Architectural Science Review, 2013
Vol. 56, No. 4, 297–305, http://dx.doi.org/10.1080/00038628.2012.684871

Taylor & Francis
Taylor & Francis Group

Simulation of the effect of downtown greenery on thermal comfort in subtropical climate using PET index: a case study in Hong Kong

Liang Chen* and Edward Ng

School of Architecture, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong S.A.R., China

Understanding how greenery can improve outdoor thermal comfort is important in downtown planning. This article presents a simulation approach to investigate the cooling effect of downtown greenery on the urban microclimate, primarily air temperature and solar radiation, and therefore pedestrian thermal comfort during summertime in Hong Kong. The numerical simulation software of ENVI-met was used to generate microclimate data for a downtown development site with and without greening design scenarios. Two types of scenarios were tested, one being 50% of tree coverage and the other being 30% of grass coverage with modified building design. The simulation results were transformed into geographic information system (GIS)-supported format using self-developed computer programs. Another computer module was developed to assess pedestrian thermal comfort based on the human–biometeorological index of physiological equivalent temperature (PET) within a GIS framework. Thermal comfort maps were generated accordingly. Through visualization and analysis using the ArcGIS software, it was shown that both the tree scenario and the grass scenario can reduce the average PET of the domain by 0.4K, suggesting that strategic design of urban greenery can effectively improve the downtown urban environment and outdoor thermal comfort.

Keywords: ENVI-met; geographical information system; physiological equivalent temperature; urban greenery

Introduction

Urban greenery is important for downtown vitalization. It not only provides pedestrians with pleasurable visual scenes, but also provides shading, improves air quality, reduces noise levels and contributes to the mitigation of the urban heat island effect. The microclimatic impact of vegetation in the urban environment with aspect to temperature reduction has been extensively studied (Huang *et al.* 1987, Oke *et al.* 1989, Jauregui 1990/1991, Avissar 1996, Shashua-Bar and Hoffman 2000). As Dimoudi and Nikolopoulou (2003) have pertinently summarized it, trees can benefit cities by effectively improving the urban thermal environment through the following physical processes: (1) reduction of solar heat gain on walls, windows and roofs through shading; (2) reduction of the building long-wave exchange with the sky as building surface temperatures are lowered through shading; (3) reduction of the conductive and convective heat gain by lowering dry-bulb temperatures through evapotranspiration during summer; and (4) increase of latent cooling by adding moisture to the air through evapotranspiration. Therefore, the promotion of urban greenery is a primary concern in downtown planning, and various practice guidelines and strategic schemes have been implemented around the world with respect to green space provision (Tokyo Metropolitan Government 2007, Department of Environmental Conservation 2009, UNEP 2009). On the other hand, understanding the effect of urban greenery on urban microclimate has been a continuous research endeavour. Over the last decade, a number of research projects have been conducted in various climates to investigate the detailed relationship between urban vegetation, urban geometry, and boundary layer climate and human thermal comfort (Jonsson 2004, Chen and Wong 2006, Gulyas *et al.* 2006, Ali-Toudert and Mayer 2007, Chang *et al.* 2007, Giridharan *et al.* 2008, Shashua-Bar *et al.* 2009, Lin *et al.* 2010, Wong and Jusuf 2010).

The objective of this research is to take a simulation approach to study the cooling effect of urban greenery in summertime with respect to the unique hot and humid subtropical climate of Hong Kong. The mitigation effect of greenery on pedestrian thermal comfort will be focused. A formalized simulation process is presented. The numerical environmental simulation model of ENVI-met (Bruse 2010) was used to generate microclimate data for a downtown development site with and without greening design scenarios. Computer programs and modules were developed to assess human thermal comfort based on human–biometeorological models, and also to implement the simulation process within a geographic information system (GIS) framework. The results were visualized and

---

*Corresponding author. Email: chenliang@cuhk.edu.hk analysed using the ArcGIS software. A site in the central business district (CBD) area of Hong Kong was selected as a case study to demonstrate the effectiveness of the present simulation approach.

Background

Hong Kong is a metropolis located on the south coast of China (22°15′N, 114°10′E). It is one of the world's most compact cities, with its seven million inhabitants living in around 260km^2 of developed land. Hong Kong has a typical subtropical climate with a hot and humid summer. During the hottest summer months from June to September, the daily maximum temperature can be up to 31°C, and the relative humidity is commonly above 80% (HKO (Hong Kong Observatory) 2010). Under these circumstances, how to mitigate the thermal load of the downtown area and provide effective cooling measures is a key task in Hong Kong's urban (re)development. Although the scarce space for urban vegetation makes this task more challenging than any other places in the world, increasing governmental concerns have been addressed through initiatives, such as the Greening Master Plan by the Civil Engineering and Development Department (CEDD) (HKCEDD (Hong Kong Civil Engineering and Development Department) 2010), and the strategic plan for sustainable urban living by the Buildings Department (HKBD (Hong Kong Buildings Department) 2009).

