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Article

# Enlarging the Human Climate Niche: Integrating Urban Heat Island in Urban Planning Interventions

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## Abstract

This article explores the potential of linking the scholarship on the human climate niche and heat island research. One such combination leads to a better understanding of the liveability of urban areas and thereby offers a contribution to emerging healthy urban planning. Whereas former research has primarily focused on the parameters influencing urban heat island and mitigation solutions, it remains short on quantifying these solutions and conceptualising the cumulative impacts of urban heat island on health and vulnerable populations. Based on the coupling of ENVI-met computational simulation and the local climate zone method, this article quantifies mitigation solutions and associates the frequency and intensity of heat stress and health-related symptoms in various urban settings. Drawing on a real-case urban intervention in Paris, it offers a more effective health-related and comfort-focused approach to urban planning and interventions to expand the human climate niche. This should contribute to transforming the planning and conception of public spaces into “liveable refuges” for all population types, including the most vulnerable. The results stemming from the simulations of mitigation measures help design a hierarchy of interventions to tackle urban heat islands according to the intensity of their ability to reduce heat stress risk. This hierarchy is then adjusted to other parameters contributing to a healthy, liveable urban environment and urban planning, making interventions on urban heat islands a matter of (multidimensional) care for urban dwellers.

## Keywords

health; human climate niche; liveability; microclimates; simulations; urban heat island

## Issue

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## 1. Introduction

Various works on climate change and biodiversity loss have put the emphasis on one specific transformation: the shrinking number of shelters and refuges for various species (Shaffer, 2018; Tanner et al., 2017), making urban places somewhat alternative refuges (Uchida et al., 2021). What this process entails is that their various “environmental niches” are highly threatened by variegated pressures. As explained by Xu et al. (2020, p. 1350), “all species have an environmental niche, and despite

the advances in technology, humans are unlikely to be an exception”; this niche is characterised by a set of climatic features that have a decisive influence on thermal comfort as well as on life expectancy. Passing certain (climatic) thresholds would thereby lead to both the shrinkage of this niche and an enhanced level of vulnerability for the affected populations, endangering (human) liveability in certain areas. Ensuring the conservation of this environmental niche is then a major health issue, health being here broadly construed as the combination of physical, mental, and social well-being (Capeille, 2018).

One such conservation entails preventive (and also corrective) measures to preserve correct/healthy living conditions. Amongst the places where the pressure on the niche is increasingly problematic and challenges the liveability of human settlements, urban areas seem to concentrate the highest threats, mainly due to the urban heat island (UHI) effect (along with other factors such as pollution or access to resources, which are closely intertwined with UHI). The UHI effect is a phenomenon that occurs in cities and is attributed to the difference in temperatures between an urban area or a metropolitan area and its surrounding rural areas. This phenomenon's formation can be traced to different parameters, which are characteristic of dense cities (Santamouris, 2020). Congested urban morphologies and dark impervious surfaces favour shortwave radiation trapping and heat absorption. Coupled with anthropogenic heat and extremely high temperatures, amongst other things, UHI intensity can reach up to +10 °C.

Yet scant works try to articulate these issues of the liveability of urban areas and climatic transformations with the types of urban planning interventions that can be achieved in already built areas. Surprisingly enough, while some research has put forward an urban liveability index (Higgs et al., 2019), this index does not take environmental issues into account beyond access to green spaces or air pollution, and largely neglects the elements integral to thermal comfort and the sanitary effects of UHIs. In this article, we show how interventions for healthy urban planning targeting UHI prevent the degradation of this niche at a microlevel.

One should acknowledge that the articulation of UHI and health concerns is by no means a completely new topic. It has even been at the core of seminal works on the topic, as early as Webster's contribution in 1799 with his *Brief History of Epidemic and Pestilential Diseases* (as cited in Meyer, 1991, and Stewart, 2019). At that time, Webster insisted on the prejudice against health exerted by the extreme heat of cities and sketched what can be considered a pre-discovery of the functioning of modern urban climate. Provocatively enough, in 1807, Caldwell even suggested that the most comfortable place in cities to escape from the health effects of heat would be jails, due to their thick walls and small windows. These premises for understanding UHI effects in relation to urban health placed emphasis on the need to integrate heat in the design of a sanitary city.

With the acceleration of climate change, these pressures on the thermal conditions of urban areas are reaching a new threshold, leading to a shift in the approach of urban design: the traditional comfort-oriented perspective on UHI (as detailed in Watkins et al., 2007) is increasingly becoming replaced by a health-oriented perspective (D'Onofrio & Trusiani, 2018). One such shift follows recent development in the research as well as in professional practices, in light of project-based literature on urbanism favourable to health (Capeille, 2018), which identifies factors of crisis and vectors of well-being

within cities. Following this vein, we scrutinise urban planning practices in favour of healthy urban planning, seen through the lenses of UHI effects. In this article, we argue that analysing UHI and modelling it at a microclimatic level (Mayer & Höppe, 1987) offers tools to design urban planning interventions, preserving, if not enlarging, the human climate niche by limiting UHI. Through one urban project in Paris inspired by the principles of healthy urban planning, we model and analyse both the contributions of the planned interventions to UHI reduction and the heat- and health-related potential of other interventions on other determinants integral to UHI (Santamouris et al., 2004). Through this, we produce a UHI-oriented hierarchy of urban interventions that can contribute to improved liveability of the concerned areas.

In the next sections of this article, we show through a literature review how UHI, health issues, and urban planning interventions can be articulated and somewhat form a nexus, illustrating the interest of localised climate modelling to identify places where the effects are the most prevalent, and where the interventions could contribute to a diminution of this effect (Section 2). Drawing from the modelling of an urban project in Paris with ENVI-met software (Section 3), we simulate the various effects of UHI-oriented urban interventions adopted on that site (Section 4). We expand this first simulation beyond the already planned interventions and test a larger set of possible solutions to provide a hierarchy of possible interventions for healthy urban planning, whose aim is to lower UHI and thus enhance the liveability of some urban projects (Section 5). The various possibilities of urban interventions are then further discussed in terms of urban arbitrages (Section 6).

## 2. How to Link Health, Urban Heat Island, and Urban Planning: Literature Review

Looking at UHI induces an understanding of its effects on surfaces, but also on urban dwellers. These effects are often reduced to psychological impacts linked with discomfort. Yet one can clearly identify a series of direct and indirect effects on health due to UHI. They all contribute to increasing the vulnerability of people affected by UHI.

A growing body of literature is placing emphasis on the development of "urban ills," or "big city diseases," amongst which one could list UHI (Li et al., 2021). This can be taken metaphorically, as in Li et al.'s text, to denounce the important stress generated by various forms of density, but also materially and physically through a systemic analysis of the articulation between UHI and health.

### 2.1. Urban Heat Island as an Accelerator of Health Issues

The articulation between UHI and health issues reveals the role of catalyst played by UHI on various forms of health issues. The existence of UHIs acts as an accelerator of heat waves and makes them particularly lethal

(Robine et al., 2008; Vandentorren et al., 2004). This has to be determined cautiously by distinguishing between the types of temperatures (surface temperature and air temperature; Stewart et al., 2021) to robustly grasp the magnitude of UHI and its health effect. As documented in various works, UHI enhances the severity of extreme heat events, such as heat waves, and thereby contributes to an increase in morbidity and mortality (Gosling et al., 2009; Nogueira et al., 2020).

