DUAL STAGE SIMULATIONS TO STUDY THE MICROCLIMATIC EFFECTS OF TREES ON THERMAL COMFORT IN A RESIDENTIAL BUILDING, CAIRO, EGYPT

Mohamad Fahmy [1, 2] **Stephen Sharples,** [1] Ali Eltrapolsi, [1, 3]

[1] *School of Architecture, University of Sheffield, Sheffield, UK.*

[2] *Department of Architecture, Military Technical Collage, Cairo, Egypt*

[3] *Department of Architecture, Faculty of Engineering, Gar-Younos University, Banighazi, Libya.*

ABSTRACT

This paper describes an outdoor-indoor thermal investigation of a multifamily residential building during summer in Cairo, Egypt.

Initially, microclimate meteorological data was generated for an urban settlement with and without trees being incorporated in to the development. The software ENVI-met was used for this first stage. Two kinds of tree planting (15m high Ficus Elastica and 20m Yellow Poinciana) were simulated, together with the existing scenario that has no trees.

Next, the energy analysis package DesignBuilder used the modified microclimate data from ENVI-met to simulate indoor comfort levels in the residences. The Predicted Mean Vote (PMV) was used to quantify thermal comfort. The study found that the best indoor comfort levels were achieved using the 15m high Ficus Elastica trees in the urban site. The main conclusion from this investigation is that new urban developments in Cairo shouldn't only consider trees planting at the planning stage, but also a specific type should be used for better outdoor-indoor performance. Moreover, results indicate that raw weather data files used without microclimate physical adjustments are not adequate for detailed comfort analysis and indoor-outdoor simulations should be coupled for better representing indoor climate.

Key words: ENVI-met, Design Builder, Urban trees, PMV, Microclimate, Solar radiation.

INTRODUCTION

Urban climatology has been a growing field of research over the last few decades (Arnfield 2003). Urban vegetation influences urban climate and hence pedestrian comfort levels along with indoor ones (Dimoudi and Nikolopoulou 2003; DOE 1995; Oke et al. 1989). Urban tress not only help to control heat gain and mitigate urban heat islands, (Huang et al. 2008; Taha 1997), but also reduce noise levels (Gidlof-Gunnarsson and Ohrstrom 2007; Lam et al. 2005). The effect of urban climate on the indoor environment is, potentially, to reduce heat gains and buildings energy demands (Akbari 2002; Givoni 1998; Huang et al. 1987). Despite different trees' foliage differentiate solar access to its environment, (Kotzen 2003; Kumar and Kaushik 2005), there still a lack in supplying climate knowledge to improve design, (Oke 2006). Furthermore, while indoor comfort and energy simulation packages are used increasingly (Jentsch et al. 2008), today, more than 30 years went since the sustainable development concept was firstly launched in the 1970s (Brundtland 1989), indoor simulations still tend to be isolated from an important element affecting urban microclimate, such as urban trees. Apart from urban trees, there is a good understanding and establishment in literature that urban form, land use, presence of natural geographical structures, urban / rural settings etc, are all affect microclimate, (Ali-Toudert 2005; Fahmy and Sharples 2008c; Fahmy and Sharples 2009a; Givoni 1998; Swaid 1992).

Urban trees thermal behaviour advantages and disadvantages are also well established, (Oke et al. 1989). Urban trees main advantage as a bioclimatic responsive design element is to produce shadow whereas its main disadvantages is blocking wind, (Yoshida et al. 2006). Urban canyons and spaces thermal behaviour at micro and local scales differ from city centres to suburban and onward to rural and open areas, (Oke 2006). According to (ASHRAE 2005) the accuracy of weather data files used in building simulation design packages depends on the site typology, its landscape, the method of meteorology measurements and the time period of years for the statistically generated data (Radhi 2009). The compiled weather data derived from open-air measurements above and outside the urban canopy layer does not represent the micro scale details of urban sites within the canopy layer. In addition, packages cannot allow for the effects of specific urban trees types - for example, the different leaf area densities and evapotranspiration rates of urban trees that influence solar access and heat exchanges if planted around buildings.

