INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **30**: 44–57 (2010)
Published online 12 March 2009 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1869

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Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel

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ABSTRACT: Microclimate formation and its significance in urban planning was examined through two components that predominate in affecting the city's climate: built-up morphology and urban shade trees.

The methodological approach focus is on a generalization procedure for quantifying the thermal effect of any studied situation through parameterization of the vegetated variables and the built-up forms. The analysis is integrative, using empirical climatic data followed by an analytical study for generalization and sensitivity analysis using an integrative model, the Green CTTC model.

Three urban tree species predominant in the Tel Aviv gardens and streets, with different canopy characteristics, and three levels of building densities were analysed to determine their thermal effect on an urban street microclimate. The variables were parameterized according to six basic cooling attributes for the studied tree species in urban gardens in Tel Aviv, and according to three geometric built-up parameters for the studied urban street.

The integrative modelling approach of considering all changes simultaneously was illustrated on an urban boulevard in Tel Aviv. The analysis demonstrates the shortcomings of piecemeal modelling and the merits of the integrative approach.

The study indicates the importance of urban trees in alleviating the heat island effect in a hot and humid summer. The tree cooling effect was found to be strongly related to the built form geometry. In all the studied cases, the thermal effect of the tree was found to depend mainly on its canopy coverage level and planting density in the urban street and little on other species characteristics.

The methodology of analysis presented in this paper can be applied to develop an operational tool in assessing for an urban open space the integrative thermal effects of different tree species, and of the varied urban morphology and the interaction between them.

KEY WORDS urban shade trees; Mediterranean climate; vegetation cooling effect; microclimate modelling; Green CTTC model

Received 12 October 2007; Revised 11 January 2009; Accepted 12 January 2009

1. Introduction

Design strategies for sustainable passive cooling in urban planning for mitigating heat island intensity are becoming important in terms of energy savings and improved human thermal comfort (Steemers, 2003; Yezioro *et al.*, 2006; Grimmond, 2007). This mitigation is important from the scientific aspect by means of reducing the urban warming and heat stress, and from the policy aspect by reducing costs of energy consumption. The focus of this study is on the microclimate modelling of open spaces within the Urban Canopy Layer (UCL) which is the climate in the streets between the buildings and beneath the roof level (Oke, 1987), as these spaces cover more than two thirds of the urban area of a modern city (Shashua-Bar and Hoffman, 2004). Among the variables to be modelled are the vegetation coverage (Saito *et al.*, 1990/1; Grimmond *et al.*, 1996; Jonsson, 2004), the thermophysical properties of the built-up elements (Rosenfeld *et al.*, 1995; Akbari *et al.*, 2003), the geometry of the studied open space (Oke, 1988; Swaid and Hoffman, 1990/1; Mills, 1997) and the surrounding building forms (Meir *et al.*, 1995; Ratti *et al.*, 2003).

The quantitative analysis followed in this paper is through the use of parameterization of the vegetated variables and the built-up forms. Three urban tree species are studied in open spaces; they predominate in the

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Tel Aviv gardens and streets and differ in their canopy characteristics and coverage levels. The effects of these trees in summer can then be applied to urban sites with various built-up configurations. The typology of the studied building forms is parameterized through a generic model for urban streets. The interaction thermal effects of vegetation with the urban building density are estimated through simulations using the analytical Green CTTC (Cluster Thermal Time Constant) model (Shashua-Bar and Hoffman, 2002) for predicting the diurnal air temperature variations in a given UCL site.

1.1. Background

Design strategies for sustainable urban planning are important in passive cooling and in finding sustainable energy sources for mitigating the urban heat island intensity and heat stress. A potentially powerful means for passive cooling in the urban context is vegetation, particularly shade trees. One of the strategies for urban heat island mitigation is the provision of urban parks in order to enhance evaporation (Grimmond, 2007). In a study conducted in Colombo, Sri Lanka (Emmanuel and Johansson, 2006), shading is proposed as the main strategy for reducing air and radiant temperatures, especially achieved by deep canyons, covered walkways and shade trees. The measurement results showed a maximum difference of 7 °C, while temperature differences between sunlit and shaded urban surfaces reached up to 20 °C. Recent studies demonstrate the importance of modeling the UCL in urban canyon streets; It is shown that the interaction between buildings material, their location and geometry play an important role in the street heat exchange which influence its climate conditions (Erell and Williamson, 2006; Offerele *et al*., 2007; Emmanuel *et al*., 2007) and on thermal comfort (Al-Toudert and Mayer 2006, Pearlmutter *et al*., 2007) within the street.

