Empirical and Numerical Approaches in Urban Microclimate Modeling: Investigation on the Reliability

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Abstract Urban climate modeling indicates a significant development in accomplishing the urgent solutions to the current urban climate change challenge. As the demand for sustainable urban development continue to grow, researchers have derived range of strategies and methodologies to explore the urban issues. Direct field measurements and data collection have been the popular approach for urban microclimate studies. However, in recent times, numerical simulation approaches have become increasingly popular. This study presents the urban microclimate modeling of a tropical outdoor space with dense building blocks using empirical and numerical approaches. This investigation covers the evaluation of air temperature, air movement, and relative humidity. The results revealed that the two approaches are significantly correlated. However, this study points out that numerical modeling is a reliable approach in performing the hypothetical urban microclimate modeling in the high-rise building blocks. The findings therefore suggest that numerical approach is better in the study of Urban Heat Island for strategic mitigation purpose than empirical approach.

Keywords Urban configurations · Urban microclimate · Reliability study · ENVI-met simulation · Tropical context

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1 Introduction

The effect of climate change is becoming more prevalent as the city grows and make necessary provision for the increasing population. Urban Heat Island (UHI) appears to be an ongoing issue in big cities since the 1818 to 1925 as the result of continuous rapid economic activities in the urban area and is one of the major contributors to climate change [1–4]. Apart from the environmental degradation caused by UHI, poor thermal comfort, urban health problem, and high cooling loads are among other severe impact of this phenomenon which require closer attention and mitigation efforts from both professional planners and policy makers to achieve a sustainable urban environment [3–9].

The mitigation effort widely opens the opportunities for scholars to investigate the urban climate to map the alternatives of strategies and actions. This study justifies that microclimate modification is an essential component to form the UHI, besides it is also a uniform measure in assessing the urban energy balance [3, 10]. The micro-urban spaces between buildings generate urban heat generators through short and longwave radiation, surface heat storage, heat canopy, and anthropogenic heat [10]. As the most used variable in urban energy balance study, microclimate significantly affects indoor and outdoor thermal comfort. In general, modification of microclimate mainly focuses on the following variables; solar radiation, air temperature, air velocity, and relative humidity [11]. The main objective of the urban climate study is to minimize the microclimate modification that increases the UHI intensity, which would also reduce the thermal discomfort and demands of cooling loads. Therefore, the methodology of conditioning the microclimate modification is constantly explored. As each city is attached to its context in adapting to the regional climate, the approach frequently varies between one to another. This study however looks closer into the analysis of the most reliable approach to investigate the urban microclimate modeling of a dense tropical city through a comparison study.

2 Urban Microclimate Modeling

As the study on urban climate develops, Oke [12] as one of the pioneers in this area stressed three major methods in the UHI investigation; observation, theoretical, and modeling. As the focus of this study, the modeling method described as a 'simplified presentation of reality to the current theory [13]. Atkinson [14] grouped UHI modeling into the following approaches; hardware, physical equation, and dynamical numerical. This study reviewed that the category outlined by Oke [15], Svensson et al. [16], and Voogt [7] is the most discussed and relevant in the UHI modeling are as follows; numerical, physical, and empirical.

The empirical modeling method is commonly used in early urban climate study. As the main focus, the UHI investigation was performed through conventional field observation. Empirical modeling was formed by the statistical field data that then formulated into mathematical equations [17, 18]. A significant study using empirical modeling in investigating the relationship between urban canyon geometry and UHI was conducted by Oke in 1981 [19]. From this study, Oke formulated that maximum intensity of UHI in canyon space is resulted by the geometry of high Height to Width (H/W) ratio and low Sky View Factor (SVF) value [11, 20], as shown in Eqs. 1 and 2. The formulas are used as the basic model in this study; particularly in closely investigate the urban temperature behavior in relation with the UHI scenario.

$$\mathrm{dTmax} = 7.45 + 3.97 * \ln(\mathrm{H/W}) \tag{1}$$

$$\mathrm{dTmax} = 15.27 - 13.88 * \mathrm{SVF} \tag{2}$$

Physical modeling is an approach by using a scale model to represent the real scenario of urban features. Oke [19] was also among the ones to extends the empirical modeling to physical modeling. Numerical modeling applies the mathematical model into a computer simulation. The rapid development of computer technology provides solutions to the constrain of the both empirical and physical modeling approach. It simulates a more accurate and precise physical and climate features, as well as it eliminates the limitation of time, cost, and research variables Batty [21] strongly described that the computer modeling as comprehensive, detail, and allow planners to perform the more flexible hypothetical urban climate model. Bruse [22] was among the scholars that pioneered the urban climate study by developing the computer model.

