RESPONSIVENESS OF MICROCLIMATE SIMULATION TOOL IN RECOGNISING DIVERSITY IN URBAN GEOMETRY

TANIA SHARMIN[1], KOEN STEEMERS[1]

[1] The Martin Centre for Architectural and Urban Studies, Department of Architecture,
University of Cambridge, United Kingdom

ABSTRACT: Recent studies have revealed that diverse urban geometry, as found in traditional urban areas, has positive consequences in ameliorating the urban microclimate in comparison to the more regular formal urban areas. The diversity in urban forms with variable street patterns, irregular plot sizes and building heights in traditional areas can help to lower the air-temperature (Ta) as well as mean radiant temperature (Tmrt) when compared to the formal areas. In contrast, formal or planned urban areas with uniform plot sizes and building heights, show a tendency to develop higher day-time temperatures. A field measurement in the tropical megacity Dhaka reveals, varying traditional urban forms are on average 1.7^{0}C cooler in comparison to more regular formal residential areas. The aim of this study is to understand the responsiveness of the microclimate simulation tool ENVI-met 4 in identifying the variation in urban geometry as reported in the previous study. The study aims to make specific comparisons between measured and monitored data by analysing a particular challenge in complex geometry, rather than develop a statistically significant large dataset. It attempts to demonstrate how ENVI-met could benefit from using the correct input as the boundary condition. While the modelling tool asserts to produce good results by using synoptic weather information as boundary conditions, this study suggests that it is important to use representative data from the actual site and that hourly input of climatic variables as boundary information can produce the best results. Results show that modelling is able to predict the relative variations in Tmrt conditions between sites, although highly overestimated. However, in terms of Ta, modelling was unable to produce any variations between different urban geometry characteristics. This indicates that, although ENVI-met can produce sufficiently good results in predicting Ta when hourly forcing is used, it is unable to distinguish between the precise details in urban geometry features that can cause significant variations in microclimatic conditions in real situations. Thus, more robust assessment of microclimatic variables is needed for using modelling techniques in order to evaluate the impact of diversity in urban geometry and subsequent microclimatic effects in urban canyons.

Keywords: Urban geometry, ENVI-met (V4), Outdoor thermal comfort, Field measurements, Morphological diversity

