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A hybrid Python approach to assess microscale human thermal stress in urban environments

Mansoureh Gholami [a], Ariane Middel [b], Daniele Torreggiani [a], Patrizia Tassinari [a], Alberto Barbaresi [a,*]

[a] Department of Agricultural and Food Sciences University of Bologna, Italy

[b] School of Arts, Media and Engineering School of Computing and Augmented Intelligence Arizona State University, United States

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ABSTRACT

Microclimate simulations are in high demand to assess the thermal impacts of urban design and vegetation changes. Modeling accurate microclimate dynamics in complex urban settings requires extensive computing power. A hybrid Python approach is introduced to simulate human thermal exposure (mean radiant temperature, MRT) and comfort (Universal Thermal Climate Index, UTCI) in cities. The proposed model combines various engines in Rhinoceros to account for interactions between urban surfaces, tree canopies, and the atmosphere. The model was validated in hot, dry Tempe, USA, using in-situ human-biometeorological observations and then applied to urban archetypes in Bologna and Imola, Italy. MRT and UTCI were simulated at five sites in Bologna, four in Imola, and four in Tempe, with varying building heights and canopy cover for the climatologically hottest week of the year (August 3–9). The model performed well with an RMSE of 5.4 °C, an index of agreement of 0.96, and outperformed existing models for tree-shaded sites. MRT and UTCI were driven mainly by shade from dense urban forms and trees. Highrise, medium-to-high tree canopy cover archetypes were the coolest concerning thermal exposure and comfort. Sites in Tempe exceeded the UTCI categories for Very Strong or Extreme Heat Stress independent of archetype. The model enables fast and accurate assessment of urban tree planting strategies.

1. Introduction

Urbanization combined with climate change impacts has prompted researchers to develop mitigation strategies to protect cities from overheating [1] and design models to assess potential mitigation strategies [2]. Climate-sensitive urban design (CSUD) is a design strategy to reduce urban heat; it involves urban landscape planning and design that aims to create more sustainable and thermally comfortable urban environments [3,4]. Street trees are considered an essential factor in CSUD and, specifically, in relieving heat stress in cities ([5–10]; X. [11]). Tree canopies block shortwave solar radiation and decrease heat stress [12–15]. Designing accurate models for urban environments is extremely difficult because tree canopies and buildings significantly differ in their radiative, thermal, and drag properties. In addition, there is radiation exchange between buildings and trees ([16–18]; [19]. [20]).

In comparison to ground surfaces, tree canopies can transfer more radiative or thermodynamic flows into the air above the ground and cause new flows ([6,21]; Z. [22]; [23]C. [24]). Urban canopy models (UCMs) simplify morphological and micrometeorological characteristics and come in single-layer and multi-layer. The former type calculates the effect of a given urban canopy on either temperature, wind, or humidity (P. [25]; C. [24]), while the latter allows the simulation of multiple vertical urban canopy layers as well as the variables of each layer, producing more detailed street-level microclimate dispersion outputs (R. [22,26]).

Urban vegetation has been considered in many studies on a variety of levels, from microscale to mesoscale [7,27–33]. Developing models for simulating the impact of street trees started several decades ago. For example, Dupont et al. [34] initiated the integration of street tree modeling into DA-SM2-U, which is based on multi-layer urban canopies, and were able to simulate dynamic and turbulent interactions between buildings and vegetation. In 2008, a vegetated urban canopy model (VUCM) for single-layer canopies, capable of modeling detailed canopy properties, was developed [35]. Later, in 2011, the model was improved by including a lawn in the canyon [36]. Krayenhoff et al. [37] employed the Weather Research and Forecasting (WRF) model and a single-layer urban canopy model to calculate the air temperature in different

* Corresponding author.
E-mail address: alberto.barbaresi@unibo.it (A. Barbaresi).

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List of abbreviations

CFD	Computational Fluid Dynamics
CSUD	Climate Sensitive Urban Design
d	index of agreement
εg	Emissivity of the ground
εw	Emissivity of the wall
εp	Emissivity of the human body
DSM	Digital Surface Model
LCZ	Local Climate Zone
LiDAR	Light Detection and Ranging
MAE	Mean Absolute Error
MBE	Mean Bias Error
MRT	Mean Radiant Temperature
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
RH	Relative humidity
RMSE	Root Mean Square Error
Tair	Air temperature
UCM	Urban Canopy Model
UHI	Urban Heat Island
UTCI	Universal Thermal Climate Index
v	wind speed
WRF	Weather Research and Forecasting model
LR-HCC	Lowrise Blocks with High Canopy Cover
LR-LCC	Lowrise Blocks with Low Canopy Cover
LR-MCC	Lowrise Blocks with Medium Canopy Cover
MR-LCC	Mid-Rise Blocks with Low Canopy Cover
MR-MCC	Mid-Rise Blocks with Medium Canopy Cover
MR-HCC	Mid-Rise Blocks with High Canopy Cover
HR-LCC	Highrise Blocks with Low Canopy Cover
HR-MCC	Highrise Blocks with Medium Canopy Cover
HR-HCC	Highrise Blocks with High Canopy Cover

scenarios that involved planting street trees as a mitigation measure for current and future climate change in the United States.

