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Understanding ENVI-met (V4) model behaviour in relation to environmental variables

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Abstract: A parametric analysis is carried out to understand how ENVI-met (V4) responds to the following aspects which form the basis of understanding the model's behaviour: i) canyon aspect ratio, ii) cloud cover, iii) orientation, iv) wind speed and v) building height variability. The reason for using parametric modelling is that modelling techniques and calculations are made easier as they are applied to simple models and, thus, the process is verified prior to examining the real, complex situations. This is helpful for understanding the links between simple urban form and the resultant environmental characteristics and to determine the model boundary conditions for comparing the real situations. The results of the simulations include: the maximum and average (median) values of air temperature decreases in deeper canyons, but the rate of reduction reduces for canyons with an H/W ratio over 2. The average (median) mean radiant temperature also reduces in deeper canyons, but the trend is not linear. Air temperature is not affected by canyon orientation, whereas Tmrt is significantly affected by canyon orientation as the EW canyon remains exposed to high Tmrt for 8.5 hours while NS canyon is exposed for only 2.5 hours. Windy conditions result in a slightly higher air temperature and a lower Tmrt level compared to still air conditions. Increase in cloud cover has a decreasing effect on air temperature and Tmrt. And finally, the impact of diversity in canyon geometry has little impact on air temperature and Tmrt conditions.

Keywords: ENVI-met (V4), environmental variables, parametric analysis, urban geometry

Introduction

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 programme has been extensively used in urban design and thermal comfort studies for its ability to reproduce microclimatic conditions within the urban canopy layer (UCL) (Yang & Lin 2016; Roth & Lim 2016; Acero & Herranz-Pascual 2015). 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 the heat capacity of the building materials (Huttner 2012; Yang et al. 2012), a unique feature that other microclimatic simulation tools are yet to accomplish. It is thus a rare example of a model which can be used to explore the relationships between urban form and the urban microclimate.

Although, ENVI-met is a reputable model, it is still under development and the full model documentation is not yet available. Therefore, it is not easy to understand how the model behaves with the alteration of the most basic model parameters. Therefore, this study presents a simple parametric exercise to understand how ENVI-met responds to the following aspects which form the basis of understanding the model's behaviour: i) canyon aspect ratio,

ii) cloud cover, iii) orientation, iv) wind speed and v) building height variability. The reason for using parametric modelling is that modelling techniques and calculations are made easier as they are applied to simple models and, thus, the process is verified prior to examining the real, complex situations (Steemers et al. 1997). This is helpful for understanding the links between simple urban form and the resultant environmental characteristics and to determine the model boundary conditions for more complex situations and to compare with real case studies. ENVI-met simulation results were validated against measured data at real urban context in previous studies (Sharmin & Steemers 2015; Sharmin & Steemers 2016).

Methodology

The study comprises the simulation modelling of parametric case-studies (Case_1 – Case_9) to understand the impact of urban geometry parameters on microclimate. It also examines the effect of changing wind speed and cloud cover on overall microclimate. ENVI-met has certain limitations in dealing with the wind speed and cloud cover as they remain constant at the model boundary throughout the simulation period. Generic urban forms (Figure 1) have been chosen for their simple calculations to better understand the impact of urban forms on the resultant environmental characteristics.

Simulations were started from 04:00 local time (UTC+6), approximately 2 hours before sunrise. The total modelling time was 20 hour. The initial 4-hour data is excluded from analysis because it is considered as the model 'spin up' period. A worst-case scenario with high air temperature and high humidity is assumed for the study. The worst-case scenario was determined from the EPW (EnergyPlus Weather) data for Dhaka (http://apps1.eere.energy.gov/buildings/energyplus). A detail of input data can be found in **Error! Reference source not found.** and Table 2.

