ENTAC 2024
XX ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO
Maceió, Brasil, 9 a 11 de outubro de 2024

Validação espacial e temporal de simulações de microclima urbano

Spatial and temporal validation of urban microclimate simulations

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Resumo

Compreender o fenômeno das Ilhas de Calor Urbanas é crucial para a elaboração de políticas eficazes de adaptação nas áreas urbanas. Este estudo aborda a necessidade de modelos de simulação confiáveis para analisar o conforto térmico em espaços abertos. O objetivo é contribuir para a validação temporal e espacial de modelos CFD de microclima urbano. Para isso, foram realizados monitoramentos com uma estação fixa de referência e um Sistema Portátil de Monitoramento Ambiental de Baixo Custo (PLEMS) de rotas urbanas em Curitiba durante dias de verão (1); foi desenvolvido e simulado um modelo CFD no software *ENVI-met* (2); e analisadas métricas estatísticas de validação temporal e espacial do modelo de simulação (3). Os resultados indicam que, embora a validação temporal apresente alta concordância com baixas magnitudes de erro entre os dados simulados e medidos pela estação fixa de referência, a validação espacial demonstra baixa precisão do modelo na predição do conforto térmico em cânions urbanos. Comprovou-se haver diferenças entre os dados de transectos intraurbanos e os dados simulados, sendo necessária a calibração do modelo.

Palavras-chave: Conforto térmico em espaços abertos, Medições dinâmicas, CFD, Validação.

Como citar:
QUADROS, B. M. et. al Validação espacial e temporal de simulações de microclima urbano. In: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 20., 2024, Maceió. **Anais**... Maceió: ANTAC, 2024.

Abstract

Understanding the phenomenon of Urban Heat Islands is crucial for the development of effective adaptation policies in urban areas. This study addresses the need for reliable simulation models to analyze thermal comfort in open spaces. The objective is to contribute to the temporal and spatial validation of urban microclimate CFD models. To achieve this, monitoring was conducted with a fixed reference station and a Low-Cost Portable Environmental Monitoring System (PLEMS) along walking routes in Curitiba during summer days (1); a CFD model was developed and simulated in the ENVI-met software (2); and statistical validation metrics of temporal and spatial model validation were analyzed (3). The results indicate that, although temporal validation shows high agreement with low magnitudes of error between simulated data and data measured by the fixed reference station, spatial validation demonstrates low accuracy of the CFD model in predicting thermal comfort in urban canyons. There are noticeable differences between intra-urban transect data and simulated data, requiring model calibration.

Keywords: Outdoor thermal comfort, Dynamic measurements, CFD, Validation.

INTRODUCTION

Outdoor thermal comfort and CFD simulations are crucial aspects when studying urban climate and human biometeorology in various climatic and morphological contexts. Reliable validations of CFD simulation models for real urban areas against field data are essential for ensuring the accuracy of these studies. An urban simulation model is considered validated when at least one variable related to thermal field is comparable to actual measurements [1]. Air temperature and relative humidity are considered the variables most used to validate CFD models, due to their ease of obtaining. Recent research on Outdoor Thermal Comfort (OTC) highlights the significance of thermal radiation, such as the mean radiant temperature, in assessing OTC [2], [3], [4], [5]. Other studies aim to understand whether simulation results are capable to predict human thermal perception, hence OTC [6]. According to the American Institute of Aeronautics and Astronautics, validation entails assessing the extent to which a model faithfully reflects the real-world scenario for its intended purposes [7]. Several CFD best-practice guidelines emphasize the critical evaluation of CFD simulations, suggesting that their reliability is contingent upon comparisons against empirical measurement data [1]. Although ENVI-met is widely used to study urban climate and human biometeorology in various climatic and morphological contexts, many studies do not perform an adequate validation of the simulation model against field data, which suggests a gap in the literature regarding reliable validations.

In order to validate simulation models, the majority of studies adopt fixed weather stations in a limited number of points in the study domain [8] or even further away (e.g., airports meteorological stations). A relevant issue arising from this is that measured data is usually not able to capture the diversity of existing spatial patterns and their thermal implications in intra-urban canyons. According to Krayenhoff et al.