The computer simulation as the form of numerical modeling is the recent approach mostly applied to study the complex and dense urban climate. Besides, computer simulation covers most of the urban climate modeling limitations. The computer simulation does not only analyze the existing urban climate scenario but also a hypothetical scenario that eliminates time challenges. Therefore, the computer simulation is a trend approach among planners and scholars to assess the relationship between urban physical features and climate variables to achieve the most effective planning decision [23–26].

Yet, there is no one particular software covers all of the microclimate or thermal comfort variables [27]. The rapid development and intense use of computer simulation in nowadays urban climate studies do not stop the effort of scholars to include investigation on its' reliability to perform the current urban scenario with more complexity and meeting the contextual research objectives. The study of reliability or compatibility of the urban simulation tends to always perform to test the accuracy, effectiveness, and prediction of errors of the modeling approach. In short, the reliability of the numerical modeling is often performed by doing validation investigation with other modeling approaches. The example of the reliability study could be seen by comparing it with other simulation and field observations. In the context of this study, the reliability investigation seeks to closely analyze the gap of computer simulation results with the field data.

3 Methods

This study is an extended discussion of the previous study [28–31] that validates ENVI-met simulation through Oke's model. The previous study aimed to confirm the reliability of the ENVI-met from the early empirical mathematical model. Thus, this study aims to elaborate on the reliability of the ENVI-met simulation by comparing it with the field observation data. This study investigates two sites of high rise residential urban blocks, situated in a dense city center of Kuala Lumpur, Malaysia. The first site is a 19 storey block (Flat Bandar Tasik Selatan) while the second site is a 15 storey block (Surya Magna). The building configuration in the two sites is a Courtyard Canyon, with the canyon feature in the middle of the courtyard. However, the direction of the canyon in Flat Bandar Tasik Selatan faces East-West while in Surya Magna faces North-South.

The field data observation was conducted on 15 June 2015, set in the middle of the courtyard. The 24-hours data was taken by using the VelociCalc Plus 10 cm from the surface. This study presents data analysis of one of the three microclimate variables; air temperature. With the existing scenario, this study investigated four urban configurations; Courtyard, U configuration, Courtyard Canyon, and Canyon. The Sky View Factor (SVF) varies in each configuration while the Height to Width (H/W) aspect ratio remains constant. The simulation used ENVI-met V.3. The climate data was inserted in the ENVI-met simulation configuration editor are as follow: the initial temperature and inside temperature are 303.15 K and 293 K; relative humidity is 83%; albedo of walls and roofs are 0.3 and 0.5; the wind speed and direction are 1.4 m/s and 225 (South West to North East), and heat transmission wall and roofs are 1.94 W/m^2 K and 6 W/m^2 K). This study used the $250 \times 250 \times 30$ size of simulation sections as the output data.

4 Results Discussion

This urban configuration and microclimate investigation presented the validation study [31]. It justified the air temperature behavior within the canyon space from the UHI model. It compared Oke's Model (Eqs. 1 and 2) and ENVI-met simulation. The results (Tables 1 and 2) pointed out that the drop of diurnal to nocturnal air temperature developed as the SVF value increases. This situation was as presented by dTmax in Oke's model, the UHI intensities were lower when the SVF value increases. Through comparison with the Oke's model as the empirical modeling, the results validated that Envi-met urban simulation was a suitable approach for this study.