In 2020, the Building Effect Parameterization with Trees (BEP-Tree) model, which had distinct street tree simulation features, was introduced as a multi-layer urban canopy model. It was evaluated using radiation and turbulent exchanges, air temperature, and humidity of an urban canopy layer [38]. Mussetti et al. [31] developed a model based on the BEP-Tree to extend its functionality for nocturnal radiation simulation. Various simulation tools have been developed to model human thermal exposure (driven by mean radiant temperature, MRT) in complex built environments, including trees. Ladybug and Honeybee [39] hosted in the Rhinoceros platform can analyze complex 3D models based on surface temperatures and sky view factors. ENVI-Met [40], a 3D computational fluid dynamics model, has become popular over the last decade for calculating MRT. However, ENVI-Met is computationally expensive and can require weeks to run. Ladybug tools can simulate various complex geometries at a shorter simulation time but do not include airflow. RayMan [41] models MRT based on hemispherical photos and standard meteorological information but is point-based. SOLWEIG [42] simulates MRT through the simulation of shortwave and longwave radiation fluxes in six directions (upward, downward, and from the four cardinal points) and angular factors, but it is limited in simulating longwave exchanges between trees and urban materials and their effects on the flow field ([43]; C. [44]). Thus, developing a methodology to comprehensively model all complex interactions between trees and surfaces on a neighborhood scale is necessary. The approach should be precise and computationally efficient enough to simulate urban canopies. Here, a hybrid Python-based human--biometeorological model was developed to evaluate pedestrian-level thermal exposure and comfort in neighborhoods with varying tree and building densities. The model accounts for multi-layer urban canopies, e.g., street trees and shrubs, and how they interact with built environment surfaces and the overlying atmosphere. Model simulations yield hourly MRT and UTCI maps at fine resolution. The model was validated using human-biometeorological street-level observations and used to assess the effect of building and tree density in various urban archetypes in Bologna (Italy), Imola (Italy), and Tempe (USA) neighborhoods.

2. Methodology

2.1. Hybrid Python approach

The model presented here is a hybrid model in Grasshopper/Rhinoceros developed in Python 3.8.1 to combine three engines: EnergyPlus, QGIS, and OpenFOAM. Each engine simulates a subset of parameters for thermal comfort calculations. The interrelations of those parameters are modeled using a comprehensive Python script (Fig. 1). In the first simulation step, input weather data for model forcing is generated from standard meteorological information. Hourly dew point temperature, global solar radiation, and direct/diffuse decomposition models are generated based on dry bulb temperature (T_{air}), relative humidity (RH), wind speed (v), and sky cover from a weather station in the Urbana Bologna neighborhood [45] and https://mesowest.utah.edu/for the Tempe campus (nearby Phoenix Sky Harbor airport). The built environment for Bologna is represented in Rhinoceros using various sources. A digital surface model (DSM) was created in SOLWEIG [46] based on a 0.5-m-resolution LiDAR dataset. Geometric input data for buildings and topographic data for land cover types were imported from vector layers provided by the Municipality of Bologna using QGIS. These layers were created for two neighborhoods with a resolution of 1 m. 3D trees in the neighborhoods were defined by trunk and canopy diameters and simulated using 3D models of trees that most closely matched the canopy shape and height with a transmissivity of 0.02. For the Tempe area, the 3D built environment was generated manually. Trees were placed based on a processed 2014 LiDAR point cloud. For all sites, the built-up area surrounding the studied zone is modeled as far as 500 m to minimize boundary effects during the simulation. Finally, MRT maps were generated using the Grasshopper/Ladybug MRT calculator. The Universal Thermal Climate Index (UTCI) is calculated using the Grasshopper/Ladybug Outdoor Comfort Calculator.

2.2. Study sites

The model was validated for a study area (four sites) in Tempe, Arizona, USA (Fig. 2), and then applied to two neighborhoods (9 sites) in two cities (Bologna, Imola) in the Bologna metropolitan area, Italy (Figs. 3 and 4). Tempe (33°25′28.6″N, 111°56′18.6″W) is a city in the Phoenix metropolitan area in the Southwestern United States with a population of 192,000. Tempe has an arid subtropical climate with a summer daytime maximum air Temperature of 50 °C (period of record: 1953–2013) and overnight lows between 27 °C and 29 °C during the summer months [47]. June is the driest month, with an average annual rainfall of 2 mm, low relative humidity (13.28 %), and an average of 12.61 h of sunshine. The study area in Tempe includes the main campus of Arizona State University and the adjacent Mill Avenue district (Tempe downtown area). Buildings are primarily three-to four-story office and commercial buildings and mixed-use, highrise apartments currently under construction. The area can be characterized as an open midrise Local Climate Zone (LCZ) transitioning to an open highrise LCZ.

The Bologna metropolitan area (44° 29′ 56.2380″ N, 11° 19′ 39.3276″

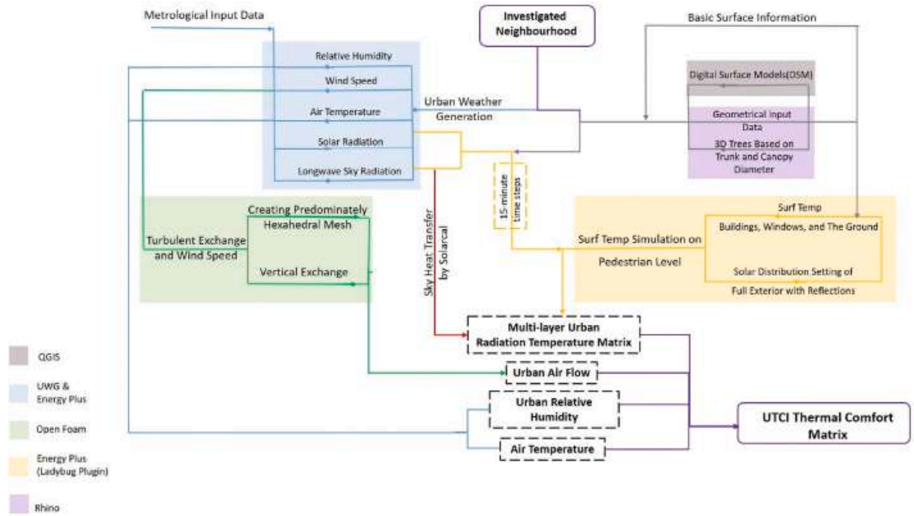

Fig. 1. Flowchart of the presented hybrid Python approach and interrelation between parameters.