The cooling effect of urban parks creates a Park Cool Island (PCI), and is most pronounced in urban environments which have high urban heat island intensities (Spronken-Smith and Oke, 1998). Studies in hot humid cities indicate that urban trees in parks and streets can generate cool islands leading to a large PCI effect (e.g. Bernatzky, 1982; McPherson and Dougherty, 1989; Oke, 1989; Dimoudi and Nikolopoulou, 2003). Besides the positive effect of the green areas on the urban climate, several empirical results (e.g. Jauregui, 1990/1; Grimmond *et al*., 1996; Potchter *et al*., 2006) indicate that in some cases, during the daytime hours, the vegetated areas can be warmer than the surrounding built-up environment, leading to unpleasant microclimatic conditions. It appears that the cooling effect of vegetation may differ from site to site, depending on the vegetation type and coverage, the surface temperatures, and the built-up surroundings. This interrelation between vegetation coverage and its surroundings is most noticeable in the context of an urban open space, such as the urban street. As opposed to the urban park, the trees' effect is local and is greatly influenced by the increased energy load received from surface surroundings (Kjelgren and Montague, 1998; Kuttler *et al*., 2007).

In the context of large green areas as compared to built-up surroundings, the impact of PCI of well-treed parks can reach a maximum of 4–5 °C during day time, while at night the PCI is small and reaches up to 1 °C (Sham, 1991; Saito *et al*., 1990/1; Ca *et al*., 1998; Potchter *et al*., 1999). It has also been shown that the park cooling effect extends beyond the park. The range effect was found to depend mainly on the park size and on the distance of the built-up surroundings from the park border (Honjo and Takakura, 1990/1; Jauregui, 1990/1; Spronken-Smith, 1994; Ca *et al*., 1998; Upmanis *et al*., 1998).

In microscale cases, the study of vegetation effects on the UCL microclimate is quite recent. Besides the properties of the vegetation species, three other main factors affect the microclimate of an open space: (1) The geometry of the open space obtained as the aspect of the surrounding buildings' height to the width of the street (Oke, 1987), (2) The thermophysical properties are the thermal inertia of the built materials within the urban open space, and (3) The anthropogenic heat release, mainly the transportation and fuel consumption for domestic use in the flanking buildings of the open spaces. These factors were found to affect the vegetation effect and thus introduce an interaction effect (Shashua-Bar *et al*., 2006). In addition to the climatic variables, the effect of the above three factors and of vegetation depends on various variables which are under the control of the designer (herein named as control variables). The overall effect of the various control variables within an urban space can be significant in hot climatic regions in terms of energy savings and improved human comfort. In temperate and hot regions, the maximum thermal effects in summertime of these variables on the UCL microclimate is of the order of 3–4 °C for vegetation in urban parks (e.g. Oke, 1989; Taha *et al*., 1991; Potchter *et al*., 1999), about 1 °C for wall albedo modification, (Shashua-Bar and Hoffman, 2004) and up to 7 °C for differences of building forms (Shashua-Bar *et al*., 2006). These thermal impacts are significant, taking into account that the average daily range of the summer air temperature in temperate climates, as found in the Mediterranean region, are of the order of 6–10 °C (Bitan and Rubin, 1994). According to Akbari *et al*. (2001), urban trees in streets can have a substantial cooling effect on the urban air temperature, and can reduce cooling energy demand by 20%.

1.2. Objectives

The study examines the factors affecting the microclimate and its significance in urban planning through two components that dominantly affect the city's climate: built-up density and urban shade trees. The study seeks to develop an operational tool for assessing the integrative thermal effects of different tree species and the site's built-up elements, and the interaction between them in an urban open space.

DOI: 10.1002/joc

2. Methodology

2.1. Methodological approach

The methodological approach in this study is focused on generalization. The generalization procedure for quantifying the thermal effect of any studied situation is achieved here through parameterization of the variables according to basic measurable attributes. This process is applied for two main control variables namely, the built-up density and the urban shade trees. The tree thermal characteristics are parameterized by attributes namely, the tree coverage, canopy thermal characteristics including canopy solar absorptivity, canopy solar transmissivity, canopy thermal time constant, and the tree cooling coefficient due to evapotranspiration, and to changes in the tree's heat storage. The built forms are parameterized by three geometric relations (aspect ratio, building depth ratio, and spacing ratio) representing the various building form configurations.