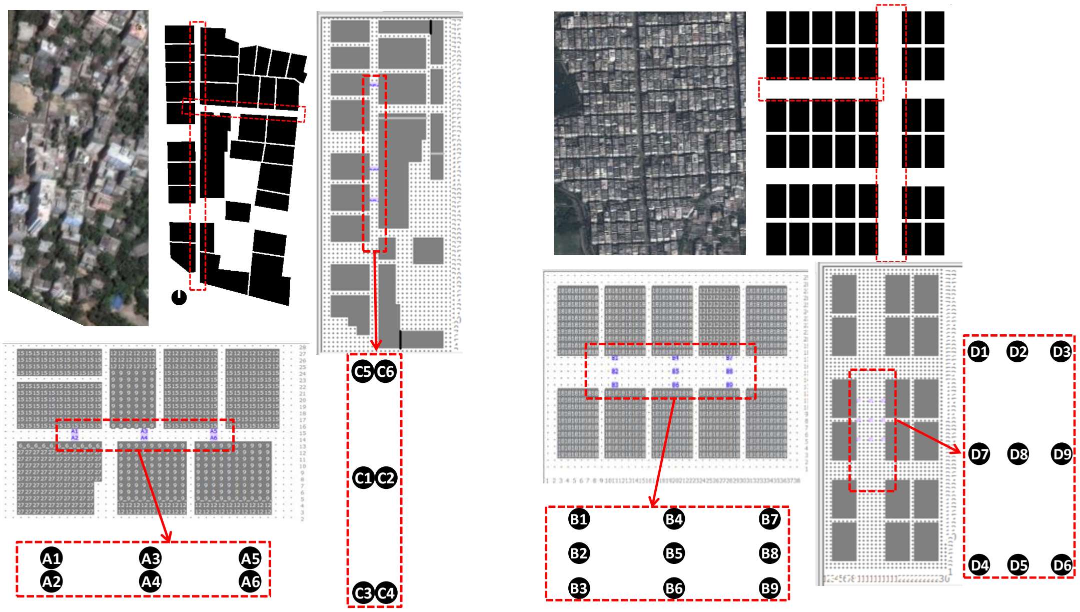
INTRODUCTION

Urban microclimate is a complex consequence of different parameters which involves innumerable natural and urban processes. The natural parameters like air temperature and humidity, vapour pressure, wind speed, solar radiation, soil temperature and humidity are very sensitive to any 3-dimensional changes in the urban settings. Due to the diverse processes involved, causing different microclimates, one of the most feasible ways to predict their impacts is through the use of numerical methods (Bruse, 1999). Therefore, numerical modelling and computer simulation techniques are playing increasingly important roles in present day thermal comfort and building performance studies in the urban context. Furthermore, the constraints associated with in-situ measurements makes numerical modelling more convenient in terms of comparing theoretical models as well, with different combinations of parameters.

The study uses numerical modelling to identify the implications of the environmental diversity in relation to the diversity in urban forms. Environmental diversity is a fundamental design criterion alongside thermal comfort in urban spaces (Sinou & Steemers, 2004; Steemers, Baker, Crowther, Dubiel, & Nikolopoulou, 1998; Steemers, Ramos, & Sinou, n.d.; Steemers & Ramos, n.d.). Variability in urban forms can promote the environmental diversity and create favourable microclimatic conditions in a tropical warm-humid climate (Sharmin, Steemers, & Matzarakis, 2015). Studies in the mid-latitude and tropical climate cities have shown, even though deep urban canyons can improve day-time microclimate, they could generate a nocturnal urban heat-island effect (Qaid & Ossen, 2014). Due to the inconsistency between day and night situations, uniform, homogeneous canyons are not climatically ideal for tropical, hot-humid climate. A field measurement in the tropical megacity Dhaka reveals, varying traditional urban forms are on average 1.7^{0}C cooler in comparison to more regular formal residential areas (Sharmin et al., 2015).

The aim of this study is to examine the proficiency of a numerical modelling tool - Envi-met (V4) (Bruse, 2015) - in distinguishing variable versus uniform urban geometry conditions as identified during the field measurements. It aims to quantify the microclimatic differences measured between actual case study areas with variable and uniform geometry, mainly in terms of air temperature and mean radiant temperature and subsequently compares the differences with modelled variations.

ENVI-met is an advanced simulation system that recreates the microclimatic dynamics of the outdoor environment by addressing the interaction between climatic parameters, vegetation, surfaces, soil and the built environment. The new features in ENVI-met V4 include simple forcing of air temperature and humidity in 2m level which needs simple input data, such as, initial temperature of atmosphere, specific humidity at model top and maximum and minimum values over a 24h cycle. The forcing also has the option to input the values on an hourly basis which is collected either from weather stations or directly from on-site measurements. This study uses both simple forcing (i.e. at the start of each run) and hourly forcing (for air temperature and humidity) options to perform modelling of the case-study areas. ENVI-met has been extensively used in urban design and thermal comfort studies for its ability to reproduce microclimatic conditions within urban canopy layer (UCL) (Ali-Toudert & Mayer, 2007; Chen & Ng, 2012; Krüger, Minella, & Rasia, 2011). Although there are several microclimatic tools such as RayMan (Matzarakis *et al*, 2010), SOLWEIG (Lindberg *et al*, 2008), Townscope (Teller & Azar, 2001) ; ENVI-met is particularly popular for its high temporal and spatial resolution; its advanced 3D interface and modelling techniques and its ability to adjust air temperature and relative humidity. The latest version considers heat capacity of the building materials (Huttner, 2012; Yang, Zhao, Bruse, & Meng, 2013): a unique feature that other microclimatic simulation tools are yet to accomplish. ENVI-met is based on the fundamental laws of fluid dynamics and thermodynamics, while other models such as RayMan and SOLWEIG are 3D radiation models. It is thus a rare example of a model to use to explore the relationships between urban form and the urban microclimate.



(a) Traditional residential area

(b) Formal residential area

Figure 1. Case study models showing receptor points in east-west and north-south urban canyons: a) Traditional residential area, b) Formal residential area.