Case_1-Case_4: Cases 1 to 4 include simple east-west oriented (EW) urban canyons with H/W ratios ranging from 1 to 4. The canyon width remains fixed at 10m and the building height increases from 10m to 40m from Case_1 to Case_4. Table 3 includes the model geometry parameters with their measurement points. Receptors (measurement points) have been placed in the middle of the length of each canyon. Hence, the receptors in Case_1 are named A1, B1, C1; in Case_2 A2, B2, C2 and so on.

Case_2 is considered as the base case for all the following simulation models.

Case_2 and Case_5: Case_2 has been compared with Case_5 in order to examine the impact of orientation. The models have same H/W ratio and SVF with different orientations. For Case_5, the receptors are: A5 (west), B5 (centre) and C5 (east). All input data are kept the same except for wind direction which is now parallel to the canyon orientation.

Case_2 and Case_6: This section examines the impact of wind speed for EW canyons. Case_6 has exactly the same geometry as Case_2. All input data are kept the same except for wind speed. Case_6 has receptors at the same locations as in Case_2 called A6, B6 and C6.

Case_2, Case_7 and Case_8: This section examines the impact of cloud cover for EW canyons having the same canyon geometry. Case_2 has a cloudless condition, whereas Case_7 and Case_8 have medium and high cloud coverage respectively. The receptors are A7, B7, C7 and A8, B8, C8 for Case_7 and Case_8 respectively.

Case_2 and Case_9: This section compares the effect of canyon variability in terms of building height. All input data are kept the same except for building heights. Case_9 has a variable canyon with buildings ranging from 6m-30m, whereas Case_2 has a uniform building height of 20m. The heights were chosen randomly.

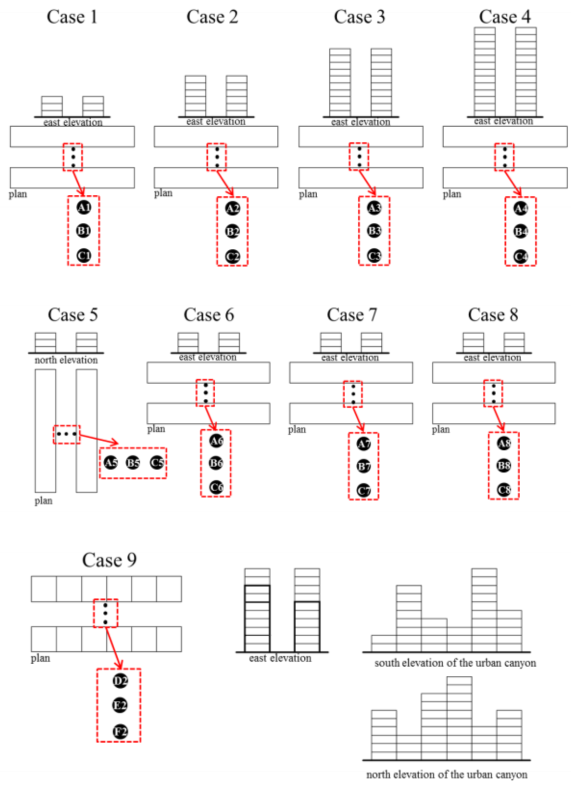

Figure 1. Parametric case study models showing plan, elevations and receptor points

Table 1. Common input data for parametric analysis

Model area	
Main Model Area	80m x 50m
Grid Size in metre Dx = size of X grid Dy = size of Y grid Dz = size of Z grid	dx=2, dy=2, dz=3
Construction material	
Building Material	Wall: 10” brick wall (burned), Roof: light-weight concrete
Soil	Road: asphalt, Pavement: paved concrete-grey
Position	
Longitude (^{0})	90.23
Latitude (^{0})	23.24
Start and duration of the model	
Date of simulation	05/04/2015
Start time	04:00
Total simulation time (h)	20
Initial meteorological conditions	
Roughness length at measurement site	0.1
Initial temperature of atmosphere (k)	32.35^{0}C
Simple forcing: Air temperature (K)	Min 300, at 05:00 h; Max 311, at 14:00 h
Simple forcing: Relative humidity (%)	Min 43, at 14:00 h; Max 87, at 05:00 h
Specific humidity at model top (2500 m, g/kg)	7

