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Courtyard microclimate ENVI-met outputs deviation from the experimental data

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ABSTRACT

It is necessary to determine if the tools used in the process of building performance calculation accurately reflect the real conditions, with the objective of introducing simulation in the design process of buildings. The aim of this study is the assessment of the effectiveness of the software ENVI-met v4 on the prediction of the thermodynamic performance of courtyards by means of comparing between field data obtained from simultaneous monitoring of three courtyards and the results obtained from the software simulations. The results of the study show a significant difference between monitored and simulated data for air temperature inside the courtyards. And the difference between outdoor temperature and courtyard temperature is too important not to be considered in building efficiency calculations. For that reason, ENVI-met it is not an accurate software to be used in the process of design of this kind of architectural transitional spaces that can be very important in order to design nZEB in some climates.

1. Introduction

The sustainable development of our society is one of the main challenges we face nowadays. Considering a future of climate change, in which the reduction of the energy consumption will be needed, the research into ways of saving energy is essential. Within the European framework for 2030, sustainable cities and communities is one of the 17 goals of sustainable development. The Directive 2010/31/UE, EPBD, of the European Parliament, relative to the energy performance of buildings, declares that Member States must assure A fulfilment of the Zero Energy Consumption (nZEB) requirements by every new building by 31 December 2020.

There is a necessity of taking advantage of the opportunities to reduce the energy consumption of buildings both in the previous design and in the refurbishing of the existing ones. Geometry and surface properties of buildings generate microclimates, formerly analysed by Ogyay [1], Oke [2] and Givoni [3], which can be the key in the energy development of buildings. In this sense, special attention must be paid to the elements of the building that contribute to passive conditioning, such as courtyards.

The courtyard has been traditionally used in hot climates as an element providing light, ventilation and helps conditioning of the building. Previous research manifests the relationship between geometry, energy performance and the context of the architecture [4,5]. As an element of passive conditioning, the courtyard is especially relevant in the present situation of climate change, accelerated by the high energy consumption we are facing nowadays [6]. It has been proven to be a significant element with a cooling effect on buildings [7–10].

The thermodynamic effects explaining the performance of the courtyard are affected by a variety of factors such as geometry, the presence of vegetation or water, or wind among others [11,12]. All of them have an influence on the temperature distribution inside the courtyard. This distribution is explained by the physical phenomena known as stratification, convection and flow patterns [13]. Courtyard could be a key element in the design of nearly zero energy consumption buildings at some latitudes. They are an interesting element not only from the point of view of thermal comfort in the space of the courtyard, but also because of its direct effect on the reduction of the energy consumed by the building.

Being able to predict these effects and decide which design techniques can make the courtyard more efficient is an objective of the present research, as they are key elements that can be employed to achieve the goals of sustainable development of cities. Current tools and regulations do not allow an efficient use of the environmental benefits of courtyards, or even penalize it. Design tools are not able to simulate the microclimate created by courtyards, and even consider them as detrimental to the building due to exposure to outdoor climatic conditions. There is a general belief that a compact building is more efficient than a

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Table 1
Results of experimental validations carried out in other studies.

Author	City	R^2	RMSE	Area	Scale (m)
Taleghani et al. [10]	Netherlands	–	0,26	Courtyards	10 × 50
Ghaffarianhoseini [12]	Kuala Lumpur	0,96	–	Courtyard	24 × 24
Salata et al. [21]	Rome	0,88	1,89	Courtyard	27 × 30
Nasrollahi et al. [22]	Shiraz	0,87	–	Courtyard	12 × 12 h = 8
Forouzandeh [18]	Hanover	–	3,05	Courtyard	14 × 6 h = 7
Middel et al. [23]	Phoenix	–	1,74	Urban neighbourhood	115 × 120
Song and Park [26]	Changwon	0,52	4,83	Urban open spaces	200 × 200
Hedquist and Brazel [29]	Phoenix	0,89	2,9	Urban neighbourhood	200 × 200
Acero et al. [19]	Bilbao	0,92	–	Urban squares and park	300 × 200
Lee, Mayer and Chen [25]	Freiburg	0,85	0,66	Urban neighbourhood	150 × 150
Duarte et al. [30]	Sao Paolo	–	1,61	Urban	300 × 300
Ketterer and Matzarakis [31]	Stuttgart	0,88	0,28	Urban	180 × 180
Wang and Zacharias J [32]	Beijing	0,81	–	Urban district	300 × 600
Wang et al. [33]	Toronto	0,6–0,83	–	Urban	300 × 300
Jänicke et al. [34]	Berlin	0,89	1.35	Urban façade	80 × 110
Qaid and Ossen [35].	Putrajaya	0,69	1,82	Urban Boulevard	460 × 380
Taleghani et al. [36]	Netherlands	0,8	1,2	Urban neighbourhood	90 × 90
Yang et al. [37]	Guangzhou	0,94	1,01	Urban park	255 × 255
Gusson and Duarte [20].	Sao Paulo	–	1,9	Urban	–

porous one. Conversely, some studies have monitored a reduction of the temperature in courtyards up to 8 °C in hot climates [13,14], which means an important benefit regarding energy consumption and comfort, given that a reduction of 1 °C in air conditioning has been reported to entail an energy consumption increase of 8%, according to IDAE (Spanish Institute of Diversification and Energy Consumption Reduction). Hence the possibility of courtyard modelling for the prediction of their performance is a fundamental objective for the improvement of the efficient design of buildings. Therefore, the analysis of the available software is needed to find an adequate tool that takes into account all these variables in the process of design.

This analysis and calculation is a complex issue which requires a powerful simulation tool providing accurate results and flexibility: powerful enough to calculate the Navier-Stokes equations that define the behaviour of the fluid mechanics coupled with those equations defining thermodynamic behaviours; with sufficient flexibility, so that the model can be modified according to the adjustments needed when comparing them to the physical reality and the possibility to include all the parameters affecting the performance of the courtyard [15].

Thus, the use of powerful calculation software based on CFD (Computational Fluid Dynamics) to finite elements is required. Among the different tools capable of simulating outdoor environment based on CFD we can find ANSYS Fluent, IES. VE, Design Builder and ENVI-met as the most used ones. Since ANSYS Fluent is a software mainly designed to simulate fluid models and turbulence, it requires a not proportional amount of time and effort to be applied to buildings. Design Builder is a specific software for architecture that has been reported not to accurately simulate the temperature in the courtyards [16]. Since we are interested in the performance of outdoor spaces, the most suitable software seems to be ENVI-met, which we describe as follows.

The aim of this paper is the assessment of the effectiveness of the software ENVI-met v4 in the prediction of the thermodynamic performance of courtyards by means of comparing field data obtained from simultaneous monitoring of three courtyards and the results obtained from the software simulations.