The control variables studied in this paper in modelling the UCL microclimate are multivariate in nature. The vegetation variable covers many tree species, each having different cooling potential due to its properties. Likewise, the built forms cover different types of open spaces in urban streets, pavilions, and courtyard housings. The multiplicity of the factors calls for developing a generalization procedure in order to reach generality and meaningful quantitative results. Thus, online analyses for each individual type are not only cumbersome, but will hinder decision making in identifying a preferred choice among possible alternatives.

Besides parameterization, the analysis is integrative. It starts by an empirical study to describe the actual situation followed by an analytical study for generalization and sensitivity analysis. The quantification of thermal effects for each attribute and built form aspect, the total thermal effect of the major variables of vegetation and building density, as well as the thermal interaction between them are estimated using a well-validated analytical model, the Green CTTC model.

Figure 1 shows the modelling procedure followed in this study in quantifying the effects of the system's control variables. The figure shows a set of variables affecting the microclimate and to which the designer can assign appropriate values. The level of these variables can be controlled; hence, they are named in the paper as control variables. The control variables consist of urban space geometry, thermophysical properties, anthropogenic factors, and the vegetation in a given urban open space. In this study, two main analysed control variables are the urban space geometry and urban trees and their interrelationship effects on microclimate. This interrelationship effect is analysed through modelling using parameterization of the main attributes of each of the two impacts: for the urban space geometry, three built-up ratios, and for the urban trees, six attributes that capture the thermal effect of tree cooling.

The paper's sections are as follows: Section 2 describes the studied sites and the measurement setup. Section 3 reports on the experimental study and the empirical findings. The analytical study is described in Section 4, which includes a short description of the model formulation, its suitability for simulation purposes, and its validity in predicting air temperature variations for the studied sites. The section also discusses the estimated value of the tree's cooling effect and its dependence on the urban built-up density. Section 5 illustrates the shortcomings of piecemeal modelling and argues for the merits of the integrative approach.

2.1. Sites and observations

The study considers the case of a hot humid climate in summer. It was conducted in the city of Tel Aviv in Israel (32°06′N 34°47′E), situated on a plain along the east coast of the Mediterranean Sea. The city has a subtropical climate, Csa according to Koeppen classification (Potchter and Saaroni, 1998), its climatic conditions are a result of the combined effect of the geographical location, the influences of the Mediterranean Sea, and of urbanization. During the summer season, the city suffers from hot and humid climatic conditions: The daily maximum temperature is around 29.0–30.0 °C on average, with minimum relative humidity around 61%. The daily minimum temperature is around 22.2 °C, with average relative humidity around 83%. Heat stress in summer is noticeable during most of the daytime hours. The wind regime is influenced by the Mediterranean Sea breeze which blows during the day from the west and northwest, whereas during the night, it is affected by a light land breeze, which blows from the east and southeast (Bitan and Rubin, 1994). Significant heat island intensities were recorded in Tel Aviv at midday and nighttime during the summer (Bitan *et al.*, 1992) and winter (Saaroni *et al.*,

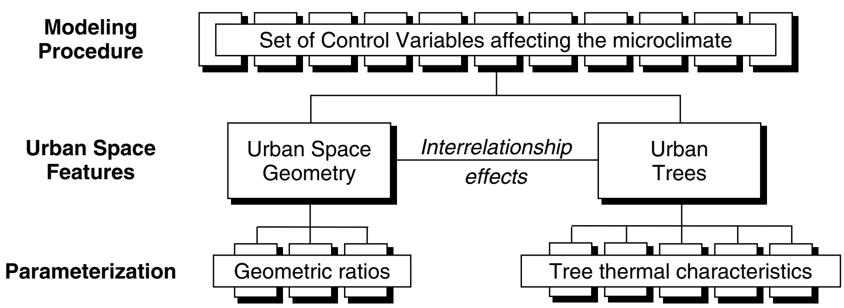


Figure 1. The urban open space microclimate modelling procedure.