(2021), model validation should be performed at multiple points in space to improve methodological rigor and understanding of complex dynamics in the urban canopy layer through observations and modeling. The application of a portable environmental monitoring system seeks to overcome such limitations [10]. Recent studies collected thermal data via transects to validate seasonal simulation models from cold to extremely hot conditions [11]. While fixed stations present the advantage that the position of the sensors remains unchanged during the observation period, transects allow sampling from a variety of intra-urban canyon situations. This way, a spatial model validation is potentially more adequate to represent spatial diversity.

OBJECTIVE

The aim of the present study is to contribute to the validation of CFD urban microclimate simulations by employing intra-urban canyon transects as an alternative or a complementary approach to fixed stations.

METHOD

The method used is based on three main steps, basically: first, to conduct transects, then to model the surveyed area, and finally to calibrate the model. For that, we developed a cost-effective monitoring unit in order to carry out transects on a pre-defined route (1), devised the areas of interest (2), elaborated a simulation model in ENVI-met (3), and proposed validation methods for comparative analyses (4).

PORTABLE LOW-COST ENVIRONMENTAL MONITORING SYSTEM (PLEMS)

Figure 1 presents the construction details of the device (termed Portable Low-cost Environmental Monitoring System, PLEMS). The data collected by the sensors are GPS locational data (1); air temperature and air humidity (2); globe temperature (3); wind speed (4); illuminance (5); sound pressure levels (6) and CO_2 concentration (7). The collected data can be viewed in real time on an LCD screen attached to the equipment and, within a 90-second cycle, data are stored in a ".csv" file.

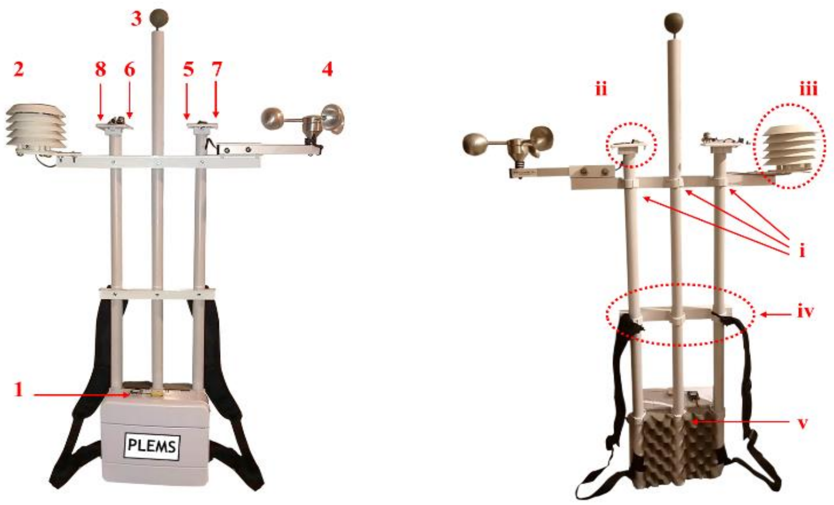
The casing consists of an electric distribution enclosure to which two 0.80 meter and a 1.00-meter PVC tubes were fixed with plastic clamps (i) in the center, so that the globe thermometer is not shaded. To position all the sensors aligned, two switch plates (ii) were used. To protect the air temperature and humidity sensor, a solar shield (iii) (3D-printed via Thingiverse) was printed in PLA and varnished, with an aluminum foil film fitted to the cover, as recommended by HAM [12]. To allow people with different heights to use the equipment, there are adjustable bar and straps (iv). In the present study, the height of the sensors was adjusted to 1.90 meters in relation to the ground; and the globe at 2.10 meters.

Calibration of the sensors (Source: The authors.

Table 1) was carried out in a climate chamber with limited thermal control against reference equipment: the SENSU comfort meter developed at LMPT/UFSC and a Kestrel 3000 propeller anemometer (Source: The authors.

Table 2) [13].