E) has an extent of 3700 km^2 and a population of approximately 1,000,000. The region has a mid-latitude, humid subtropical climate characterized by cold winters and hot, humid summers. Summers are warm and mostly clear, and winters are cold and partly cloudy. Throughout the year, air temperature typically varies from −0.5 °C to 31.11 °C and is rarely below −5 °C or above 35.5 °C. July has an average maximum temperature of 30 °C. The coldest month is January, with an average minimum temperature of −1 °C. The wettest month is November, with 95 mm of rainfall. The sunniest month is August, with approximately 11 h of sunshine. The driest month is July, with 43 mm of precipitation. The City of Bologna has about 26,600 urban trees and 11 km^2 of green space over its total 140 km^2 area. Street tree canopy covers 6 % of the City of Bologna, varying from 0 % to 70 % per block. The Bologna neighborhood selected for the study has an area of 1450 m × 600 m and features highrise, midrise, and lowrise buildings [49] with varying canopy cover. The neighborhood in Imola, a city with a 204 km^2 area and a population of approximately 70,000, has a size of 900 m × 500 m with a 9 % street tree canopy cover and lowrise buildings.

2.3. Urban form archetype classification

In each city, a few main urban morphological archetypes[] were selected to measure the effect of heterogeneous urban forms on microclimate parameters. The archetypes are similar to the LCZ classification scheme but are smaller in length scale (building blocks, not neighborhood scale) [50] and include information on tree canopy cover density (medium, low, or high). Bologna features five archetypes (Fig. 2a): a) lowrise blocks with high canopy cover (LR-HCC), b) highrise blocks with low canopy cover (HR-LCC), c) mid-rise blocks with low canopy cover (MD-LCC), d) highrise blocks with medium canopy cover (HR-MCC), e) lowrise blocks with low canopy cover (LR-LCC). Imola has four archetypes (Fig. 2b): a) lowrise blocks with high canopy cover (LR-HCC), b) mid-rise blocks with medium canopy cover (MR-MCC), c) mid-rise blocks with low canopy cover (MR-LCC), d) highrise blocks with high canopy cover (HR-HCC). In Tempe, the selected archetypes are primarily open (Fig. 2c): a) lowrise blocks with low canopy cover (LR-LCC), b) lowrise blocks with medium canopy cover (LR-MCC), c) highrise blocks with low canopy cover (HR-LCC), and d) midrise blocks with high canopy cover (MR-HCC).

3. Model validation

Model performance was assessed in Tempe, Arizona, USA, where instrumentation for in-situ human-biometeorological observations was available. The model was validated using fieldwork campaign data from MaRTy, a mobile human-biometeorological weather station. Hourly transects were conducted on June 7 and 8, 2018, from 8:30h to 20:30h and on July 3 and 8, 2019, at 12:30h (peak solar radiation), 15:30h (peak T_{air}), and 20:30h (after sunset), traversing the Tempe Mill Avenue District and Arizona State University's main campus (Fig. 3). The transect followed the procedure outlined in [48] to minimize sensor lag [51]. Five validation sites were selected that represent distinct microclimate zones (MCZs) [52]: two open sites with sky view factor (SVF) of 0.93 and 0.80 over asphalt and grass, respectively; one enclosed site (SVF = 0.13) in an urban canyon over concrete; and two tree-shaded sites (SVF = 0.33 and SVF = 0.02) over concrete and grass, respectively. MaRTy observed georeferenced 6-directional longwave and shortwave radiation flux densities with three Hukseflux 4-Component Net Radiometers to calculate MRT and also observed T_{air}, RH, and v at pedestrian height.

Validation days were hot, clear sky summer days with light winds (0.7 ms^{-1} on average), low RH (11.1 % on average), peak T_{air} of 39.0 °C–40.9 °C, and peak MRT of 64.8 °C–69.4 °C (Fig. 4). Overall, the model performed well with a Root Mean Square error (RMSE) of 5.37 °C and an index of agreement d = 0.96. The model has a small systematic RMSE of 0.6 °C and a larger unsystematic RMSE of 4.6 °C, indicating that model parameters are appropriate and most of the error is random. The overall Mean Bias Error (MBE) is 3.5 °C, meaning the model overestimates MRT. The Mean Absolute Error (MAE) is 4.5 °C. The model performs best for open sites with an RMSE of 5.1 °C and performs better than most existing tree models (see discussion) with an RMSE of 5.4 °C, which is close to the accuracy requirement of ±5 °C set in the ISO 7226 standard [53] for heat stress studies.

4. Results

After successful validation, the model was applied in Bologna, Imola, and Tempe to simulate MRT and UTCI in four to five building archetypes with varying tree canopy cover (Fig. 2). The climatologically hottest week of the year was simulated in Bologna (August 3–9) for all sites using data from the Urban Weather Generator as forcing (Figures Supp. 1–4). Hourly MRT was spatially averaged for all archetypes (Fig. 5, section 4.1), and intra-archetype MRT distributions were averaged over the week (Fig. 6, section 4.1). UTCI was investigated for all archetypes (Fig. 7, section 4.2), which allows the comparison of hot and humid conditions in Bologna and Imola to hot and dry conditions in Tempe because UTCI combines T_{air}, RH, v, and MRT in a comprehensive index.

