilakopoulou, K. Improving the microclimate in a dense urban area using experimental and theoretical techniques—The case of marousi, athens. *Int. J. Vent.* **2012**, *11*, 1–16.
31. Fintikakis, N.; Gaitani, N.; Santamouris, M.; Assimakopoulos, M.; Assimakopoulos, D.; Fintikaki, M.; Albanis, G.; Papadimitriou, K.; Chryssochoides, E.; Katopodi, K.; *et al.* Bioclimatic design of open public spaces in the historic centre of tirana, albania. *Sustain. Cities Soc.* **2011**, *1*, 54–62.
32. Gaitani, N.; Spanou, A.; Saliari, M.; Vassilakopoulou, K.; Papadopoulou, K.; Pavlou, K.; Santamouris, M.; Lagoudaki, A. Improving the microclimate in urban areas: A case study in the centre of Athens. *Build. Serv. Eng. Res. Technol.* **2011**, *32*, 53–71.
33. *Presentation—European Architectural Competition for the Creation of a New City Centre*; OKRA Landscape Architects: Delft, The Netherlands, 2013; p. 14.
34. Chu, S. *Memorandum for Heads of Department Elements: Installation of Cool Roofs on Department of Energy Buildings*; Department of Energy of the United States of America: Washington, DC, USA, 2010; p. 2.
35. Yang, J.; Wang, Z.; Kaloush, K. *Unintended Consequences—A Research Synthesis Examining the Use of Reflective Pavements to Mitigate the Urban Heat Island Effect (Revised April 2014)*; Arizona State University National Center for Excellence for SMART Innovations: Tempe, AZ, USA, 2013.
36. Nakaoukubo, K.; Hoyano, A. Numerical analysis on radiant environment of outdoor living space considering the influence of spatial form and material. *J. Environ. Eng.* **2006**, *73*, 957–964.
37. Kondo, Y.; Ogasawara, T.; Udoh, K. Influence of radiation by cool pavement on thermal sensation of pedestrians. *J. Environ. Eng.* **2006**, *74*, 323–330.

38. Nunes, J.; Zolio, I.; Jacinto, N.; Nunes, A.; Campos, T.; Pacheco, M.; Fonseca, D. *Misting-Cooling Systems for Microclimatic Control in Public Space*; PROAP Landscape Architects: Lisbon, Portugal, 2013; pp. 1–16.
39. Ishii, T.; Tsujimoto, M.; Yamanishi, A. The Experiment at the Platform of Dry-Mist Atomization. In Proceedings of the Annual Meeting of the Architectural Institute of Japan, Tokyo, Japan, 20 July 2008.
40. Ishii, T.; Tsujimoto, M.; Yoon, G.; Okumiya, M. Cooling System with Water Mist Sprayers for Mitigation of Heat-Island. In Proceedings of the Seventh International Conference on Urban Climate, Yokohama, Japan, 29 June 2009.
41. Yamada, H.; Yoon, G.; Okumiya, M.; Okuyama, H. Study of cooling system with water mist sprayers: Fundemental examination of particle size distribution and cooling effects. *J. Build. Simul.* **2008**, *1*, 214–222.
42. Yoon, G.; Yamada, H.; Okumiya, M. Study on a Cooling System Using Water Mist Sprayers, System Control Considering Outdoor Environment. In Proceedings of the Korea-Japan Joint Symposium on Human-Environment Systems, Cheju, Korea, 29–30 November 2008.
43. Farnham, C.; Nakao, M.; Nishioka, M.; Nabeshima, M.; Mizuno, T. Study of mist-cooling for semi-enclosed spaces in Osaka, Japan. *J. Urban Environ. Pollut.* **2011**, *4*, 228–238.
44. Velazquez, R.; Alvarez, S.; Guerra, J. *Control Climatico de los Espacios Abiertos En Expo 1992*; College of Industrial Engineering of Seville: Seville, Spain, 1992. (In Spanish)
45. Nouri, A.S.; Matos Silva, M. Climate Change Adaptation and Strategies: An Overview. In *Green Design, Materials and Manufacturing Processes*; Bártolo, H., Ed.; Taylor and Francis: Lisbon, Portugal, 2013; pp. 501–507.