288 THE IMPACT OF BUILT FORM ON THE URBAN MICROCLIMATE AT THE SCALE OF CITY BLOCKS

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ABSTRACT

Following the first oil crisis, Philip Steadman concluded that as a result of the twentieth-century developments in architecture "the means for environmental control within and around buildings, which was formerly achieved through effects of mutual shading, enclosure and wind protection, [were] lost" (Steadman 1975). Nevertheless, subsequent building regulations further strengthened the already prevailing design emphasis on single buildings by introducing energy measures that largely disregarded the effects of the surrounding environment [of the local climate]. While in countries with mild to moderate climates wintertime energy conservation became the primary preoccupation, climate model projections indicate rising temperatures and prolonged heat waves in these parts of the world. As a consequence, architects and planners increasingly find themselves ill equipped to address the challenges of climate change.

The aim of this paper is to assess the microclimate performance of built form at the scale of city blocks. The study takes four metropolitan urban block typologies from Budapest as models. The purpose of this analysis is to obtain basic understanding regarding the interaction between built forms and microclimates in general, and to gain knowledge regarding the microclimatic behavior of these existing typologies in particular. The understanding of the performance of these forms is necessary both for developing climate-sensitive design principles and for proposing effective climate mitigation strategies.

The comparative numerical simulation study utilizes ENVI-met and MATLAB. The models are compared on the basis of diurnal air temperature, mean radiant temperature and Predicted Mean Vote cycles. The analysis found mean radiant temperature a good indicator of the built form's influence on the canopy layer thermal environment. It is sensitive to directionalities in the model and signals problematic periods and places with high surface and air temperatures. Consequently, mean radian temperature that governs outdoor thermal comfort on warm and hot days is also useful to analyzing and understanding the effects of mutual shading.

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1. INTRODUCTION

Regional climate simulations for Hungary revealed a continuing trend of temperature increase (Bartholy, Bozó, and Haszpra 2011). Compared to the base climate of 1961—1990, the mean annual temperature rise in the near future (2021—2050) is projected to remain between 1—2°C, whereas by the end of the century a 3—4°C rise is estimated (Horányi 2011). Summer is expected to experience the largest temperature increase: 1.7—2.6°C in the near future and 3.5—6.0°C in the distant future. Compared to other seasons, summer projections also carry the greatest uncertainties (Bartholy and Pongrácz 2011). Regarding extreme temperature events, warm events (such as the number of heat waves, summer, hot and extremely hot days) are expected to rise, while the number of frost days will diminish (Bartholy and Pongrácz 2011).

Given these projections and the profession's preoccupation with single buildings and wintertime energy conservation, architects and urban designers increasingly find themselves ill equipped to address the challenges of climate change. In light of these, the aim of this paper is to investigate the effect of built from on the urban microclimate by means of numerical simulation, and consequently to explore new avenues to re-learning the role of mutual shading.

2. MATERIALS AND METHODS

The methodological approach adopted in this study consists of three steps. During the first, the digital models of selected cases are developed. Then, local climate characteristics and required weather parameters for the simulation are selected. Finally, the numerical models are run and the results analyzed. This study utilizes ENVI-met for microclimate simulations and MATLAB for the analysis and visualized of the results.

2.1. Model domain and data

Based on literature review and map studies, four urban block typologies were identified for the study: the nineteenth-century configuration of attached courtyard apartment buildings, the perimeter block, the Zeilenbau design (or linear blocks), and the hybrid form with short towers on a unifying base (see Figure 1). These typologies represent the main stages in the two-decade-long development of urban block configurations in Budapest. Their corresponding digital models were adapted to ENVI-met (see Figure 2). Each model consists of nine identical urban blocks arranged in a three-by-three grid layout, which are separated by 18 m wide roads. The rectangular urban blocks have a size of 78 m x 150 m. The heights of the buildings are set to 24 meters uniformly in all typologies, except for the base in the hybrid configuration, which is set to 6 meters. The mode resolution is 6 m horizontally and 3 m vertically. Walls and roofs have 1.1 W/m2K heat transmission coefficient, and a 0.4 albedo. Regarding ground surface materials, gravel asphalt was assigned to roads, whereas within urban blocks the areas not covered with buildings were left unsealed as silt-loam soil. Besides the effect on built-form, the influence of orientation is also evaluated by rotating the typologies 90° counterclockwise in 30° increments. During these simulations all parameters were kept constant, except for the wind direction, which followed the rotation of models and therefore retained its relative direction.