The Central Market is a large old market building, about 100 m × 40 m × 20 m ($L \times W \times H$) in size, and located at the busy district of Central, Hong Kong (Figure 1). The massive building bulk not only blocks ventilation, but also raises the local thermal load dramatically. The Chief Executive of Hong Kong has proposed the 'Conserving Central' initiative in his 2009–10 Policy Address, and tasked the Urban Renewal Authority (URA) to revitalize the Central Market, aiming to improve the air quality and introduce more greenery to create an additional amenity space for the public. In this context, URA has recently launched the 'Central Oasis' project, and several design conceptual schemes, such as the 'Central Gateway' have been proposed (URA (Urban Renewal Authority) 2011). These schemes emphasize the heritage conservation and functional renovation of the Central Market. At the same time, a detailed analysis on the microclimatic effect of potential greening schemes is expected to complement the design and planning decision-making process. This article presents a simulation study along this line.

Figure 1. Central market.
Source: http://maps.google.com/.

Verification of ENVI-met

ENVI-met is a three-dimensional numerical microclimate model for simulating surface–plant–air interactions in urban environment (Bruse and Fleer 1998, Bruse 2010). It provides both spatial (0.5–10m resolution) and temporal variations (finest 10s resolution) of the urban boundary layer climate. It is free software and has been applied in a number of research projects in urban climatology to simulate the effect of urban vegetation on urban microclimate (Chen and Wong 2006, Ali-Toudert and Mayer 2007, Emmanuel *et al*. 2007, Wong *et al*. 2007, Fahmy and Sharples 2009, Okeil 2010).

ENVI-met is particularly suitable for the objective of this study in that it allows complex urban geometry and different urban vegetation covers to be modelled with high spatial resolution. However, because the simulation model is based on solving differential equations and is very sensitive to configuration settings, it needs to be verified properly to be applicable in Hong Kong's unique urban environment and climate condition. In this sense, a field measurement was carried out in a typical high-density urban environment in Tsuen Wan (TW), Hong Kong, to collect meteorological data which are used to verify and calibrate the settings in ENVI-met. The field measurement was a spot measurement between 2:30 to 4:30 pm on 21 June 2008, and a total number of 9 points were surveyed (Figure 2). Measurement results included air temperature, solar radiation, wind speed and relative humidity. Detailed specifications of the field measurement are not the focus of this study, and are given in (Ng *et al*. 2008).

An ENVI-met model was built according to the exact urban geometry and vegetation cover of the site. Weather conditions, such as the air temperature, cloud cover and wind speed of the day (21 June 2008) were initially input into the model. The model was run for 24h starting at 6 am and ending at 6 am the day after, as suggested by the technical manual of ENVI-met to overcome the influence of the initialization of the model. The simulation results were recorded. The simulation results of the surveyed points, namely the air temperature (T_a) and the mean radiant temperature (T_{mrt}), were extracted, plotted and compared with the field measurements. Notably T_{mrt} was calculated based on the equation proposed by ASHRAE (ASHRAE 2001). Regression analyses were used to compare the measured

Figure 2. Map for the field measurement and surveyed spots in TW. The model domain in ENVI-met is also shown.

and simulated data. Another thing noteworthy is that though ENVI-met also generated wind speed and relative humidity data, they were not included in the regression analysis. The main reason was that the measurement revealed low wind speed and high relative humidity with very small deviations in the domain: for most of the surveyed points, wind speed was below 1m/s and relative humidity was around 80%, which were in the same order as the simulation results by ENVI-met. In such a case, human thermal comfort is affected more significantly by the changes in T_a and T_{mrt}. Therefore, only these two parameters were used in the model verification. The comparisons between measurement and simulation results for T_a and T_{mrt} are shown in Figures 3 and 4, respectively.

The comparisons show reasonable agreement between the measured and simulated data, with R^2 of the order of 0.745 and 0.615 for T_a and T_{mrt}, respectively. The usefulness of ENVI-met in modelling the intra-urban air temperature and radiation variations in Hong Kong's urban environment during summertime is therefore confirmed. The verified simulation settings are given in Table 1. These settings are used in this study.

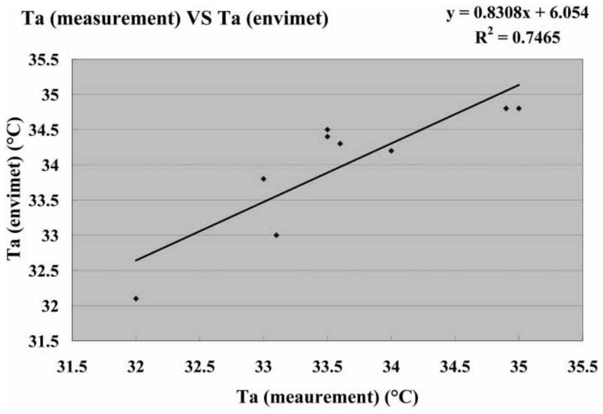

Figure 3. Comparison of the measured and simulated air temperatures (T_a).

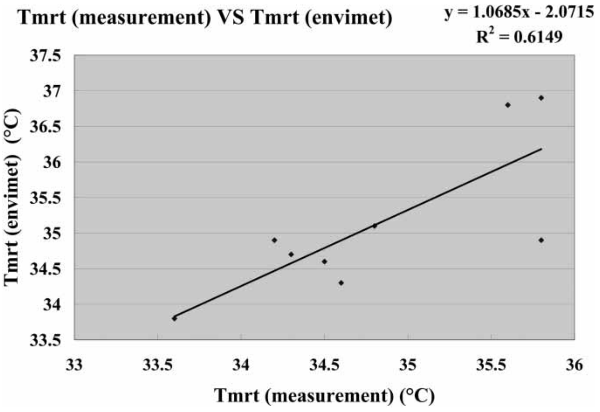

Figure 4. Comparison of the measured and simulated mean radiant temperatures (T_{mrt}).

