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COMPARISON OF THE RESULTS OF TWO MICROCLIMATOLOGICAL MODELS AND MEASUREMENTS

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Summary: The present paper analyses the thermal comfort conditions of a typical summer day in a popular playground simulated by two micrometeorological models, ENVI-met and RayMan in a Central-European city, Szeged. The thermal comfort conditions of the study area were quantified by the Physiologically Equivalent Temperature (PET). The outputs of the simulations were compared to each other and than they were collated the onsite measurements which were carried out in a sun-exposed and in a shaded point of the investigated area. According to the models, the highest heat load in the selected time intervals occurred in the middle parts of the playground, which were exposed to the sun, while more comfortable conditions could be experienced in the shade of the vegetation and the buildings. Based on the comparison of the measured and modelled data, both models underestimated the real thermal parameters under sun-exposed conditions. However, in the shade RayMan was more accurate, and here the measured and modelled PET values were almost identical. Beside these results, the main positive and negative features of the applied models are also discussed in the paper.

Key words: thermal comfort, ENVI-met, RayMan, Physiologically Equivalent Temperature (PET), playground

1. INTRODUCTION

In urban environments, the use of artificial materials with inappropriate thermal properties, the lack of green spaces, the overcrowding, as well as the accelerated anthropogenic heat and air pollution have an increasing adverse effect on the citizens (Unger 1999). Considering the projected tendency of the global air temperature changes and the heat waves which are expected to occur with an increased frequency and extended durations in the future, this issue will become even more significant (IPCC 2013). To mitigate the impacts of the observed and projected stressful thermal conditions, an effective coordination of multi-disciplinary teams (consisting of climatologists, urban planners, architects, and psychologists among others) is required (Eliasson et al. 2007). Urban planners and architects should seek to support climate-sensitive planning and site-specific design with precise microclimate knowledge. Moreover, they should meet the needs and behavioural attitudes of the citizens and visitors of open spaces under various thermal conditions. However, nowadays the aesthetic aspects of the area design often have priority, while the actual demands of the visitors and the function of the area seem to be disregarded.

In order to foster the climate-sensitive awareness of the planners, micro-bioclimatological simulations can provide an effective support by modelling the various spatial and temporal microclimatic patterns in urban spaces with different designs (Bruse

2004). Application of micro-scale models can represent a valuable tool to create thermal stress maps, which can illustrate the thermal differences in public spaces or even in a small part of the city with relatively high temporal and spatial resolution. Since microclimate modelling can also be performed on fictional situations, the influences of an altered design (e.g. change in land use, vegetation or building density) on the environment and human comfort conditions can be considered and predicted already in the planning phase. Moreover, consequences of future climatic trends may be simulated by changing the meteorological input data, e.g. using projected temperatures based on the climate change scenarios (Huttner et al. 2008).

Over the past years, the number of available microclimate models and simulations has increased rapidly. Although these tools involve many assumptions and simplifications (Ali-Toudert and Mayer 2007), they seem to be the most affordable and cost-effective option for the simulation of the interactions between the complex urban surface and the microclimatic conditions. Due to their simplicity, short computing time and free availability, the most popular and widely applied models in Central-Europe are RayMan (Matzarakis et al. 2007) and ENVI-met (Bruse 2004).

This study examines the applicability of these two models in the urban planning practice by comparing the model results of a typical summer day with onsite microclimate measurements in a popular playground. The study aims to evaluate the effectiveness of the models in different planning phases.

2. MATERIALS AND METHODS

2.1. Description of the study area

The investigated area is located in the centre of Szeged (46°N, 20°E, 82 m above sea level), a medium-sized city in the south-eastern part of Hungary. Szeged belongs to the climatic region Cf according to Köppen's classification (temperate warm climate with uniform annual distribution of precipitation) or to the climatic region D.1 according to Trewartha's classification (continental climate with a long warm season) (Unger et al. 2000, Balázs et al. 2009).