DOI: 10.1002/joc

2000). The results indicate maximum warming up to 5 °C from air temperature measurements between the city centre and its surrounding areas indicating the existence of an urban heat island. From remotely acquired thermal readings, differences up to 10 °C in surface temperature were recorded indicating the existence of an surface heat island due to differences in urban texture, vegetated areas, and anthropogenic activities.

Table I lists the data of measurements and the tree coverage level for each site. Three tree species with different canopy characteristics and canopy coverage levels were studied: The Ficus retusa tree (common name: Indian Laurel Fig) with a highly dense and broad canopy (about 14 m in diameter), the Tipuana tipu tree (common name: tipu tree) with a moderate size canopy (about 10 m in diameter), and the Phoenix Dactylifera tree (common name: Date Palm) with a sparse and narrow canopy (about 6 m in diameter). These three species of shade trees are dominant in the Tel Aviv gardens and streets. Some basic characteristics of the three tree species are shown in Table II.

All three species were studied from measurements in situ in different urban gardens. The Ficus tree was studied in Tagore Garden in the Ramat-Aviv area. The Tipuana tipu was studied in the Reading Garden in the Ramat-Aviv area. The third tree species, the Date Palm tree (planted over grass), was studied in a garden situated in the Tel Aviv University area. The distance between any two gardens is less than 1 km.

In addition to the garden sites, an urban boulevard at the centre of Tel Aviv city was also studied, namely, Chen Boulevard, with Ficus trees planted along it. The measurements were conducted in the boulevard and in an urban street, Iben Gvirol Street parallel to it, which has no trees. Both sites are north–south oriented, having similar building density, with an aspect ratio of 0.4, and both carry heavy vehicular traffic.

2.3. Measurement setup

Campbell automatic meteorological stations were set up in the centre of each urban garden, representing the three studied tree species. In the case of the urban streets, Campbell automatic meteorological stations were set up simultaneously in the middle of the boulevard and the street canyon on a traffic island. Air temperature and relative humidity were measured at 1.5 m above ground, and wind velocity and direction at 2 m height. Figure 2 shows the map of the studied sites' locations.

The instruments included Campbell HMP45C-type temperature and relative humidity sensors. The sensors were installed inside a Gill Multi-Plate 41 002 unaspirated radiation shield. The temperature and relative humidity accuracy of the sensors is ±0.2 °C and ±2%, respectively. Wind velocity and direction were measured using Young 05 103 anemographs. Sensor accuracy was ±0.3 m/s for the velocity, and 3° for the direction. Readings were taken every second with the resulting data averaged and stored every five minutes using a Campbell 21X data logger. For wind direction, the mode direction was stored. All the instruments were calibrated, checked, and compared before and after the experiment under the same conditions. According to specifications of the screen manufacturer (Young Co, 1998), the screen may overestimate the air temperatures during the daytime hours (up to 1.5 °C under stable calm conditions, and less than 0.7 °C and 0.4 °C with winds of 2 and 3 m/s, respectively). In order to avoid erroneous conclusions stemming from the screen effect, temperatures of stations exposed to different wind velocities were compared to those of a station sheltered from the wind. Temperature differences were less than 0.2 °C, indicating that the error effect due to the small ventilation in the exposed screens in the park was negligible. It should also be noted that during most hours during the day, wind velocity was between 1.5 and 3 m/s, so that the screens had natural ventilation.

In addition, mobile instruments were also used for evaluating some of the site parameters, such as the solar absorptivity and canopy solar transmissivity factors, and the tree coverage levels. The experimental study for all the sites concerns the summer situation. Besides the onsite measurements, climatic diurnal data corresponding to the measurement days, on solar radiation, wind velocity, ground surface and air temperatures, and humidity, were obtained from a meteorological station at Beit-Dagan, located in a rural environment at a distance of about 7 km southeast of Tel Aviv. The data were used