Urban trees examined to study if (i) the use of raw weather data file without micro-local effects is satisfactory and (ii) if an urban site such as that examined performs better with or without trees and with which kind of urban trees is most effective. Consequently, a pre-design stage has to be considered to generate the influence of actual urban details on the data compiled within weather files.

Urban simulations were performed using ENVI-met, which results were simulated within Design Builder to assess indoor comfort levels. ENVI-met is a 3-D CFD numerical model that is capable of simulating complete built environment surface-air-plant thermal interactions based on the fluid dynamics and heat transfer fundamentals, (Bruse 2008). ENVI-met model is used in this study rather than for example the CTTC model introduced by (Swaid et al. 1993) regardless its improvements, (Shashua-Bar et al. 2004). Preference came from ENVI-met applies a soil-plant-air sub-model and its plants database that depend on the plant numerical physiological representation using height, Albedo, leaf area density, stomata resistance, etc in addition to the main model complete meteorological outputs. ENVI-met is professionally used in literature and validated for assessing built environment, (Ali-Toudert and Mayer 2007a, 2007b; Fahmy and Sharples 2008c; Fahmy and Sharples 2009a). In this paper it will be used as meteorology generator to assess effects of two trees for indoor analysis. Meteonorm, (METEONORM 2009; Radhi 2009), meteorological generator could have been used but again it will not stand for trees physiological effects.

Indoor simulations were performed using Design Builder which is 3-D comprehensive interface built over the Energy Plus dynamic model that can simulate indoor thermal interactions, (DesignBuilder 2009).

SIMULATION METHODOLOGY

Building and Environment

The urban site studied in this paper is part of the second district in the fifth community, which lies in New Cairo just out the first ring road of Cairo. It is on a micro scale from the urban climate point of view and is located at 30° 18'N and 31° 63'E. New Cairo's climate is mixed dry, semiarid (ASHRAE 2005).

The simulated day of the first stage was the 7th June, which is in the middle of a typical summer week for Cairo. Meteorological entries were the statistical hourly data of June, table 1 illustrate main input data used in stage one. In fact, the specific day does not matter as the objective was to study the difference in indoor comfort levels produced due to urban details regardless the day. The New Cairo site currently has almost no trees; hence, the first stage model has been used in three situations. The first one without trees, the second using 20m high Yellow Poinciana trees and the third using 15m high Ficus Elastica trees (in addition to grass green converge).

The rooms examined were on the middle floor of a typical three-storey multifamily apartment block. It consists of two apartments on each floor with five people per family. The building has 3 floors each of them 3m height. Ground floor area is 300m2 where typical floors are 330m2. The northern and southern façades have about 11% glazing of their area for each whilst the western and eastern have about 5% for each. Figure 1 shows an aerial view of the site and the residential building used in the simulation.

Table 1: main input data used in stage one.

PARAMETER	VALUE
Ta, air dry bulb temperature	300.55˚ K
RH, relative humidity	51%
V, wind speed	3.5 m/s at 10m height
Soil temperature	299.25˚ K at 0-0.5m and 297.15˚ K at 0.5-2m
Soil humidity	70% at 0-0.5m and 80% at 0.5-2m depth
U value Walls	1.7
U value Roofs	2.2
Albedo Walls	0.25
Albedo Roofs	0.15
Albedo Pavement	0.40
Albedo trees & grass	0.20

Figure 1.a: 0.6m resolution Quick bird 2008 satellite image of the site and building examined in the study.

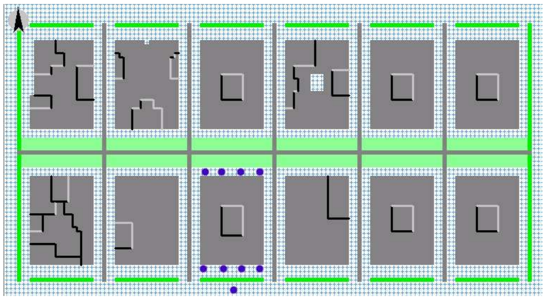

Figure 1.b: snapshots positions in Base case.