This catalytic aspect of UHI is even reinforced when combined with degrading air quality (Richard et al., 2021). There is a direct correlation between the production of the smog effect and high air temperatures, thereby reinforcing the UHI effect. A smog bubble forms when hot air lifts pollutants and particle matter (such as PM10, PM2.5, O<sub>3</sub>, and NO<sub>2</sub>) to higher altitudes. Cooler air from the outskirts of the city heats up and stops penetrating the city centre. The hot air cushion can generate an inversion at night, preventing the city from cooling and preventing the air from mixing with fresh air from the countryside (Krusche et al., 1982). The combination of UHI and air quality pollution increases the risk of developing several health effects such as asthma, chronic bronchitis, lung irritation, and cancer, and increases hospital admissions resulting from cardiovascular and respiratory diseases (Dandotiya, 2019). These health effects are predominantly linked to anthropogenic emissions, mainly coming from car exhausts and factories.

As climate change has been proven to exacerbate the UHI effect (Chapman et al., 2017), its catalytic power becomes an increasingly important threat to urban dwellers' health and their climate niche.

## *2.2. Urban-Heat-Island-Related Health Risks: Direct and Indirect Risks*

UHI has long been considered a matter of concern by urban planners and the associated academic literature, but not for purely sanitary reasons. In a large amount of research, the objective is to assess and transform thermal comfort to improve the physical perception of space but not to limit health-related risks (Erlwein & Pauleit, 2021; Mittermüller et al., 2021). Yet a growing body of literature, coming from the urban health field rather than urban planning, details how UHI can be linked to a wide range of health impacts (Hammer et al., 2020).

These effects of UHI can be sorted into two categories: critical direct effects and indirect aggravation of existing conditions. Figures from the Centres for Disease Control and Prevention demonstrate how extreme heat events and heat stress more generally, bolstered by UHI, can directly lead to heat exhaustion and heat stroke (Kovats & Hajat, 2008). Records from recent experiences with heat waves show that extremely hot temperatures are correlated with an increase in excess mortality and morbidity (Guo et al., 2018). The 2003 European heat wave was recorded at the time as the hottest summer since at least the 14th century. France, and

specifically very urbanised areas, was highly affected during that period, recording 18 consecutive days with temperatures above 35 °C (Météo France, 2020) and experiencing abnormal mortality levels largely due to this phenomenon.

Indirect effects can also be observed through the exacerbation of certain medical conditions: UHI will, for instance, reinforce effects related to diabetes, obesity, cardiovascular diseases, and asthma (Reid et al., 2009). It has been recorded that morbidity related to respiratory admissions increases by 4.5% for every 1 °C increase in temperature above the human climate niche threshold for the 75+ group (Michelozzi et al., 2009). Mortalities due to respiratory complications tend to peak three weeks after exposure to extreme heat stress (Michelozzi et al., 2009). People with chronic diseases and underlying conditions are also vulnerable during heat waves, as the body is less efficient at regulating core temperatures due to a decreased thermoregulatory ability. Obese and overweight individuals are considered in some studies to be 3.5 times more susceptible to fatal heatstroke (Kenny et al., 2010).

Neuropsychiatric damage has also been reported as an indirect health effect of heat. In fact, heat exposure for an extended period can lead to worse moods, depression, and suicidal tendencies in some individuals. It also harms cognitive performance via reductions in memory, attention, and processing speed (Obradovich et al., 2017). Coupled with direct health effects and increasing air pollution due to heat, these combinations increase the vulnerability of the human body and the rates of morbidity and mortality.

## *2.3. Heat-Related Health Issues as a Socially Situated Phenomenon*

Yet, these elements should not eclipse the fact that heat-related health issues are a socially situated phenomenon (Basu & Samet, 2002), linked to urban living conditions (Friel et al., 2011). This shows how health is conditioned by the qualities of the built environment, and somewhat reflects other forms of social inequalities such as access to systems or services that will thwart the physical and medical effects of UHI.

Individuals living in poor-quality buildings and unable to afford air conditioning are, for instance, more at risk of heat illnesses, as an air conditioner or a working fan can reduce heat-related risks by 80% and 30% (Kenny et al., 2010). Poor-quality constructions in general largely reinforce the health-induced effects of UHI, notably by night, when the body is recovering. During the night, the geometric shape of dense cities traps short-wave radiation from the sun, creating long-lasting hot zones. Furthermore, dark materials that form the urban morphology release all their accumulated heat, during the night, conversely slowing down the cooling of the ambient air temperatures (Atelier Parisien d'Urbanisme, 2017). This accounts for various UHI-induced health

disorders: Most heat-related strokes happen at night due to the canyon effect and the thermal properties of dark materials. At night-time, high temperatures significantly influence sleep patterns, increasing susceptibility to chronic illnesses and diseases. Studies show for instance that a +1 °C deviation in night-time temperatures produces an increase of three insufficient nights of sleep per 100 individuals per month (Obradovich et al., 2017).

These various elements demonstrate the close relationship between health issues, UHI, and the built environment. They are highly intertwined and clearly determinants of the human climate niche: Working on UHI mitigation through urban interventions thus brings about an improvement in health conditions for urban dwellers. From an urban planning perspective, this clearly raises questions about the need to grasp the precise features of UHI to transform both the built environment and city dwellers' health. The challenge is therefore to identify interventions according to their capacity to limit UHI. Microclimatic modelling offers a fruitful approach to testing this, as developed in the next sections.

### **3. Methodology: Modelling Microclimatic Conditions to Address the Health–Urban Heat Island–Urban Planning Nexus**

#### *3.1. Modelling Microclimatic Urban Conditions*

Whereas previous research has primarily focused on the parameters influencing UHI and mitigation solutions, it remains short on quantifying these solutions and conceptualising the cumulative impacts of UHI on health and vulnerable populations (Enete et al., 2014; Ulpiani, 2021). Mitigating the UHI effect, and thus reducing urban temperatures, revolves around treating three main controllable parameters (environmental parameters deemed uncontrollable) that influence UHI: morphological, surficial, and anthropogenic (ADEME, 2012; Santamouris et al., 2004). Morphological solutions refer to altering the built environment, considering its shape, size, organisation, distribution, orientation, exposure, and density to adopt an urban fabric more resilient to heat. Surficial solutions consist of adopting lighter and permeable surfaces, as well as using the cooling potential of vegetation and water bodies. Anthropogenic solutions promote active mobility and support more sustainable buildings to reduce carbon emissions over their life cycle. Hence, for the purpose of this article, we simulated solutions resting on these parameters in a specific urban project in Paris (designed by AIA Life Designers) which is inspired by the principles of healthy urban planning. Based on the coupling of ENVI-met computational simulation and the local climate zone (LCZ) method, we quantify both the mitigation solutions planned for the site and other interventions tackling UHI key parameters (surficial, morphological, and anthropogenic), in order to offer

a panorama of the urban planning possibilities to tackle the UHI-health-planning nexus.

The LCZ method, developed by Stewart and Oke (2012), is used to identify the UHI intensity based on a defined set of properties on already existing territories. It rests on the idea that certain “types” of urban configurations display similar thermal behaviours. This approach is considered a fairly quick method that gives an idea of the UHI intensity without the use of computational simulations, and consequently informs urban decision-making processes (Lensholzer, 2015).