2. Materials and methodology

2.1. Software

ENVI-met is designed to analyse microclimates through the fundamental laws of fluids and thermodynamics, being able to simulate interactions between buildings, soil, vegetation and air. For this reason, it is widely used in the study of urban microclimates. It is designed for 3d modelling with a typical horizontal resolution from 0.5 to 5 m and a time frame of 24–48 h with a time step of 1–5 s. This resolution allows the analysis of small-scale interactions between individual buildings, surfaces and plants [17]. In contrast, it presents some limitations when it comes to defining the initial boundary conditions for the calculation. The most significant one is the constant wind speed and direction during the simulation, and the same occurs with the cloudiness rate, unlike the air temperature and humidity which can be modified throughout the day.

This software has been accepted for its use in the simulation of urban microclimates in several previous studies. Aysan Forouzandeh [18] validates it by contrasting data from the simulation with field data obtained from a courtyard in Hanover, Germany. However, errors are detected in the mean radiant temperature for sun-exposed areas. The same inaccuracy is detected by Acero and Herranz-Pascual [19], and it affects the software accuracy to predict thermal comfort parameters. On the other side, Gusson et al. [20] ratify the use of ENVI-met in urban zones of the subtropical climate of Sao Paulo. Salata et al. [21] suggest a procedure to fit ENVI-met simulation outputs to experimental data. Several studies, once they validate the use of the software with a case study, use ENVI-met to predict the effect of different factors on the urban microclimate, such as geometry and orientation [10,12,22], urban morphology [23], albedo of the surfaces [12], the presence of vegetation [12,24–26], and its implications in the thermal comfort of users [19,27]. It has been used even to analyse the role of vegetation in archaeological sites [28]. Table 1 shows a selection of papers that use ENVI-met along with some statistical parameters used to validate the simulations. These parameters are the coefficient of determination (R2) and the Root Mean Square Error (RMSE) which, in order for a model to be considered reliable, must tend to the following values: R2 → 1, RMSE → 0.

It can be seen that the results are quite variable, ranging from a R2 of 0.52–0.96, and a RMSE from 0.26 to 4.83. Furthermore, not many of the studies that analyse ENVI-met are focused mainly on the microclimate generated in courtyards, especially in hot dry climates, and the courtyards are not the typical dimensions of Spanish building courtyards. For that reason, the main objective of this research is the demonstration of the software as a tool capable of predicting the thermodynamic performance of this kind of courtyards, where temperatures 8 °C below the outdoor temperature can be reached during the hottest periods of the year. In this way, ENVI-met could be a useful tool for the architectural design of these traditional spaces of the Mediterranean climate. This research uses the software ENVI-met v.4.3.1 to perform the microclimate simulations.

Fig. 1. Location of the cases studies.

Fig. 2. Images of the studied courtyards.

Table 2
Geometric characteristics of the courtyards.

Courtyard	Dimensions (m)	Height (m)	AR (H/W)	Sky View Factor	Albedo
Case 1. Residential.	7.4 × 3.1	12.6	4.1	0.03	0.8
Case 2. School.	7.0 × 11.0	8.9	1.3	0.12	0.8
Case 3. Residential	7.5 × 13.2	10.7	1.4	0.12	0.4

The process used in the study consists of two steps. First, the simultaneous monitoring of the selected courtyards for the gathering of field data. Second, the simulation of the courtyards with ENVI-met v.4. Results of both steps are contrasted in order to find the conclusions of the research about the effectiveness of the software for its use in the building design process.

2.2. Courtyard description

The first step of monitoring has been designed to obtain data from courtyards of different geometries in identical climate conditions. Three courtyards in Seville (Spain 37°17′01″N 5°55′20″W, elevation 42 m a.s.l.) have been monitored during the same period of time. The location of the buildings can be seen in Fig. 1. Seville is located in an area of Csa category of Köppen climate classification [38]. It consists of hot and dry summers with maximum mean temperatures of 36 °C in July and warm winters with mean temperatures of 10.9 °C in January. Mean annual precipitation is 539 mm [39]. The studied courtyards belong to buildings located in the urban area, and they have been selected according to the common dimensions of courtyards in Spain [4]. In terms of Spanish regulations, the area is classified as B4, which implies summers of the highest climate severity in Spain [40].

The characteristics of each courtyard (Fig. 2) are described and summarized in Table 2. The geometry of each courtyard is described by means of its Aspect Ratio (AR), i.e., the correlation between the height and width of the courtyard as described by Hall [41]:

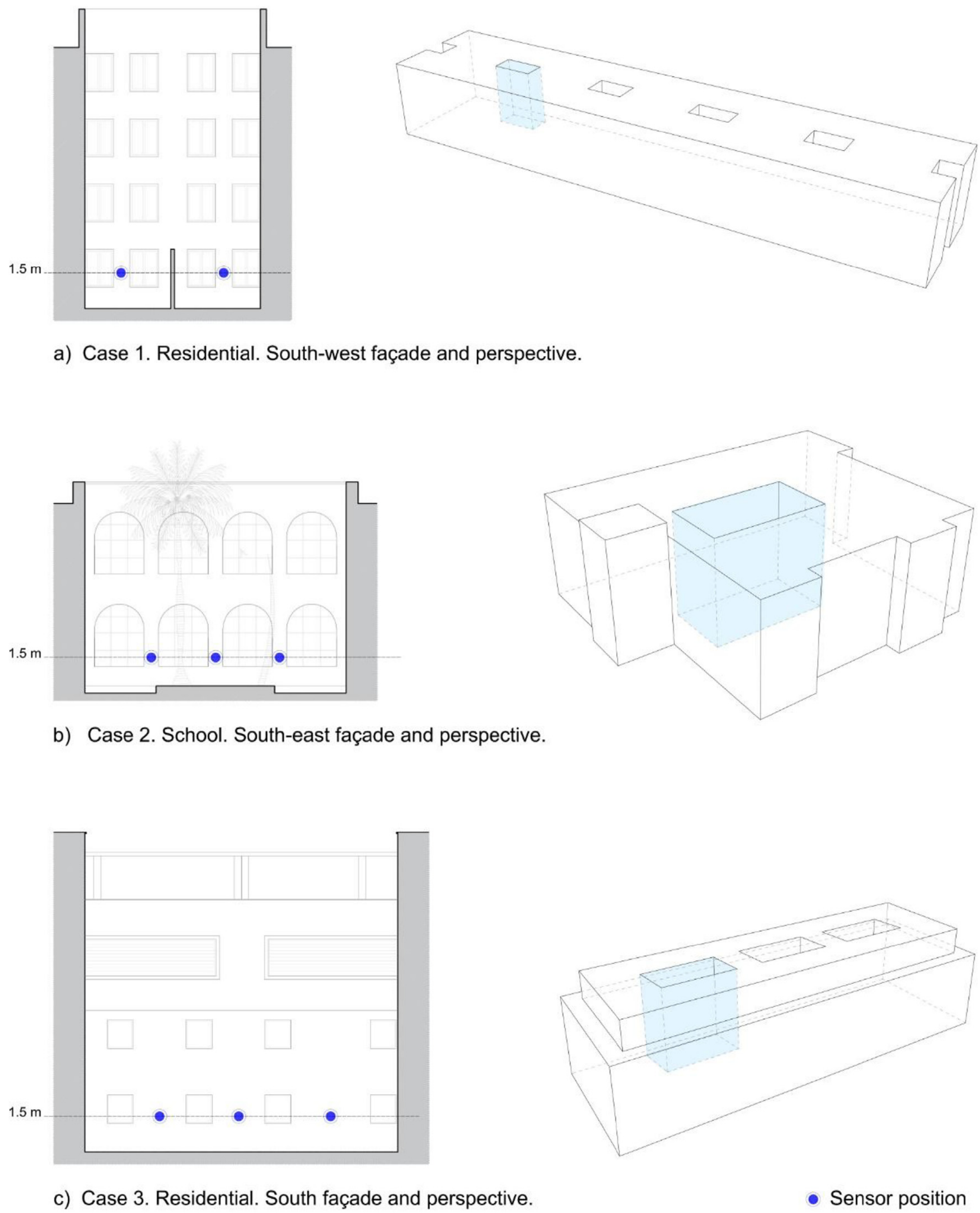

Fig. 3. Sensor position in courtyards.

AR = h_{max}/W,

where h_{max} = maximum height of the courtyard and W = width of the courtyard.

This concept has been employed in several studies because of its relation to heat flows in urban settings [42] and the urban albedo heterogeneity in cities [43]. The other factor to describe the courtyards is the Sky View Factor (SVF) which is the ratio of radiation that is received by a specific point to that which would be received from the whole hemispheric radiant environment around that point [44]. It is also related to the geometry of the courtyard and it has been reported to be a significant parameter regarding thermal comfort and energy performance among others [45].

- **Case 1. Residential:** This building is located in an area of high compactness but low-height edifications and few green areas nearby. The building typology is characterized by deep courtyards in order to provide daylight to the indoor bedrooms. The dimensions of the courtyards are 7.4 × 3.1 m and 12.5 m height. This provides an AR of 4.1 and a SVF of 0.03. The wall, displaying some windows, has a coating material of cement mortar white coloured. The ground surface is covered with ceramic tiles. It lacks any kind of shading, although its depth protects most of the wall surface against direct solar radiation.
- **Case 2. School:** The school is a two-story building and it is organized around the inner courtyard by means of a closed gallery allowing access to the classrooms. The rectangular inner courtyard,

Fig. 4. Sensor shield.

with a dimension of 11.0 × 7.0 m and 8.9 m height displays an AR of 1.3 and a SVF of 0.12. The coating material of the walls is cement mortar white coloured and it has large windows. The ground of the courtyard is covered with flowerbeds and tiles. Two palm trees in the centre of the courtyard protect it from direct solar radiation during the middle hours of the day.

- **Case 3. Residential.** It is located in an area with similar urban conditions to the first case, however displaying a broader area of vegetation around it. The building presents three inner courtyards with 7.5 × 13.2 m and a mean height of 10.7 m which means an AR of 1.4 and a SVF of 0.12. The courtyards are divided by the stairwells of the building and provide light to the bedrooms. The cladding of the courtyard walls is cream colour stone, red painted cement mortar, and small glazed windows. The ground is covered with grey tiles.

Table 3
Measured variables, technical data of the instrument and observation parameters.

Situation	Sensor	Variable	Accuracy	Range	Resolution	Interval
Courtyards	TESTO 174H	T^a	± 0.5 °C	− 20 a +70 °C	0.1 °C	15 min
		Hr	± 0.1%	0 a 100%	2%	15 min
Outdoor	PCE-FWS 20	T^a	± 1 °C	− 40 a +65 °C	0.1 °C	10 min
		Hr	± 5%	12 a 99%	1%	10 min
		Wind	± 1 m/s	0 a 180 km/h	–	10 min

2.3. Monitorig

The measurement of field data was performed in June, between the fourth and the ninth, in the hot and dry period of the year, when the positive effect of courtyards is expected to be higher.

In the campaigns, the measured parameters are air temperature, humidity and wind speed outside the courtyards through a meteorological station model PCE-FWS 20 placed on the roof of Case 3. Data from this instrument has been validated through comparison with data from AEMET (Spanish Agency of Meteorology) [46] (See Fig. 5). Inside the courtyard, air temperature and humidity have been recorded by sensors model TESTO 174 H at the lower level. The position of the sensors is represented in Fig. 3. Sensor were protected from solar radiation with shields of an insulating material (Fig. 4) in order to avoid overheat. Table 3 summarizes the main technical data of the measuring devices.

2.4. Simulation

After the on-site measurements, the next step was the simulation of the thermodynamic performance of the courtyards with the software ENVI-met v4. The characteristics of the models of each simulated courtyard are summarized in Fig. 7 and Table 4.

We agreed on simulating the 8th of June, which presented the highest night temperature, as well as a high day temperature. The hourly temperature and humidity and the mean wind speed and

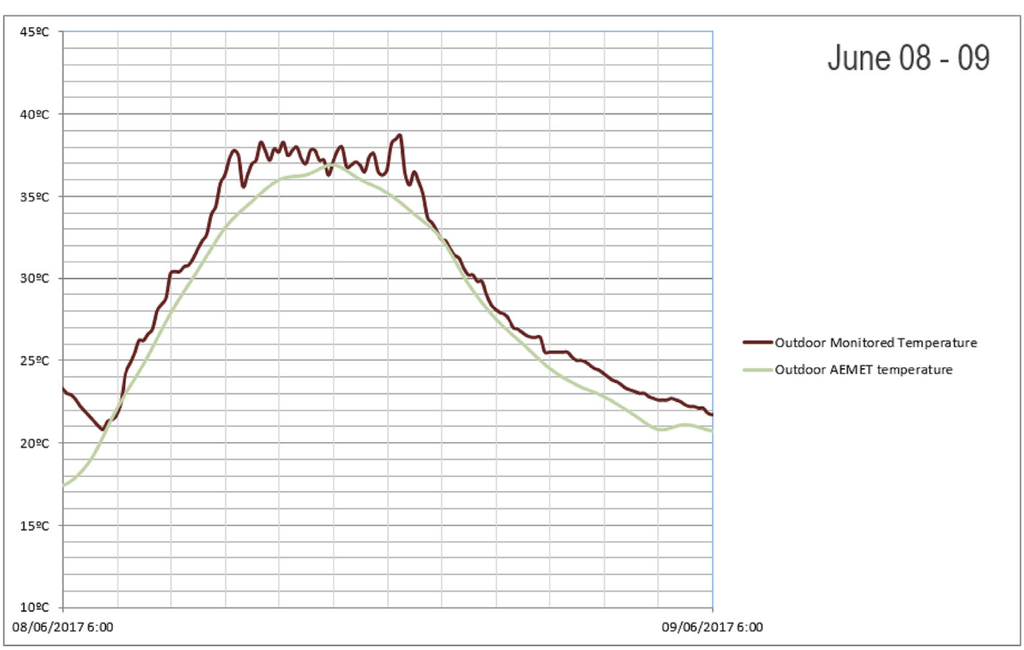

Fig. 5. Comparison between AEMET and Outdoor Station monitored temperature data.