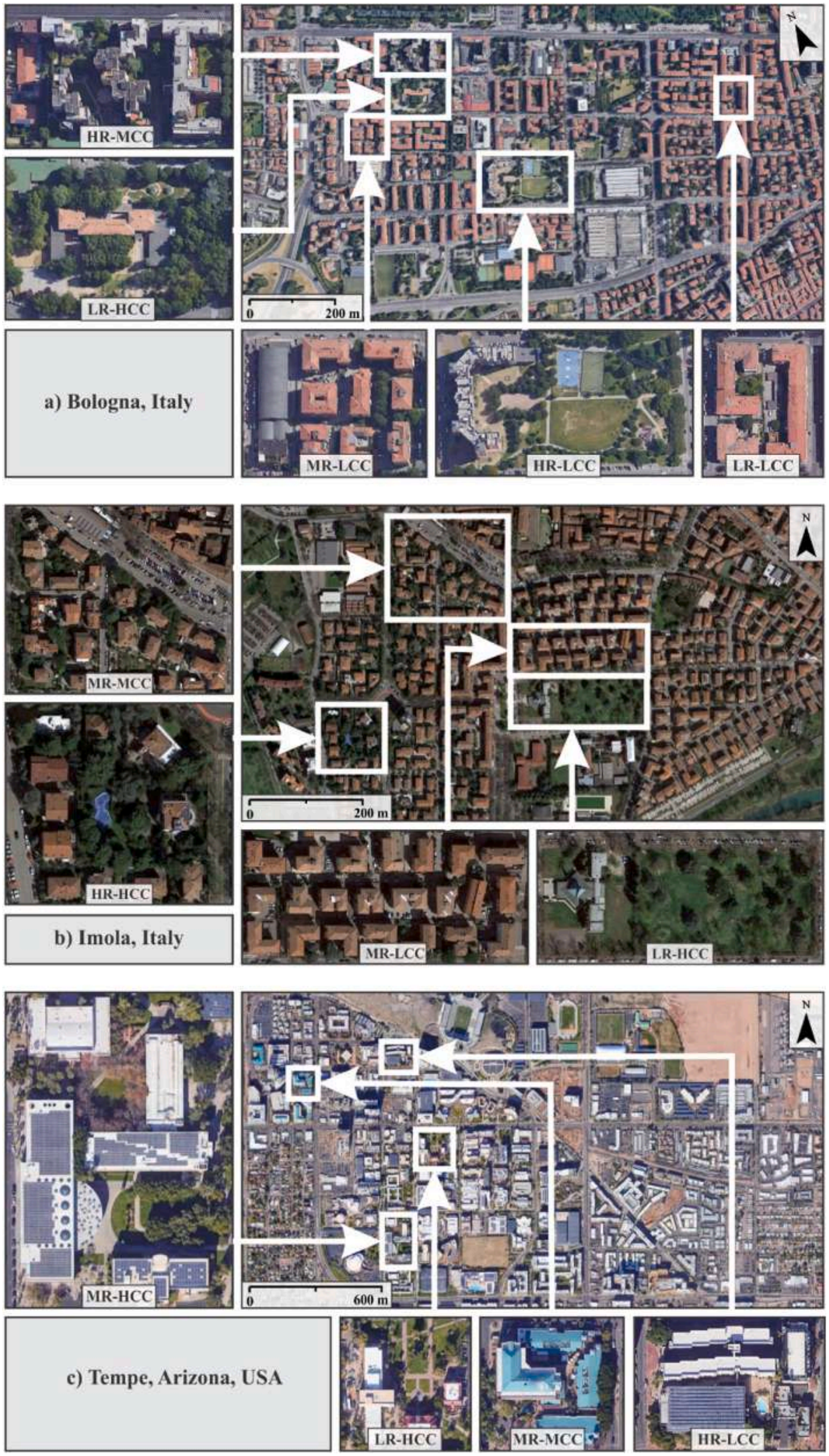

Fig. 2. Study areas and urban form archetype classifications in a) Bologna, Italy; b) Imola, Italy; and c) Temp, Arizona USA; Source: Google Maps.

4.1. Mean radiant temperature simulations for archetypes

Fig. 5 shows hourly, diurnal MRT under clear sky conditions during the one-week study period (August 3–9) in Bologna (a), Imola (b), and Tempe (c) archetypes. In Bologna, MRT varies significantly between sites, with a difference of up to 20 °C between HR-MCC and HR-LCC. Although MR-LCC has low tree canopy cover, building walls prevent shortwave radiation from reaching the ground between densely arranged buildings, and spatially averaged MRT stays below 40 °C at all times. MR-LCC features dense urban forms and would be classified as a

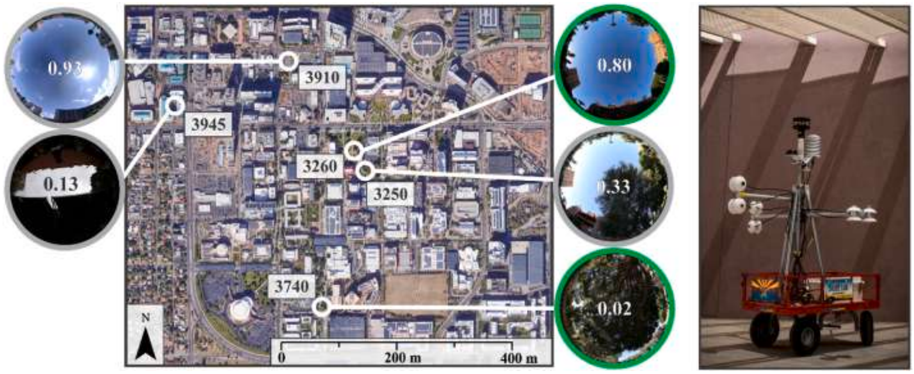

Fig. 3. Map of validation sites on and near Arizona State University's main campus in Tempe, Arizona. Fisheye photos represent hemispherical views of the sky with the sky view factor noted in the fisheye. Photos were taken at 1.1 m height with a Canon EOS 6D and Canon EF 8–15-mm f/4 Fisheye USM Ultra-Wide Zoom lens. Photo borders denote the ground cover of the location (green = grass, grey = impervious). Human-biometeorological sensor setup MaRTy to the right [48]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