Since the study focuses on the summertime performance of urban block typologies, the climate conditions adopted in the baseline model are represent to a typical July day in Budapest. The climatic data needed to configure ENVI-met were obtained from the literature (Bacsó 1959; Réthly 1947). July 7th was selected as the start date of the simulation. Since the above sources lacked data on the diurnal distribution of hourly mean solar radiation in July, characteristic values were derived from METEONORM (METEOTEST 2009). In the course of a brief analysis, hourly solar radiation values of clear sky days with daily mean temperatures close to that of the typical July day identified by Bacsó (1959) were examined. Consequently, the adjustment factor within ENVI-met was set to closely reproduce the shortwave radiations patterns identified by the analysis. Using the monthly mean values of July (Bacsó 1959), wind speed and direction values were set to 2.8 m/s and to northwest, respectively. The source of ground temperature was also Bacsó (1959). Due to the lack of soil humidity data, relative ground humidity values were determined through a trial-and-error approach.

Figure 1: The block of courtyard apartments, the perimeter block, the Zeilenbau configuration and the hybrid block (Google Maps 2010)

Figure 2: The model equivalents of the four typologies: T1, T2, T3 and T4

2.2. Method of analysis

Simulations started at the first hour of July 7th and run for 48 hours. In order to avoid errors due to model start-up only second-day results were analyzed. Furthermore, the analyses were limited to the canopy air above the central block, where the canopy height was set at 24 meters (the uniform height of buildings within the domain). The reason for introducing spatial boundaries is twofold. On one hand, disregarding the surrounding eight blocks within the three-by-three layout reduces edge effects. On the other hand, since the aim of the study is to reveal the effect of built form on the climate within the urban block, eliminating the effect of streets, in addition to the peripheral blocks, was evident.

In order to manage the spatial and temporal complexity characteristic to urban microclimates, a simple method utilizing areal averages is introduced. The concept is briefly illustrated on Figure 3. The left image shows the extracted canopy from the central block. The next graph to its right is an isolated horizontal section (showing temperatures values at a given height and time) from which a median value is calculated. Once this procedure is repeated for each height in a given time step, the obtained values are assembled. The result is a stack of cells, were the vertical order of air layers is retained and the magnitude of the suited parameter is indicated by colors (see third image from left in Figure 3). If such stacked values are produced for every time step and aligned horizontally, the outcome is a patchwork of colored cells, as seen on the right side image in Figure 3. When representing the results, MATLAB's pseudocolor plot is used with interpolated shading to smoothen out the large time steps used in simulations.

This method's advantage is that while it simultaneously reveals characteristic conditions across the entire depth of the canopy, it also retains the relative position of adjacent air layers. Justification for this approach can be made on two grounds. First, it provides feedback on the microclimatic effect of buildings across the entire canopy. Second, given that humans in urban environments are generally exposed to several microclimates in a short period of time, median values calculated over a reasonably sized area at the street level could serve as a 'quick-and-dirty' method to evaluating comfort conditions,.

Besides the areal averages method, urban heat island (UHI) magnitudes and diurnal temperature range (DTR) reductions are also calculated. These parameters are difference measures generally computed against a rural reference stations in field measurements. In this study, the baseline model that consisted of no buildings and was configured to mimic the conditions of a typical summer day in Budapest served as reference. Although urban heat island magnitudes are generally recorded 2 meters above the ground, values reported in this study refer to volumetric medians calculated for the theoretical canopy section above the central block. Besides nighttime heat island magnitudes, daytime ‘cool island’ values are also reported. The diurnal temperature range (DTR) reductions, which is the difference between the daily temperature range measured at the reference station and in an urban setting, is also calculated as a volumetric median for the canopy section, using the baseline model as reference.