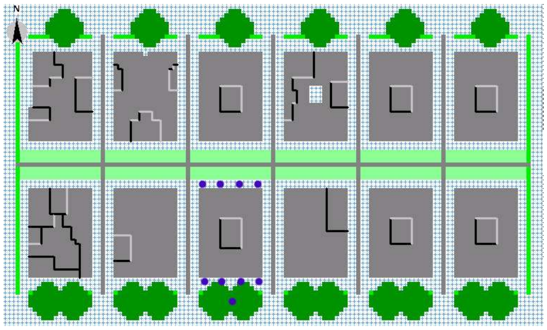

Figure 1.c: Modified case regardless tree type.

Trees modelling

Two trees are studied modify existing situation, the *Peltophorum Pterocarpum* (commercially Yellow Poinciana) and *Ficus Elastica* (commercially Indian Rubber Plant). Ficus Elastica is an evergreen dense tree with 12-15m mature height, and 4-6 trunk height. The Yellow Poinciana is a deciduous less dense tree that can reach up to 20m height and up to 6m trunk height, (Aiad 1999; USDA 2009). Trees were numerically modelled after (Lalic and Mihailovic 2004) to generate 10 values of trees' leaf area density, LAD. LAD, is the total leaves area in the unit volume of a tree horizontal slice, (Law et al. 2001b). Eventually, these 10 values needed by ENVI-met plants database were added to represent trees in simulations of the first stage.

Software cycling

As the main passive technique used is to produce shadows by applying urban trees, the built form stayed the same in all cases without modifications. This is to study only trees different foliage effects that are not considered by indoor simulation packages. The first simulation stage used ENVI-met 3.1 (Bruse 2008) to generate urban climate meteorology. This is to record the near-building meteorology, which in turn is affecting the indoor environment comfort levels and energy consumption. ENVI-met is capable of generating climate conditions at different heights; hence, the selected generated data from the snapshots was at 4.5m a.g.l. (above ground level), representing the middle height of the facade. Cairo has almost northern prevailing wind. Consequently, northern façade is expected to show higher speeds rather than the southern one. Moreover, as the southern façade receive the maximum radiation whilst northern facade receives minimum radiation, records were averaged from nine snapshot receptors. Eight of them at 0.5m away from the building and the last one under trees in front of the main façade, figure 1/b, c. In the second stage of the analysis, DesignBuilder 1.9 was used with these weather data in an EPW format to simulate each urban case effect on the indoor comfort level at this height. EnergyPlus3.0, (DOE 2009), was used to produce comma separated value (CSV) weather files from the widely used Typical Meteorological Year (TMY2) of the energy plus file (EPW) to write the ENVI-met output in and to modify the exact site coordinates. Eventually, the reverse cycle is done to convert the new data to EPW again. The generated data introduced to the original file was from 10.00-15.00 LST, local solar time (UTC+3). Generated meteorology in the first stage were the hourly means of dry bulb temperature, wet bulb temperature, relative humidity, global radiation, direct radiation, diffuse radiation and wind speed recorded from snapshots.

Indoor comfort assessment was made in terms of Fanger’s Predicted mean Vote (PMV), (ISO7730 1984), which is calculated every 15 minutes. Comfort levels have been simulated for an original weather data file despite it uses hourly means of open-air measurements above canopy layer. While in this paper, the weather data produced are hourly means within canopy layer. To illustrate the effect of different vegetative details, the No Trees situation is considered the reference file to compare its PMV with that produced with 15m and 20m tree files.