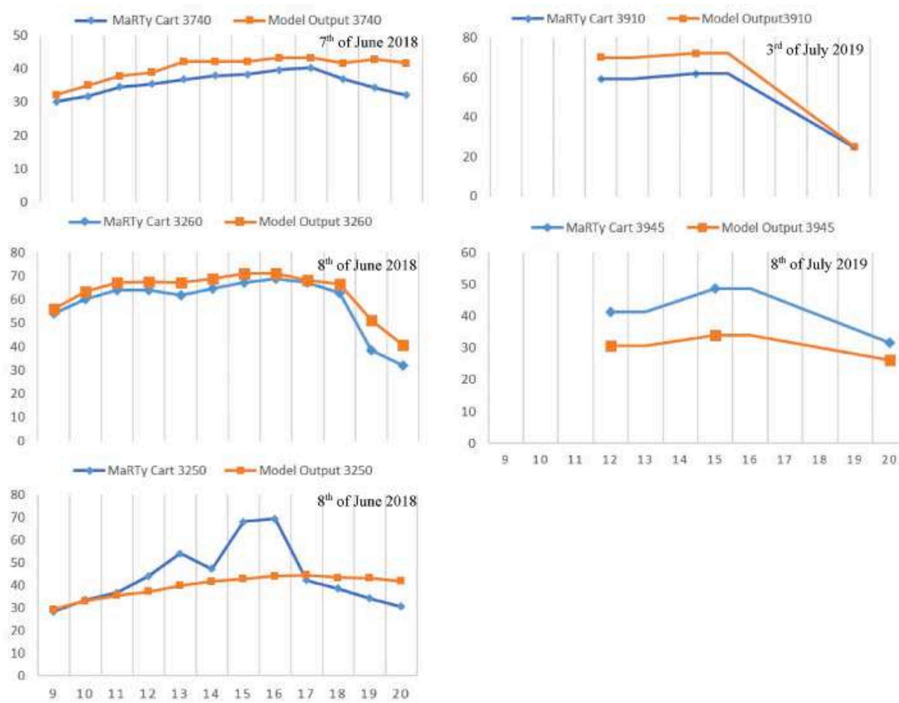

Fig. 4. Comparison of model output and MaRTy measurements at the validation sites in Tempe, Arizona, USA (Fig. 3).

compact mid-rise Local Climate Zone (LCZ) [54] at the neighborhood level. The two archetypes in Bologna with the highest average MRT are HR-MCC (62.0 °C on August 5) and LR-HCC (53.8 °C on August 5). Large, open, sun-exposed spaces and longwave trapping between close midrise buildings mostly drive high MRT. Fig. 6 illustrates the impact of shade on the spatial distribution of MRT. While HR-LCC exhibits lower MRT values around the C-shaped, 24-m-tall building and the trees in this archetype, most areas are exposed to intense shortwave radiation for most of the day.

In Imola, a small community-scale park representing archetype LR-HCC experiences the highest spatially averaged MRT values (65.1 °C on August 5). The park has a sparse canopy cover with few trees spread out across an extensive lawn. In contrast, archetype HR-HCC is the coolest overall, with average MRT peaking at 45.9 °C on August 5 and not exceeding T_{air} by more than 10 °C. HR-HCC has tall buildings surrounded by closed tree canopy cover, with almost all areas shaded by buildings or trees (Fig. 5 b). Archetype MR-LCC is an excellent example of effective shade from urban form that creates cool pedestrian spaces, with average MRT only exceeding 50 °C twice (August 3 and August 5) despite low tree canopy cover.

Tempe Downtown and Arizona State University's campus can be classified as open midrise LCZ. Archetype HR-LCC north of campus has highrise buildings and a multi-story parking structure surrounded by large, open spaces to the south (Figs. 2 and 5 c), yielding the highest MRT average of 66.8 °C on August 8. The coolest archetypes are MR-MCC (peaks at 59.5 °C on August 8) and LR-HCC (peaks at 59.5 °C on August 8). MR-MCC has dense midrise buildings arranged in a courtyard formation, providing ample shade for most of the day, while LR-HCC achieves cooling through shade from mature trees.

4.2. *Thermal stress simulations for archetypes*

To compare the thermal performance of urban form archetypes in Bologna, Imola, and Tempe, differences in dry vs. humid climate must be considered using a comprehensive thermal comfort index because MRT does not consider humidity. The UTCI spatial distribution was