Simulation methodology

System structure

A formalized simulation process is presented. Figure 5 shows the integrated system structure. The ENVI-met model was used to simulate the urban microclimate, primarily T_a and T_{mrt}. The simulation results were used to calculate the spatial variation of human thermal comfort based on the physiological equivalent temperature (PET) (Mayer and Höppe 1987). Both the microclimatic and the PET datasets were transformed into GIS-supported format, and visualized and analysed using the ArcGIS software. Computer

Table 1. Verified ENVI-met simulation settings.

Applicable period	Initial temperature	Start time	Relative humidity at 2 m (%)	Wind direction	Wind speed at 10 m level (m/s)	Albedo of roofs	Albedo of walls
June	Daily minimum	6 am	70–90	East	0.5–1.5	0.3	0.2

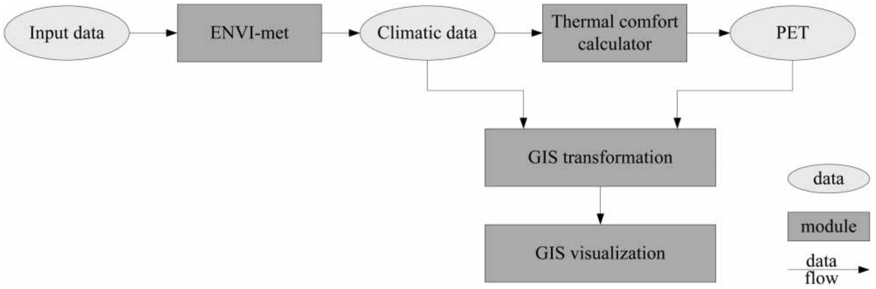

Figure 5. System structure.

modules were written in the programming language of Java for PET calculation and also for GIS transformation.

Thermal comfort simulation

The PET (Mayer and Höppe 1987, Höppe 1993, 1999) is a temperature dimension index measured in °C. It is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature and sweat rate equal to those under the conditions to be assessed (Höppe 1999). PET is particularly suitable for outdoor thermal comfort analysis in that it translates the evaluation of a complex outdoor climatic environment to a simple indoor scenario on a physiologically equivalent basis that can be easily understood and interpreted. PET has been widely applied in human–biometeorology studies in areas with various climates (Matzarakis *et al*. 1999, Ali-Toudert and Mayer 2006, Emmanuel *et al*. 2007, Thorsson *et al*. 2007, Mayer *et al*. 2008, Wong and Jusuf 2010, Cheng *et al*. 2012). It is also adapted in this study. The original computer program developed by Höppe as published in (VDI 1998) was re-implemented in Java to allow automatic read-in of microclimatic data and also export of results (Figure 5). Another significant modification made to the original program is that the Java program was written in an object-oriented manner, meaning that each person is associated with an individual set of thermo-physiological parameters and also local meteorological conditions (Table 2). In this way, the assessment of the thermal comfort for different groups of people could be investigated easily by changing the personal settings. Also, this approach makes it straightforward to calculate the PET over an entire domain, which is done by putting a person at each location of the domain and calculating the local PET. This module was verified by comparison with the results generated by the original program.

Table 2. Attributes of a PET object.

Personal parameters	Meteorological parameters
Age	T_a
Gender	T_{mrt}
Body weight	Relative humidity
Height	Wind speed
Clothing index	
Activity	

GIS-support transformation

ENVI-met uses a self-defined format, which makes the results difficult to be incorporated in other software applications, such as GIS systems. In this aspect, a GIS-transformation module was implemented using Java. The simulated microclimatic data and also the thermal comfort assessment results were transformed into ESRI ASCII grid format, which can be easily loaded in any GIS platforms. In this study, the transformed results were loaded as raster files in the ArcGIS software and visualized and analysed using the rich set of built-in functions.

Case study

Simulation domain

The map of the model domain is shown in Figure 6 (left). The domain size is selected to be 210m × 240m. An ENVI-met model was constructed according to this map, for example, building size and height. Due to the shape editing limitation in ENVI-met, the domain was rotated to make the edges of the buildings normally orientated. Also, some details of the buildings were discarded. This is necessary because having too many details will make the simulation unstable and even crash in the worst case. The spatial resolution of 3 m is used to allow the simulation to finish within a reasonable time. A snapshot of the constructed ENVI-met model is also shown in Figure 6 (right).