RESULTS AND DISSCUTION

Comfort analysis

Weather data generated in the first stage using ENVI-met were very different from the original scenario, especially for the solar radiation. It is influenced by the trees' foliage and canopy characteristics. Radiation records were 0 w/m^2 from 16.00 LST onward regardless a reduction adjusting factor should be applied to the generated data [(Ali-Toudert 2005) used an adjustment factor of 0.84 for simulation overestimated outputs]. Solar adjustment factor is a value can be used to fit ENVI-met radiation values to observed values; it varies from 0.5-1.5 and should be applied in the input configuration file if a field measurement takes place. Figure 2 shows the three simulated and original solar radiation data. To assure this output was viable a sun path analysis using ECOTECT5.6, (AutoDesk 2008), was performed (see Figure 3) and showed the solar positions and radiation on the building facades. At early-simulated time, ENVI-met predicted reduced direct short-wave radiation levels compared to the original data due to the obstruction by buildings when sun was at low altitude. By solar altitude increases, more short-wave radiation is gained within site. By altitude decreases afternoon (13.00 LST), more short-wave radiation is obstructed again. The diffused radiation at all times is less than corresponding airport value due to the blockage from buildings at site. The shorter 15m Trees performed better in intercepting radiation as a whole trend. For example, global radiation values recorded were 948, 898 and 886 w/m^2 for NoTrees, 20mTree and 15mTree respectively whereas 1103 w/m2 is the measurement at airport. There is no explanation for the only discrepancy result of global radiation at 12.00 LST of 1012, 906 and 883 w/m^2 respectively in comparison to 888 w/m^2; it can be owed to the software overestimation, which is included in radiation and hence PMV results plotted.

Wind speeds did not exceed 0.1 m/s in all three cases due to the southerly position of the building plot and the trees, whilst the original wind data did not fall below 1.5 m/s. Explanation is owed to the wind angle of attack over the whole buildings group and the close distance of trees canopies to southern facade. The near wall wind speed is not affected at all with wind vortex if produced within urban canyon, as the southern façade and tree canopy are almost same body. The southern position of the building plot itself is responsible of that beside the close distance between each two back-to-back buildings. In addition to the different heights from measured at 10.0m to simulated at 4.5m.

As ENVI-met plant model is using a soil-plant-air sub-model, RH is increased within site environment due to the high soil water content used in the configuration input file. The applied water content is about triple the actual measured soil water content. In fact, specific water levels supplied means extra cost in real practice. The reason to increase soil water input is to suggest providing sufficient water by irrigation for trees evapotranspiration to take effect. Figures 4 and 5 show comparisons of air temperature (DBT) and relative humidity (RH) for the generated and the original file. As a result, the simulated environment is warmer and more humid due to the buildings and vegetation. This lead to increasing indoor PMV levels compared to those produced from the original raw weather files. Nevertheless, PMV values derived from generated files is different from each other and giving impression about different foliage effects. Moreover, the original file did not account for four aspects. First, the urban details around the building, i.e. the original data come from a weather station at an airport site that is in the open desert. Second, the original site location has nothing to do with the real urban location of the building, i.e. solar positions and radiations are different. Third, the measuring height of the original weather file is different from the generated one that is a representation for the whole building; i.e. 4.5m a.g.l. Fourth, the original data collected using meteorological instruments while the generated data simulated.

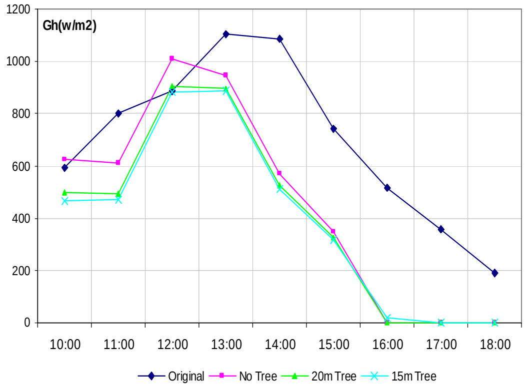

Figure 2: Global radiation generated compared with original.