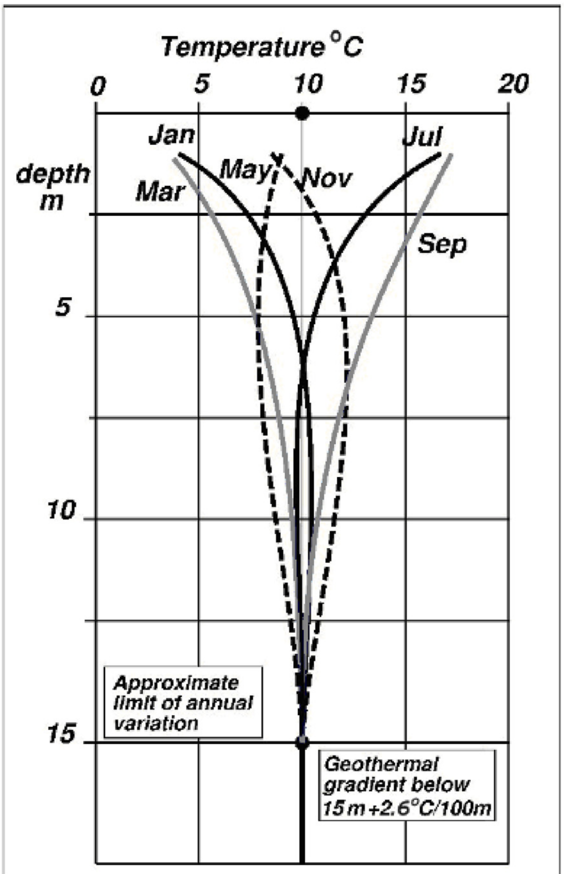

Fig. 6. Thermal profiles of soil depending on the month in Mediterranean areas.

direction were input parameters in the simulation. These data were obtained from the monitoring campaign (Table 6). In addition, the temperature of the soil was another needed input in the simulation, which has been obtained from Fig. 6 [21,47], as well as the specific humidity at 2500 m height, calculated using the method described by Aysan Forouzandeh [18].

Table 5 shows the main input data of the simulation. Given that ENVI-met needs an initialization time to provide accurate outputs, we chose to simulate a total amount of 40 h, starting on 7th day, and only take the last 24 h as valid output of the simulation.

The process for the fitting of the software outputs to the monitored data involved going through different simulations in which the resolution and the time frame have been modified to obtain the best possible results. A few combinations of Lateral Boundary Conditions (LBC) have been tried until concluding Forced/Open to display highest accuracy.

Table 4
Description of the model dimensions of each courtyard.

Parameters	Case 1. Residential	Case 2. School.	Case 3. Residential
Number of grid cells	86 × 65 × 25	70 × 64 × 25	79 × 55 × 25
Size of the cells (m) (x,y,z)	2 × 2 × 1 Telescoping factor 15%. Start at 10 m height.	1 × 1 × 1 Telescoping factor 15%. Start at 12 m height.	2 × 2 × 1 Telescoping factor 15%. Start at 12 m height.
Nesting grids	4	4	2
Model rotation out of grid north	50 nnw-se (long axis)	−24 nne-sw (long axis)	6 e-w (long axis)

3. Results

3.1. Monitoring results

Results obtained from the monitoring of the three courtyards confirm the previously reported tempering effect of courtyards, even if this effect is not equally beneficial in every case. Fig. 8 shows the air temperature monitored in the outdoor and the mean of the sensors at 1.5 m (the height of human use) in the courtyards as well as the wind speed in the outside during the whole period.

Maximum outdoor temperature ranged from 37 °C to 40 °C in the period and minimum temperature at night between 16 °C and 21 °C. The mean wind speed is around 3 km/h, which is not considered to have a significant influence in the performance of the courtyards based on previous research.

The courtyard displaying best performance, which implies the highest outdoor-indoor temperature gap, corresponds to case 1, Residential, up to 11 °C at 19.00 h. This is due to the fact that it is a deep courtyard with a higher AR than the others and a lower SVF, which prevents the solar radiation from reaching the lowest levels of the walls. However, because of the depth of the courtyard, an overheating effect occurs during the night, since the accumulated heat during the day does not escape easily and the temperature of the courtyard becomes higher than the outdoor during the night.

Courtyard in Case 2, School, with a lower AR, also rises up to an

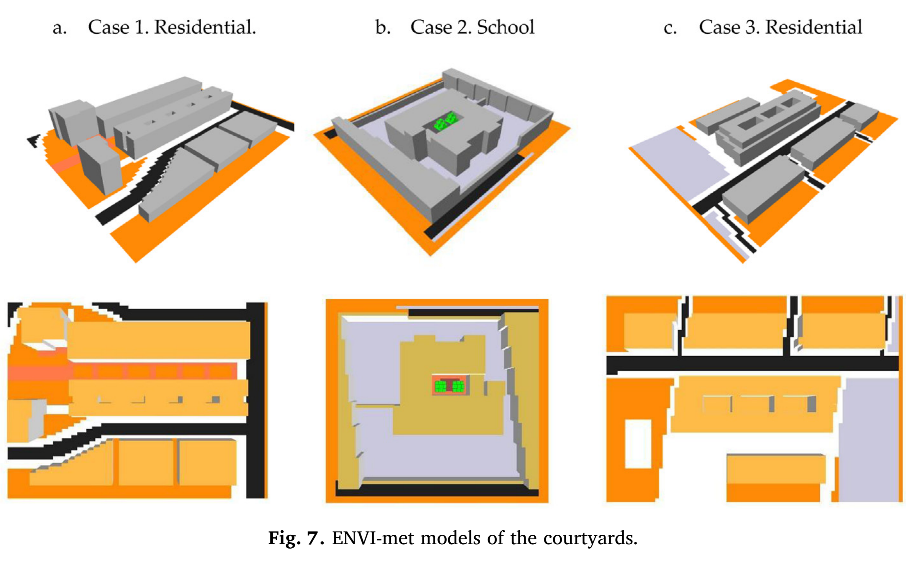

Fig. 7. ENVI-met models of the courtyards.

Table 5
Major input variables for ENVI-met.

Meteorological inputs	Air temperature and relative humidity	Hourly data in Table 6
	Wind speed and direction	3 km/h = 0.83 m/s-135°
	Specific humidity at 2500 m	4.5 g/kg
	Roughness length	0.1 m
Vegetation	3D tree	Palm (Case 1)
Building	Walls and Roof Materials	Table 7
Soil	Initial conditions for soils	Upper Layer (0–20 cm): 293 K/50%
	Materials (Table 7)	Middle Layer (20–50 cm): 289 K/60%
		Deep Layer (50–200 cm): 285 K/60%
Simulation	Start Simulation Day (DD.MM.YYYY)	07.06.2017
	Start Simulation Time (HH:MM:SS)	07.00.00
	Total Simulation Time (hours)	40 h
	Save Model State (min)	30 min

Table 6
Outdoor hourly air temperature and relative humidity from weather station. (day 08/06/2017).