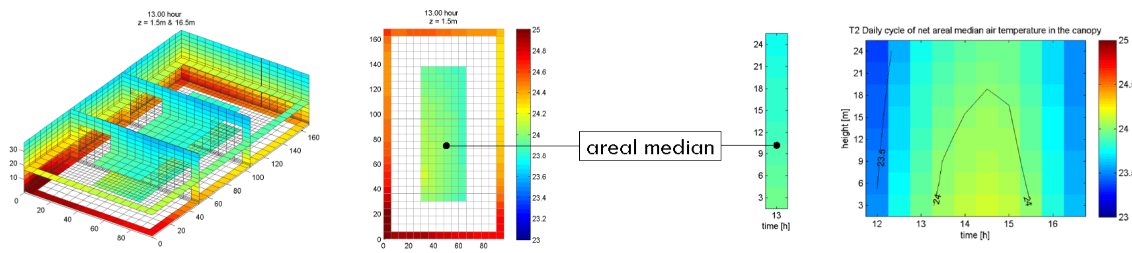

Figure 3: The method of producing pseudocolor plots from areal median air temperature values

3. RESULTS AND DICUSSIONS

3.1. The influence of form

The easiest way to summarize the diurnal differences between the four configurations by means of urban heat island (UHI) magnitudes and diurnal temperature range (DRT) reductions, as presented in Figure 4. DTR reduction in the canopy is the least in case of the Zeilenbau (T3) configuration, whereas in case of the other three densely built-up typologies it is nearly 3°C (see the left graph on Figure 4). Additional differences between the configurations are signaled by the night and daytime UHI magnitudes (see center and right graphs on Figure 4). According to the heat island measures the diurnal temperature cycles of T1, T2 and T4 are offset by about 0.3°C: the warmest configuration is T4 and the coolest is T1. The distinctions between the denser configurations reveal that the DTR reduction does not necessarily occur symmetrically around the daily mean temperature, and that the generally reported nighttime UHI does not mean a uniform increase in the canopy air temperature, but can occur parallel with daytime ‘cool island’. In this respect, T1 compared to T4 not only provides greater protection from daytime extreme temperatures by about 0.7°C, but also remains nearly as much cooler at night.

In order to gain insight to the vertical distribution of climatic conditions, pseudocolor plots of various areal median climate parameters are presented in the following four figures. Figure 5 displays diurnal air temperature values. The plots are in line with previous observations: the highest daytime and the lowest nighttime temperatures are observed at the Zeilenbau configuration (T3). In case of the spatial-temporal distribution of air temperature, relative values to the baseline condition are more telling (see Figure 6). This comparison reveals that typologies remain warmer at night and cooler at day than baseline configuration to a varying extent. The nighttime cooling is greatest at T3 configuration, which provides the best conditions for both radiative and convective cooling. However, the low density and openness of the configuration that facilitates nighttime cooling also contribute to greater daytime temperatures: the well-exposed surfaces increase higher surface temperatures, while the lack of courtyards ensure that the warm air remain well-mixed and distributed relatively evenly within the canopy. In contrast, at the denser but still open configuration (T4) the mutual shading of towers ensures lower daytime temperatures, but still results in warmer nighttime conditions. The daytime cooling effect is strongest in case of courtyard typologies (T1 and T2), perhaps because the heavier cold air of courtyards remain separated from the well mixed, but warmer air of the street.

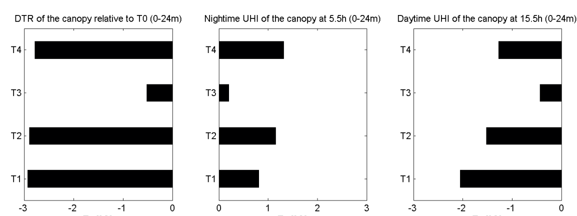

Figure 4: DTR reduction, day- and nighttime UHI magnitudes for all four typologies, calculated relative to the baseline condition

Figure 7 presents the pseudocolor plots of areal median MRT values for all configurations. The differences between the four graphs demonstrate the effect of spatial configurations on the radiant temperature within the canopy. The tapering in MRT plots indicates the effect of mutual shading, or radiation obstruction, which decrease with increasing sun angles. As it is expected, configurations with large open areas (such as T2 and T3) have the highest MRT values. In case of T4, the interference between the towers results a characteristic MRT pattern with a slight slump around noon. The icicle shape pattern of T1 marks the average time and extend when solar radiation reaches down the tiny courtyards. The rather symmetrical MRT plots are the result of spatial symmetries in all four typologies and the special alignment of models with cardinal directions. The PMV pseudocolor plots, presented on Figure 8, are dominated by the MRT. The main difference between the PMV and MRT pattern is that comfort extremes have shifted slightly to the right, as a result of the nearly two hour lag between the temperature and solar radiation cycles.