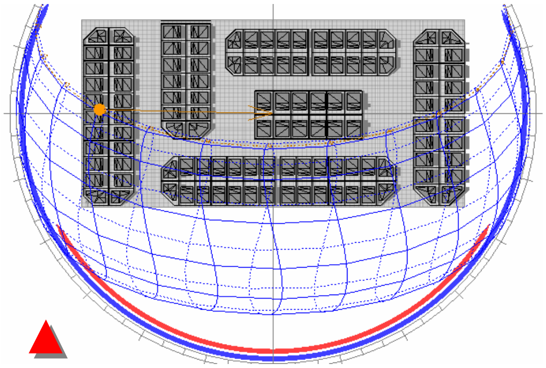

Figure. 3: Solar position analysis by ECOTECT 5.6.

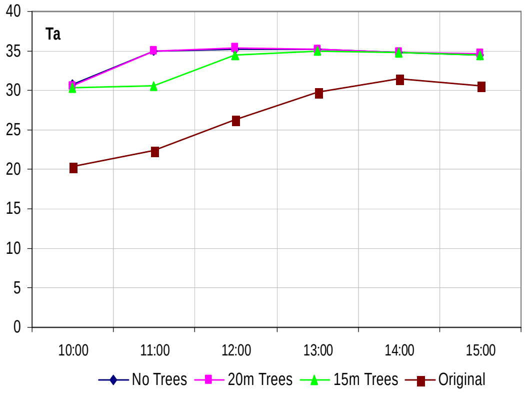

Figure 4: RH generated compared with original.

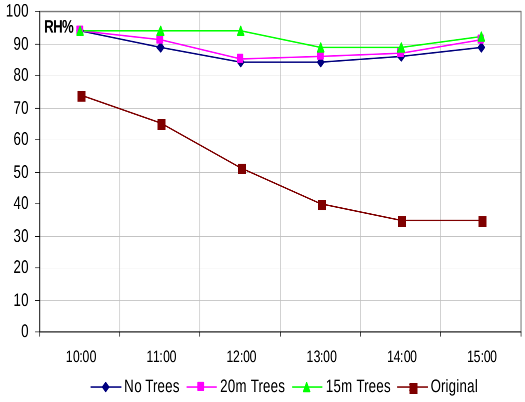

Figure 5: RH generated compared with original.

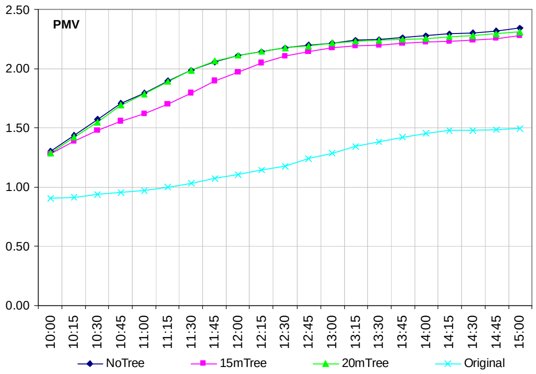

Figure 6: PMV generated compared with original.

PMV comfort assessments are presented in Figure 6. The upper curves are for the base and modified cases, the last curve is for PMV values generated from the original weather file. Results show differences between the 15m Trees situation and both No Trees and the 20m Trees from 10.30 to 12.45 LST.

PMV difference reached 0.2 from 11.00 to 12.00 LST, the better indoor comfort level achieved by using 15m Trees. PMV was calculated as 2.1 for No Trees and 20m Trees and 1.9 for 15m Trees at 11.45 LST. Differences then decrease to be 0.1 towards the end of the simulated time. The Ficus Elastica 15m trees showed better indoor comfort levels because this tree's foliage intercepted more solar radiation within its shadow area. The much reductions were before the sun zenith time at 13.00 LST at which the built environment and trees intercept more short-wave and sky long-wave radiations. After maximum solar height, direct and diffused radiations start to decrease. The less differences between comfort records occur afternoon where the sensible heat from ground and trapped by and under trees canopies affect the ambient conditions and close PMV records to each other. The more dense tree foliage (of the 15m tree), the more trapped sensible heat within canopies and under trees, i.e. less nocturnal cooling rate in comparison to open field measurements at airport.