Figure 1: Location of sensors and construction details of the PLEMS.



Source: The authors.

Table 1: Accuracy of components (prototype and reference equipment)

Variable	Prototype	Accuracy	Reference equipment	Accuracy
Air temperature	AHT10	± 0.3°C	SENSU®	± 0.2°C
Relative humidity		± 2%		± 3%
Globe temperature	DS18B20	± 0.5°C		± 0.2°C
Wind speed	ANBR-1	± 5%	KESTREL 3000®	± 3%

Source: The authors.

Table 2: Summary of calibration results

Variable	Kruskal-Wallis test (*p-value*)	Regression equation	R^2	MAE with validation
Air temperature	0.2144	N/A	0.9754	0.24
Relative humidity	0.0001	RH'= 0.9535*RH +1.8994	0.9955	0.55
Globe temperature	0.0455	Tg'=1.0845*Tg - 1.6575	0.9982	0.13
Wind speed	0.2728	N/A	0.9706	0.09

Source: The authors.

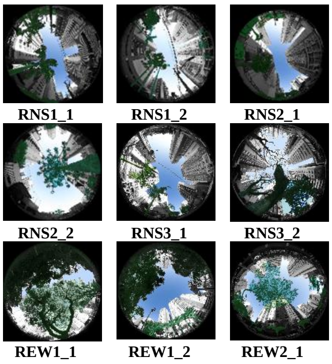
STUDY AREA AND WALKING ROUTES

Curitiba is the coldest state capital in Brazil, located at 25º25'48'' S and 49º16'15'' W and at a mean altitude of 920 meters above sea level. According to the Köppen-Geiger classification, the city of Curitiba is Cfb (Temperate oceanic climate), characterized by a temperate climate with mild summers. While in the coldest month (July) the average temperature is 12°C, in the hottest month (February) the average is 23°C. The absolute minimum and maximum temperatures recorded in these months are -2°C and 32°C, respectively [14]. Throughout the year, the easterly wind has a greater frequency of occurrence.

The study area was selected due to the heterogeneity in terms of morphological factors and urban greenery, also taking into account safety aspects for carrying out field measurements at given times of day. Thus, the study area comprises diverse aspect ratios (shallow, medium and deep street canyons), different solar orientations (north-south and east-west street axes), locations with and without vegetation (Figure 2). Additionally, in order to verify whether a wearable device was able to correctly capture urban-related signals during the thermal walks, a comparison was drawn to a reference weather station (Table 3) placed on the rooftop of a building within the study area, and to a local weather station [15] close to the area.

The area was surveyed at the reference onsite weather station and at the 12 monitoring points, spread over six segments, each formed by two blocks, which are analyzed and named according to their urban morphology and solar orientation condition, resulting in three north-south segments of the route (RNS) and three east-west segments (REW). The linear segments are approximately 250 meters long each, resulting in a total distance of 1.5 km covered in one hour. Dynamic measurements were interrupted by 3-minute stops at the 12 points of interest. The 3-minute stop was considered as the minimum amount of time needed to gather local microclimate data accounting for the response time of the embedded sensors and anemometer readings in a standstill condition. This allows a more reliable representation of the microclimatic conditions of the investigated points, which would not be possible in a continuous dynamic monitoring without stopping. Four days with forecasts of clear sky were selected for the thermal walks at three-time stamps (local time 9am, 3pm and 9pm) in summer (16, 17, 18 and 19 March 2023).

Figure 2: Hemispherical photos the 12 monitored points and the reference station.



Source: The authors.

Table 3: Accuracy of reference weather station on the rooftop

Data Logger HOBO MX 1102ª	Measuring range	Accuracy	Resolution	Sampling interval
Air temperature	0-50°C	±0.21°C from 0°C to 50°C	0.024°C at 25°C	1 min
Relative humidity	1-90%	±2% from 20% to 80% typical to a maximum of 4.5% including hysteresis at 25°C; ±6% typical below 20% and above 80%	0.01%	1 min

Source: The authors.