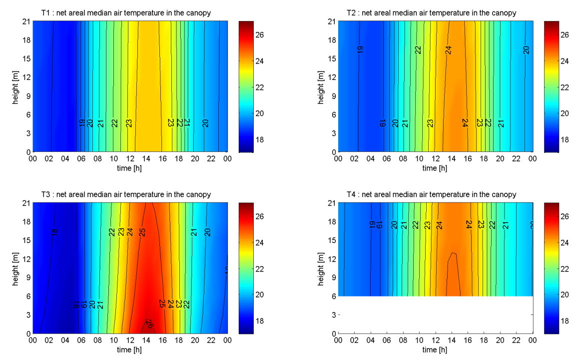

Figure 5: The diurnal course of areal median air temperatures within the canopy, calculated for all four typologies

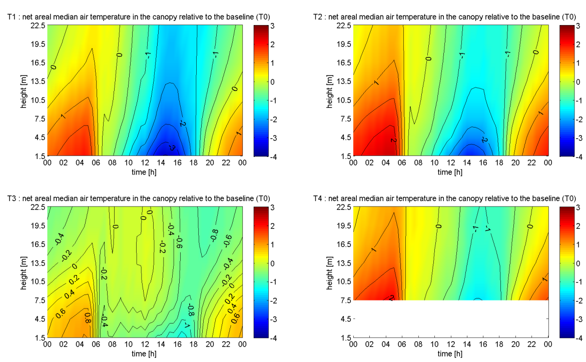

Figure 6: The diurnal course of relative areal median air temperatures within the canopy, calculated for all four typologies relative to the baseline condition

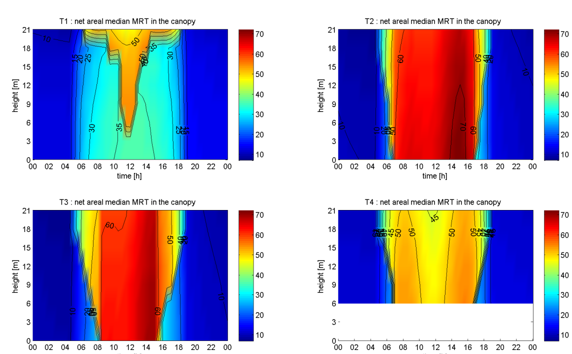

Figure 7: The diurnal course of areal median MRT within the canopy, calculated for all four typologies

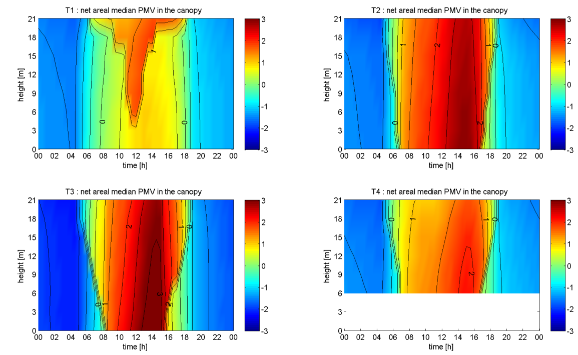

Figure 8: The diurnal course of areal median PMV within the canopy, calculated for all four typologies

3.2. The effect of orientation

The orientation study, were the four models were rotated 90° counterclockwise at 30° increments, resulted twelve additional configuration. In order to quickly assess the cases, the results are presented in reference to the baseline condition by means of boxplots. Figure 9 shows the potential air temperature, MRT and PMV differences calculated for theoretical canopy sections for the entire diurnal period. Based on the top graph that illustrates changes in air temperature, different orientations have little to no effect on the typologies' temperature distribution. In case of the densely built up configurations, model rotation results slight reductions in air temperatures. Here, lowest temperatures occur at 60°, from which point on temperatures start to rise again. In contrast, model rotation result a continuous temperature rise in T3. Overall, the effect of orientation is greatest in case of configurations with large, unshaded open spaces (e.i. T2 and T3). Here, the difference between the warmest and coldest diurnal canopy median temperatures exceeds 0.4 °C.