ENVI-met is a three-dimensional simulation software that forecasts the impact of urban interventions on the surrounding environment and takes into account an array of different indicators, which explains its growing use in academic articles (Crank et al., 2018; Simon et al., 2018). In this project, ENVI-met is being used to quantify the cooling effect of different solutions that can be implemented in an urban setting. The quantitative data resulting from the simulation of several microclimates can assist architects and urban planners in making their projects safer for users and vulnerable populations. The purpose of our simulations is to identify possibilities to create shelters and thereby mitigate UHI and enhance the human climate niche. To produce a possible hierarchy of urban interventions according to their health-related impact, all microclimates have been simulated under the same conditions on one specific site.

#### *3.2. Application in a Parisian Case Study*

The case study is located in Paris, in a dense urban area (Figure 1). Records from previous heat waves have shown that Paris suffers from an intense UHI that can reach up to +10 °C (Météo France & Agence Parisienne du Climat, 2018), which makes it an interesting case to explore. The site is categorised as an LCZ 2 (compact mid-rise) due to its morphology of four to eight-storey buildings, and the recurrence of dark asphalt with the exception of a few planted areas. The local surficial properties favour heat absorption and the intensification of the UHI effect (the site's average albedo reaches 0.2 and impervious surfaces cover around 80%), and the morphological configuration suggests a higher risk of diurnal thermal discomfort for pedestrians due to limited shading from the buildings, coupled with the small presence of trees.

The urban project (as designed by AIA Life Designers and not yet fully implemented) seeks to transform the area's liveability through various urban interventions on surficial parameters, ranging from doubling the presence of various strata of vegetation to removing 70% of the existing asphalt surfaces and using less reflective materials to avoid thermal discomfort for pedestrians (Crank et al., 2018). These interventions were conceived in terms of urban comfort and were not associated with a quantified measure of their impact on UHI. It thereby offers an interesting site to simulate the contributions of these interventions to mitigating UHI. Correlatively,

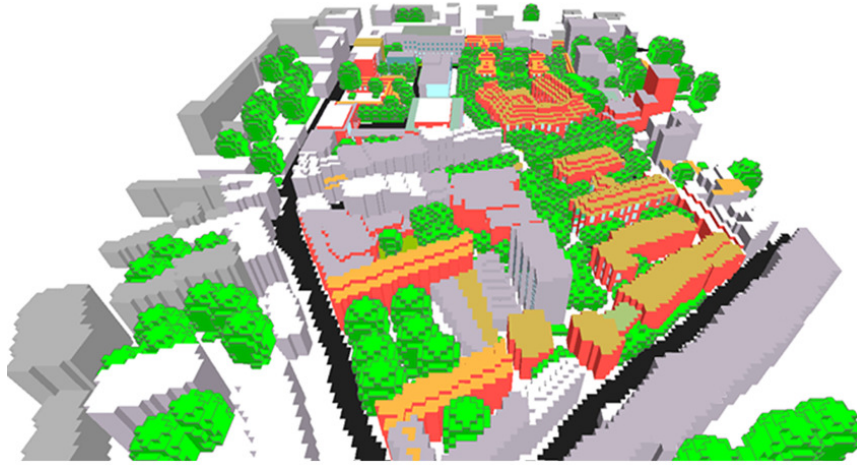


Figure 1. 3D representation of the case study from ENVI-met.

even if not directly measurable, these contributions will have health-related impacts by increasing the climatic liveability of the area and then maintaining the human climate niche.

The differences between the existing state of the site and the projected one with solutions displayed can be seen in Figure 2. The changes between the two states are listed as follows:

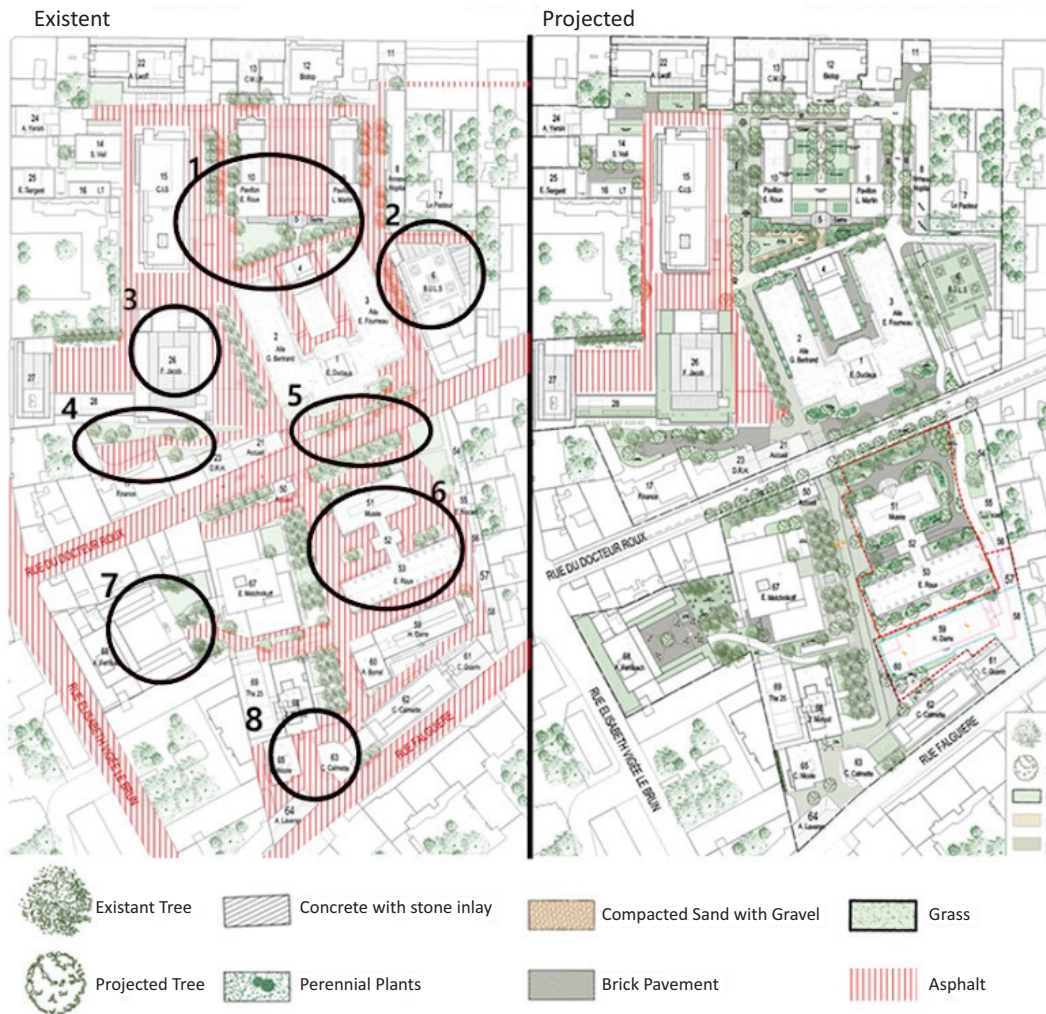


Figure 2. Comparison between the existing state of the chosen site and the intervention plan. Source: Courtesy of AIA Life Designers.