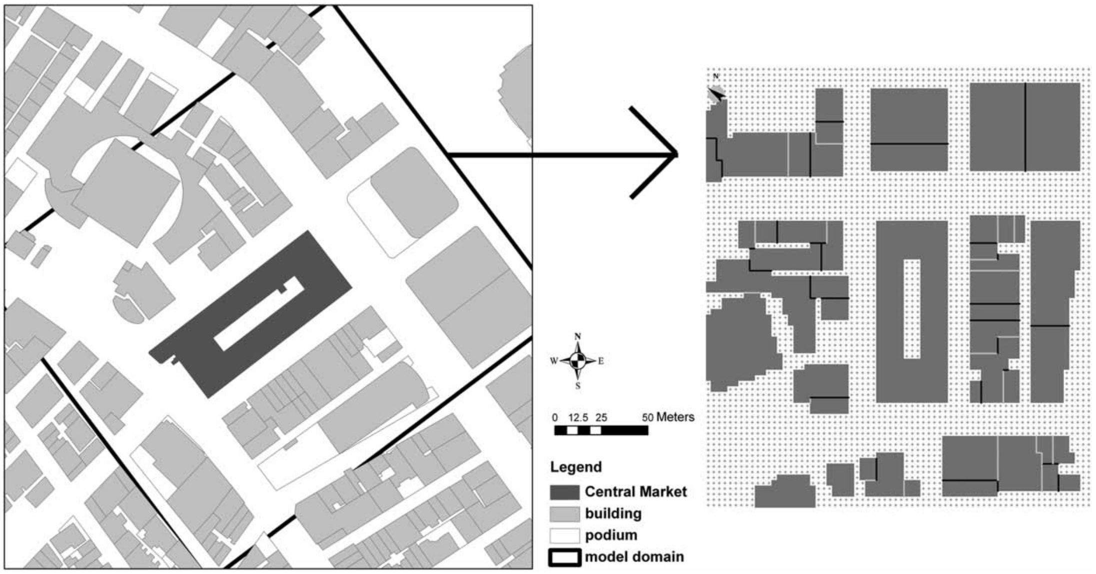

Figure 6. (left) Map of the model domain: central market. (right) Snapshot of the ENVI-met model.

Greening scenario configurations

Three cases were tested (Figure 7). The first one is the bare case meaning no changes were made to the Central Market building. In the second case, trees were planted on the ground and rooftop, and also in the courtyard. The trees covered 50% of the site area and were randomly arranged. Mature 20m dense distinct crown trees were selected in ENVI-met. The default leaf area density (LAD) setting in ENVI-met was used, where the height of the tree was divided into 10 equivalent segments, and LADs for each height segment from bottom-up were 0.075, 0.075, 0.075, 0.075, 0.250, 1.150, 1.060, 1.050, 0.920 and 0m^2/m^3, respectively. In the third case, a design scheme proposed by the Buildings Department, Hong Kong Government according to the Sustainable Building Design Guidelines (SBD) was adapted. In this scheme, the old building was replaced with a narrower but higher building plus a podium, and grasses were planted on the podium top and on the ground covering 30% of the site. Fifty centimetres tall grass of average density was selected in ENVI-met.

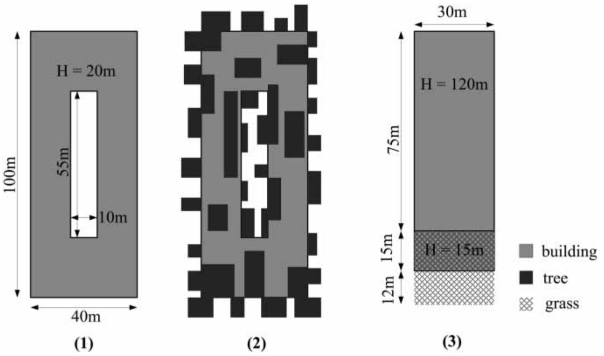

Figure 7. Top views of the models for the three test cases manipulating different designs of the central market building: (1) bare case; (2) tree case; and (3) SBD grass case. Figures are not drawn to scale and are used as indicative.

Results and discussions

A typical summer day, June 23, was simulated. Verified model settings (Table 1) were used. The weather data recorded by Hong Kong Observatory and published on its website were input into the model. The simulation was run on a PC with 3.0GHz CPU and 3.48GB of RAM. Each run took about 1 day clock-time. The resulting microclimatic data for 2 pm were extracted and analysed, since summer afternoon is the most crucial time for Hong Kong in terms of thermal comfort. Data at 2m level were analysed to study the microclimate and human thermal comfort condition at pedestrian level. The data were transformed using the GIS-transformation module into ESRI ASCII format files, and loaded and visualized in ArcGIS. Figure 8 shows the spatial variation of T_a for the bare case. In comparison, Figures 9 and 10 show the spatial variation of T_a difference between the tree case and the bare case, and between the SBD case and the bare case, respectively. Notably in the SBD case, new ground space was achieved because of the smaller site coverage ratio, which was not used in the comparison (Figure 10). Similar maps were also generated for T_{mrt}, as shown in Figures 11–13.

A 'typical' human subject as suggested by Höppe (1999) was used to calculate PET, which is a 35-year-old male, 1.80m tall, 75kg in weight, with a clothing index of 0.5 clo, which is typical summer clothing, and has a metabolic rate of 80W indicating light activity level. The person was located at each grid of the outdoor space, and a PET value was calculated based on the local T_a and T_{mrt}. As discussed in the previous section, the spatial variations of wind speed

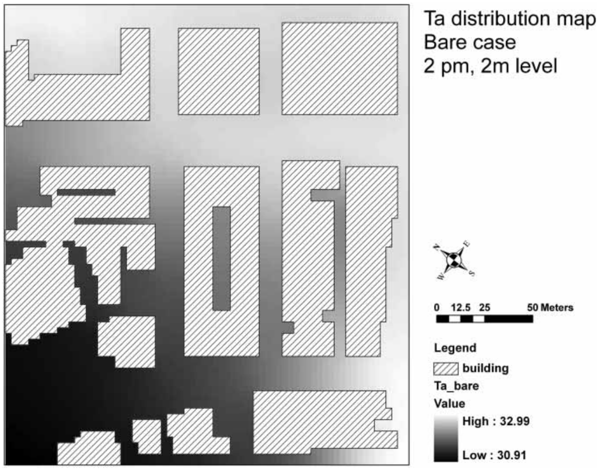

Figure 8. Spatial variation of T_a for the bare case.