Table 2. Model-specific input data for parametric analysis

	Case_1-Case_4	**Case_5**	**Case_6**	**Case_7**	**Case_8**	**Case_9**
Canyon orientation	east-west (EW)	north-south (NS)	EW	EW	EW	EW
Wind speed measured at 10m height (m/s)	0.1	0.1	4	0.1	0.1	0.1
Wind direction (deg) (0^0 = from north, 180^0 = from south)	90	180	90	90	90	90
Cover of low clouds (octas)	0	0	0	2	5	0
Cover of medium clouds (octas)	0	0	0	2	5	0
Cover of high clouds (octas)	0	0	0	2	5	0

Results and discussion

Impact of geometry

This section presents the impact of increasing H/W ratio on simulated microclimatic conditions from Case_1 to Case_4. Figure 2 shows the boxplots of air temperature and Tmrt for all four cases. They represent average values during 08:00-18:00 hours at the three measurement points (receptor) at each site. The receptor data was recorded at half-an-hour intervals, so there are 21 data points for each receptor between 08:00-18:00. Here, the case studies are ordered by their geometric characters: H/W ratio of 1 to 4 for Case_1, Case_2, Case_3 and Case_4 respectively.

The comparison of the maximum and median values of air temperature shows that they reduce in the deeper canyon (Figure 2a). The maximum values for Case_1 to Case_4 are 37.7^{0}C, 36.3^{0}C, 35.9^{0}C and 35.6^{0}C respectively and the median values are 36.0^{0}C, 34.9^{0}C, 34.7⁰C and 34.5⁰C respectively. The rate of reduction is higher between first two cases in comparison to the subsequent three cases.

Table 3. Geometry parameters of the parametric cases

Case number	**Case_1**			**Case_2**			**Case_3**			**Case_4**		
Receptor	A1	B1	C1	A2	B2	C2	A3	B3	C3	A4	B4	C4
H/W ratio	1	1	1	2	2	2	3	3	3	4	4	4
SVF	0.334	0.387	0.334	0.191	0.214	0.191	0.152	0.148	0.152	0.135	0.143	0.135

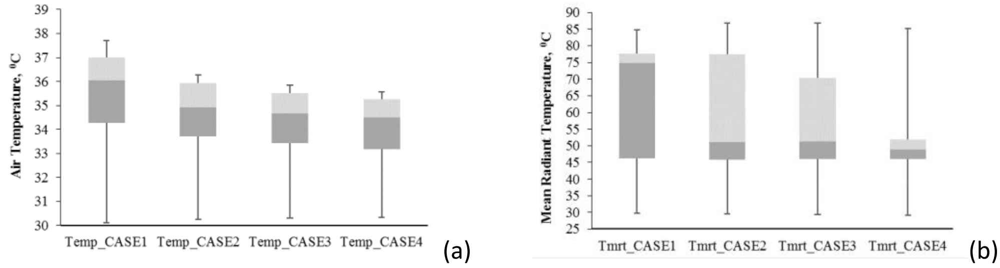

Figure 2. The average values of (a) air temperature and (b) mean radiant temperature simulated during 08:00-18:00 in all three receptors in Case_1 to Case_4