The study has been carried out in four steps. Firstly, field measurements are carried out in actual case-study areas (Scenario_1). Secondly, case study areas have been modelled in ENVI-met and a comparison of microclimatic conditions between the modelled sites has been done (Scenario_2). Actual microclimatic measurements from the field-study are used as the model boundary condition. Thirdly, in Scenario_3 the same case-study areas are modelled using boundary conditions from the worst case scenario (obtained from EPW (EnergyPlus Weather) file for Dhaka. In this scenario all sites have the same boundary condition in order to understand how they respond to the differences in the urban form. Finally, microclimatic deviations among case-study areas reported from modelling in the second and third scenarios is evaluated against the actual differences reported in field measurements.

Methodology

Study area

The study was carried out in two different residential areas in Dhaka with different urban geometry characteristics. The first site is a traditional settlement, while the second is a relatively newly built area with formal arrangements. The traditional residential area (TRA) is characterised by a compact built environment, high density, high aspect ratio, winding street pattern and variable building heights (Fig 1, Table 1). On the other hand, the formal residential area (FRA) also has a compact form and high density settlement; but lower aspect ratio with streets arranged in a grid-iron pattern and most importantly, a uniform building height (Fig 1, Table 1). The measurements were carried out in east-west (EW) and north-south (NS) oriented canyons in both areas. For the traditional area the canyons are termed as TRA1EW and TRA1NS and for formal area FRA2EW and FRA2NS for east-west and north-south canyons respectively.

Table.1 Physical properties of case-study urban canyons

Microclimatic site	Sky View Factor	Canyon Aspect Ratio	Building Height Range	Terrain roughness class	percentage of green	Percentage of built-up area
Traditional area	0.12-0.2	1.13–5.25	3–27 m	6 - 7	<10%	70%-80%
Formal area	0.2–0.35	1.29–1.8	15-18 m	6 -7	<10%	60%

Scenario 1_field-study measurements

Climatic parameters were measured during the field-study measurements of the four urban canyons that included air temperature, relative humidity, windspeed and globe temperature. Globe temperature was subsequently used to calculate mean radiant temperature (Tmrt) using the following formula (Thorsson & Lindberg, 2007).

$$\text{Tmrt} = \left[\frac{(T_g + 273)^4 + (1.10 \times 10^8\, v^{0.6})(T_g - T_a)}{(\varepsilon D^{0.4})}\right]^{1/4} - 273 \text{............} \quad (1)$$

Here, Tmrt is mean radiant temperature (◦C), *Tg* is globe temperature (◦C), *Ta* is air temperature (◦C), *v* is air velocity (m/s), *D* is globe diameter (m) (=0.04 m in this study) and *ε* is emissivity (=0.97 for flat grey-coloured globe).

Table 2. Geometry parameters of the case-study models

TRA1EW			TRA1NS			FRA2EW			FRA2NS		
Receptor name	H/W ratio	SVF	Receptor name	H/W ratio	SVF	Receptor name	H/W ratio	SVF	Receptor name	H/W ratio	SVF
A1	3.5	0.156	C1	4.5	0.108	B1	1.8	0.205	D1	1.3	0.239
A2	3.5	0.145	C2	4.5	0.116	B2	1.8	0.265	D2	1.3	0.289
A3	2.8	0.155	C3	3.5	0.098	B3	1.8	0.209	D3	1.3	0.239
A4	2.8	0.156	C4	3.5	0.113	B4	1.8	0.192	D4	1.3	0.239
A5	3.3	0.156	C5	2.6	0.143	B5	1.8	0.238	D5	1.3	0.281
A6	3.3	0.132	C6	2.6	0.204	B6	1.8	0.2	D6	1.3	0.239
						B7	1.7	0.21	D7	1.3	0.236
						B8	1.7	0.284	D8	1.3	0.299
						B9	1.7	0.225	D9	1.3	0.236
Average	3.17	0.15		3.53	0.13		1.77	0.23		1.30	0.26
Standard deviation	0.342	0.010		0.850	0.039		0.050	0.031		0.000	0.026

Measurements were carried out on two different days in September 2014 which had equal average air temperature as per the data collected from Bangladesh Meteorological Department at Dhaka. Each day measurements were carried out in two streets of the same area from 9:00am and 6:00pm with two sets of instruments. Air temperature, relative humidity and globe temperature was recorded at 5min intervals, while wind speed was recorded at 1min intervals. Since the aim is to compare field measurement data with simulated data to understand the performance of ENVI-met, the data collected from two different sites were sufficient to demonstrate discrepancies. This study reveals, with examples from two case study areas, how ENVI-met modelling can be improved by using the right input as boundary condition. If a larger data set was used instead, this would not make the argument any stronger. A detailed description of the measurements, instruments and any limitations and assumptions can be found in Sharmin et al (2015).