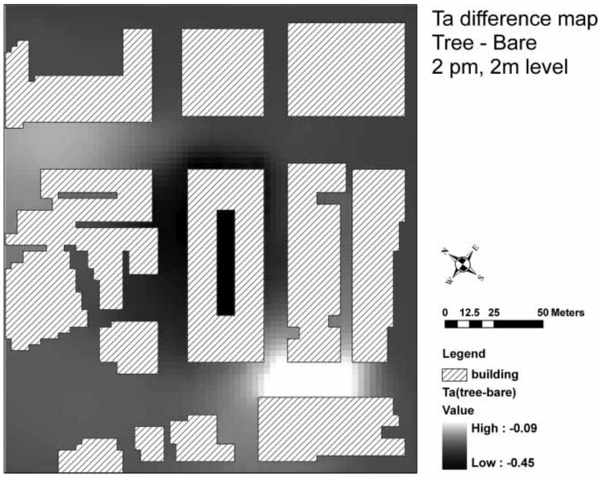

Figure 9. Spatial variation of T_a difference between the tree case and the bare case.

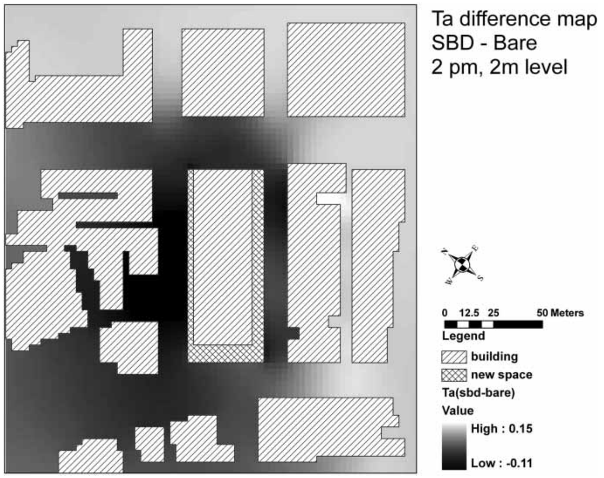

Figure 10. Spatial variation of T_a difference between the SBD case and the bare case.

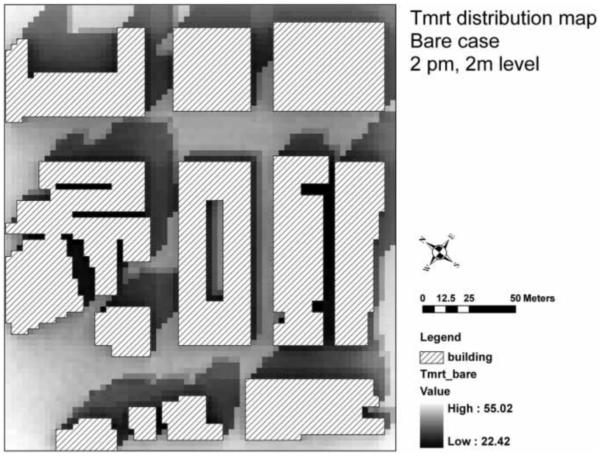

Figure 11. Spatial variation of T_{mrt} for the bare case.

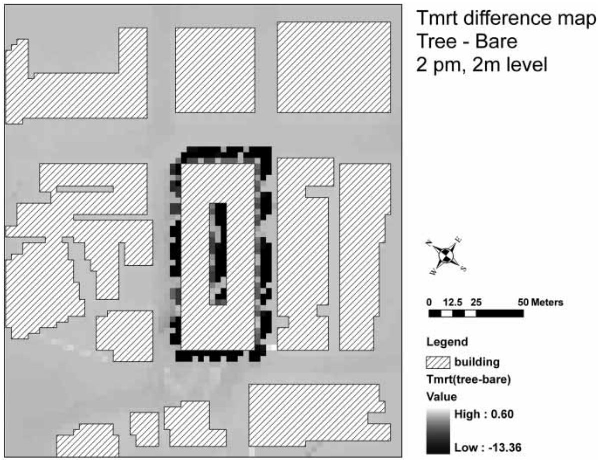

Figure 12. Spatial variation of T_{mrt} difference between the tree case and the bare case.