CONCLUSION

This paper has suggested and demonstrated an approach to urban scale thermal comfort and energy analysis using a combination of microclimate urban scale modelling (using ENVI-met) and building scale simulation (using Design Builder). The shading technique using urban trees at building facades were applied to study its effects on the indoor thermal performance in terms of the comfort scale PMV.

As indoor thermal analysis packages don't stand for urban trees; its radiant interactions and evapotranspiration effects, dual stage outdoor-indoor simulations had to be held.

In the first stage, three urban situations have been simulated using ENVI-met in which a selected building had three situations of No Trees, 15m Trees and 20m Trees surrounding its facades. Second stage performed using DesignBuilder after compiling generated meteorology from the first stage.

The results from this study indicate that urban vegetation details are having crucial effect on indoor comfort levels and have to be considered for assessment in the site examined and in building simulations as a whole. Despite trees introduced wind speed blockage and high rates of humidity to the site, comfort levels differed from corresponding records at airport weather station especially until noon. Hence, raw data files are not adequate to be used directly with indoor thermal analysis packages for such as DesignBuilder, EnergyPlus and others. Moreover, the 15m tree Ficus Elastica tree showed less comfort levels rather than the 20m Yellow Poinciana tree when its effects have been introduced to the data file used for indoor comfort study. Consequently, it can be concluded that each tree type has its specific impact on the urban microclimate, indoor comfort and, in turn, on the energy demand could be needed for mechanical cooling. Eventually, specific trees types can be not only selected for its urban thermal behaviour but also for its better indoor impact. This draw attention and raises further approaches to investigate about simulation packages' accuracy and whether it need additional tools to account for real urban details, or to apply same methodology used in this paper.

REFERENCES

Aiad, S., 1999. Egyptian Plants: A Photographic Guide, Part I; Hymns in Nature, in Arabic. Dar Al-Shrouk Book Shop, Cairo.

Akbari, H. 2002. Shade trees reduce building energy use and CO2 emissions from power plants. Environmental Pollution, **116**: S119-S126

Ali-Toudert, F., 2005. Dependence of Out Door Thermal Comfort on the Street Design in Hot and Dry Climate. Institute of Meteorology, PhD. Thesis, Freiburg, Germany.

Ali-Toudert, F., and Mayer, H. 2007a. Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. Theoretical and Applied Climatology, **87**: 223-237.

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

Arnfield, A.J. 2003. Two Decades of Urban Climate Research: A review of Turbulence, Exchange of Energy , Water and the urban heat islands. International Journal of Climatology, **23**: 1-26.

ASHRAE, 2005. ASHRAE Hand Book of Fundamentals (SI Edition). American Society of Heating, refrigerating, and Air-Conditioning Engineers Inc., Atlanta.

AutoDesk. 2008. ECOTECT V5.6, [Online], Available: www.ecotect.com/autodesk. Accessed 21/4/2009.

Brundtland, G.H. 1989. Global change and our common future. Environment **31**: 16-20, 40-42.

Bruse, M. 2008. ENVI-met V3.1, a microscale urban climate model, [Online], Available: www.envi-met.com. Accessed 18/3/2009.

DesignBuilder. 2009. DesignBuilder [Online], Available: http://www.designbuilder.co.uk/content/view/43/64/. Accessed 21/4/2009.

Dimoudi, A., and Nikolopoulou, M. 2003. Vegetation in the Urban Environments: Microclimatic Analysis and Benefits. Energy and Buildings, **35**: 69-76.

DOE. 1995. Landscaping for Energy Efficiency, US Department of Energy, National Renewable Energy Laboratory NREL.

DOE. 2009. EnergyPlus Energy Simulation Software, [Online], Available: www.apps1.eere.energy.gov/buildings/energyplus/cfm/reg_form.cfm. Accessed15/1/2009.

Fahmy, M., and Sharples, S., 2008c. Passive design for urban thermal comfort: a comparison between different urban forms in Cairo, Egypt. PLEA 2008 - 25th Conference on Passive and Low Energy Architecture, University Collage of Dublin, Dublin, 22nd to 24th October 2008. Dublin, UK, October 22-24.