Hour	Outdoor Temperature (°C)	Relative Humidity (%)	Hour	Outdoor Temperature (°C)	Relative Humidity (%)
0:00	26.6	48	12:00	36.3	19
1:00	26.3	42	13:00	37.0	15
2:00	25.1	45	14:00	37.7	18
3:00	24.1	46	15:00	37.0	10
4:00	23.8	44	16:00	37.1	18
5:00	23.8	48	17:00	36.9	20
6:00	23.0	52	18:00	36.6	20
7:00	21.3	57	19:00	36.5	26
8:00	22.5	48	20:00	32.4	34
9:00	26.2	35	21:00	30.2	37
10:00	30.3	30	22:00	28.1	49
11:00	31.8	24	23:00	26.7	51

8.5 °C gap. The vegetation protects it from solar radiation in the central hours of the day. Its low height and higher SVF allows ventilation during the night, reaching the same temperature than outside, refreshing the courtyard.

The courtyard showing the worst performance is Case 3, Residential. Despite presenting a similar geometry to Case 2, even with a slightly higher AR, it lacks of shading elements or vegetation and shows a lower albedo on the surface, which results in a lower gap of 7 °C. Furthermore, the different orientation of the courtyard has a role in this result, due to the fact that solar radiation reaches the courtyard more deeply. Nevertheless, there is still an important contribution to the thermal efficiency of the building.

Fig. 9 summarizes the monitoring data from the 8th of June, the selected one to compare with the ENVI-met simulations. It shows the clear difference in the performance of the three courtyards that we will try to simulate. The results illustrate that not only geometry is important in the performance of the courtyard, but also other factors, such as vegetation or shading elements, which can improve the benefits offered by a courtyard whose geometry does not seem ideal from a previous analysis.

3.2. Simulation results

Among the several variables that ENVI-met is able to simulate, only data of air temperature in the courtyard and in the building surroundings are analysed, considering the interest of this study to corroborate whether this software provides accurate predictions of the relation between these two values.

Data for the comparison is taken from a point inside the courtyards at 1.5 m height (the same height than sensors in monitoring) where the temperature is lower, and a point in the outside street, avoiding points near the boundary of the model where simulation results may be inaccurate. These points are represented in Fig. 10.

Outputs of ENVI-met are compared to monitoring data. In order to evaluate the accuracy of the data from ENVI-met, Figs. 11–13 compare the hourly evolution of the simulated air temperature in each courtyard

Table 7
Physical properties of the materials used in the simulations.

Physical properties	Walls Material	
	Mortar	Tile
Thickness(m)	0.02	0.05
Absorption	0.6	0.5
Transmission	0	0
Emissivity	0.9	0.9
Reflection	0.8 (white) 0.35 (red)	0.5
Specific Heat capacity (j/kgK)	1000	800
Thermal conductivity (W/mK)	0.4	0.84
Density(kg/m3)	875	1900
Colour model		

Physical properties	Soil materials			
	Brick Road	Asphalt	Concrete	Loamy Soil
Roughness Length	0.01	0.01	0.01	0.015
Albedo	0.3	0.2	0.4	0.2
Emissivity	0.9	0.9	0.9	0.98
Colour model				

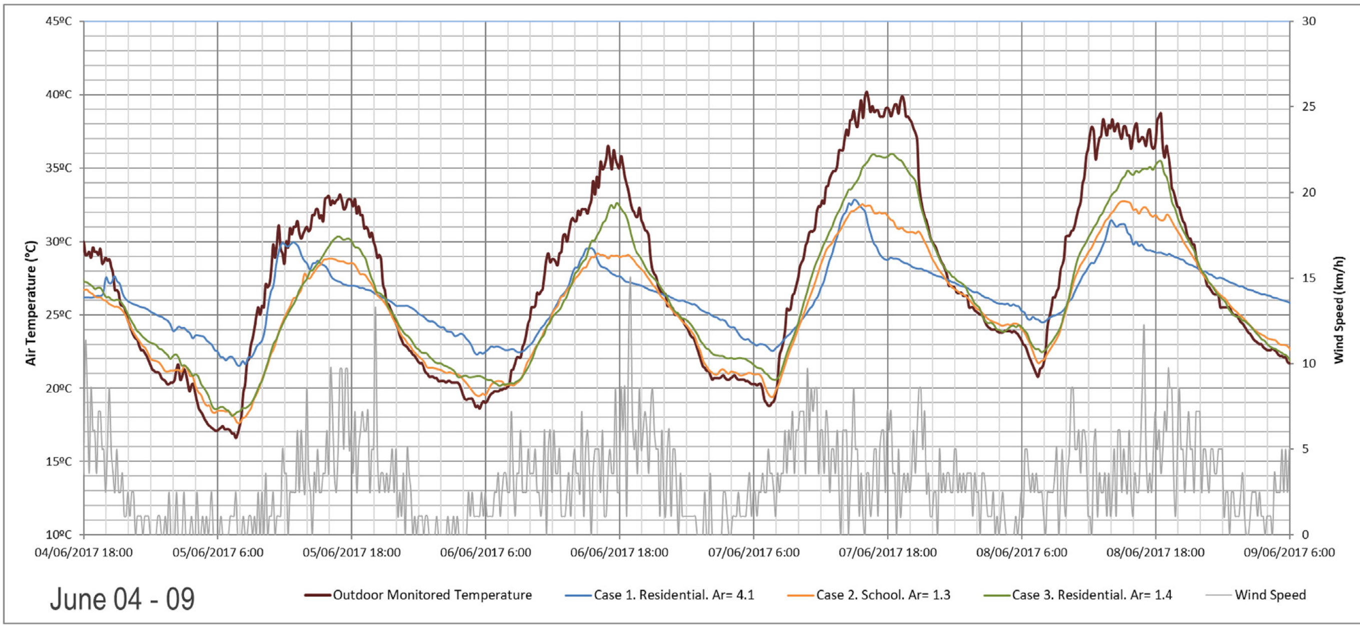

Fig. 8. Monitoring data of Air Temperature and Wind Speed in courtyards and outside from June 4 to 9.