1. The soil of the first highlighted area is changed from impervious asphalt to compacted sand and gravel; the presence of vegetation is also increased.
2. The roof of the second area is transformed from concrete to green.
3. In the third area, a similar roof transformation occurs.
4. The asphalt in the fourth area is removed and replaced by brick tiles. Perennials are also added to the green areas to form three layers of vegetation.
5. The pavement of the fifth area is planted with trees.
6. The sixth area is planted with perennials and more trees.
7. The soil type is changed from asphalt to paving stone and is planted with more trees and perennials in the seventh area.
8. In the eighth area, asphalt is replaced by deactivated concrete with stone inlay.

The methodological protocol followed a two-step approach. First, the case study (as is and with the planned interventions) was simulated with meteorological data that depicts a heat wave that previously hit Paris in 2018. The simulated period spans three days, with a maximum temperature of 37.3 °C, a minimum temperature of 21 °C, and a mean temperature of 29.3 °C. ENVI-met was used to model, simulate, and analyse the gathered data. The mean radiant temperature (MRT) and potential air temperature (PAT) indicators were chosen to measure the intensity of UHI. The MRT is a heuristic indicator, as it highlights thermal radiant exchanges of surfaces in the thermal environment (Kántor & Unger, 2011).

Second, we expanded simulations to other types of interventions that were not planned for this site, regardless of their potential financial constraints. These interventions were selected based on the controllable parameters influencing UHI (surficial, morphological, and anthropogenic), and we tested their consequences on the temperature of the area. Through this, we can observe the contributions to lowering UHI from the various options that would constitute patterns of healthy urban planning. The results of these simulations open up the possibility of forming a hierarchy of urban planning actions according to their cooling potential and hence their potential to limit health issues relating to UHI.

#### 4. Results: Simulations of Urban-Heat-Island-Related Actions

The results stemming from the simulations of the existing state and the intervention state of the chosen site confirm the theoretical observations outlined above. In the existing phase, with the exception of some planted areas, the MRT of asphalt surfaces reaches up to 55 °C. The surfaces that benefit from the shading effect of nearby trees and buildings have an MRT spanning between 25 and 30 °C. In the projected phase, we notice that the entire

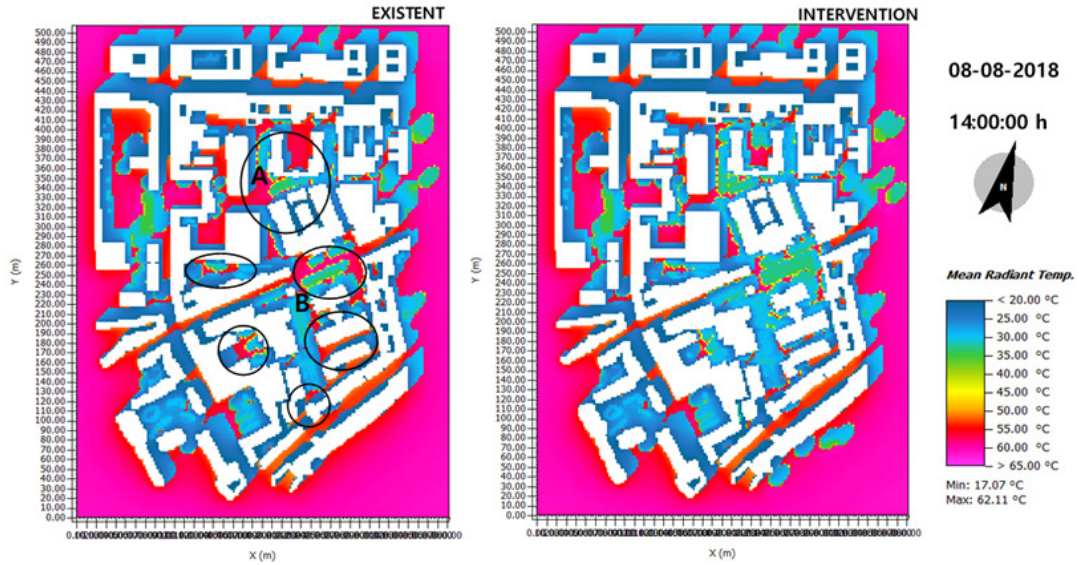
site benefits from a lower MRT in comparison to the existing state, except the north-western area, which is a technical zone with underground parking that underwent little to no modification. In the eight highlighted zones below, we observe a remarkable reduction of the MRT of about 30 °C, mainly due to the surficial modifications (a category that includes vegetation).

In order to analyse the evolution of UHI during the simulated period of three days, we determined the most frequented areas of the site. Six points were scattered across the main exterior zones for an analysis combining both MRT and PAT indicators. As the simulations show similar patterns in the six points, and to avoid repetition, only two of them are presented here: A and B, the two most frequented points (Figures 3 and 4).

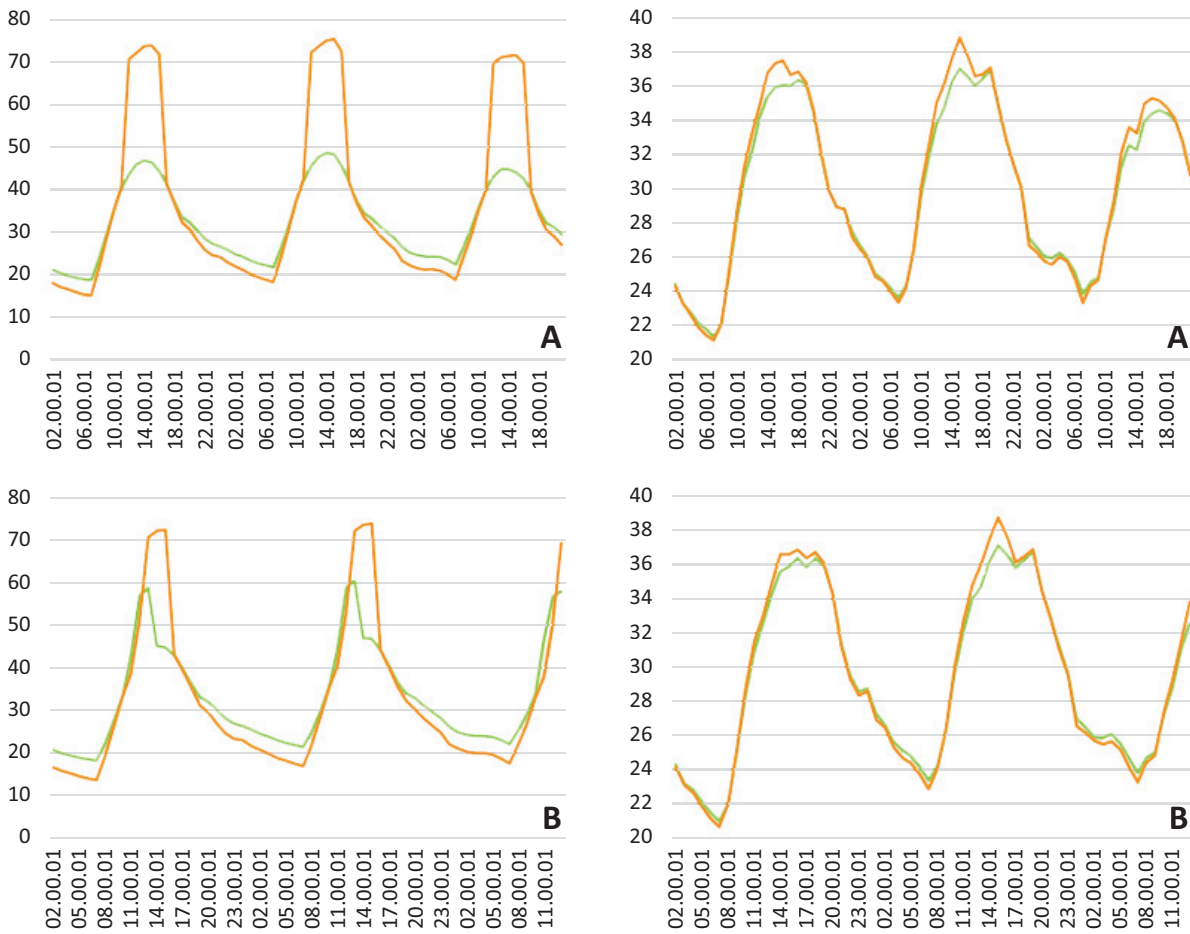
In the projected phase, Point A (Figures 3 and 4) is situated in an area dominated by vegetation and permeable soil (grass and a pathway of compacted sand and gravel). The compacted sand and gravel have no energy storage capacity due to their porous nature, but a high albedo, hence cooling down immediately in the evening (Atelier Parisien d'Urbanisme, 2017). Furthermore, trees cover the area, as well as some perennials. In its existing phase, this area consisted solely of grass and a few trees at its extremities. The simulation results show that there is a 27 °C difference in the MRT measured at 1.5 m during the day, and more precisely from 10 am to 6 pm due to the intervention. The 27 °C delta can be attributed to evapotranspiration and the shading effect of the trees.