Table 3. Input data for case-study models

	Scenario_2	Scenario_3
Position: Longitude (^{0}), Latitude (^{0})	90.23, 23.24	90.23, 23.24
Date, Start time, Simulation time (h)	16/09/2014, 4:00:00, 20	5/04/2015, 4:00:00, 20
Roughness length	0.1	0.1
Initial temperature	30.86^{0}C	32.35^{0}C
Simple forcing: Air temperature (K): TRA1EW; TRA1NS; FRA2EW; FRA2NS	Min 301(5:00) Max 309.5(11:00); Min 300(5:00) Max 309.1(11:00); Min 301(5:00) Max 311.6 (12:00); Min 301(5:00) Max 309.3(12:00);	Min 300 (5:00) Max 311 (14:00)
Simple forcing: Relative humidity (%): TRA1EW; TRA1NS; FRA2EW; FRA2NS	Min 57(11:00) Max 87(5:00); Min 58(11:00) Max 90(5:00); Min 51(14:00) Max 88(5:00); Min 61(12:00) Max 88(5:00);	Min 43 (14:00) Max 87 (5:00)
Specific humidity at model top (2500 mg/kg)	TRA1EW: 9 TRA1NS: 9 FRA2EW: 10.8 FRA2NS: 10.8	7
Wind speed at 10m height (m/s)	TRA1EW: 4.5 TRA1NS: 4.5 FRA2EW: 0.5 FRA2NS: 0.5	0.5
Wind direction (deg)	135	135
Low clouds: low/ medium/ heavy	2/2/2	0/0/0

Scenario 2_ Modelling using field measurement data as boundary condition

The same four urban canyons in Scenario 1 have been modelled using actual field-study measurements as input (Fig.1). The objective of this section is to understand whether ENVI-met (V4) can reproduce the environmental conditions closer to the real situation with the use of actual measurement input. Urban geometry parameters and input data of the case-study models are presented in Table 2 and Table 3 respectively.

Scenario 3_ Modelling using identical boundary condition from standard EPW weather file

Scenario 3 examines the microclimatic variables resulting from simulation of the four urban canyons (Fig.1) to check if the differences recorded between sites during the field measurements is consistent with the model version of inter-site-variances. Identical climatic information from EPW data for Dhaka is used as model boundary condition for both sites, in order to see the impact of their different geometry characteristics. It is envisaged that with input parameters being identical, the resultant microclimate within the urban canyons will reflect the effect of respective urban forms. Climatic information for a hot-humid summer day (April 5, 2014) was selected for the study to represent a worst case scenario. Wind conditions were not discussed in details because an inherent limitation of ENVI-met is that wind speed and its direction remains fixed throughout the simulation. Therefore, wind speed was intentionally kept low at 0.5m/s in order to maintain its effect at minimal level and the effect of geometry is highlighted. However, during field measurements the wind speed of the traditional area (3.2 m/s on average) was found to be significantly higher than the formal area (0.1 m/s on average) which will have influenced the comfort situation. Despite the higher wind speeds in the traditional area, which would undermine any air temperature reduction advantages, these areas still achieve cooler conditions than the formal areas due to higher aspect ratio. Input data of the case-study models are also presented in Table 3.