SIMULATION MODEL

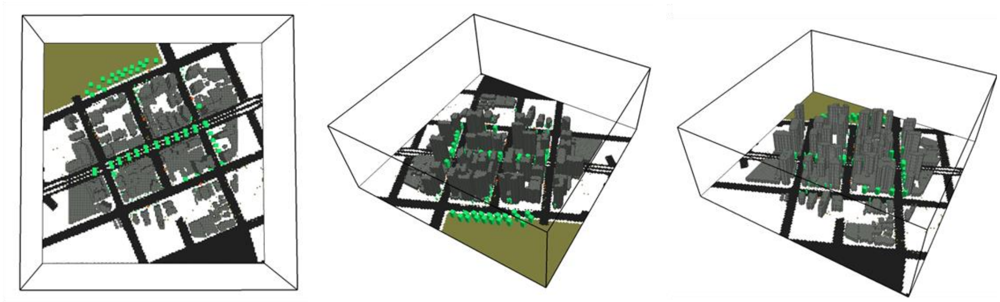
ENVI-met was selected for its ability to simulate the surface-plant-air interactions in an urban environment at high spatial and temporal resolution [16]. There are two different methods of atmospheric forcing applied in ENVI-met simulations: Full Forcing (FF) and Simple Forcing (SF). The choice between these approaches may depend on factors such as the specific requirements of the simulation, available data, computational resources, and the desired accuracy. FF implies a more detailed and comprehensive representation of atmospheric conditions, while SF suggests a more simplified approach. The primary distinction between SF and FF lies in the temporal resolution of input data from the reference meteorological station. SF only allows the input data of air temperature and humidity on an hourly basis, alongside fixed values for wind speed, wind direction, and cloud cover. Conversely, FF enables the input of several variables, such as air temperature, wind speed and direction, radiation, cloud cover, and precipitation, with a time resolution of 30 minutes. As dynamically-measured field data gathered with PLEMS lie within the hour, in this study the FF method was used.

To perform the simulations, a 3D model of the study area was created (Figure 3). The domain is a grid of 167 × 167 × 20 cells (cell size of 3 × 3 × 10m) whereas the lowest grid box is split into 5 subcells for greater resolution at the pedestrian level. The lowest grid box is characterized by a vertical spacing of 2 m for the first 10 m height. This distance is very close to the measurement height of the wearable device, which corresponds to 1.80m.

Data related to existing trees at the measurement points were inserted in the computational model in terms of species, height, LAI (leaf area index) and LAD (leaf area density) (Table 4). As ENVI-met simulates vegetation based on LAD, the LAI collected was converted to LAD according to the procedure put forth by Lalic and Mihailovic [17], considering the 10-layers homogeneous. The LAI was estimated using the technique of hemispherical photography and photo processing in *Hemisfer 3.2* software. This technique stands out for its precision and adaptation to various photographic equipment and field studies.

The layout of the study area was based on shapefile data made available by the city's municipal urban planning sector [18] which was updated in 2023. The building heights were estimated from onsite observations and Google Street view images. A summary of all input parameters and values for the parametric study can be found in Table 5.

Figure 3: ENVI-met model.



Source: The authors.

Table 4: Definition of trees in the ENVI-met corresponding to the 12 points monitored.