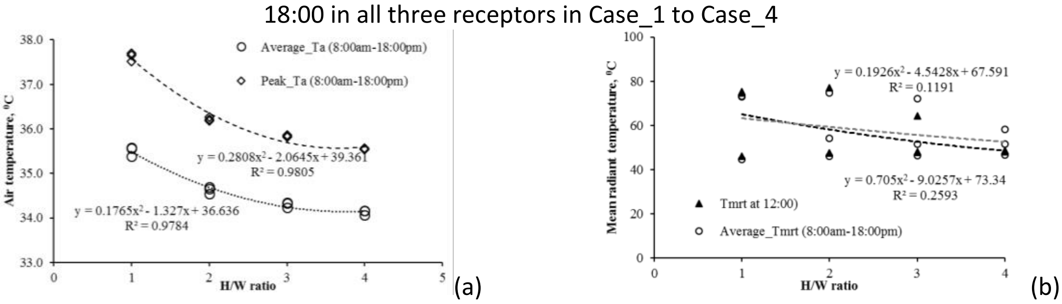

Figure 3.(a) Trend of air temperature against increasing H/W ratio, (b) Trend of Tmrt against increasing H/W ratio

The regression line in Figure 3a shows that air temperature reduces in deeper canyons. This is in agreement with Lobaccaro & Acero (2015) who demonstrated that the maximum daily temperature within the urban canyon decreases with an increase of H/W ratio.

Figure 2b shows Tmrt between 08:00-18:00 considering all receptor points in Case_1 to Case_4. It shows that all urban canyons irrespective of their geometry will reach a maximum Tmrt of above 84⁰C and a minimum Tmrt around 30⁰C during 08:00-18:00. This is mainly due to the cloudless condition set in the modelling and thus the presence of direct shortwave radiation. The trend line in Figure 3b shows Tmrt between canyons from Case_1 to Case_4 represented by two-degree polynomial regression lines. The R^2 values suggest Tmrt will generally reduce in deeper canyons.

Impact of orientation

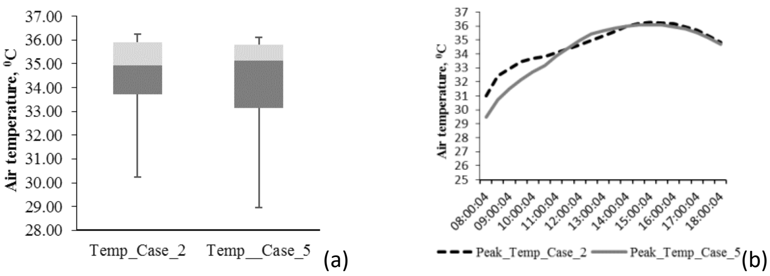

Figure 4. (a) Comparison of air temperature, (b) Progression of peak air temperature between EW and NS urban canyons during 08:00-18:00

The impact of orientation between canyons having the same H/W ratio is discussed here. Comparing the east-west (EW, Case_2) and north-south (NS, Case_5) canyons did not produce any significant difference in air temperature, as can be seen in Figure 4a. However, the NS canyon had a lower minimum temperature (by 1.3^{0}C). By looking at the progression of peak air temperature, (among three receptor points in each case) (Figure 4b), a maximum difference of 1.7^{0}C can be found between NS and EW canyons with the latter being higher. The EW canyon has higher air temperature during the morning from 08:00-10:30 than the NS canyon, with rest of the day showing minor differences.

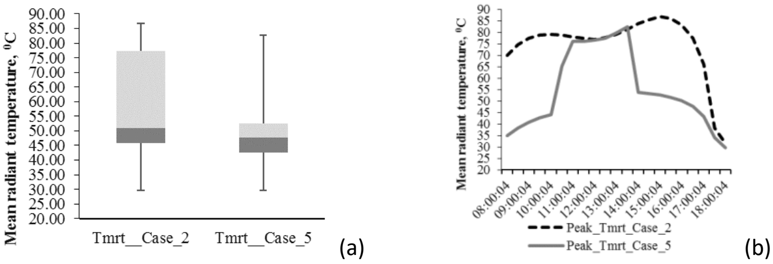

Figure 5. (a) Comparison of mean radiant temperature, (b) Progression of peak mean radiant temperature between EW and NS urban canyons

In terms of Tmrt, the NS canyon was found to have significantly lower values than the EW canyons with 50% of the total data bunched between 42.6 -52.6^{0}C and 45.9 -77.5 ^{0}C in the case of NS and EW canyons respectively (Figure 5a). The EW canyon remains exposed to Tmrt above 70.0^{0}C for 8.5 hours (between 08:00-16:30), while NS canyon is exposed for only 2.5 hours (between 11:00-13:30). This clearly shows that ENVI-met simulation responds to the orientation of the canyon.