The further reliability study on the simulation approach is presented in this paper. The results of this reliability study are also discussed according to the microclimate data from each case site. Overall, regression analysis on the two case sites of Flat Bandar Tasik Selatan (FBTS) and Surya Magna (SM) shows the

Table 1 Comparison of Oke's model and Envi-met: East–West

Urban configuration and SVF	Oke's model $dT_{max} = 15.27 - 13.88 * SVF$ (°C)		Drop of Envi-met air temperature (diurnal–nocturnal) (°C)	
Courtyard (0.275)	11.45	dT_{max} decreases when SVF increases	0.27	Drop of air temperature develops by the increase of SVF [a]U configuration shows higher air temperature when faces West
U (0.309)	10.98		0.78[a]	
Courtyard Canyon (0.438)	9.19		0.45	
Canyon (0.676)	5.89		1.32	

Source Yola et al. [31]

Table 2 Comparison of Oke's model and Envi-met: North–South

Urban configuration and SVF	Oke's model $dT_{max} = 15.27 - 13.88 * SVF$ (°C)		Drop of Envi-met air temperature (diurnal–nocturnal) (°C)	
Courtyard (0.611)	6.79	dTmax decreases for the higher SVF	1.13	Drop of air temperature increases as the SVF develops
U (0.694)	5.64		1.19	
Courtyard Canyon (0.707)	5.46		2.5	
Canyon (0.793)	4.26		2.96	

Source Yola et al. [31]

significant correlations between the two discussed empirical and numerical approaches (Table 3). However, the analysis indicates the small gap between the simulated and observed microclimate data. This situation is due to the unrecorded variables in the existing scenario that was not recorded in the simulation. Among the variables are building material properties, anthropogenic heat from vehicles and air conditioning, green area, and other vertical obstructions in sites.

The significant correlation findings from regression analysis point out that the computer simulation and field observation are both valid approaches to study the

Table 3 Microclimate regression analysis of observation and simulation

Canyon direction	Reg. analysis	Air temperature	Relative humidity	Wind velocity
East–West	P value	0.000	0.000	0.000
	R^2	0.709	0.834	0.939
	RMSE	0.140 °C (0.4%)	3.460% (4.6%)	0.035 m/s (4.3%)
North–South	P value	0.000	0.002	0.022
	R^2	0.977	0.804	0.602
	RMSE	0.262 °C (0.7%)	1.60% (2.2%)	0.015 m/s (2.2%)

microclimate study. Specifically, this study stresses that the computer simulation presents the identical pattern of result with the field observation with the tolerable margin error. In the context of this study, the field observation data validates the ENVI-met simulation as an effective tool of the numerical approach to investigate the microclimate in the dense urban configurations.

5 Conclusions

The development of urban climate study is a part of the positive response to numerous effects of climate change which requires urgent attention from both city planner and policy makers. Thus, understanding valid approach(es) to reliably explore the implications of urban growth and the resulting challenges is an essential stage in urban climate study development. This will provide a range of opportunities to generate comprehensive strategies to address climate change mitigation actions. The regression analysis was adopted in this study to investigate the correlation between the empirical and numerical approach, by comparing the results of the observed and simulated microclimate data of a hypothetical urban configuration in dense tropical residential site contexts. The results showed a significant correlation between the two approaches. The finding shows that ENVI-met simulation provides a strongly reliable results in the assessment of urban microclimate variables. It can also be inferred for the present study that the reliability of these results is due to ENVI-met efficiency, the available features, and the level of accuracy the technology brought to bear in modelling both two and three-dimension urban climate data. Finally, ENVI-met offers the opportunity to model a hypothetical urban configuration which is a limitation of other empirical modelling methods. Therefore, this study provides a scientific justification and the reliability of the results and hence strongly recommend the ENVI-met as an alternative approach in urban climate study.