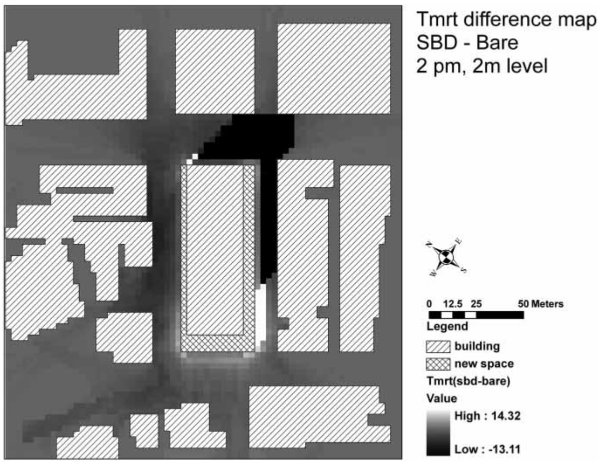

Figure 13. Spatial variation of T_{mrt} difference between the SBD case and the bare case.

and relative humidity in the domain will have a minor effect on human thermal comfort. Therefore, constant values were assigned to the two microclimatic parameters, being 1m/s for wind speed and 80% for relative humidity. Figure 14 shows the spatial variation of PET for the bare case. Maps comparing the PET difference between the tree case and the bare case, and between the SBD case and the bare case are shown in Figure 15 and 16, respectively.

Some preliminary findings can be derived from the maps. The main finding is that both design scenarios will significantly modify the microclimate of the development site, especially for solar radiation. Compared with the bare case, the tree case can provide more shading; therefore, it will result in lower T_{mrt}, especially under the trees where the reduction in T_{mrt} can be up to 13.36 K (Figure 12). Also, the trees will cool the neighbourhood area, and reduce T_{a}. The maximum reduction in T_{a} is 0.45 K, which occurs in the courtyard under the trees, and this value decreases as the distance from the trees becomes bigger (Figure 9). These results are in accordance with findings revealed by similar studies (Chen and Wong 2006). A general conclusion can be derived that greenery will provide cooling effect to the surrounding urban environment, as indicated by the maximum PET reduction in the order of 6.19K under the trees (Figure 15). In the SBD case, the most significant microclimatic effect is that the tall building provides substantial shading area, and creates deep street canyons with lower T_{mrt} up to 13.11 K (Figure 13). On the other hand, more concrete ground is exposed to sunlight due to smaller site coverage ratio, which results in a slightly increase in ambient T_{a} in the order of 0.05K for most locations (Figure 10). A detailed quantitative and statistical analysis of the comparison is shown in Table 3.

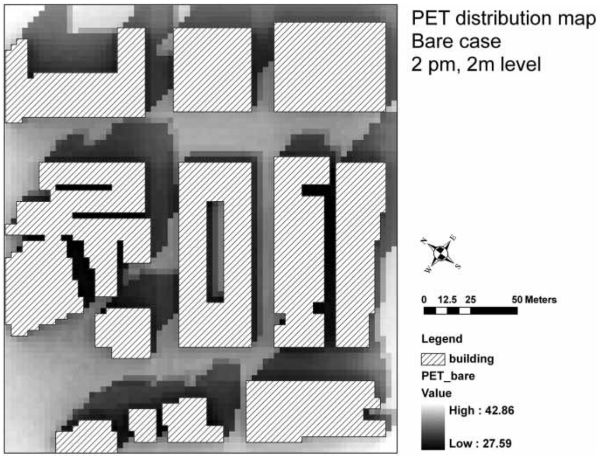

Figure 14. Spatial variation of PET for the bare case.

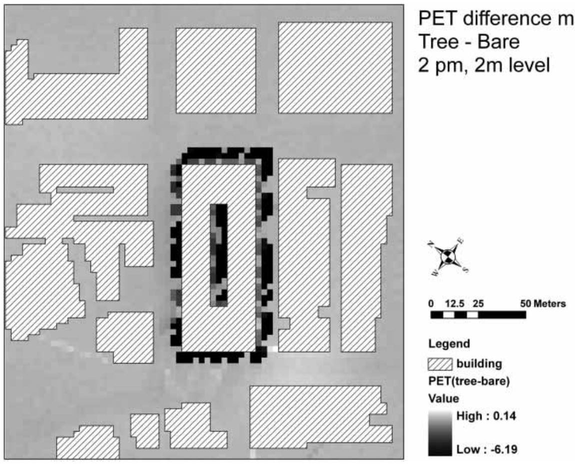

Figure 15. Spatial variation of PET difference between the tree case and the bare case.

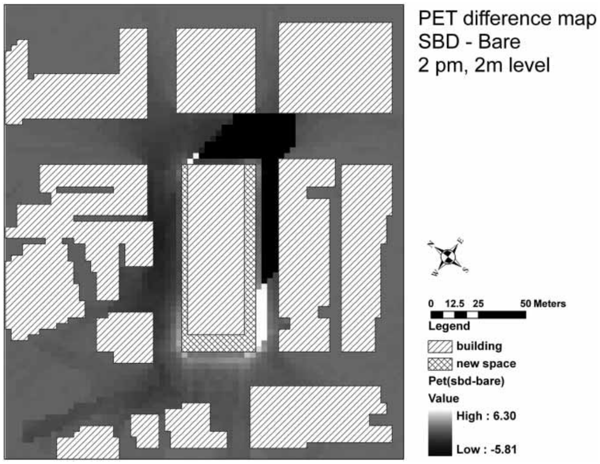

Figure 16. Spatial variation of PET difference between the SBD case and the bare case.

Table 3. Statistical summary of simulated results for the three cases, including maximum value (max), minimum value (min), mean value (mean) and standard deviation (std_dev) for T_{a}, T_{mrt} and PET. The area of outdoor space is also shown.