Impact of wind speed

This section discusses the impact of wind speed between the canyons having the same canyon geometry and climatic input. It is evident that wind speed has some effect on air temperature as the maximum air temperature rises by 1.2^{0}C when wind speed increases from still air conditions (Case_2) to windy conditions (Case_6) (Figure 6a). In other words, increased wind undermines the temperature reducing benefits of deeper canyons. From the progression line of peak air temperature (Figure 6b), it can be seen that a windy condition (Case_6) results in a higher air temperature than the still air conditions (Case_2) throughout the middle period of the day from 11:00-15:30 with the highest difference reaching up to 1.5^{0}C at 14:00.

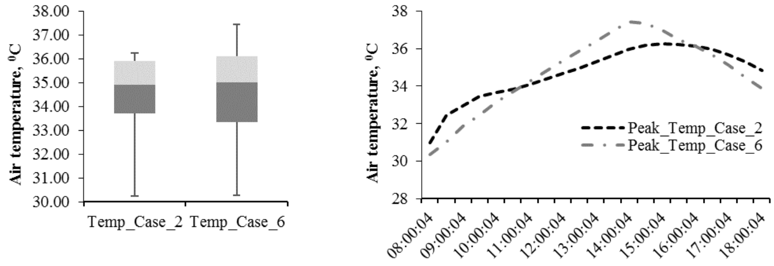

Figure 6. (a) Comparison of air temperature, (b) Progression of peak air temperature between Case_2 and Case_6

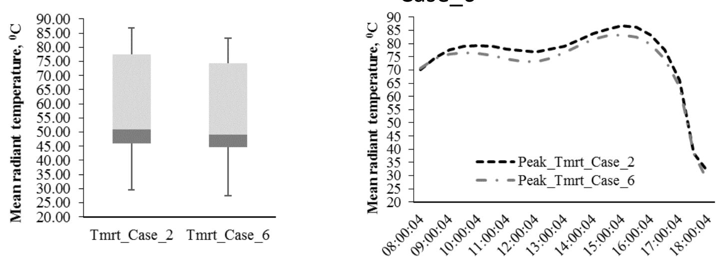

Figure 7. (a) Comparison of mean radiant temperature, (b) Progression of mean radiant temperature between Case_2 and Case_6

In the case of Tmrt, maximum Tmrt reduces from Case_2 to Case_6 by 3.6^{0}C (Figure 7a). Wind speed is an important parameter for measuring Tmrt, because Tmrt reduces as wind speed increases. From the progression of peak Tmrt, it can be seen that Case_6 has constantly lower values throughout the day with the maximum difference of 4.0^{0}C reached at 11:30 (Figure 7b). Therefore, in ENVI-met simulations, windy conditions are found to have resulted in slightly higher air temperatures and a lower Tmrt level compared to the still air conditions.

Impact of cloud cover

This section discusses the impact of increasing cloud cover for the same urban canyons with the same climatic input except for the cloud cover. As the cloud cover increases from 0/0/0 cloud cover (Case_2: no cloud cover) to 2/2/2 (Case_7: medium cloud cover) and 5/5/5 (Case_8: heavy could cover), the average (median) air temperature decreases from 34.9^{0}C to 34.5^{0}C to 34.3^{0}C respectively (Figure 8a). The maximum difference between Case_2 and Case_7 is 2.2^{0}C and between Case_7 and Case_8 is 0.3^{0}C (Figure 8b). This suggests that the reduction of air temperature with the increase in cloud cover is not linear.