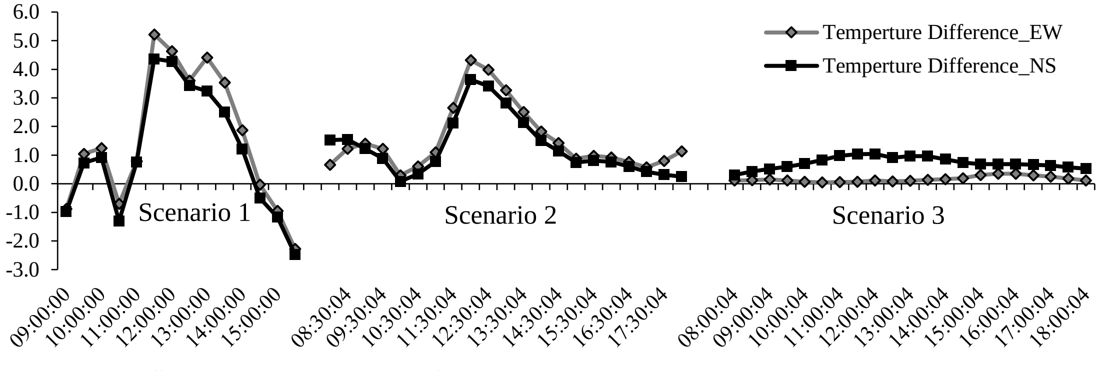


Figure 2. Air temperature difference between traditional and formal residential areas in east-west and north-south canyons in Scenario_1, Scenario_2 and Scenario_3

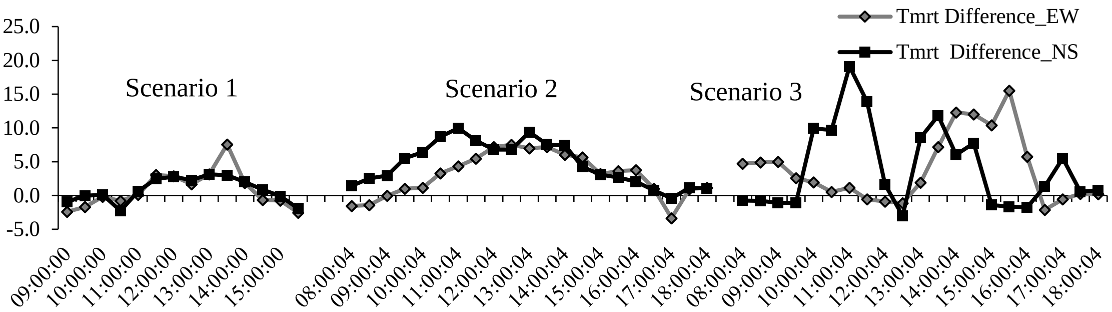


Figure 3. Tmrt difference between traditional and formal residential areas in east-west and north-south canyons in Scenario_1, Scenario_2 and Scenario_3

Table 4.Correlation between measured (Scenario_1) and simulated (Scenario_2 using field measurements as boundary condition) air temperature (Ta), mean radiant temperature (Tmrt), windspeed (v) and relative humidity (RH) for each site (p values 0.000 or higher)

Site Name	Ta	Tmrt	*v*	RH
	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)
TRA1EW	0.79(0.000)	0.60 (0.01)	-0.75 (0.000)	0.72 (0.000)
TRA1NS	0.80(0.000)	0.32 **(0.7)**[1]	-0.56 (0.01)	0.71(0.000)
FRA2EW	0.90(0.000)	0.76 (0.000)	0.42**(0.07)**	0.92(0.000)
FRA1NS	0.87(0.000)	0.68(0.001)	0.69 (0.002)	0.75(0.0000)

Table 5.Correlation between measured (Scenario_1) and simulated (Scenario_3 using identical boundary condition) differences between traditional and formal areas in EW and NS urban canyons in terms of air temperature (Ta), mean radiant temperature (Tmrt), windspeed (v) and relative humidity (RH)

Difference	Site Name	Ta	Tmrt	*v*	RH
		Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)
Difference in EW canyons between formal and traditional area	TRA1EW & FRA2EW	**-0.57 (0.32)**	**-0.25 (0.39)**	**0.39 (0.16)**	-0.62 (0.02)
Difference in NS canyons between formal and traditional area	TRA1NS &FRA1NS	0.77 (0.001)	**0.24 (0.39)**	0.53 (0.05)	0.61(0.02)

RESULTS AND DISCUSSION

Comparison between the scenarios: Air-temperature

Significant differences were found in air temperature between the formal and traditional areas in both EW and NS canyons during field measurements. Half hourly variations show up to 5.2^{0}C and 4.4^{0}C differences in EW and NS canyons respectively between formal and traditional areas (Fig. 2). The maximum differences, based on a 5-minute frequency, were found to be 6.2^{0}C and 5^{0}C. The side by side comparison of the scenarios in Fig. 2 is presented to assist the comparison of field measurements (Scenario 1) with the simulated scenarios (Scenario 2, Scenario 3). Other research has reported a 7^{0}C air temperature variation from field-study measurements between sites with various aspect ratios in a similar climate in Colombo (Emmanuel & Johansson, 2006). Furthermore, a previous study in the related context in Dhaka has also found 4.5^{0}C variation in maximum air temperature in urban canyons with aspect ratio between 0.3 and 2.8 (Ahmed, 1994).