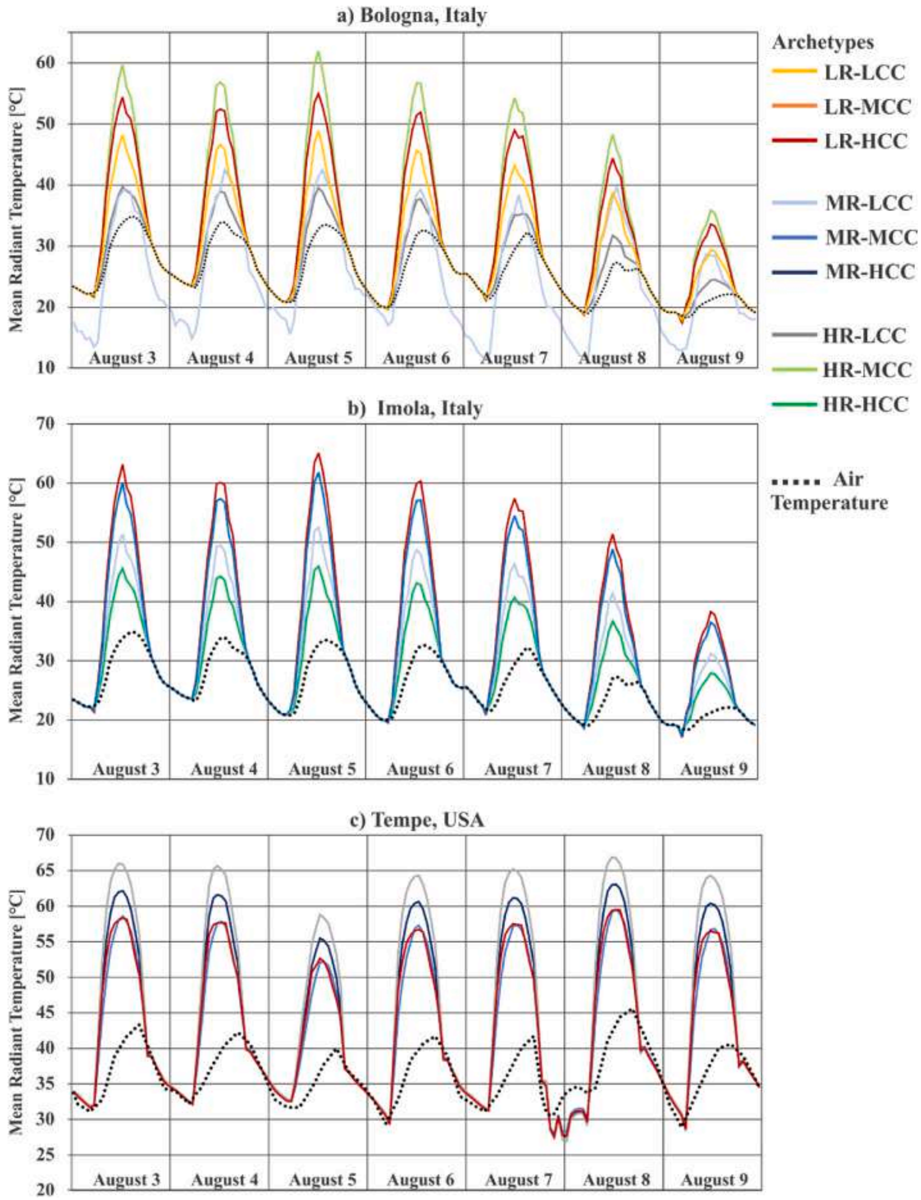

Fig. 5. A week of simulated diurnal Mean Radiant Temperature (MRT) spatial averages of investigated archetypes in (a) Bologna, Italy; (b) Imola, Italy; and (c) Tempe, Arizona, USA. Archetypes are a combination of lowrise (LR), midrise (MR), and highrise (HR) buildings surrounded by low tree canopy cover (LCC), medium tree canopy cover (MCC), and high tree canopy cover (HCC). Hourly air temperature at the nearest airport is provided as a reference (dashed line).

calculated at the pedestrian level for all archetypes for August 3–9 (Fig. 7). UTCI and MRT display similar diurnal curves, keeping the order from the coolest to hottest archetypes but exhibiting different magnitudes.

In Bologna, thermal stress in archetypes LR-HCC and HR-MCC falls in the "very strong heat stress" category (Table 1) on the hottest day of the year, August 4, when T_{air} is 39.6 °C at noon. Conversely, with a UTCI of 32.3 °C at noon on the same day, archetype MR-LCC exhibits moderate heat stress and is the most thermally comfortable archetype in Bologna due to ample shade from dense midrise buildings.

In Imola, heat stress is generally higher than in Bologna. With a UTCI of 43.4 °C (very strong heat stress) at noon on August 4, the archetype LR-HCC is the hottest and most uncomfortable urban form. Meanwhile, HR-HCC is the coolest archetype, with a mean UTCI of 37.5 °C on the same day. Areas close to buildings are 1–2 °C warmer than open sun-exposed areas due to added longwave radiation from vertical surfaces. Similarly, tree-shaded areas are 0.5–1.5 °C cooler than shaded areas close to buildings.

Most of Arizona State University's campus is a "walk-only zone" designed for pedestrians, but UTCI falls in the category of "Extreme Heat Stress" in most archetypes. On August 8, an extreme heat day with T_{air} peaking at 45 °C, UTCI surpasses 53 °C in the HR-LCC archetype. MR-MCC is the coolest archetype due to the courtyard-like arrangement of dense midrise buildings, yet UTCI still falls into the "Very strong heat stress" category for all days except August 8 ("Extreme heat stress").

A comparison across study sites reveals that trees and taller buildings can lower UTCI to the "Strong heat stress" category in Bologna and Imola but not Tempe. Although conditions in the Italian archetypes are more humid than in Tempe, the intense solar radiation is the biggest driver of UTCI in the dry Southwestern US and elevates heat stress conditions by two categories. In addition, archetypes in Tempe are more open with more sun-exposed areas than in Bologna and Imola due to higher street-to-width ratios and more parking lots.