Point	Tree species	LAI m^2m^{-2}	LAD m^2m^{-3}	Albero 3D plants (height)	User 3D plants
RNS1_1	*Archontophoenix cunninghamiana*	0.33	0.03	01PLDM Palm, large trunk, dense, medium (15m)	PLDM03
RNS1_2	*Araucaria angustifolia*	0.28	0.03	0000PP - Pinus Pinea (15m)	00PP03
RNS2_1	Bare	N/A	N/A	N/A	N/A
RNS2_2	*Araucaria angustifolia*	0.92	0.09	0000PP Pinus Pinea (15m)	00PP09
RNS3_1	*Washingtonia filifera*	0.14	0.01	01PLDM Palm, large trunk, dense, medium (15m)	PLDM01
RNS3_2	*Jacaranda mimosifolia*	1.38	0.14	0000JM Jacaranda mimosifolia (15m)	00JM14
REW1_1	*Tipuana tipus*	2.49	0.25	01CMSM Cylindric, medium trunk, sparse, medium (15m)	CMSM25
REW1_2	*Tipuana tipus*	0.48	0.05	01CMSM Cylindric, medium trunk, sparse, medium (15m)	CMSM05
REW2_1	*Caesalpinia leiostachya*	0.75	0.08	02OLSL Cylindric, large trunk, sparse, large (25m)	OLSL08
REW2_2	*Caesalpinia leiostachya*	2.37	0.24	02OLSL Cylindric, large trunk, sparse, large (25m)	OLSL24
REW3_1	*Plinia cauliflora*	0.34	0.03	02OMSS Cylindric, medium trunk, sparse, small (5m)	OMSS03
REW3_2	Bare	N/A	N/A	N/A	N/A

Source: The authors.

Table 5: Summary of input and test parameters, and the corresponding values for validation simulation of study area of Curitiba.

Parameter	Definition	Input value
Start and end time	17 March 2023, 23:00PM - 19 March 2023, 23:00PM	-
Size of grids (m)	3 x 3 x 10	-
Grid generation	Equidistant grid (Lowest cell split into 5 sub-cells)	-
Domain size (m)	501 x 501	-
Meteorological conditions	Air temperature (°C)	Full forcing[a]
	Relative Humidity (%)	Full forcing[a]
	Solar radiation (W/m²) *Short Wave dir., Short Wave dif. and Long Wave*	Full forcing[a]
	Inflow direction (°)	88[a]
	Wind speed at 10m (m/s)	2.84[a]
	Soil temperature (°C) *Upper, Middle and Deep layer*	20, 20, 19
	Cloud cover (oktas)	0[b]
	Lateral boundary condition	Open
Buildings'/roads' information	Streets orientation	N-S and E-W
	Wall, road and roof albedo	0.3
Tree information	See Erro! Fonte de referência não encontrada.	-

[a] Data obtained from INMET station.
[b] Data obtained from Radiosonde [19].

Source: The authors.

VALIDATION OF THE ENVI-MET MODEL

In order to analyze the accuracy of the *ENVI-met* software model in terms of predicting climate factors, temporal and spatial validations have been carried out (Table 6). Simulation performance was evaluated using following indicators: the Root Mean Squared Error (RMSE), the Mean Absolute Error (MAE), the Mean Bias Error (MBE), the Willmott index of agreement (d) and the Pearson coefficient of determination (R^2). Metrics are determined by equations 1, 2, 3 and 4. While RMSE represents the quadratic mean of the errors produced in the validation process between measured and simulated data, MAE results in the absolute mean between collected and simulated data. Therefore, the smaller the values of these statistical equations, the better the representation of the real scenario [20]. Both the d index and R^2 indicate greater quality of fit as they approach 1. Analyzing different indices simultaneously avoids the misinterpretation that checking a single metric can cause. The indicators must reach acceptable values in relation to other reviewed articles that validated ENVI-met models [21], [22], [23]. Based on this, the validation criterion used in this study is RMSE≤4.3℃; MAE≤3.7℃; R ≥0.67 and d≥0.75.

$$RMSE = \sqrt{N^{-1}\sum_{i=1}^{N}(Pi - Oi)^2} \quad \text{(Eq 1)}$$

$$MBE = N^{-1}\sum_{i=1}^{N}(Pi - Oi) \quad \text{(Eq 2)}$$

$$MAE = N^{-1}\sum_{i=1}^{N}|Pi - Oi| \quad \text{(Eq 3)}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2}\right] \quad \text{(Eq 4)}$$

Where, N is the number of cases, P is the value predicted (i.e. simulated) by the model, O is the observed value (i.e. measured) and Ō is the average of the observed values.

Table 6: Summary of validation models: temporal validation and spatial validation.