The middle graph on Figure 9 presents the influence of orientation on the relative MRT values. Owing to the evenly distributed building masses in case of T1 and T4, mean radiant temperatures are hardly affected by different exposures. In contrast, the radiant temperatures of the other two configurations exhibit strong orientation dependence: with rotation T2's values shift towards the negative end (indicating more shading), while an opposite trend is true for T3. In both cases the median values are slightly above zero, which indicate that in comparison to the baseline configuration the greater part of T2 and T3 increased little to none during the analyzed diurnal period. Changes primarily affect the lower half of dataset, signaling changes in the pattern and extent of shading. The common characteristic of these configurations is the presence of large, open spaces. In these typologies, the trends of mean radiant temperature owing to model rotation, correspond well with the orientation of rectangular open spaces: they peak when the squares are aligned along the east-west axis. The effect of orientation on the human thermal comfort index (PMV) relative to the baseline condition concludes this analysis on the bottom graph of Figure 9. The results reflect the combined influence of the air and mean radiant temperatures, above discussed.

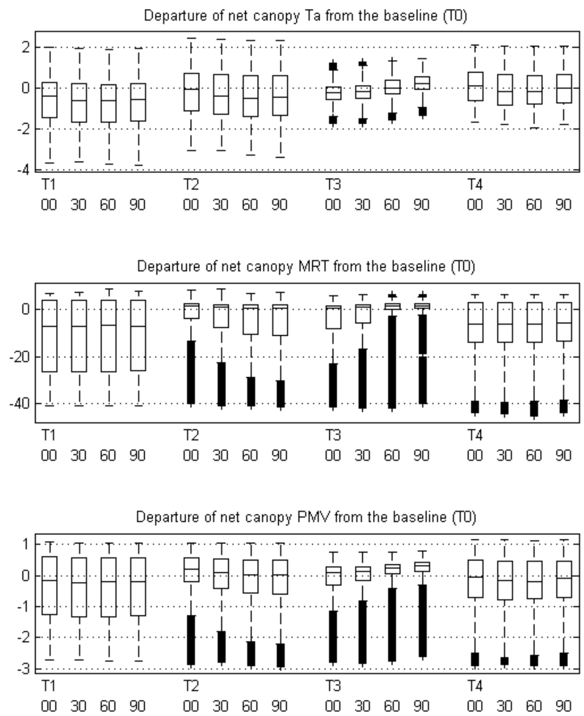

Figure 9: The influence of orientation on the diurnal canopy layer microclimate, presented as divergence from baseline values (top air temperature, middle MRT and bottom PMV)

The cardinal changes in the diurnal temperature cycles owing to different exposures are presented by means of DTR reduction and UHI magnitudes on Figure 10. Similarly to the results above, the bars indicate that orientation have little effect on denser configurations with well distributed building masses. Here, the lowest diurnal temperatures cycle occurs at 60° rotation. In contrast, T3 has a gradually increasing temperature trend with decreasing DTR reduction, growing nighttime heat and diminishing daytime cool island. In general, model orientation results greater or lesser changes, but it does not affect the relative ranking of typologies.

In the remaining part, the influence of orientation will be presented typology T1 in detail. The pseudocolor plots of median temperatures at different orientation and relative to the baseline condition are shown on Figure 11. With model rotation, the daytime cooling effect extends vertically across the canopy, while the nighttime heat island effect decreases slightly and reaches the lowest point at 60°. The role of directionalities in the model is best illustrated by the pseudocolor plots of radiant temperatures (see Figure 12. With each 30° rotation, MRT peak occurs about half an hour earlier, until it disappears at 90°. The thermal comfort pseudocolor plots on Figure 13 the combined effect of potential air and mean radiant temperatures.

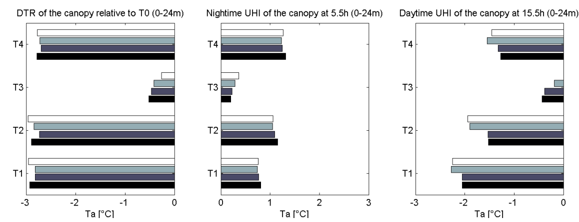

Figure 10: Canopy layer DTR reduction and day- and nighttime UHI magnitudes relative to the baseline condition calculated for all four orientation. The bars from the bottom up indicate: black 0°; dark gray 30°; light gray 60°; white 90°.