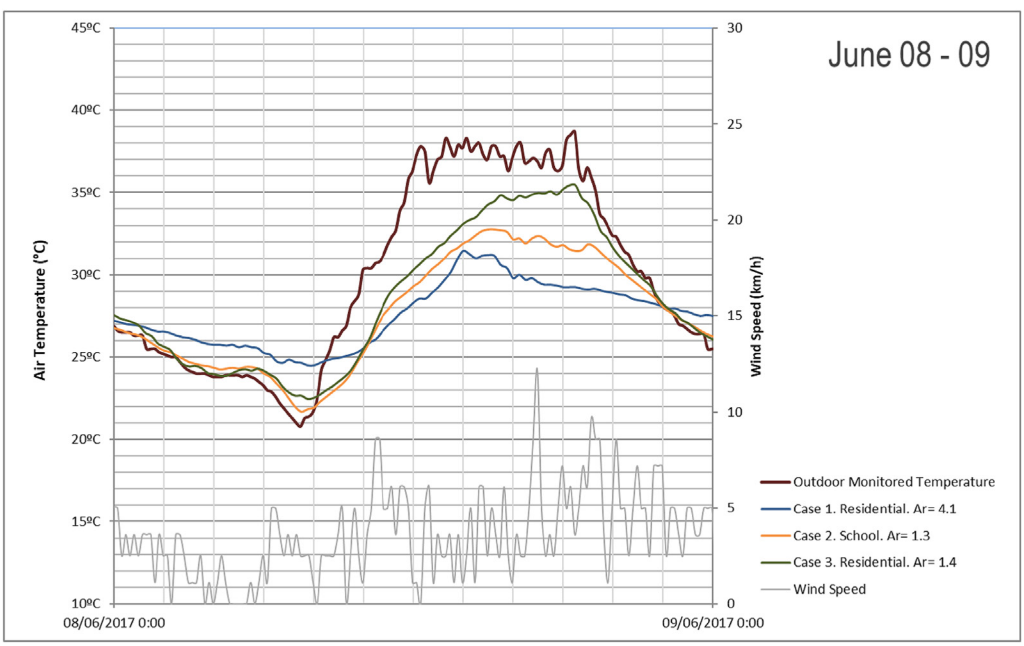

Fig. 9. Monitoring data of Air Temperature and Wind Speed in courtyards in June 8.

with the monitored data, where contrasts among the courtyards are observed. Both, the simulated outdoor air temperature and the monitored one, describe a similar pattern. However, the inner air temperature in courtyards is lower in monitoring than simulation. Both show a reduction of the outdoor air temperature, although this reduction is higher in the monitoring. Case 1: Residential shows the maximum divergence between monitored and simulated temperature in the courtyard, up to 6 °C. Monitoring records a higher gap between outdoor and indoor temperature in courtyards than the simulations. It is important to notice that, in this case, ENVI-met has not been able to reproduce the overheating of the courtyard of Case 1: Residential during the nights.

It is also of relevance to point out that higher agreement is observable for the outdoor temperatures (red lines in Figs. 11–13) than for the courtyard temperatures (green lines).

Fig. 14 reflects the thermal gap between courtyard/outdoor air temperature obtained by means of both the ENVI-met simulation (solid line) and the real monitored data (dash line). Each courtyard corresponds to a different colour so it can be easily appreciated the difference between the monitored versus simulated behaviour of each courtyard. Simulated courtyard temperatures are in all cases around a maximum of 2–4 °C below simulated outdoor temperatures. Nevertheless, this value does not seem to have any relation to the real factors that improve the performance of the courtyard, since it is higher in the courtyard with the worst real performance (Case 3).

The accuracy of the simulations has been analysed by means of the statistical parameters commonly employed to contrast the performance of the model simulation. In this study, the analysed parameters are the coefficient of determination (R2), the Root Mean Square Error (RMSE), Systematic Root Mean Square Error (RMSEs) and Unsystematic Root

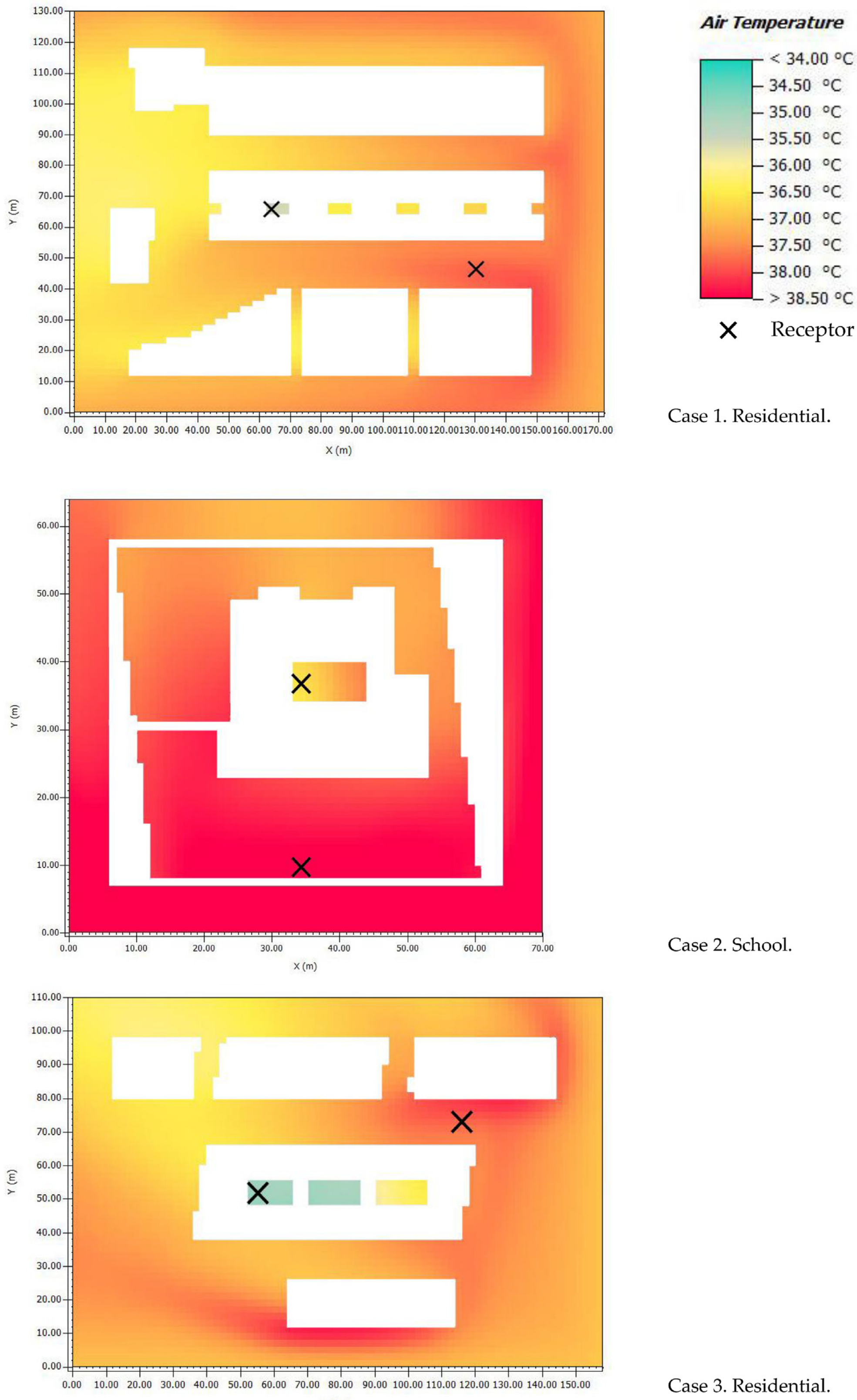

Fig. 10. Simulated Air temperature at 1.5 m of the ground of each courtyard at 16.00 h of June 8th.