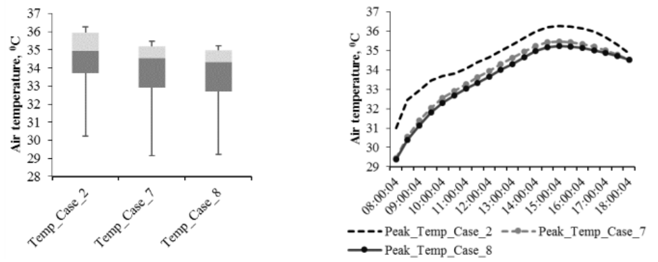

Figure 8. (a) Comparison of air temperature, (b) Progression of peak air temperature between Case_2, Case_7 and Case_8

A clearer trend is visible in terms of Tmrt, which shows a significant reduction with the increase of cloud cover. Again, the trend is not linear. The progression of peak Tmrt in Figure 9b shows Case_2 reaches very high Tmrt ranges (above 70.0^{0}C and reaching up to 87.0^{0}C), whereas Case_7 has milder situations and Case_8 lower still, being in complete overcast conditions. Therefore, in ENVI-met simulations, an increase in cloud cover can be seen to have a decreasing effect on Ta and Tmrt.

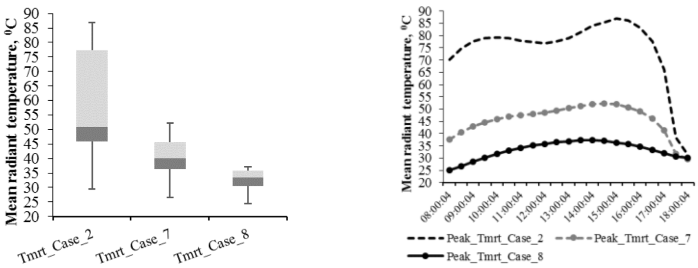

Figure 9. (a) Comparison of mean radiant temperature, (b) Progression of peak mean radiant temperature between Case_2, Case_7 and Case_8

Impact of height variability

This section compares microclimatic dynamics between two urban canyons, one with variable building heights and the other with uniform building heights. The variable canyon (Case_9) has a slightly higher SVF (0.240) than the uniform canyon (Case_2, SVF=0.199) (Table 4). The receptor points are placed to capture the microclimatic conditions at the middle of the canyon. However, the SVF or H/W ratio of the receptors located in the middle of the canyon do not represent its height variability. Therefore, height variability is measured by considering the standard deviation of H/W ratio (H/W ratio_STDEV) variation across the length of the canyon using points X_1-X_6 in Case_2 and points Y_1-Y_6 in Case_9 (Figure 10). The standard deviation of SVF (SVF_STDEV) is not considered, as SVF is not a perfect parameter to capture the physical irregularity of urban canyons (Krüger et al. 2011). The same boundary conditions have been used for both models.

Table 4. Comparison of urban geometry parameters between the uniform (Case_2) and variable canyons (Case_9)

Case Study	Receptor name	SVF	Average SVF of the receptor points	Measurement points across the length of the canyon as shown in 10	H/W ratio of Measurement points across the length of the canyon	Standard deviation
Case_2	A2	0.191	0.199	X_1, X_2, X_3, X_4, X_5, X_6	2, 2, 2, 2, 2, 2	0
Case_2	B2	0.214				
Case_2	C2	0.191				
Case_9	D2	0.202	0.240	Y_1, Y_2, Y_3, Y_4, Y_5, Y_6	1.80, 2.00, 1.75, 2.15, 1.90, 1.30	0.291
Case_9	E2	0.290				
Case_9	F2	0.228				

Results show that Case_9 has a slightly lower maximum air temperature, by 0.35^{0}C, than Case_2 (Figure 11a). A similar difference (a maximum of 0.39^{0}C at 13:00) is visible from the progression of the peak air temperatures during 11:30-17:00 (Figure 11b). When comparing the mean radiant temperature across all receptors in both case studies, no significant difference could be found (Figure 12a). Again, the progression of peak Tmrt in Figure 12b does not show much difference except for a slight decrease in Case_9 during the middle of the day. Regarding average Tmrt, Case_9 is more exposed to solar radiation during the morning (09:00-10:00) and the afternoon (14:30-15:00) than Case_2 (Figure 12b).