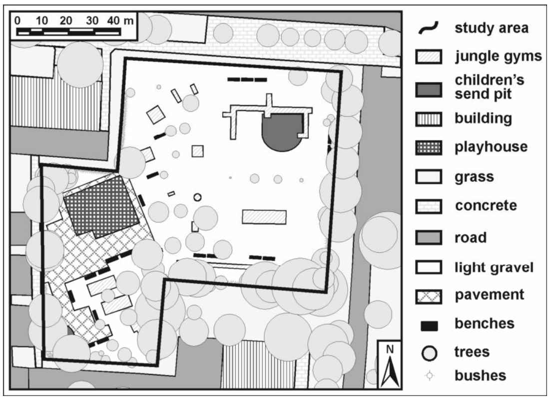

Fig. 1 Map of the investigated playground

The study area is one of the most modern and popular playgrounds in Szeged with an approximate area of 3,300 m^2. The surface of the playground is primarily covered by light-coloured gravel, while the immediate vicinity of a playhouse is covered by paving stone. A large number of deciduous trees are planted mainly at the boundaries of the playground, but in the middle part of the area there are only a few trees, which are too young to provide relevant shade (Fig. 1). Therefore in the morning and early afternoon hours considerable part of the area is exposed to the direct sunlight. In the playground children can choose from several toys such as jungle gyms, swings and slides, moreover 20 benches offer seating places to the visitors (Fig. 1).

2.2. Methods

The present paper analyses the spatial and temporal patterns of the thermal comfort conditions in the examined playground, which were simulated by two micrometeorological models, ENVI-met and RayMan. The models were run with the input data of a typical hot, cloudless and relatively windless summer day (12th July 2011), since under these conditions the developed thermal and microclimate differences are expected to be clearly observable. From the outputs of both models, two typical dates (11 a.m. and 5 p.m.) were selected to represent the daily course of the comfort parameters. The results obtained from the simulations were compared to each other as well as to the onsite measurements (see Section 2.2.3.).

thermal sensation	very cold	cold	cool	slightly cool	neutral (comfortable)	slightly warm	warm	hot	very hot
PET (°C)	4	8	13	18	23	29	35	41	
physiological stress level	extreme cold	strong cold	moderate cold	sligthly cold	no stress	sligthly heat	moderate heat	strong heat	extreme heat

Fig. 2 PET scale for different human thermal sensation and stress levels (based on Matzarakis and Mayer 1996)

The thermal comfort conditions were quantified by the widely used human bioclimatological index, Physiologically Equivalent Temperature (PET). PET is defined as the air temperature at which, in a typical indoor setting, the heat budget of the body is balanced with the same core and skin temperature as those under the prevailing complex outdoor conditions (Höppe 1999). The PET value ranges were defined according to different Central European thermal sensation and physiological stress levels (Matzarakis and Mayer 1996) (Fig. 2).

The software Surfer 8 was used to interpolate the grid of the modelled PET values and to create the heat stress maps.

2.2.1. Model simulation with ENVI-met

ENVI-met is a three-dimensional microscale climate model, which is capable to simulate the interactions between the urban design and the microclimate with relatively high temporal (10 min) and spatial (0.5–10 m) resolution (Bruse 2004). The simulation requires two groups of model input data. The 'Area input file' includes the morphological elements (buildings, plants, land covers etc.) and the 'Configuration file' contains the basic settings (such as the durations of the simulated time period and the time steps) as well as the necessary initial meteorological parameters related to the simulation.

In the present study, ENVI-met was run with a spatial resolution of 1.5 m and the results were referred to the bioclimatological reference height of 1.1 m. The required initial meteorological data included the air temperature, the relative humidity (both measured at 12 a.m.), the average wind speed, the most frequent wind direction and the specific humidity (Table 1). These parameters were obtained from the meteorological station of the Hungarian Meteorological Service located at a distance of about 6 km from the playground, except for the specific humidity, which was acquired from Wyoming Weather Web (2013) The model started at midnight and 24 hours were allowed to the modelled parameters to stabilise (time designations in this section refer to the timescale of the model). The simulation finished at 7 p.m. CEST (one hour after the closing time of the playground), therefore the total simulated time was 43 hours (Table 1). The output of the model was saved every 30 minutes to a predefined folder.