	Bare case	Tree case	SBD case
T_{a}(max) (°C)	32.99	32.75	33.11
T_{a}(min) (°C)	30.91	30.67	30.97
T_{a}(mean) (°C)	32.20	31.90	32.25
T_{a}(std_dev)	0.65	0.64	0.68
T_{mrt}(max) (°C)	55.02	54.86	54.99
T_{mrt}(min) (°C)	22.42	22.41	22.42
T_{mrt}(mean) (°C)	40.32	39.79	39.32
T_{mrt}(std_dev)	7.5	7.64	7.79
PET(max) (°C)	42.86	42.62	42.96
PET(min) (°C)	27.59	27.38	27.62
PET(mean) (°C)	35.62	35.18	35.22
PET(std_dev)	3.32	3.39	3.42
Outdoor space area (m^2)	26,028	26,028	26,703

It can be seen from Table 3 that the tree case can effectively reduce the ambient thermal load and block the sun, and therefore results in an average mitigation of 0.30K in T_{a} and 0.53K in T_{mrt}. Consequently, the resulting thermal comfort level, as measured by PET, could be reduced by 0.44K on average. With respect to air temperature reduction, the result is in comparison with the lower air temperature of 0.81K in urban parks than the surrounding areas in Taiwan (Chang *et al*. 2007), and 1.3K in the Singapore study (Chen and Wong 2006) where the climates are similar to Hong Kong. Explanation for the smaller temperature difference owes to the limited greenery coverage: in both scenarios, the implemented greening schemes are quite sparse as compared to the investigated domain and not in the same scale as urban parks. Nevertheless, given the high thermal load and the scarce space for greenery development in Hong Kong's CBD area, any feasible mitigation to the thermal environment should be considered as beneficial.

On the other hand, the SBD case provides more shading because of the tall building, therefore reduces average T_{mrt} by 1K; however, it will cause a small elevation in T_{a}, being 0.05K on average. The overall PET is also reduced by 0.40K owing to the significant decrease in pedestrians' solar exposure when walking in the created street canyons. At the same time, the SBD case can provide an extra 675m^2 of outdoor spaces as compared with the bare case and the tree case, because the ground coverage of the new building is much smaller than the old one. The comparison proves that both the SBD proposal and the tree scenario can mitigate the local thermal load around the Central Market development site. Tree-planting appears to be a more effective means in reducing the ambient air temperature, on the other hand strategic design of buildings can also achieve a higher level of thermal comfort by providing pedestrians with shelters against the sun and more open space.

These findings serve as a proof-of-concept to show how microclimatic simulations can help to incorporate the implementation of greening schemes in downtown development and visualize the potential cooling benefits of different design scenarios. Admittedly, the findings are rather coarse from a climatological or bio-meteorological point of view. And the scenarios tested are yet to be expanded to include more design variables. For example, earlier studies have revealed that there is a close relationship between the cooling and insulating properties of greenery and the leaf area index (LAI) (Chen and Wong 2006). Moreover, building layout and street orientation will also affect the local microclimatic condition significantly (Ali-Toudert and Mayer 2007). These considerations should also be incorporated in further studies to make the investigation more comprehensive. Future work includes conducting longer term on-site microclimatic measurement, monitoring and classification of plant data, and employing finer-scale numerical models such as CFD models for more detailed simulation.

Conclusions

This article presents a preliminary study which investigates the cooling effect of urban greenery and its mitigation effect on downtown human thermal comfort. A formalized computer simulation approach is presented. The ENVI-met model is verified and used to simulate microclimate data for a downtown development site with and without greening design scenarios. Computer modules are developed to integrate the ENVI-met model with GIS platforms, and to assess human thermal comfort based on the human–biometeorological index of PET. The Central Market in the CBD area of Hong Kong is used as a case study. Different greening design scenarios with changes in building geometry and vegetation cover are tested. With detailed microclimatic simulation and GIS-based data analysis, it is found that, 50% tree coverage of the development site, or 30% grass coverage with strategic building design can both reduce the average PET of the domain by 0.4K. The case study demonstrates how the present simulation approach can help to analyse and visualize the potential cooling effect of different greening design scenarios to support design decision-making. Also, the GIS-support feature of the simulation process is expected to be easily adapted by town planners. Future work of the study includes considering more design variables and conducting longer-term microclimatic surveys.

Acknowledgements

The study is partially supported by a contract research grant from the Planning Department, the Government of Hong Kong S.A.R. The authors wish to thank the Planning Department for providing the building data, and also Prof. Michael Bruse for providing the access to ENVI-met. Thanks are also given to the group members for their help on conducting the field measurement.

References

Ali-Toudert, F. and Mayer, H., 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, 41, 94–108.

Ali-Toudert, F. and Mayer, F.H., 2007. Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons. *Solar Energy*, 81, 742–754.

ASHRAE, 2001. *ASHRAE Fundamentals Handbook 2001 (SI Edition)*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Avissar, R., 1996. Potential effects of vegetation on the urban thermal environment. *Atmospheric Environment*, 33 (3), 437–448.

Bruse, M., 2010. *ENVI-met homepage* [online]. Available from: www.envi-met.com [Accessed 4 November 2010].

Bruse, M. and Fleer, H., 1998. Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model. *Environmental Modelling & Software*, 3, 373–384.

Chang, C.R., Li, M.H., and Chang, S.D., 2007. A preliminary study on the local cool-island intensity of Taipei city parks. *Landscape and Urban Planning*, 80 (4), 386–395.