When the case-study areas were simulated using the climatic information from the field-study (Scenario_2), air temperature shows high proximity to the actual values

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[1] p value is highlighted bold in case of non-significant correlations.

(Scenario_1). A correlation analysis between the measured and simulated values (Table 4) shows correlation and significance (p-values) for air temperature. In this case (Scenario_2), the differences between the traditional and formal areas were similar to the differences found in the field-study (Fig. 2). However, when the same boundary condition is used for all sites for the simulated models in Scenario_3, there was no significant difference in a EW canyons between traditional and formal areas and therefore a negative ($r = -0.57$) and non-significant (p value = 0.32) correlation was found between measured and simulated differences (Table 5). Even though a NS canyon shows a significant and strong correlation ($r = 0.77$, p value = 0.001), the simulated model was unable to predict the actual differences found in the field-study. While the field study reported a maximum difference of 5^0C, the simulation model produced only a 1^0C difference in a NS canyon between traditional and formal residential areas. This means, the diversity in urban geometry between case-study sites had little effect on air temperature in simulated model.

The sites were chosen because of their similarities with respect to key determinants of the urban microclimate (materials, albedo, vegetation, etc.) with only urban form being different. In simulation models (Scenario_2 and Scenario_3), the same building material and albedo is assumed for all cases. Therefore, the resultant microclimatic conditions are primarily a function of the geometry of the sites. It indicates ENVI-met is unable to distinguish between geometric variations in terms of air temperature. This is also evident in the negative correlation between measured and simulated differences in air temperature between traditional and formal areas in the EW urban canyons (Table 5).

The height-to-width ratios of traditional site TRA1EW and formal site FRA2EW have a variability of 0.34 and 0.05, and sites TRA1NS and FRA2NS have variability of 0.85 and 0.0 respectively, measured by the standard deviation of their H/W ratios (Table 2). The standard deviation of SVF did not properly represent their variability as the canyons are already very compact and narrow. Krüger *et al*. (2011) in their investigation of urban geometry in Curitiba, Brazil has also found that in spite of irregularities in building heights and location on a crossing street, some measurement points had similar SVF values. The study further suggests that SVF is not an effective parameter to explain irregularities in dense urban geometries. However, in spite of the variability in H/W ratio there was almost no deviation in air temperature in the simulated models in Scenario_3. This suggests ENVI-met is not sensitive enough to the irregularity of urban geometry characteristics as can be seen in real conditions. Other studies have also reported inaccurate evaluations of surface albedo and air temperature (Acero & Herranz-Pascual, 2015).

Air temperature in ENVI-met is calculated by the combined advection-diffusion equation in which the change in air temperature is affected by the deviation of long wave radiation (Huttner, 2012). The limitations in measuring the longwave radiation in ENVI-met could have affected the calculation of air temperature in Scenario_3. When hourly forcing of air temperature is used in the modelling, a correlation up to 0.97 ($r = 0.9$ in this study, Table 4) has been found between measured and modelled values (Acero & Herranz-Pascual, 2015). However, with using the simple forcing only, the subtle differences between geometric characters of the case study areas remain unexplained in modelling and are unable to produce expected differences.

Comparison between the scenarios: Mean radiant temperature

The actual differences in Tmrt between traditional and formal areas in EW and NS urban canyons were small as found during field measurements (Scenario_1). The reasons are cloudy skies as well as shadow patterns in the canyons. In the simulation model for Scenario_2 actual case-study areas were modelled using the field measurements as boundary condition. A cloudy condition was assumed for the simulation model. However, the cloud condition remained constant throughout the simulation model which was not the case during field measurements. Therefore, the correlation between simulated (Scenario_2) and measured (Scenario_1) Tmrt was not as strong as the correlation for air temperature (Table 4). In addition to this, the Tmrt calculation differed from actual measurements due to limitations in wind speed calculation in ENVI-met. Similar to cloud conditions, wind speed and direction also remains constant throughout the simulation period. Therefore, the correlation between simulated and measured wind speed is either negative or non-significant in most of the cases (Table 4). In traditional areas, where greater turbulence was observed, ENVI-met was unable to model wind speed with accuracy. Simulations of airflow studies in Curitiba, Brazil (Krüger *et al*., 2011) have also found that ENVI-met tends to overestimate wind speeds within the canyon for input wind speeds over 2 m/s. For wind speeds below 2 m/s, ENVI-met predictions are consistent with field data. Similarly, in this study better correlation between measured and simulated wind speed was found in formal areas with an input wind speed of 0.5m/s as boundary condition.