References

1. Sachindra DA, Ng AWM, Muthukumaran S, Perera BJC (2015) Impact of climate change on urban heat Island effect and extreme temperatures: a case study. Q J Royal Meteorol Soc
2. Fatwa N (2020) Strengthening the role of Sharia Public banking in the Indonesian construction industry: towards an atmosphere of sustainable urban development. IOP Conf Series Earth Environ Sci 436(1):
3. Gartland LM (2008) Heat islands: understanding and mitigating heat in urban areas. Earthscan
4. Schmauss A (1925) Eine miniaturpolarfront. Meteorol Z 42:196
5. Arifwidodo S, Chandrasiri O (2015) Urban heat island and household energy consumption in Bangkok, Thailand. Energy Proc 79:189–194
6. The Heat Island Group (2005) Retrieved February 10, 2015, retrieved from http://eetd/lbl/gov/HeatIsland/
7. Voogt J (2004) Urban heat island: hotter cities. American Institutes of Biological Sciences

8. Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, Assimakopoulos DN (2001) The impact of urban climate on the energy consumption of buildings. Sol Energy 70(3):201–216
9. Oke TR (1987) Boundary layer climates. Routledge, New York
10. Weber F (2015) Towards mitigative buildings and urban environments. In: The 31th international PLEA conference passive low energy architecture, 9–11 September 2015. Bologna
11. Erell E, Pearlmutter D, Wiliamson T (2011) Urban microclimate: designing the spaces between buildings. Earthscan
12. Oke TR (1982) The energy basic of urban heat island. J Royal Metereol Soc 108(455):1–24
13. Liu Y (2009) Modelling urban development with geographical information systems and cellular automata. CRC Press, Boca Raton
14. Atkinson BW (2003) Numerical modelling of urban heat-island intensity. Bound Layer Meteorol 109(3):285–310
15. Oke TR (1984) Towards a prescription for the greater use of climatic principles in settlement planning. Energy Build 7(1):1–10
16. Svensson M, Eliasson I, Holmer B (2002) A GIS based empirical model to simulate air temperature variations in the Göteborg Urban Area during the night. Climate Res 22(3):215–226
17. Masson V (2006) Urban surface modeling and meso-scale impact of cities. Theoret Appl Climatol 84:35–45
18. Balázs B, Unger J, Gál T, Sümeghy Z, Geiger J, Szegedi S (2009) Simulation of the mean urban heat island using 2D surface parameters: empirical modeling, verification and extension. Meteorol Appl 16(3):275–287
19. Oke TR (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. J Climatol 1:237–254
20. Givoni B (1998) Climate considerations in buildings and urban design. Van Nostrand Reinhold
21. Batty M (2013) The new science of cities. Massachusetts Institute of Technology
22. Bruse M, Team (2015) ENVI-met website. Available at http://www.envi-met.com/. Retrieved on 2nd Feb 2015
23. Yola L, Siong HC (2014) Modelling and simulation approach of assessing urban form. Emerging trends in commerce, economics, humanities and social sciences (CEHSS). Int Res J Humanit Environ Issues, 25–26 Feb 2014. Kuala Lumpur
24. Yola L, Siong HC (2015) Validation of 3D microclimate simulation as quantitative analysis for urban configuration study in hot and humid region. International joint conference. SENVAR-iNTA-AVAN, 22nd–27th July 2015. Universiti Teknologi Malaysia
25. Yola L, Siong HC (2016) Computer simulation as an alternative approach in climatically responsive urban configuration study. International conference of low carbon Asia (ICLCA) 2016, 23rd–25th Nov 2016. Universiti Teknologi Malaysia
26. Yola L, Siong CS (2017) Computer Simulation as an Alternative Approach in Climatically responsive urban configuration study. Chem Eng Trans 56(2017):505–510
27. Vidmar J, Roset J (2013) Evaluation of simulation tools for assessment of urban form based on physical performance. Environmental physics for architects. Faculty of Architecture, Ljubljana, Slovenia
28. Yola L, Siong HC (2017) Computer simulation as an alternative approach in climatically responsive urban configuration study. Chem Eng Trans 56:505–51
29. Yola L, Siong HC, Djaja K (2020) Climatically responsive urban configuration in residential area: research gaps. AIP Conf Proc 2020(2255):0700141
30. Yola L (2020) Canyon effects in urban configurations: tropical context study. IOP Conf Series Earth Environ Sci 436(1):012028
31. Yola L (2018) Impact of urban configurations on microclimate and thermal comfort in residential area of Kuala Lumpur. PhD dissertation. Universiti Teknologi Malaysia