Validation	Temporal	Spatial
Meteorological data	Rooftop station	Wearable device
Period	48 hours	9am, 3pm and 9pm (local time)
N. Receptors	01	12
N. Statistic data	48	36
Validation criteria	RMSE≤4.3°C/13.0%; MAE≤3.7°C/11.2%; R^2≥0.67 and d≥0.75	

Source: The authors.

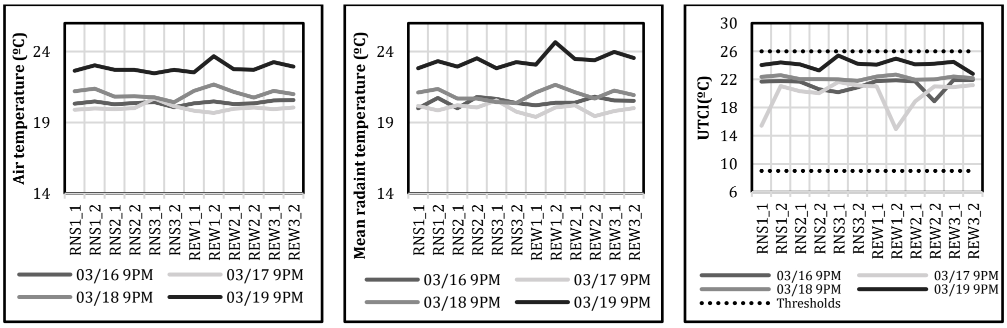
The ENVI-met model generated for the study area presents 13 receptors points corresponding to the locations of the monitoring points. Stationary data measured by the fixed reference station (one point) and dynamic data measured with the wearable device (12 points) allowed comparisons between simulated data and onsite measurements. Temporal validation consists of a 48-hour period for comparison with the fixed reference station measurement. Spatial validation comprises the three times of the day (i.e., local time 9am, 3pm and 9pm) with data gathered with PLEMS.

RESULTS AND DISCUSSION

SELECTION OF SIMULATION DAYS

To select the representative days for analyzing the thermal behavior of urban canyons in a CFD model, a comparative analysis was carried out for nighttime data (9 pm local time) aiming at conditions that best represent the Urban Heat Island (UHI) effect (Figure 4). The two last monitoring days (March 18th and 19th) present quite a similar point-by-point variation of the air and mean radiant temperature. The first two monitoring days (March 16th and 17th) were partially clouded, with increased cloudiness at night. Based on such preliminary visualization, March 18th and 19th were selected for an in-depth analysis.

Figure 4: Ta, Tmrt and UTCI in summer at 9 pm, with lower and upper comfort thresholds for the UTCI.



Source: The authors.

TEMPORAL VALIDATION OF THE ENVI-MET MODEL

For understanding the procedure of the software validation and comparison with the experimental data, temporal validation was addressed at a single spot, representing the fixed station (ref point in Figure 2). Through this process it was possible to evaluate the model accuracy and reliability of the microclimate simulation by the most commonly method used in urban microclimate simulation.

The field measurement results from the roof fixed station were compared with the simulation results of a receptor at the same position in ENVI-met. As shown in Figure 5 and Table 7, results indicate very strong agreement between simulation and measurement data (d ~ 0.97, d ~ 0.97) with medium error magnitudes (RMSE ~ 1.45℃ and 6.72%, MBE ~ -0.75℃ and -3.60%). The temporal validation model reaches the validation criteria and provided reliable microclimate output for this type of comparison.

Figure 5: Temporal validation for air temperature and relative humidity.