As can be seen in Fig. 3, both simulations (Scenario_2 and Scenario_3) have predicted that Tmrt in the formal area is higher than in the traditional area. This is in agreement with field measurements (Scenario_1).

Although they are overestimated in both cases, Tmrt in Scenario_3 in particular is unrealistically high. This varies far from real situations because model boundary conditions are not similar to actual conditions. A worst-case scenario with a cloudless condition is assumed for Scenario_3 and for this reason Tmrt conditions are significantly higher than actual situation. Therefore, instead of using actual values of Tmrt; differences between traditional and formal areas in EW and NS urban canyons in Scenario_1 (measured) and Scenario_3 (simulated) has been examined for correlation analysis in Table 5.

In this study Tmrt in the ENVI-met simulations is further overestimated due to the fact that ENVI-met has a tendency to calculate higher shortwave radiation during the daytime (Acero & Herranz-Pascual, 2015). Along with shortwave radiation, errors have been reported in calculating diffuse/ reflected shortwave radiation and longwave radiation. An overall imprecise calculation of the radiation fluxes are reported by (Huttner, 2012). Furthermore, the shadow pattern can vary substantially due to the horizontal model resolution which leads to a significant Tmrt variation in the clear sky conditions. The exposure to direct solar radiation can also be miscalculated by rough estimation of building heights as well as the resolution of the vertical grid.

CONCLUSION

The integration of only two case study areas (with two streets in each case) conducted over two days could seem to have restricted the wider implication of the study. However, the study does not aim to present detail statistical analysis of microclimatic conditions of the city. A separate study has been done covering elaborate statistical analysis of eight street canyons in six case-study areas conducted over a three year field-study. Partial results are published in Sharmin *et al. (2015*). This study addresses a specific argument: whether or not microclimatic modelling techniques are able to address the impact of diversity of urban form upon microclimatic conditions and find out what the limitations are and what could be done to improve their implementation in assessing microclimatic conditions. Results from this study imply it is necessary to use the most characteristic weather information from case study areas in lieu of synoptic weather information as boundary conditions to produce credible results. The results produced in this manner could address differences in urban geometry and capture their consequences on microclimatic conditions.

It is understood that the geometry and the aspect ratio of urban canyons play a crucial role in moderating the microclimate at the street level. Microclimatic analyses from the field measurements also reveal the potential of combining diversity of geometry with aspect ratio (Sharmin et al., 2015). This study has examined the shortcomings of modelling techniques to respond adequately to variable urban geometry characteristics. The result has shown ENVI-met was unable to distinguish between areas having different urban geometry characteristics, particularly in terms of air temperature. Significant variation was seen in mean radiant temperature as well. Furthermore, the values were highly overestimated. There are several reasons for these deviations: First of all, despite the fact that ENVI-met has one of the highest spatial resolutions available for microclimatic modelling, the computation time associated with this makes it less user friendly. Even with fairly high resolutions like 2m x 2m, many detail morphological aspects are disregarded, which has significant consequences on solar exposure and thus affects the radiation budget. Errors have been found in estimating direct short wave and diffuse/ reflected shortwave and longwave radiation. Thus the calculation of Tmrt can produce major deviations from on-site measurements. Air temperature is also altered as this is affected by longwave radiation estimation. Thus, even though ENVI-met is a useful tool to examine typical meteorological conditions, users need to be aware of the above limitations when using such modelling techniques. Finally, this study has revealed that significant effects caused by morphological characteristics are not always captured. This can lead to important urban design opportunities being overlooked.

ACKNOWLEDGEMENTS

This paper is drawn from research funded by the Schlumberger Foundation “Faculty for the Future Award” at the University of Cambridge.

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