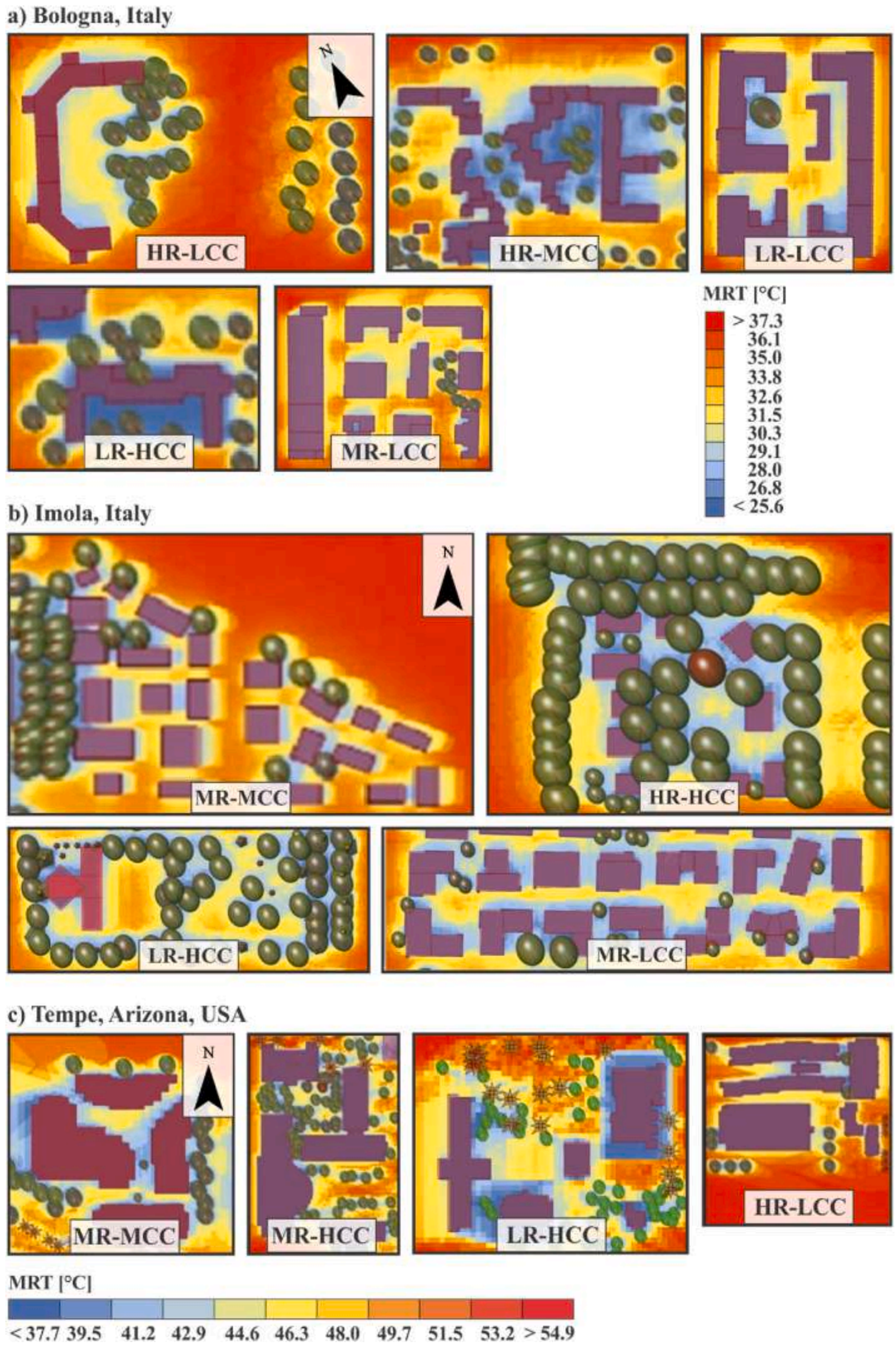

Fig. 6. Spatial variations in MRT (hourly averages for a time period from August 3–9) for archetypes in a) Bologna, Italy; b) Imola, Italy; c) Tempe, USA. Note that the color scale for Tempe differs from that for Bologna and Imola due to extreme MRT values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

The proposed model performed well with an overall RMSE of just over 5 °C for MRT, which is the acceptable error margin for heat stress studies according to ISO 7226, as used in prior studies[56–60]. Most studies have reported larger MRT discrepancies for existing models, especially when simulating tree-shaded locations [61]. and Gál and Kántor [56] assessed the performance of RayMan and ENVI-met in Tempe, USA (hot and dry climate) and Szeged, Hungary (warm and temperate climate), respectively. RayMan produced an RMSE of 8 °C for five sites at an urban square in Szeged and an error of 12.4 °C for seven sites in Tempe Downtown (a similar study area as this study). For ENVI-met, Gál and Kántor found a lower RMSE of 6.9 °C, while Crank et al. reported an RMSE of up to 16.1 °C. Both author teams note that the most common reason for MRT discrepancies is shading mismatches caused by the spatial coarseness of the models. These findings are further corroborated by Acero et al. [62], who found RMSE ranges of 7.4 °C–19.0 °C for MRT modeled with ENVI-met in a neighborhood in Bilbao, Spain (temperate oceanic climate). Future ENVI-met studies may report smaller errors due to improvements in the model's radiation scheme, which further increase computational complexity but significantly improve accuracy [63,64].

Colter et al. [65] investigated the impact of tree and engineered shade on MRT in Phoenix, USA urban parks (hot and dry climate) using

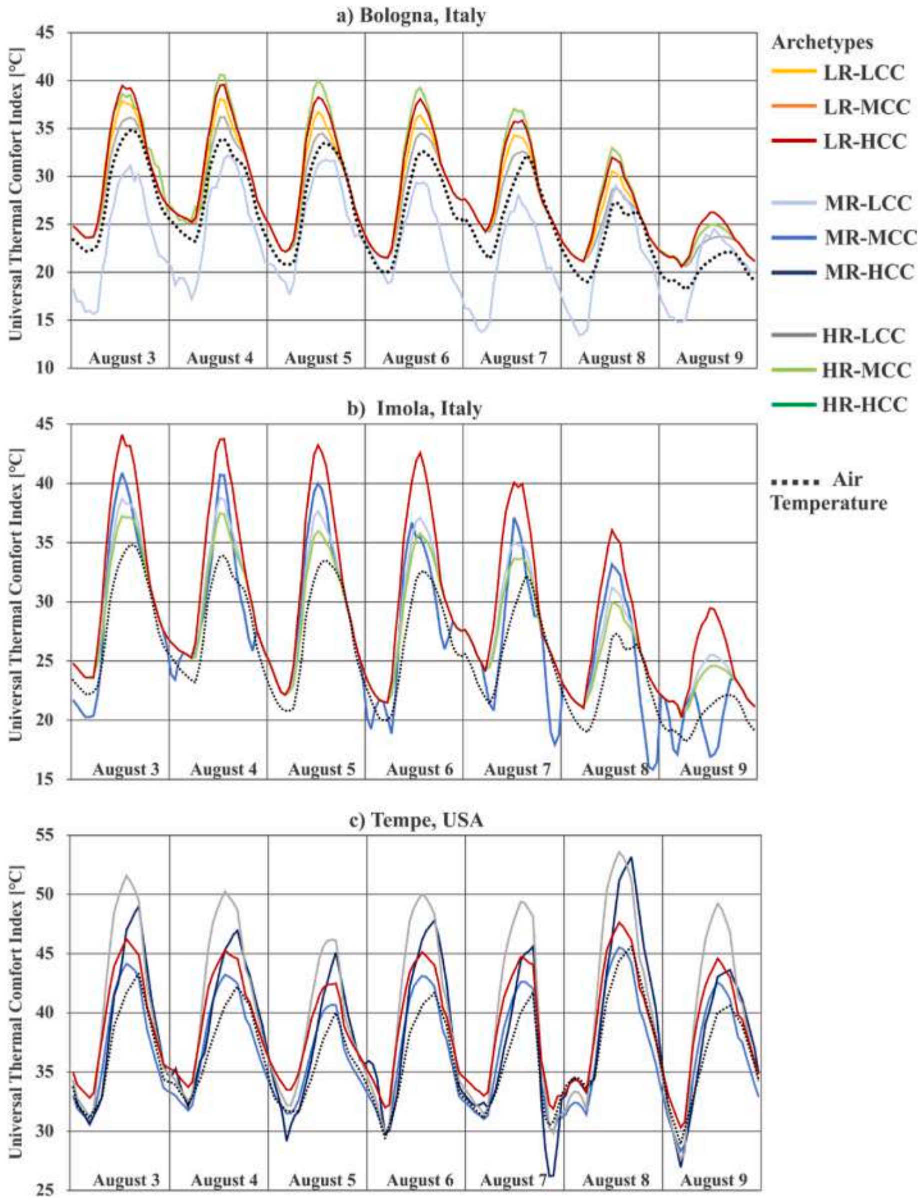

Fig. 7. A week of simulated UTCI spatial averages of investigated archetypes in (a) Bologna, Italy; (b) Imola, Italy; and (c) Tempe, Arizona, USA. Archetypes are a combination of lowrise (LR), midrise (MR), and highrise (HR) buildings surrounded by low tree canopy cover (LCC), medium tree canopy cover (MCC), and high tree canopy cover (HCC). Hourly air temperature at the nearest airport is provided as a reference (dashed line).