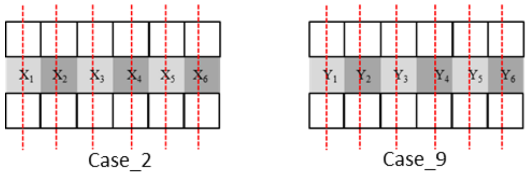

Figure 10. Measurement points across the length of the canyon

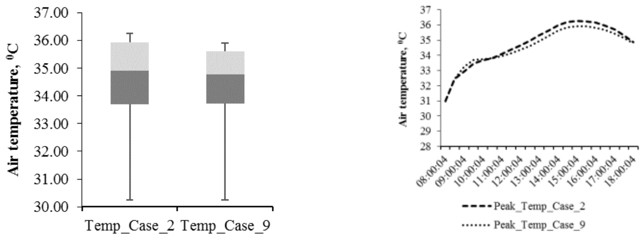

Figure 11. (a) Comparison of air temperature, (b) Progression of peak air temperature between uniform and variable conditions during 08:00-18:00

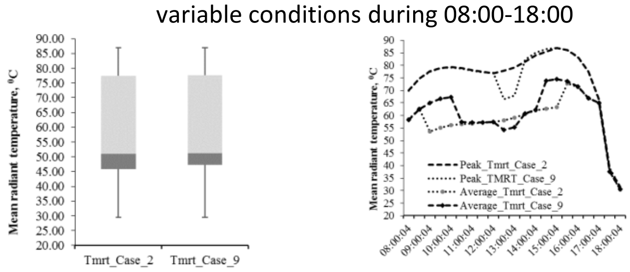

Figure 12. (a) Comparison of mean radiant temperature, (b) Progression of peak and average mean radiant temperature between uniform and variable conditions

Since no significant difference was noted between Case_2 and Case_9 from the simulation results, it is probably fair not to investigate parametric cases any further to test the effect of variability. However, this particular comparison between Case_2 and Case_9 has some limitations, for example Case_9 has a different average height (17.3 m) and density compared to Case_2. It also has a higher average height on the south elevation. Further research can explore variation in more detail, for example, diversity on the south, but constant on the north side, etc. However, in this study, because the initial theoretical test shows little impact of canyon diversity in the simulation model, no further cases were examined.

Discussion and conclusion

Synopsis of findings from the analysis

In ENVI-met (V4) microclimatic simulations:

- The maximum and median values of air temperature decrease in deeper canyons, but the rate of reduction reduces for canyons with an H/W ratio over 2.
- The average (median) mean radiant temperature reduces in deeper canyons, but the trend is not linear.
- The impact of canyon orientation on air temperature is insignificant.
- Tmrt is significantly affected by canyon orientation as the EW canyon remains exposed to high Tmrt for 8.5 hours while NS canyon is exposed for only 2.5 hours.
- Windy conditions result in a slightly higher air temperature and a lower Tmrt level compared to still air conditions.
- Increase in cloud cover has a decreasing effect on air temperature and Tmrt.
- The impact of diversity in canyon geometry has little impact on air temperature and Tmrt conditions.

The above findings apply to ENVI-met (V4) simulations only. The findings of this study may be useful in interpreting the microclimatic simulation results for real urban situations, where the input parameters for one situation may vary from the other. The understanding will help in deciding the most important parameter that is causing the difference between different situations.

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