Table 1 Basic input parameters of the ENVI-met

Temperature (K)	294
Relative humidity at 2 m (%)	75
Wind speed at 10 m (ms^{-1})	3.3
Wind direction (°)	10
Spec. humidity at 2500 m (gkg^{-1})	7
Roughness	0.1
Total simulation time (h)	43
Start of simulation	00:00:00

2.2.2. Model simulation with RayMan

RayMan is a small-scale radiation and bioclimate model which calculates the complex radiation fluxes and the thermal bioclimatic indices, such as PET (Matzarakis et al. 2007). RayMan simulates the short- and long-wave radiation flux densities from the three-dimensional surroundings in both simple and complex urban environments, on the basis of parameters such as air temperature, air humidity, global radiation (or cloud cover), time of day and year, albedo of the surrounding surfaces and their solid-angle proportions. Beside these parameters, the model requires input data on surface structures of the study area (buildings and trees) and on personal parameters. However, this model is not capable of taking into account the different types of land cover.

We used four parameters as input meteorological data for the simulation: the 10-min averages of the air temperature [°C], the relative humidity [%], the wind velocity [ms^{-1}], and the global radiation [Wm^{-2}], obtained from the Hungarian Meteorological Service as mentioned above. Wind speed data at 10 m a.g.l., were reduced to 1.1 m a.g.l. using the equation applied by e.g. Gulyás et al. (2006). The global radiation data were modified by the model according to the obstacles (surface structures, such as buildings or trees). The personal input data referred to a typical European male, who is 35 years old, 1.75 m tall, and weights 75 kg. The spatial distributions of the thermal comfort indices were determined through a new interpretation of the RayMan model. From the input parameters 10-min PET values were calculated by the model along a 3 m × 3 m grid network (i.e. the spatial resolution was 3 m), using 764 simulation points (Fig. 3b).

2.2.3. Onsite measurements and comparison of the modelled and measured PETs

During the onsite measurements air temperature [°C], relative humidity [%], wind speed [ms^{-1}], as well as short- and long wave radiation fluxes [Wm^{-2}] were recorded in the studied playground. The data were collected between 10 a.m. and 6 p.m. every minute by two mobile micro-bioclimatological stations at the reference height (1.1 m). One of the stations was always located in the shade (VK1), while the other station was exposed to the sun (VK2). From these onsite data 10-min average PET values were calculated.

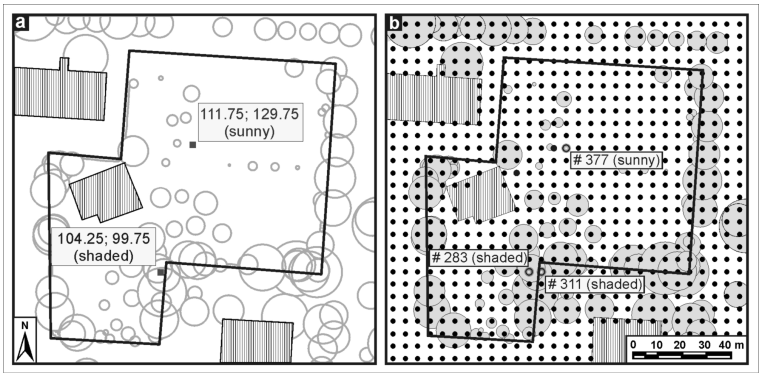

Fig. 3 The two selected cells of the ENVI-met (a) and the three chosen grid points of the RayMan (b) for the comparison to the onsite measurements

The comparison was based on two cells from the 'Area input file' of ENVI-met and three points from the grid network of RayMan, according to the positions of the two mobile stations, one situated in a sun-exposed and one in a shaded location. On the ENVI-met map their positions were identified with the coordinates (111.75; 129.75) and (104.25; 99.75), respectively (Fig. 3a). The first point (sunny condition) was represented on the RayMan map by its equivalent point #377 (Fig. 3b). However, the equivalent position of the second point (#283) in the RayMan model was exposed to the sun from the early afternoon hours. Therefore, by substitution, a nearby point was selected on the RayMan map (#311), which was not exposed to the sun in the afternoon (Fig. 3b).

3. RESULTS AND DISCUSSIONS

3.1. Comparison of the spatial and daily PET patterns simulated by the models

Based on the results of the ENVI-met and RayMan models, at 11 a.m. heat load was dominant almost in the whole area (Fig. 4). According to both heat stress maps, in the northern parts of the playground warm thermal conditions were found with a PET of 29–35°C. Furthermore, the darker patches in the central part of the ENVI-met map indicate PET values of 35–41°C, which corresponds to hot thermal sensation.