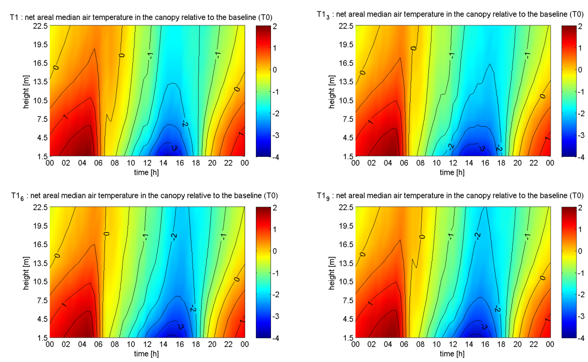

Figure 11: The diurnal course of T1's areal median air temperature relative to baseline condition calculated for all four orientations

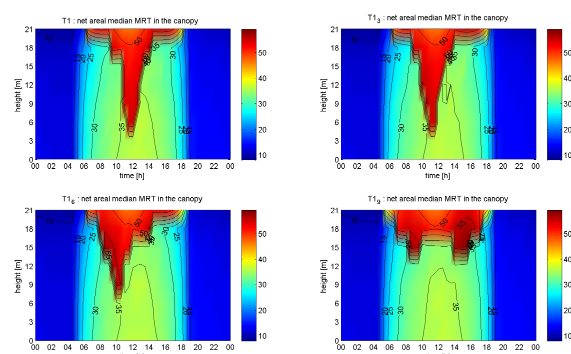

Figure 12: The diurnal course of T1's areal median MRT calculated for all four orientations

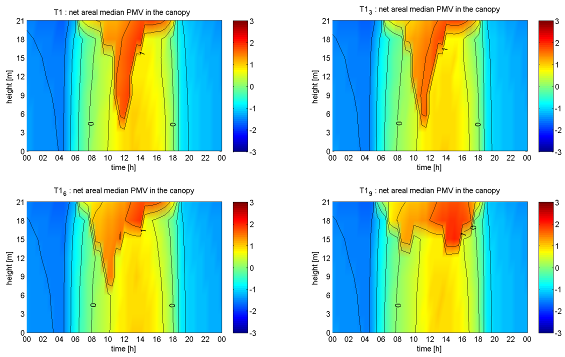

Figure 13: The diurnal course of T1's areal median PMV values calculated for the canopy layer at all four orientations

4. CONCLUSIONS

A numerical simulation study was undertaken to investigate the effect of built form and orientation on the microclimate within urban blocks. Four urban block typologies rotated 90° counterclockwise in 30° increments were compared in this paper. The analysis found mean radiant temperature a good indicator of the influence of built form on the canopy layer thermal environment. It is sensitive to directionalities in the model and signals problematic periods and areas with high surface and air temperatures. Based on findings, at uniform building height the key spatial parameters governing the urban microclimate are the site coverage (or building plan area fraction), the openness of the configuration (i.e. the presence or absence of courtyards) and the distribution of building masses. The study also found that the effect of built form is more decisive than orientation, especially at configurations with high site coverage and evenly distributed buildings. In case of typologies with large open squares (T2, T3), increased temperatures are shown to correspond with the east-west alignment of the rectangular spaces. The influence of smaller directionalities in configurations, such as those of tiny courtyards in T1 configuration, are rather limited and are best revealed by fine scale analyses.

The evaluation of ENVI-met's performance by means of a short-term air temperature and humidity measurement is currently on its way. However, due to the model's limitation to account for the heat stored in building materials and due to the assumptions made in MRT calculation (Ali-Toudert 2005; Huttner 2012; Kántor and Unger 2011) the presented results should be treated as indicative rather than conclusive. Despite its shortcomings, ENVI-met is currently the only numerical model to the author's knowledge that is designed for the simulation of urban microclimates, and allows for a thorough analysis of canopy layer conditions.

Controlling the radiative environment within the canopy is shown to be a key strategy in mitigating the UHI effect and reducing the human heat stress (Ali-Toudert and Mayer 2006; Ali-Toudert et al. 2005; Emmanuel 2005; Emmanuel, Rosenlund, and Johansson 2007). Furthermore, it has been demonstrated that for combating rising summertime temperatures the reduction of radiation fluxes is far more beneficial climate adaptation strategy than the modification of the wind environment (Matzarakis and Endler 2009). Consequently, given mean radiant temperature's connection to human comfort, surface temperatures and indirectly to building energy use, the analysis of the canopy layer radiative environment offers a viable approach in developing effective climate adaptation strategies for various urban environments.

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