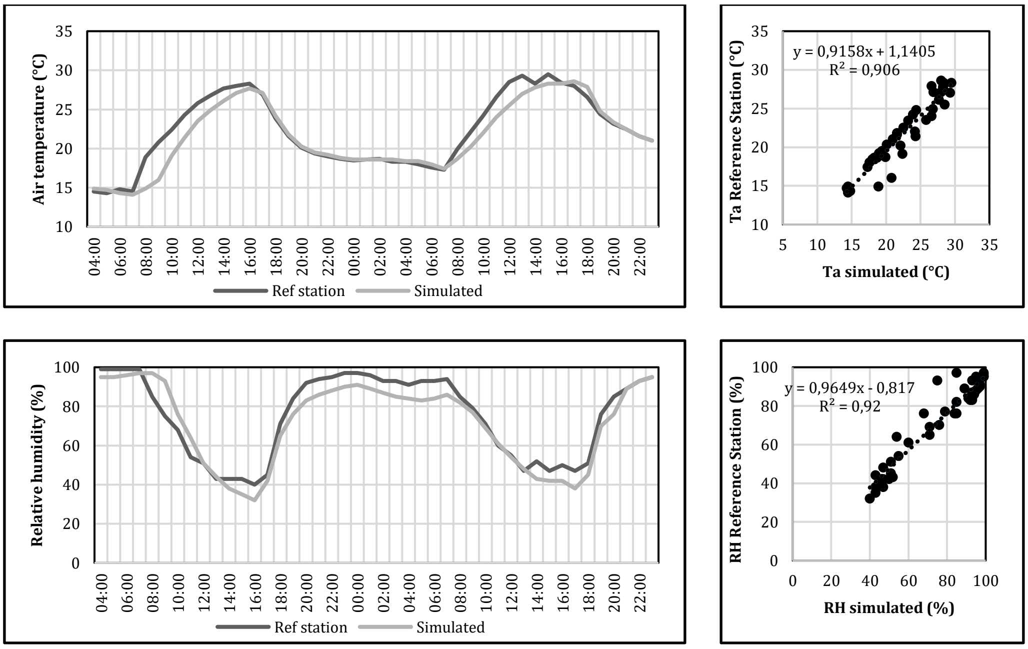
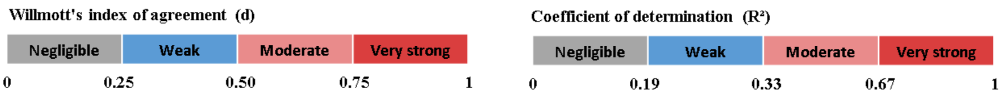


Table 7: Statistical results of temporal validation.

	RMSE	MBE	MAE	R^2	d
Ta	1.45	-0.75	0.90	0.91	0.97
RH	6.72	-3.60	5.35	0.92	0.97



Source: The authors.

SPATIAL VALIDATION OF THE ENVI-MET MODEL

Spatial validation results indicate that the simulation slightly underestimates air temperature in the morning and at night, and overestimates in the afternoon. Conversely, the relative humidity exhibits an overestimation in all periods. Several issues may influence the simulated temperature and relative humidity. As ENVI-met requires a single wind direction and speed which is maintained fixed throughout the entire simulation period, we used the prevailing wind direction on March 19th, which might have influenced differences found between simulation and transects results.

The spatial validation model does not reach the validation criteria. As it can be seen in Figure 6 and Table 8, results indicate weak agreement between simulation and measurement data (d ~ 0.45, d ~ 0.23) with medium error magnitudes (RMSE ~ 1.06°C and 11.94%, MBE ~ -0.03°C and 11.18%). The spatial validation proves that there are differences between the intra-urban transect data and the simulated data, requiring model calibration. The simulation model is flawed and not able to capture intra-urban idiosyncrasies that have presumably affected microclimate in the evaluated points.

Figure 6: Spatial validation for air temperature and relative humidity.