During the night, we notice that the MRT in the existing conditions is lower by around 3 °C. This is attributed to the fact that trees have a reverse influence during the night, trapping radiation under their canopies (Perini et al., 2018) and leading to slightly higher nocturnal MRTs. This high reduction in MRTs by around 27 °C between the two cases leads to the intervention state having roughly 2 °C lower PATs at some points during the day. This reduction is directly correlated with the cooling and shading effect stemming from the deployment of the different strata of vegetation.

Point B (Figures 3 and 4) is situated in an area with less vegetation in comparison to Point A. In the existing phase, point B has an asphalt surface and one tree. In the intervention state, Point B has a surface of deactivated concrete with stone inlay, which has a higher albedo than asphalt, as well as additional vegetation on the sides. We notice that, unlike the first case, both the existing and the intervention states receive direct solarisation, with the existing one receiving sunlight between 10 am and 2 pm, and shade from 2 pm onwards; however, due to the intervention state's lower albedo surface, the MRT is reduced by about 12 °C at 1 pm. Between 2 pm and 5 pm, while the existing phase is receiving direct sunlight, the intervention phase benefits from the shading effect of the added trees and thus has an MRT reduced by about 30 °C. Similarly to Point A, this reduction in MRT results in a lower PAT, albeit to a lesser extent, by about 1.5 °C at some points during the day.



**Figure 3.** Comparison of the MRT at 1.5 m elevation between the existing state of the case study and the intervention plan generated on ENVI-met.



**Figure 4.** Comparison between the existing state of the case study (orange) and the intervention plan (green) looking at the MRT and PAT for the duration of the simulation at 1.5 m, generated on ENVI-met. Notes: The left side graphs show the MRT, and the right side shows the PAT; points A and B can be spotted on the map in Figure 3.



To summarise, this difference between the existing and intervention states of the site highlights the importance of the changes implemented. Even though the intervention was mainly based on surficial parameters, its effect was felt with a 30 °C reduction of MRTs during sun hours, creating a more liveable environment for site users to form places to be occupied not to be avoided. In that sense, this intervention increased the liveability of the area and contributed to maintaining the human climate niche at this microlevel.

### 5. Discussion: How to Hierarchise Urban-Heat-Island-Related Interventions

This simulation of the microclimatic and health-related effects of an urban project can be extrapolated to other types of interventions that are within the scope of UHI-controllable parameters (surficial and morphological) and were not adopted in the chosen site.

Therefore, we simulated the potential of water bodies, fountains, morphological transformations, and other surficial transformations such as the use of different types of vegetation. As mentioned beforehand, these microclimates were simulated under similar conditions to the case study, but for a shorter period due to hardware limitations. As such, the results presented here stem from microclimates located in Paris, and simulated under extreme heat conditions for 24 hours, with a mean temperature of 29.3 °C, a maximal temperature of 37.3 °C, and a minimum temperature of 21 °C. Soil temperatures were set at 22.5 °C and soil humidity at 70%.

The simulation provides the possibility to test the cooling potential and consequently the health-related impacts of these various interventions, and to rank them accordingly (Table 1), as detailed in this section. This approach allows us to put the interventions chosen in the site into perspective from a UHI-oriented point of view, and to discuss their contribution to the human climate niche.

**Table 1.** Results of the hierarchisation of the cooling effect (PAT) of all simulated solutions on ENVI-met.

Solution	Description	Measuring point	Cooling potential (PAT)	Remarks
1. Fountains	Size: 8 × 12 m (metres)	10 m (metres) to the side of the fountain	-5 °C	The fountain used for this simulation is a fairly large one, which explains the high cooling effects. Works best in dry climates.
	Results are in comparison to a model without a fountain	20 m to the side of the fountain	-2.3 °C	
	Fountain facing 3 m/s direct winds	70 m to the side of the fountain	-1.5 °C	
2. Pond	Size: 28 × 54 m Depth: 4.5 m Results are in comparison to a model without a pond	1.5 m above water level, taking from the centre of the pond	-2.7 °C	The cooling effect of small and shallow ponds is insignificant. Works best in dry climates.
3. Albedo	Albedo: 0.8 Results are in comparison to a model with an albedo of 0.2	1.5 m above ground level, in an area receiving direct sunlight	-2.1 °C	A very high albedo can increase the mean radiant temperature and decrease diurnal thermal comfort.
	Albedo: 0.5 (red asphalt) Results are in comparison to a model with an albedo of 0.2 (conventional asphalt)	1.5 m above ground level, in an area receiving direct sunlight	-1 °C	
4. Vegetation	4 strata of vegetation Results are in comparison to a model without vegetation and with a surface made of asphalt (albedo 0.2)	1.5 m above ground level	-1.8 °C	Dependent on the essence of vegetation, climate type and nature of soil.
	Results in comparison to a model with grass (one stratum of vegetation)	1.5 m above ground level	-1.5 °C	
	4 strata of vegetation with a soil humidity of 70% Results are in comparison to the same model with soil humidity of 10%	1.5 m above ground level	-1 °C	