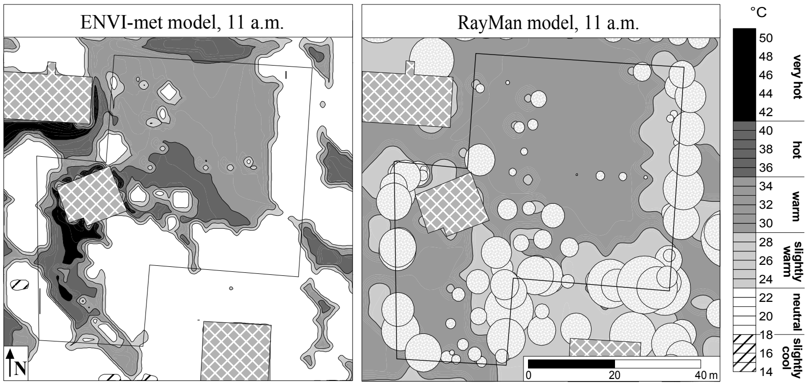

Fig. 4 Thermal stress maps based on ENVI-met and RayMan simulations at 11 a.m. CEST, 12th July 2011 (black line indicates the border of the investigated playground)

The heat stress map of ENVI-met illustrates that the highest heat load appeared around the playhouse, where PET values exceed 41°C denoting extreme heat stress (very hot thermal sensation). This can be explained by the strong heat radiation of the pavement (see Fig.1) warmed up by the direct solar radiation. Since the RayMan model cannot take into account the types of land covers this pattern cannot be observed on this map. Both models suggest that the thermal stress in the immediate vicinity of the single trees was slightly moderate; ENVI-met map shows neutral while RayMan map indicates slightly warm thermal sensation in these areas. Due to the shading effect of the dense foliage, the thermal conditions were much more pleasant near the southern and eastern boundaries of the area. Here neutral thermal conditions (18–23°C) were present on the ENVI-met map, and slightly warm (23−29°C) on the RayMan map.

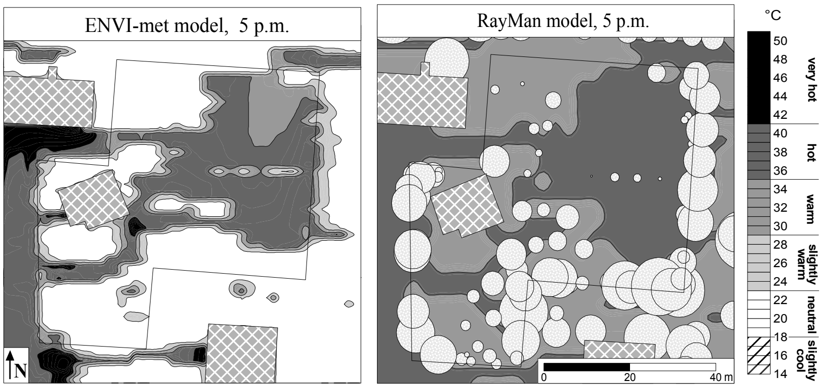

Fig. 5 Thermal stress maps based on ENVI-met and RayMan simulations at 5 p.m. CEST, 12th July 2011

Despite the lower sun elevation at 5 p.m., more stressful thermal conditions occurred in the places exposed to the sunlight than in the forenoon (Fig. 5). Both thermal stress maps show that hot thermal sensation (35−41°C) prevailed in the sun-exposed middle and eastern parts of the area. However, the effects of the single trees can be observed primarily on the ENVI-map. The heat load in the afternoon hours requires special attention, since this is the period when the playground is usually the most visited (after the end of working hours of the parents). The shading of the trees and the surrounding buildings provides slightly more pleasant thermal conditions in the southern areas and the western part of the playground. This corresponds to neutral thermal sensation (PET of 18−23°C) on the ENVI-met map, but according to the results of RayMan simulation, significant heat stress, namely warm thermal sensation (29−35°C) can be found also in the shaded areas.