Table 1
UTCI categories for thermal stress ("[55]).

UTCI (°C) range	Stress Category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress

in-situ observations and RayMan simulations. They pointed out that RayMan overestimates MRT for tree-shaded sites due to errors in longwave radiation estimates that stem from assuming homogeneous surface materials. The model proposed in this study uses the Grasshopper/Ladybug MRT calculator, which considers different surface temperatures of the surroundings depending on the materials and vegetation specified in the model. This is evidenced in the small systematic RMSE of 0.6 °C. Correct estimates of longwave radiative fluxes, including those from vertical surfaces, are critical in dense urban forms where incoming solar radiation is reduced [66,67].

Microclimate models are frequently used to investigate the thermal exposure and comfort benefits of trees for pedestrians. (Aminipouri, Knudby et al. [16] simulated the effect of adding street trees to Vancouver, Canada (temperate oceanic climate) neighborhoods with the SOLWEIG model. They reported an RMSE of 3.5 °C–6.9 °C for various LCZs with larger errors for highrise urban forms. While SOLWEIG performs similarly to our model in terms of accuracy, it does not allow users to customize tree shapes and LAI. Instead, trees are represented in a 2.5D raster format with a fixed, default transmissivity of 0.03 %, affecting model accuracy for tree-shaded locations.

Few studies have used the Ladybug and Honeybee Grasshopper plugins for Rhinoceros to model outdoor thermal exposure and comfort, similar to our approach [68]. calculated MRT and UTCI for three urban forms in Tehran (Mediterranean climate) and validated their model using globe temperature measurements. They reported a RMSE range of 1.4 °C (apartments) to 4.5 °C (organically grown neighborhood) [69].

also employed the Ladybug tools to model MRT in an urban canyon in Catania, Sicily (Mediterranean climate). In accordance with the results presented here, they found that the model tends to overestimate MRT, especially at noon, and point to possible inaccuracies in modeling ground surface temperatures in Grasshopper.

In summary, this hybrid Python approach that links various engines in Rhinoceros is comparable to other Ladybug tool studies in terms of model accuracy but outperforms microscale models such as RayMan, ENVI-met, and SOLWEIG, especially for tree-shaded locations. The proposed model has several limitations concerning atmospheric parameters. First, the MRT calculations do not include reflected shortwave radiation from facades, which is particularly important in open highrise LCZs. Second, incoming shortwave radiation is currently overestimated due to simplifications in the SolarCal algorithm. Lastly, the method ignores evapotranspiration from trees, contributing to the overestimation of heat in the study domain. However, since trees in Tempe stop evapotranspiration in hot weather conditions, the impact of this assumption is minimal. Naboni et al. [70] provide a comprehensive list of imitations.

To demonstrate the application of this model, the spatial distribution of MRT and UTCI was analyzed in neighborhood archetypes with varying building heights and tree canopy cover. It was found that both parameters are primarily driven by shade from buildings and trees. Highrise, medium-to-high tree canopy cover archetypes were the coolest urban forms, confirming previous findings that densely built environments can create local cool islands during the day [71,72].

Future research should focus on developing simulation tools that are more computationally efficient while retaining precision and reducing resource requirements. The reliability of any model depends on the accuracy of its inputs, which can be limited by data availability and the complexity of analyzing microclimates in real neighborhoods. For example, accurately simulating wind patterns at the pedestrian level requires realistic wind speed data. The current model relies on weather data files obtained at 10 m and does not accurately represent the conditions experienced at the pedestrian level. To enhance the model, further studies can explore integrating additional factors and co-simulations, such as walkability criteria, different greening strategies, and local greenhouse gas emissions. Fast and easy-to-use models will assist urban planners and designers determine optimal spaces for tree planting (see two examples in Supplemental Materials) [16]. found that the cooling potential of added street trees is greater in lower-density residential neighborhoods compared to areas with highrise or mid-rise buildings. The proposed hybrid approach can be used to further determine the optimal type of tree spacing (clustered vs. dispersed), leaf area density, and crown size in various urban archetypes.

6. Conclusions

Urbanization and climate change increasingly cause overheating, negatively impacting cities and urban planning procedures. As a heat mitigation strategy, tree planting requires human-centric, place-based microclimate knowledge of urban spaces to determine the best placement strategy for trees and the best tree size and species based on hyperlocal contexts. Simulating microclimate benefits from tree planting facilitates the planning and design process to reduce MRT and heat stress but requires computationally expensive simulation tools.

The presented hybrid model is a cohesive approach that employs various engines and uses the output of one step as input for the next step in an integrated fashion. It is easy to use for non-experts and builds on accurate 3D models of buildings and trees on top of a DSM. It can manage complex geometries of the built environment and trees, which overcomes inaccuracies of gridded models.

Street trees are now more valuable than ever for our urban environments, given how extreme heat in cities has reached concerning levels in recent decades. The number of trees must increase to counteract urban overheating, and microclimate simulation tools are essential for optimizing the distribution and placement of trees. A balance must also be created between urban management and urban engineering to maximize the benefits of trees in retrofitting strategies. The proposed model can provide urban planners and policymakers with a precise and valuable methodology for simulating the effects of trees on the human scale, pedestrian-level thermal exposure, and comfort and also help them guarantee the functionality of policies in different urban settings.

CRediT authorship contribution statement

Mansoureh Gholami: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ariane Middel:** Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Conceptualization. **Daniele Torreggiani:** Supervision, Resources, Funding acquisition. **Patrizia Tassinari:** Supervision, Resources, Project administration. **Alberto Barbaresi:** Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.111054.

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