Mean Square Error (RMSEu). In order for a model to be considered reliable, these parameters must tend to the following values: R2 → 1, RMSE → 0, RMSEs → 0, RMSEu → RMSE [48]. These parameters have been applied to the air temperatures inside and outside the courtyards.

Table 8 reports the obtained results. It is possible to notice a highly accurate simulation of the outdoor temperatures in all the models, with R2 above 0.96 and a maximum RMSE of 1.09. In contrast, the values obtained for the air temperatures in the courtyards, despite displaying a

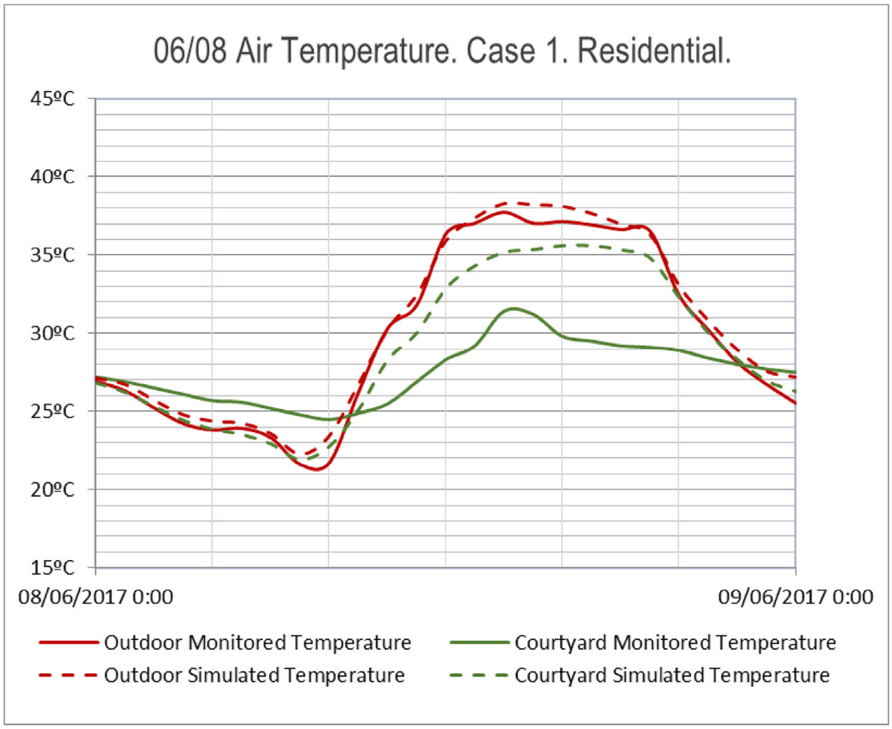

Fig. 11. Monitored and simulated temperature in Case 1. Residential.

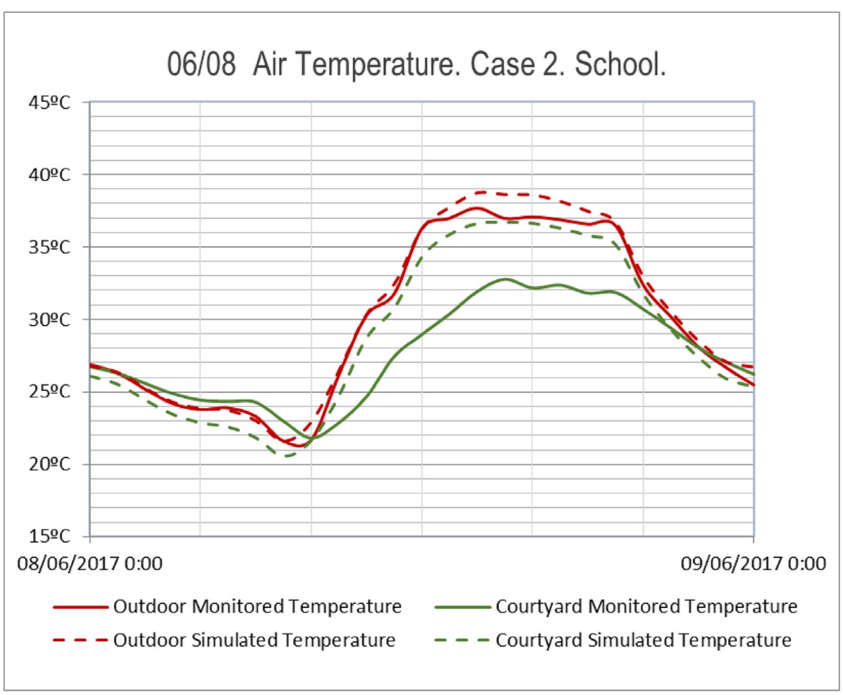

Fig. 12. Monitored and simulated temperature in Case 2. School.

R2 above 0.83, present a RMSE of 3.35 °C in the worst case. The reliability of the results from the simulation is checked through the values of RMSEu and RMSEs. The value of RMSEu is close to RMSE and RMSEs tends to 0, which means that the results of the simulation are reliable.

From the results, it is concluded that ENVI-met simulations show acceptable accuracy regarding outdoor temperatures, in the urban area surrounding the buildings, as it has been previously reported by other studies [19,23,25,30,31,36,37]. However, the simulated air temperature in the courtyards do not present such a fair agreement. Therefore, ENVI-met is able to simulate a decrease in the temperature of the courtyards of more than two degrees, thus demonstrating their tempering effect. Such prediction is however not as favourable as the real monitored performance to vindicate the role of the courtyard as a passive cooling system.