3.2. Comparison of the simulation results to the onsite measurements in the sun-exposed and shady point

According to Fig. 6, the outputs of the two applied models show remarkable differences compared to the onsite measured values in the sun-exposed point of the playground. Although the tendencies of the modelled (both RayMan and ENVI-met) and measured PET (VK2) values seem to be similar, both simulations underestimated the real thermal conditions. By the end of the day, the discrepancies became even larger. This can be explained by the fact that these models treat the obstacles (trees and building) in a simplified form (e.g. cuboids, sphere), which overshadowed the area in the investigated point already after 5 p.m. The triangle-shaped markers illustrate the magnitude of the VK2–RayMan and VK2–ENVI-met PET-differences, respectively. Based on these results, the RayMan model approximates the actual thermal conditions somewhat better. The differences were about 5−10°C, apart from the morning and evening hours when the average discrepancy between RayMan and VK2 data was 8.8°C, while in the case of ENVI-met it reached 11.0°C (Table 2). It is not surprising that this latter value is greater, since the ENVI-met simulates all the meteorological parameters (not only the radiations as the RayMan), from which it then creates the most probable weather situtation.

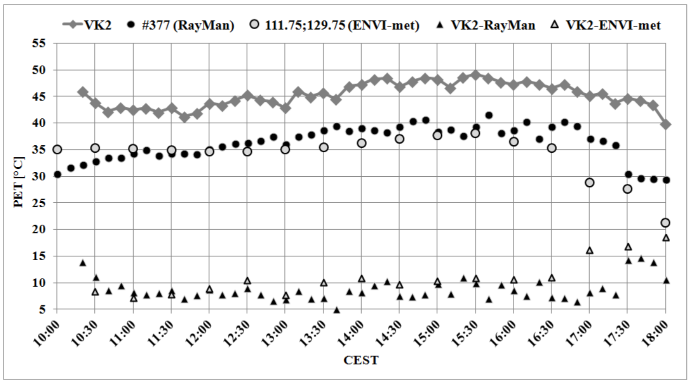

Fig. 6 Modelled and measured PET values and their differences at the sun-exposed point

Table 2 Output of the paired t-test under sun-exposed condition

	Mean (ºC)	Std. deviation (ºC)	Std. error mean (ºC)	95% Confid. interval of the difference (ºC) Lower	Upper	t	Df	Sig. (2-tailed)
VK2–RayMan	8.7896	2.0687	0.3017	8.1822	9.3970	29.129	46	0.000
VK2–ENVI-met	11.0408	3.3348	0.8337	9.2638	12.8178	13.243	15	0.000

The relationship between the modelled and measured PET values in the sun-exposed position was evaluated by means of paired t-test, and the differences between the modelled and the measured data were found to be significant at a level of 5% ($p < 0.001$) (Table 2).

As illustrated in Fig. 7, the ENVI-met model behaved similarly for the shaded and the sun-exposed situations. The thermal comfort conditions in the shaded areas modelled by the ENVI-met were cooler (neutral thermal sensation) than measured in the actual environment (slightly warm and warm sensation). The VK1–ENVI-met difference was consequently above 5°C during the day, and in the late afternoon this difference exceeded 12°C. In the shade, RayMan simulates the thermal comfort conditions much more adequately than ENVI-met; the modelled and measured PET values were almost equal during the forenoon. By the afternoon hours, however, the measured PET values (VK1) slightly increased under the trees compared to the simulated values. This can be explained by the fact that the foliages became warmer during the day due to the incoming solar radiation, thus they emitted more energy toward to the surface. This local temperature increase cannot be observed on the modelled PET map, because the input parameters of the simulation were obtained from the weather station, and furthermore the RayMan model probably did not take into account the increasing temperature of the foliage during the day. The mean discrepancy was only 1.2°C between the modelled and measured PET values (Table 3), and even the maximum difference did not exceed 3.5°C (Fig. 7).

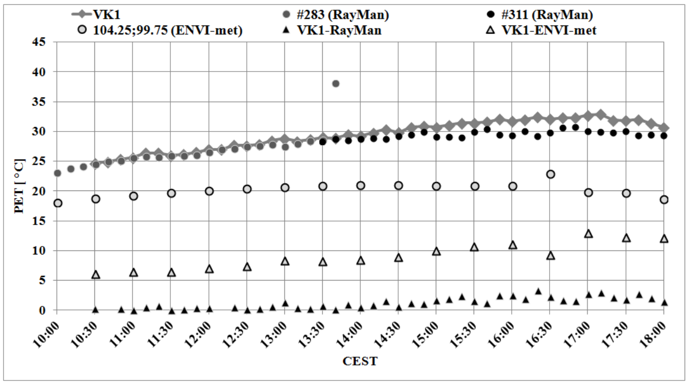

Fig. 7 Modelled and measured PET values and their differences at the shaded point