**Table 1.** (Cont.) Results of the hierarchisation of the cooling effect (PAT) of all simulated solutions on ENVI-met.

Solution	Description	Measuring point	Cooling potential (PAT)	Remarks
5. Maximising wind penetration	Windspeed = 6 m/s Results are in comparison to a model with windspeeds of 3 m/s	1.5 m above ground level	-1.5 °C	Dependent on the rugosity of the urban morphology.
	Streets with maximum wind penetration (parallel to the dominant winds) Results are in comparison to a model with minimal wind penetration (perpendicular to dominant winds)	1.5 m above ground level	-0.4 °C	
6. Morphology / aspect ratio	Aspect ratio: 1.6 Results are in comparison to a model with an aspect ratio of 0.85	1.5 m above ground level	-1.2 °C	The cooling potential can be attributed to the shadows cast by the urban morphology. However, the model with a 0.85 aspect ratio cools faster during the night, reducing in turn the intensity of night-time UHI.
7. White roofs	Albedo: 0.8 Results in comparison to a model with an albedo of 0.5	1.5 m above roof level	-0.5 °C	The cooling effect is only felt at roof level and does not contribute to the cooling of the streets below.
8. Green roofs	Substrate: 30 cm + Shrub stratum (intensive) Results are in comparison to a model with a roof albedo of 0.5	1.5 m above roof level	-0.5 °C	Provides additional benefits such as better insulation for the whole building, and better rainwater management.
	Substrate: 30 cm (intensive without shrubs) Results are in comparison to a model with an extensive green roof (15 cm substrate)	1.5 m above roof level	-0.3 °C	
	Substrate: 15 cm (extensive) Results are in comparison to a model with a roof albedo of 0.5	1.5 m above roof level	-0.3 °C	
9. Green wall	Green wall on southern elevations of buildings (ivy plant) Results are in comparison to a model with no green wall	1.5 m above ground level and 2 m away from the wall	-0.4 °C	The cooling effect is only reserved in front of the wall. Provides additional benefits for the building.

### 5.1. Water bodies and Fountains

According to our simulations, the evaporative cooling of fountains yielded the highest delta between a base scenario urban setting and the same model with a 4 × 4 m fountain in the centre of the square. When measured 10 m away from the fountain, the cooling effect is -5 °C. This cooling effect is only local as it becomes negligible further than 20 m from the radius of the fountain under

0.8 m/s winds. However, when the fountain is placed in a strategic position facing winds of 3.2 m/s, the cooling effect persists more than 70 m away (cooling of up to -1.5 °C) and is -2.3 °C at 20 m.

In fact, fountains cool the air using a different mechanism than that used by ponds. While both use evaporation to cool the ambient air, fountains mechanically release aerosols into the air, acting similarly to mist machines. According to Atelier Parisien d'Urbanisme

(2014), the effectiveness of induced evaporation is greater than that of natural evaporation. Ponds and lakes are also effective when it comes to reducing ambient temperature, albeit less so than fountains. The cooling effect of ponds is correlated with their size and depth. Our simulations show that a 28 x 54 m pond with a depth of 4.5 m reduces ambient air temperatures by 2.7 °C when measured at 1.5 m above it, and by 1 °C at 20 m away (Figure 5).

Due to the water’s thermal inertia, the same mechanism that cools the surroundings during the day, as water takes more time to heat up, acts in reverse at night, as the water body takes more time to cool, making it warmer than the ambient air surrounding it. This mechanism implies that water bodies may actually enhance nighttime UHIs (Jacobs et al., 2020). Furthermore, water bodies are the most effective in dry climates, yet can become controversial in certain configurations when accessibility to water resources is highly constrained.

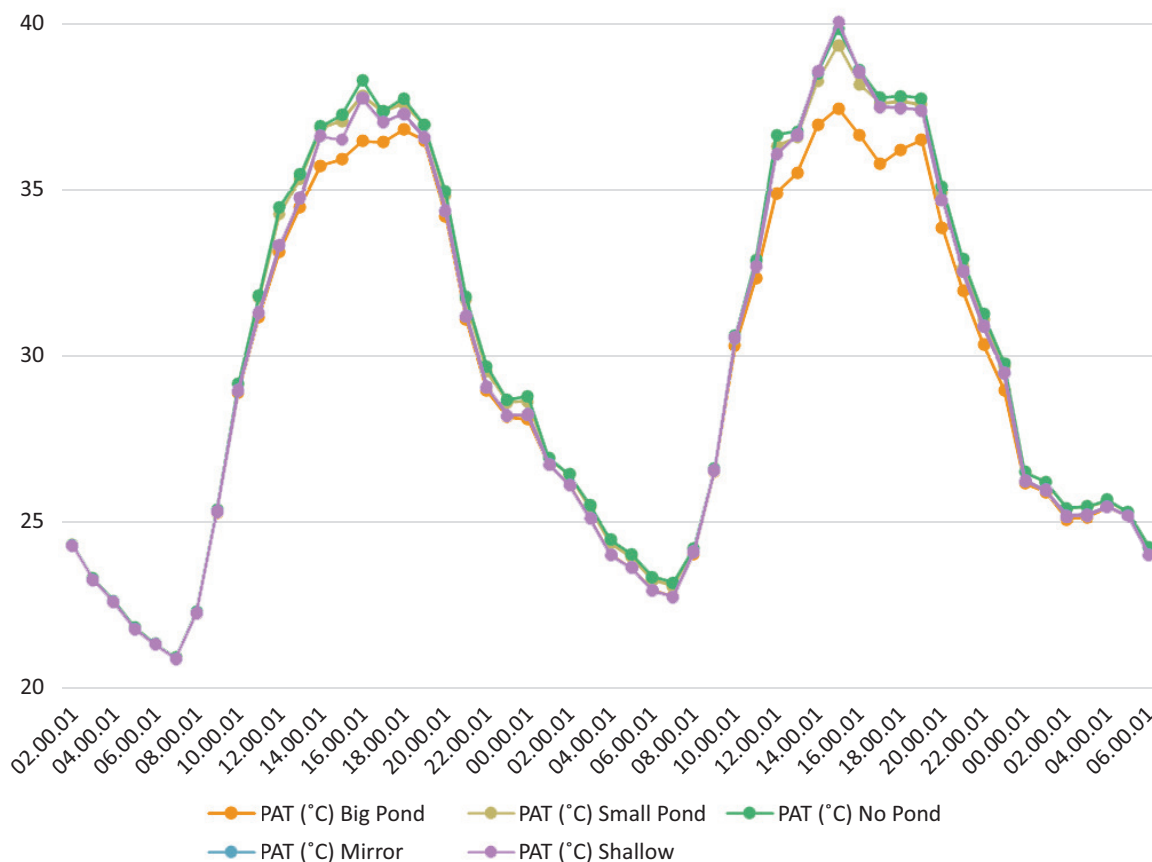
### 5.2. Morphological Transformations

Morphological parameters are highly influential in the formation of UHI. However, implementing solutions for

urban morphology entails important economic and temporal burdens, which largely explains why cities often opt for easier and cheaper solutions. Nonetheless, transforming buildings to better withstand extreme temperatures reduces the effects of heat stress on the human body. Creating openings in dense morphologies helps with airflow circulation, which dissipates heat and prevents urban canyons from becoming hot spots (Santamouris et al., 2004). Our simulations show that under West European climatic conditions such as those in Paris, a 3 m/s increase in wind speed cools down air temperature by -1.5 °C. Furthermore, a street that is parallel to the dominant winds recorded temperature deltas of -0.4 °C in comparison to a street that is perpendicular to the same dominant winds. These findings agree with the results of previous studies like Giannaros and Melas (2012) or Atelier Parisien d’Urbanisme (2017), according to which a 10 m/s increase in wind speed is correlated with a -3 °C reduction in temperature felt.