Fahmy, M., and Sharples, S. 2009a. On the development of an urban passive thermal comfort system in Cairo, Egypt. Building and Environment, **44**: 1907-1916.

Gidlof-Gunnarsson, A., and Ohrstrom, E. 2007. Noise and well-being in urban residential environments: The potential role of perceived availability to nearby green areas. Landscape and Urban Planning, **83**: 115-126.

Givoni, B., 1998. Climate consideration in urban and building design. Van Nostrand Reinhold, New York.

Huang, L., Li, J., Zhao, D., and Zhu, J. 2008. A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and urban heat island of Nanjing, China. Building and Environment, **43**: 7-17.

Huang, Y.J., Akbari, H., Taha, H., and Rosenfeld, A.H. 1987. The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings. Journal of Climate and Applied Meteorology, **26**: 1103-1116.

ISO7730. 1984. Moderate thermal environments determination of the PMV and PPD indices and specifications of the conditions for thermal comfort. International Standards Organization, Geneva, Switzerland.

Jentsch, M.F., Bahaj, A.S., and James, P.A.B. 2008. Climate change future proofing of buildings--Generation and assessment of building simulation weather files. Energy and Buildings, **40**: 2148-2168.

Kotzen, B. 2003. An investigation of shade under six different tree species of the Negev desert towards their potential use for enhancing micro-climatic conditions in landscape architectural development. Journal of Arid environments, **55**: 231-274.

Kumar, R., and Kaushik, S.C. 2005. Performance evaluation of green roof and shading for thermal protection of buildings. Building and Environment, **40**: 1505-1511.

Lalic, B., and Mihailovic, D.T. 2004. An empirical relation describing leaf-area density inside the forest for environmental modeling. Journal of Applied Meteorology, **43**: 641-645.

Lam, K.C., Leung, S., Hui, W.C., and Chan, P.K. 2005. Environmental Quality of Urban parks and open spaces in Hong Kong. Environmental Monitoring and Assessment **111**: 55-73.

Law, B.E., Cescatti, A., and BAaldocchi, D.D. 2001b. Leaf area distribution and radiative transfer in open-canopy forests: implications for mass and energy exchange. Tree Physiology Vol. , no. , pp. . Aug 2001. , **21**: 777-787.

METEONORM. 2009. Global Meteorological Database for Engineers, Planners and Education, [Online]. Available at: www.meteonorm.com/pages/en/meteonorm.php. Accessed 22/4/2009.

Oke, T.R. 2006. Towards better scientific communication in urban climate. Theoretical and Applied Climatology, **84**: 179-190.

Oke, T.R., Crowther, J.M., McNaughton, K.G., Monteith, J.L., and Gardiner, B. 1989. The Micrometeorology of the Urban Forest [and Discussion]. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, **324**: 335-349.

Radhi, H. 2009. A comparison of the accuracy of building energy analysis in Bahrain using data from different weather periods. Renewable Energy, **34**: 869-875.

Shashua-Bar, L., Swaid, H., and Hoffman, M.E. 2004. On the correct specification of the analytical CTTC model for predicting the urban canopy layer temperature. Energy and Buildings, **36**: 975-978.

Swaid, H. 1992. Intelligent Urban Forms (IUF) A New Climate-Concerned, Urban Planning Strategy. Theoretical And Applied Climatology, **46**: 179-191.

Swaid, H., Bar-El, M., and Hoffman, M.E. 1993. A bioclimatic design methodology for urban outdoor spaces. Theoretical and Applied Climatology, **48**: 49-61.

Taha, H. 1997. Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. Energy and Buildings, **25**: 99-103.

USDA. 2009. US Department of Agriculture Fact Sheets. [Online], Available: http://plants.usda.gov/ Accessed 19/2/2009.

Yoshida, S., Ooka, R., Moshida, A., Murakami, S., and Tominaga, Y., 2006. Development of Three Dimensional Plant Canopy Model for Numerical Simulation of Outdoor Thermal Environment. ICUC6, Sweden.