Table 3 Output of the paired t-test for the shaded condition

	Mean (ºC)	Std. deviation (ºC)	Std. error mean (ºC)	95% Confid. interval of the difference (ºC) Lower	Upper	t	df	Sig. (2-tailed)
VK1–RayMan	1.1603	0.9515	0.1403	0.8778	1.4429	8.271	45	0.000
VK1–ENVI-met	9.0502	2.2152	0.5538	7.8698	10.2306	16.342	15	0.000

According to the results of the paired t-test for the shaded point (Table 3), the difference between the modelled and the measured data pairs proved to be significant again ($p < 0.001$) at a level of significance of 5%.

3.3. Evaluation of ENVI-met and RayMan from practical aspects

In this chapter, the main advantages and disadvantages of ENVI-met and RayMan are summarized regarding their practical applications (Table 4).

Table 4 Main advantages and disadvantages of ENVI-met and RayMan models

	RayMan	ENVI-met
simulation	point-to-point (result: grid network)	an area by default
simulated parameters	only the complex radiation environment	all the meteorological parameters
input data	more input parameters, reduction of the wind speed (1.1 m); real meteorological data	only 1 value for each meteorological data; no wind speed reduction
preparation of input data	complex (larger database)	simplified (only 1 input value for each parameter)
obstacles, land cover	only vegetation and buildings	land cover, vegetation, buildings
shape of the obstacles	foliage: spheriform or cone, buildings: cuboids	all objects are cuboid-shaped (with grid-cell resolution)
output data model duration	even several years/simulation	max. 1–2 weeks/simulation
diurnal resolution	even 1 min	at least 10 min
investigated area	no nesting grids, no size limitation	nesting grids, limited size
duration of simulation	shorter (about 3 days/area, depending on resolution)	longer (even 1 week, depending on resolution)
accuracy	more accurate approximation of the real condition	less accurate
usability	user-friendly, less computing capacity	complex interface, more computing capacity

Table 4 highlights that RayMan models only the complex radiation environment, while ENVI-met simulates all the meteorological parameteres including air temperature, relative humidity, wind speed and solar radiation. ENVI-met requires only one input data for each meteorological parameter in the simulation, from which it creates a most probable weather situation. However, RayMan uses real meteorological parameters during the simulation, therefore its output is more accurate. Unfavourably, in the case of RayMan wind speed must be reduced manually before the simulation. RayMan is able to produce databases of several-year model time duration, while ENVI-met simulates data sets of 1–2 weeks at maximum due to the complexity of the model.

One of the most advantageous feature of ENVI-met is the capability of estimating the thermal effects of vegetation, buildings as well as the land cover. Contrary to this, RayMan takes into account only the vegetation and the buildings during the simulation. Due to the grid-cell resolution, all obstacles are cuboid-shaped in ENVI-met, while in RayMan the foliages are spheriform (deciduous trees) or cone (coniferous trees). Since ENVI-met is a very complex model the evaluation time of the simulation is much longer than that of the RayMan, and it requires more computing capacity at the same time.

4. CONCLUSIONS

The study presented the spatial and diurnal patterns of thermal comfort conditions of a popular playground on a typical summer day simulated by two micrometeorological models, ENVI-met and RayMan in a Central-European city, Szeged. The results of the simulations were compared to each other and than to the onsite measurements which were carried out in a sun-exposed and in a shaded point of the investigated area.

According to the heat stress maps of both models, more pleasant conditions occurred under the trees at the investigated times (11 a.m. and 5 p.m.), while the highest thermal load was found in the sun-exposed middle part of the area. In the afternoon (5 p.m.), however, despite the lower sun elevation the PET values were slightly increased in the middle of the playground, and the corresponding heat load was observed on the ENVI-met map, too. Based on the comparison of two models for the sun-exposed point, not only the ENVI-met, but also RayMan underestimated the measured PET values. However, in the shade RayMan was more accurate, and the mean difference between the measured and the modelled PET values was only 1.2°C. For both the sun-exposed and the shaded conditions, the difference between the modelled and the measured data was significant at a level of significance of 5%. Finally, the paper listed the main advantages and disadvantages of the simulations based on their practical applications.

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