### 5.3. Vegetation

Planting vegetation is a conventional solution that cities have been implementing to mitigate UHI. Trees cool the



**Figure 5.** Comparison of the influence of waterbodies on the PAT, depending on size and depth using ENVI-met software. Notes: Pond dimensions—Big pond (28 m wide × 54 m long × 4.5 m deep), small pond (8 m × 14 m × 4.5 m), shallow pond (28 m × 54 m × 0.5 m), and mirror pond (28 m × 54 m × 0.04 m).

air by evapotranspiration and by blocking shortwave radiation, letting only 20% through and providing shade in return (Atelier Parisien d'Urbanisme, 2017). A tree in full leaf can block up to 95% of incoming radiation (Santamouris et al., 2004). However, the effectiveness of tree cooling relies on the species used, the way it was planted, the location in which it was planted, and the number of strata used. A deciduous tree can emit up to 375 kg of water per day through evapotranspiration, which is equivalent to an energy consumption of 870 MJ, or the cooling effect of five air conditioners during 20 hours in a hot and dry climate (Santamouris et al., 2004). According to our results (Figure 5), the cooling effect of four strata of vegetation (arborescent, shrub, herbaceous, and muscular) is  $-1.8\text{ }^{\circ}\text{C}$  in comparison to a model with asphalt instead of vegetation, and  $-1.5\text{ }^{\circ}\text{C}$  in comparison with one stratum of vegetation. The interest in biodiversity lies in the diversification of spaces with more or less developed vegetation strata. By creating a mosaic of vegetation, the ecosystem becomes considerably more complex, and the richness of flora and fauna increases. The use of several vegetation strata favours evapotranspiration and refreshes the urban climate (LPO Isère, 2019).

One downside stemming from the implementation of tree solutions is the fact that they might impede wind flows (Atelier Parisien d'Urbanisme, 2017). This is correlated to the shape and size of the leaves. For example, coniferous trees facilitate wind circulation more than broadleaved trees due to their narrower shape (Choi

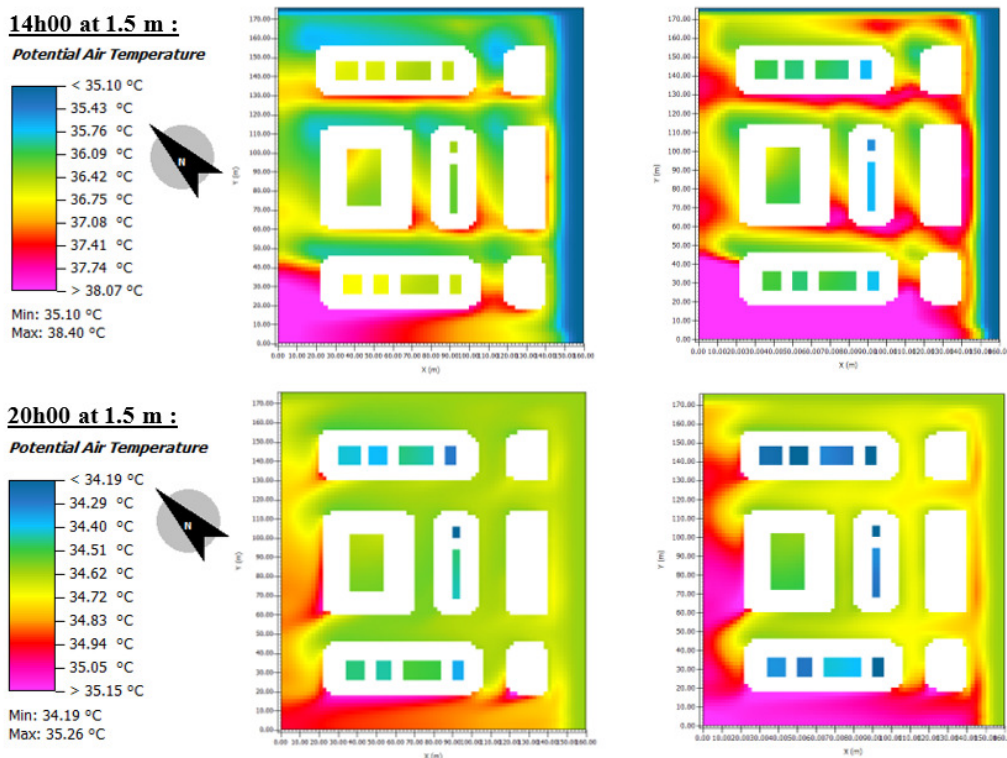
et al., 2021). This parameter is the most impactful when treating an urban canyon, since wind flow is already obstructed as it is, even before the implementation of tree solutions. Additionally, the cooling effect of vegetation is directly correlated with soil humidity. Our simulations show that a decrease of 60% in soil humidity reduces the cooling effect of trees by  $0.2\text{ }^{\circ}\text{C}$ . This explains why it remains important to have more pervious surfaces, and single continuous pits for trees all along pavements (Atelier Parisien d'Urbanisme, 2017).

#### 5.4. Changing the Albedo of Surfaces

Increasing the albedo of surfaces is another conventional solution already implemented in numerous cities worldwide, like Chicago, Zenata, Tokyo, etc. (ADEME & Agence Française de Développement, 2021; Mackey et al., 2012). A lighter surface absorbs less radiation than a darker one, reflecting it as longwave radiation. This phenomenon helps reduce air temperature. According to our simulations (Figure 6), an increase of albedo from 0.2 to 0.8 reduces air temperatures by  $-2.1\text{ }^{\circ}\text{C}$ .

Illustratively, the figure above shows the cooling effect correlated with the use of red asphalt (albedo of 0.5) instead of conventional black asphalt (albedo of 0.2). The cooling potential of the red asphalt material is  $-0.3\text{ }^{\circ}\text{C}$  in the shade, and  $-1\text{ }^{\circ}\text{C}$  when not shaded.

However, as more light is reflected by the surfaces, MRTs increase when the albedo of a material increases. As such, these high albedo materials strongly reflect