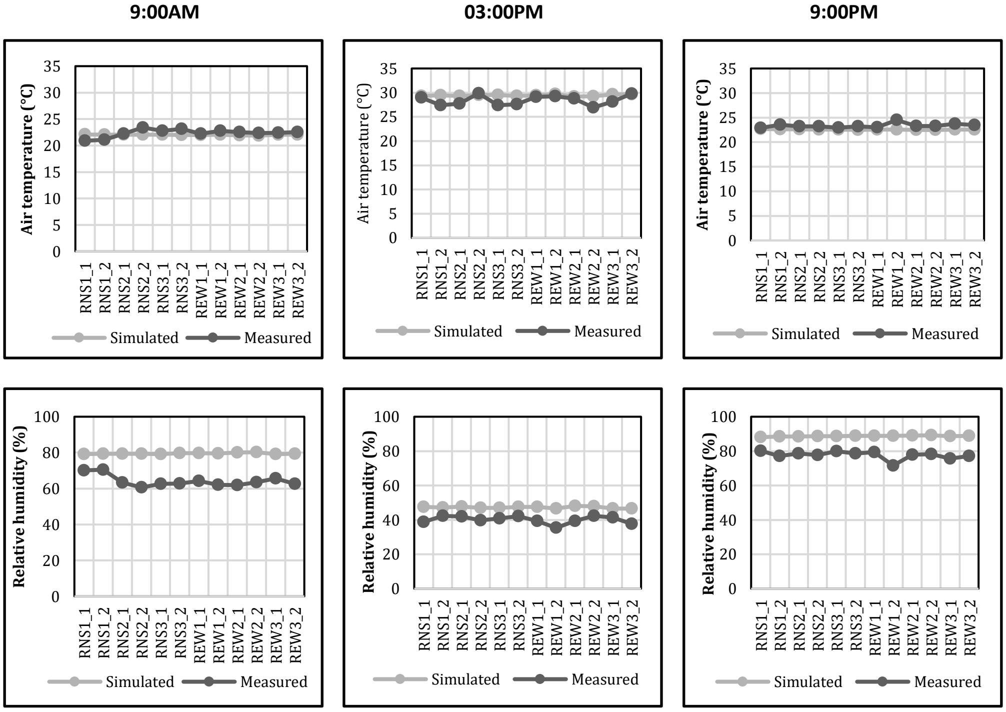
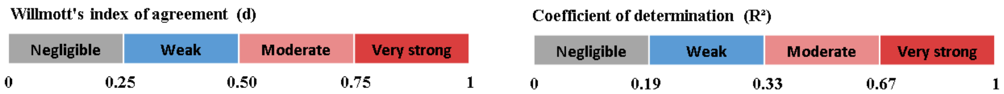


Table 8: Statistical results of spatial validation.

	RMSE	MBE	MAE	R^2	d
Ta	1.06	-0.03	0.87	0.92	0.45
RH	11.94	11.18	11.18	0.95	0.23



Source: The authors.

CONCLUSION

This paper investigates the application of intra-urban canyon transects as an alternative or a complementary approach to fixed stations for temporal and spatial validation of microclimate simulation models. Results indicate that temporal validation does not identify diversities present in the urban canyon under a human-centric comfort approach via wearable devices. Spatial validation demonstrates differences between the intra-urban transect data and the simulated data, highlighting the necessity for model calibration. The simulation model is not able to capture intra-urban peculiarities that likely influence microclimatic conditions.

Although valid as an initial analysis, the spatial validation method is simplified and can be improved in future studies. As spatial validation represents a specific time and measurements with wearable devices are dynamic, one of the topics that deserves attention is the application of a temporal correction factor on the data collected by dynamic measurement. The effect of elapsed time on the data registered with the wearable device could consider a time-dependency correction based on the fixed weather station recordings.

Integrating surveys and direct observations alongside field measurements provides a comprehensive understanding of urban areas requiring intervention. This holistic approach facilitates the identification of precise locations and optimal timings for urban interventions. Leveraging these data, accurate simulations can effectively delineate suitable mitigation strategies tailored to specific locales. By amalgamating empirical data with advanced simulation techniques, scientists can take advantage of the integration itself for optimizing both the procedures and the reliability of findings and necessity for actions.

ACKNOWLEDGEMENTS

Authors would like to thank the Brazilian government agency CAPES (Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the scholarship (88887.570164/2020-00) granted to Bianca M. de Quadros. The authors' further thanks the Horizon Europe programme under grant agreements No 101137507 (SONATA) and No. 101041255 (ERC, HELIOS). Ilaria Pigliautile further thanks the Italian funding programme Fondo Sociale Europeo REACT EU—Programma Operativo Nazionale Ricerca e Innovazione 2014–2020 (D.M. n.1062 del 10 agosto 2021) for supporting her research though the "Red-To-Green" project.

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