Chen, Y. and Wong, N.H., 2006. Thermal benefits of city parks. *Energy and Buildings*, 38, 105–120.

Cheng, V., Ng, E., Chan, C., and Givoni, B., 2012. Outdoor thermal comfort study in sub-tropical climate: a longitudinal study based in Hong Kong. *International Journal of Biometeorology*, 56, 43–56.

Department of Environmental Conservation, New York State, 2009. *2009 open space conservation plan* [online]. Available from: http://www.dec.ny.gov/lands/47990.html [Accessed 14 December 2011].

Dimoudi, A. and Nikolopoulou, M., 2003. Vegetation in the urban environment: microclimatic analysis and benefits. *Energy and Buildings*, 35, 69–76.

Emmanuel, R., Rosenlund, H., and Johansson, E., 2007. Urban shading–a design option for the tropics? A study in Colombo, Sri Lanka. *International Journal of Climatology*, 27, 1995–2004.

Fahmy, M. and Sharples, S., 2009. On the development of an urban passive thermal comfort system in Cairo, Egypt. *Building and Environment*, 44 (9), 1907–1916.

Giridharan, R., Lau, S.S.Y., Ganesan, S., and Givoni, B., 2008. Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence. *Building and Environment*, 24, 1583–1595.

Gulyas, A., Unger, J. and Matzarakis, A., 2006. Assessment of the microclimatic and human comfort conditions in a complex urban environment: modelling and measurements. *Building and Environment*, 41, 1713–1722.

Höppe, P., 1993. Heat balance modelling. *Experientia*, 49, 741–746.

Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43, 71–75.

HKBD (Hong Kong Buildings Department). 2009. *Consultancy study on building design that supports sustainable urban living space in HK* [online]. Available from: http://www.bd.gov.hk/english/documents/index_CSBD.html [Accessed 20 December 2011].

HKCEDD (Hong Kong Civil Engineering and Development Department), 2010. *Greening Master Plan* [online]. Available from http://www.cedd.gov.hk/eng/greening/ [Accessed 20 December 2011].

HKO (Hong Kong Observatory), 2010. *Monthly meteorological normals for Hong Kong* [online]. Available from: http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm#table4 [Accessed 10 August 2011].

Huang, Y.J., *et al.*, 1987. The potential of vegetation in reducing summer cooling loads in residential buildings. *Journal of Climate and Applied Meteorology*, 26, 1103–1116.

Jauregui, E., 1990/1991. Influence of a large urban park on temperature and convective precipitation in a tropical city. *Energy and Buildings*, 15 (3–4), 457–463.

Jonsson, P., 2004. Vegetation as an urban climate control in the subtropical city of Gaborone, Botswana. *International Journal of Climatology*, 24, 1307–1322.

Lin, T.-P., Matzarakis, A., and Hwang, R.-L., 2010. Shading effect on long-term outdoor thermal comfort. *Building and Environment*, 45, 213–221.

Matzarakis, A., Mayer, H., and Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology*, 43, 76–84.

Mayer, H. and Höppe, P., 1987. Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38, 43–49.

Mayer, H., *et al.*, 2008. Human thermal comfort in summer within an urban street canyon in Central Europe. *Meteorologische Zeitschrift*, 17, 241–250.

Ng, E., *et al.*, 2008. *Technical input report: methodologies and results of field measurement. Urban climatic map and standards for wind environment—feasibility study*. Technical Report for Planning Department HKSAR [online]. Available from: http://www.pland.gov.hk/pland_en/p_study/prog_s/ucmapweb/ucmap_project/content/main/reports.html [Accessed 10 April 2012].

Oke, T., *et al.*, 1989. The micrometeorology of the urban forest (and discussion). *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 324 (1223), 335–349.

Okeil, A., 2010. A holistic approach to energy efficient building forms. *Energy and Buildings*, 42 (9), 1437–1444.

Shashua-Bar, L., and Hoffman, M.E., 2000. Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings*, 31, 221–235.

Shashua-Bar, L., Pearlmutter, D., and Erell, E., 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, 92 (3–4), 179–186.

Thorsson, S., *et al.*, 2007. Thermal comfort and outdoor activity in Japanese urban public places. *Environment and Behavior*, 39, 660–684.

Tokyo Metropolitan Government, 2007. *Tokyo's urban strategy: 'Tokyo's big change: the 10-year plan'* [online]. Available from: http://www.metro.tokyo.jp/ENGLISH/PROFILE/policy04.htm [Accessed 20 December 2011].

UNEP, 2009. *UNEP environmental assessment – expo 2010 Shanghai, Chin*a. United Nations Environment Programme (UNEP), Report No. DCP/1209/NA.

URA (Urban Renewal Authority), 2011. *Central oasis* [online]. Available from: http://www.centraloasis.org.hk/ [Accessed 12 May 2011].

VDI, 1998. *VDI guideline 3787, Part 2: Environmental meteorology, methods for the human-biometeorological assessment of climate and air hygiene for urban and regional planning, Part I: Climate*. Berlin: Beuth.

Wong, N.H. and Jusuf, S.K., 2010. Study on the microclimate condition along a green pedestrian canyon in Singapore. *Architectural Science Review*, 53 (2), 196–212.

Wong, N.H., *et al.*, 2007. Environmental study of the impact of greenery in an institutional campus in the tropics. *Building and Environment*, 42 (8), 2949–2970.