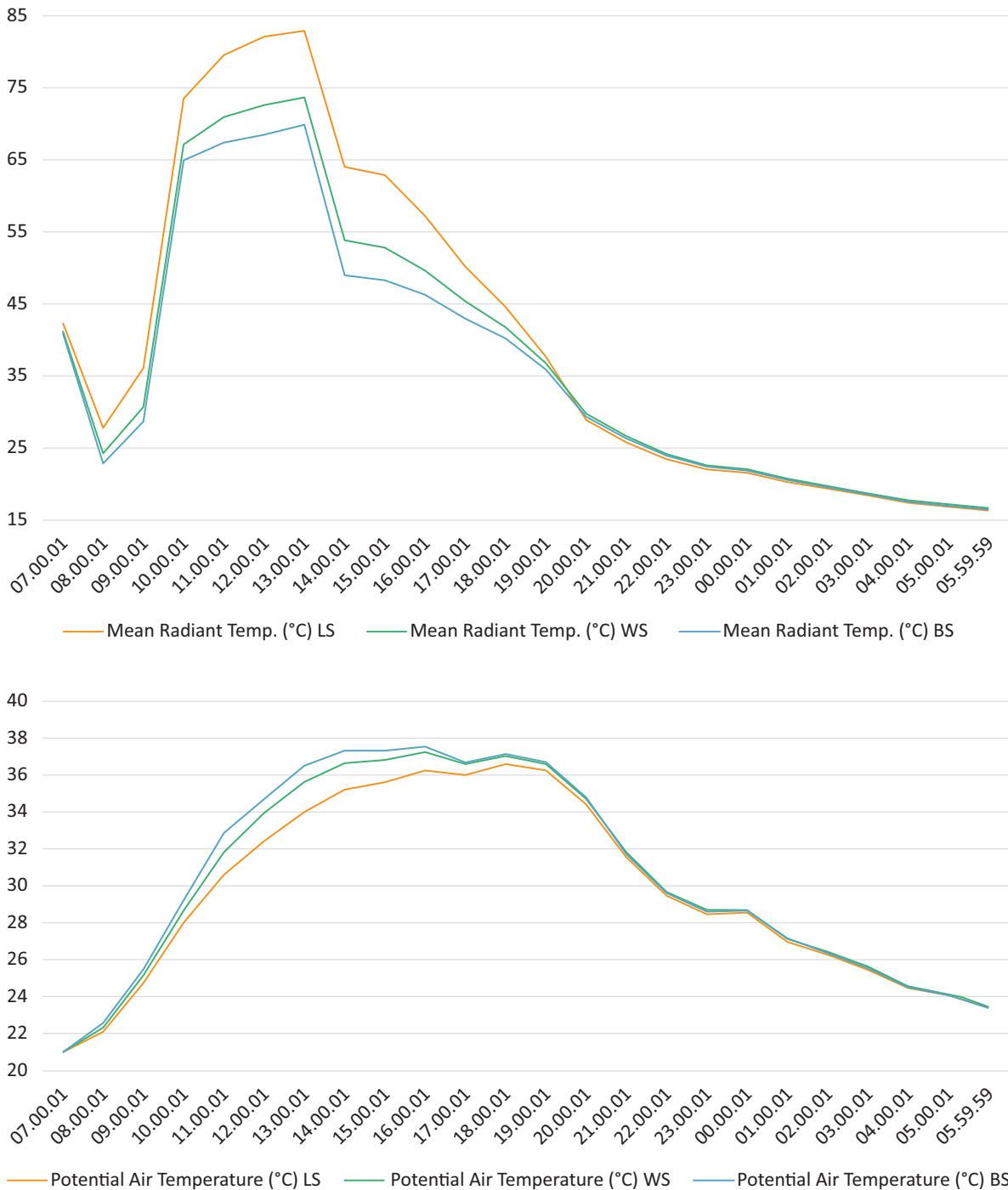


**Figure 6.** Comparison of the influence of red asphalt (left side) and black asphalt (right side) on the PAT at 2 pm and 8 pm using ENVI-met software.

sunlight at the expense of thermal comfort. The reflected solar energy dazzles pedestrians and heats them with twice the solar radiation (Atelier Parisien d’Urbanisme, 2017). Hence, in this case, the reduction in PAT is also associated with an increase in MRT by 20 °C (Figure 7). In fact, by increasing the albedo by 0.1, the physiological equivalent temperature increases by 0.8 °C (Crank et al., 2018). Coupling a higher albedo with tree canopies to shade blocks receiving solar radiation reduces the MRT by 30 °C, ensuring better pedestrian thermal comfort

during the day. In turn, the whiter surfaces accumulate less heat (from shading and from the higher albedo), which reduces the intensity of night-time UHI.

Roof solutions, especially the increase of albedo for roof surfaces, are a quick and cheap fix widely implemented in many cities. Chicago brought in policies that saw a conversion from normal roofs to white roofs associated with an area of 271 km<sup>2</sup> between 1995 and 2009. The results of these policies showed that reflective roofs produced the most intense cooling, as well as



**Figure 7.** Comparison of the influence of surface albedo on the PAT for an entire day of simulation using ENVI-met software. Notes: LS = light surface (albedo = 0.8), BS = black surface (albedo = 0.2), WS = wet surface (albedo = 0.4).

the greatest amount of cooling for the smallest amount of money invested (Mackey et al., 2012). According to our simulations, the cooling effect of white roofs (albedo of 0.8) in comparison to a base scenario (albedo of 0.5) is  $-0.5^{\circ}\text{C}$ .

Opting for a green roof is a more expensive solution, but an effective one nonetheless, with regard to temperature. Our simulations show a cooling effect associated with green roofs of  $-0.5^{\circ}\text{C}$  for intensive green roofs (30 cm + substrate with shrubs), and  $-0.3^{\circ}\text{C}$  for extensive green roofs (15 cm substrate). Furthermore, additional benefits span from green roof solutions such as better insulation and thermal comfort for the building and its occupants, better rainwater management, and more space for biodiversity to flourish inside the city. However, results also show that the cooling effect stemming from roof solutions is only felt at the roof level and does not impact the street below, reducing its contribution to healthier urban planning and an increase of the human climate niche.

The health-induced effects of these various interventions cannot be directly measured through these microclimatic simulations. Yet, various works like Di Napoli et al. (2018) have shown that an improvement of MRT and PAT is associated not only with mitigation of UHIs but also with better physiological responses to heat and a diminished risk of heat-related diseases.

## 6. Conclusive Discussions on Urban Heat Island Urban Interventions and Urban Arbitrages

The solutions suggested in this article to mitigate both the UHI effect and its health-related impacts are based on microclimatic modelling and are highly, if not solely, focused on the possibilities of lowering these effects. Their contribution to an area's liveability is thus thought of almost exclusively from a temperature-oriented perspective. Our simulations have shown that some urban planning options could be quite advantageous within this framework: In this regard, water bodies are highly effective in cooling the ambient air, with a cooling potential of  $-2^{\circ}\text{C}$  and greater in some cases. Yet this capacity is also dependent on the size of the water body and is most effective in dry climates. However, one should keep in mind the situatedness of the intervention to adequately grasp the climatic variability and the contribution of the various options, which can differ from the one presented here in other climatic conditions.

The simulations produced in this article also demonstrate the interest in associating urban planning interventions with a clear and quantified measure of their effect on temperature: This should help enrich decision-making processes when developing projects under the umbrella of healthy urbanism and could be of utmost importance to adapt urban environments to the acceleration of climate change. Combining the various solutions presented in several zones within the city should help limit the intensity of UHI during heat waves. The areas

of intervention can register air temperature cooling ranging between  $-2$  and  $-5^{\circ}\text{C}$ , proving to be highly desirable shelters for the community. In large cities where UHI intensity can reach  $10^{\circ}\text{C}$  in extreme cases, local cooling shelters can reduce UHI intensity by half in the best cases, thus enlarging, even though mostly at microlevel, the human climate niche in the process.

Yet it is important to mention that this study voluntarily disregarded some other major elements influencing urban interventions, and specifically economic ones: UHI-related urban planning solutions were not discussed here in terms of economic feasibility. The simulations should be considered here predominantly as tools for decision-makers and instruments for urban arbitrages for healthy urban planning; they have a socio-political dimension, linked to their sanitary contribution, which should be taken into account in long-term perspectives and in ways that solely the economic cost of installation will be unable to correctly grasp. They obviously need to be combined with additional elements to target vulnerable locations and populations to make the interventions as healthy and fair as possible.

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## Conflict of Interests

The authors declare no conflict of interests.

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