4. Discussion

The results that have been obtained through analysis of the

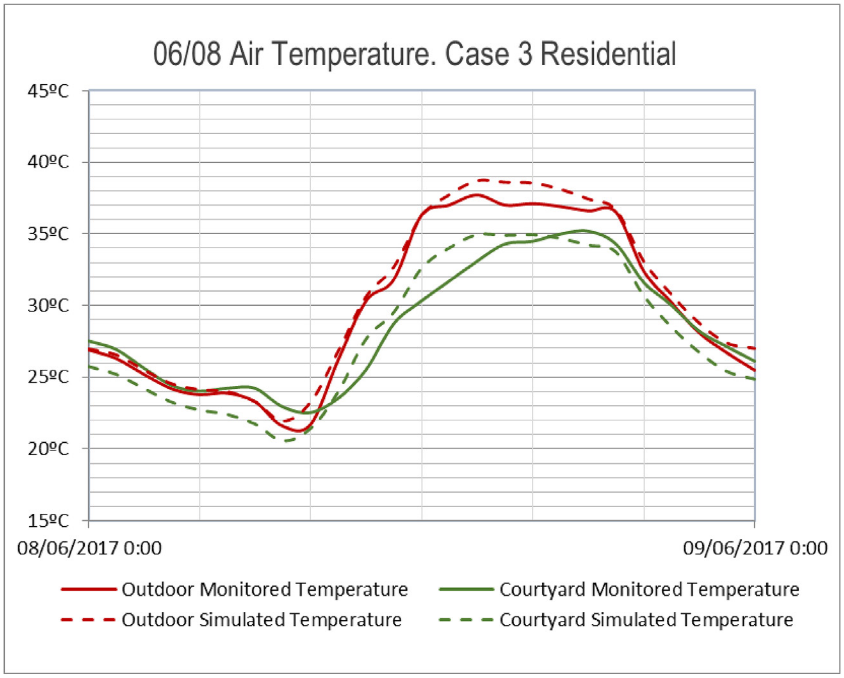

Fig. 13. Monitored and simulated temperature in Case 3. Residential.

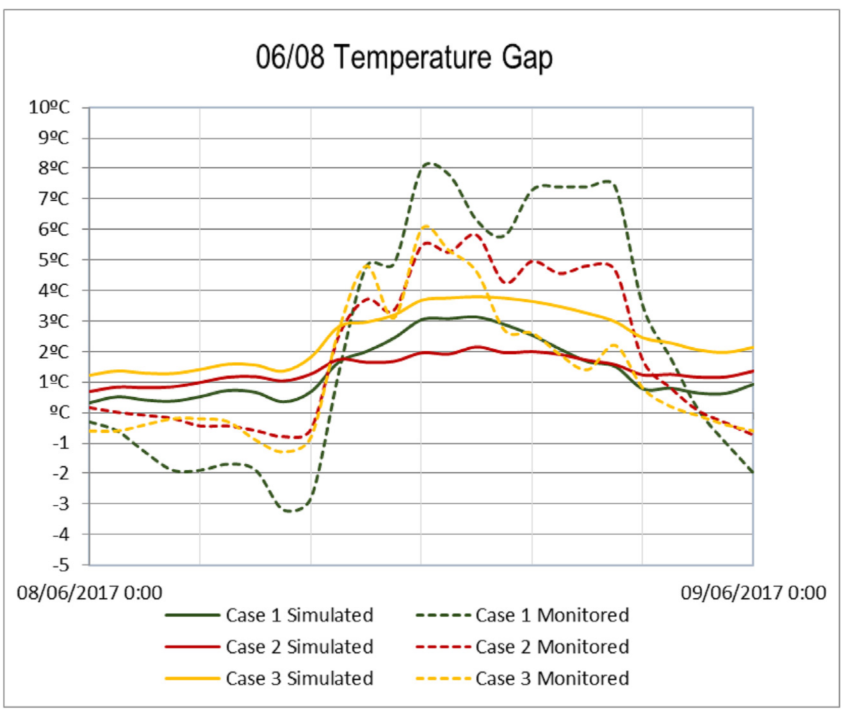

Fig. 14. Simulated and monitored temperature gap.

Table 8
Quantitative evaluation of the ENVI-met performance on the evaluation of R2, RMSE, RMSEs and RMSEu.

		R^2	RMSE (°C)	RMSEu (°C)	RMSEs (°C)
Case 1	Outdoor	0.99	0.77	1.33	0.62
	Courtyard	0.84	3.35	4.50	1.33
Case 2	Outdoor	0.99	0.73	1.46	0.83
	Courtyard	0.88	2.92	4.25	1.60
Case 3	Outdoor	0.99	0.82	1.41	0.66
	Courtyard	0.93	1.52	2.10	0.88

parameters are in accordance with those published in other research about the software. In this sense, even the value of R2 = 0.84 obtained for the courtyard of Case 1, showing the largest difference between monitored and simulated values, is inside the range of results considered as valid by other studies. (See Table 1). Regarding the value of RMSE = 3.35, slightly higher than the mean value obtained in other studies, it is also considered as valid in previous studies (up to 4.83 obtained by Song and Park [26]).

Nevertheless, in this work, whose objective is to validate the use of the software ENVI-met for the simulation of the performance of courtyards in hot climates in the design process of a building, it is considered that errors obtained in air temperature in the courtyards are too significant when taking into account its proportion with respect to the total amount of reduction of the monitored temperature of the courtyard. For that reason, it is not a satisfying value in the process of design of this kind of architectural spaces.

The limitations of the software in the simulation of courtyards may be due to different factors. First, an insufficient resolution of the software for the small scale simulation of Mediterranean courtyards. Despite being a software design for the simulation of microclimates, the majority of the validations have been carried out for broader scenarios. This explanation is supported by the fact that the best performance in our simulation has taken place in the courtyard displaying the largest area (Case 3). Furthermore, deeper courtyards seem to be worse simulated, since the results of Case 1 with an SVF of 0.03 are not so good as those of Case 2 and 3 with an SVF of 0.12. Differences between Case 2 and 3 are because of the addition of other factors such as vegetation. Nevertheless, considering the case studies analysed, a correlation between Sky View Factors and the results in ENVI-met is difficult to stablish.

It is also expected that with a longer time frame or a more defined model the results would be more similar to those obtained by experimental monitoring. This entails, however, an important increase in the calculation time and the needed computational power, which limits the usability of the software. Hence, although the results might be better, the practical use of the software in the design process would also be impossible for the majority of professionals.

5. Conclusion

From a previous analysis of the existing studies that validate the use of ENVI-met in the simulation of microclimates, it has been noticed a lack of case-studies about courtyards. The effectiveness of courtyards as elements of passive conditioning in hot and dry climates has been previously reported in several studies. Since our objective is the assessment of the possibility of using ENVI-met in the design process of a building for the prediction of positive performance of courtyards, a case-study validation of this software using typical courtyard size in our latitudes justifies the present research.

It is concluded that, although the software is able to simulate a reduction in the temperature of the courtyards, it is not as high as in the real cases. The larger the size and higher SVF of the courtyard, the better the results of the performed simulation. For that reason, although the software can be employed to understand the general tendency of a courtyard, the data it provides is not accurate enough to be used as input parameters in the process of energy consumption calculation of the building. This software is aimed at larger urban scale simulations. On the contrary, designers would require a more helpful tool for building courtyard scale simulation.

Future studies must assess the possibility of testing ENVI-met on the simulation of other parameters such as mean radiant temperature in order to validate the accuracy of the software in the prediction of thermal comfort. The analysis of more cases studies is also necessary to stablish a solid correlation between the geometry of the courtyard, daily temperature and daily temperature gap. It may also be interesting the comparison of ENVI-met with other software as Rayman or Honeybee which are also widely used in this field.

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