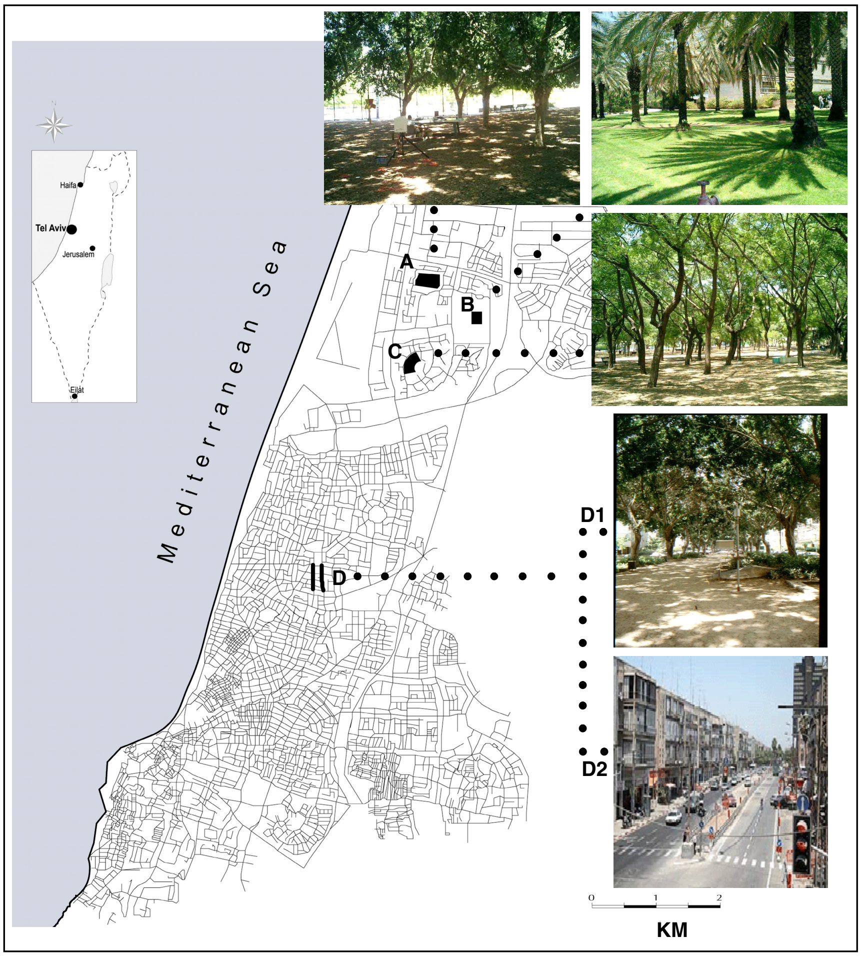
Table I. The studied sites.

Site	Date of measurements	Site area (m^2)	Bordering buildings height (m)	Tree Species	Tree coverage (%)
Urban Garden					
Reading Garden	31/7–1/08/2001	35 000	12	Tipuana tipu	70
Tagore Garden	15–16/08/2005	60 000	6–12	Ficus retusa	90
Tel Aviv University	15–16/08/2005	5000	6–12	Date Palm*	50
Urban Boulevard					
Chen Boulevard	03–06/06/1997	3000**	12	Ficus retusa	70
Iben Gvirol Street	03–06/06/1997	3000**	12	–	–

* The trees are planted over grass.
** According to width of 30 m and measured length of 100 m.

Table II. Basic characteristics of the studied tree species.

Botanical name	Ficus retusa	Tipuana tipu	Phoenix dactylifera
Family	*Moraceae*	*Fabaceae*	*Arecaceae (Palmae)*
Common name	Indian Laurel Fig	tipu tree	Date Palm
Height at maturity	10–15 m	6–15 m	10–20 m
Canopy width	Vertically growing branches, 15–20 m in diameter. Suited for formal shearing. May be pruned at any time of year to desired shade and size.	Up to 10–15 m. Broad silhouette with flattened crown. Usually wider than higher.	Large feather palm, 6 m diameter.
Trunk	Central smooth trunk, with growth of air roots which can develop into sub-branches.	Central trunk branching. Needs support as young tree especially in windy areas.	Slender trunk, 30–40 cm in diameter. Trunk patterned with base of old leafstalks. Suckers from base, natural state is clump of several trunks. Leaves at top only.
Foliage	Dense foliage. Leaves are clear lustrous green, similar in size. 	Leaves divided into 11–21 oblong; 3 cm long. Light green leaflets. 	Grey-green waxy leaves. 3 m long. Leaflet stiff and sharply pointed at top. 



A- Tagor Garden, B- TA campus garden, C- Reading Garden, D- Urban Boulevard
(where: D1- Chen Blvd, D2-Iben-Gvirol street)

Figure 2. Map of the studied sites locations. This figure is available in colour online at www.interscience.wiley.com/ijoc

for comparison purposes, such as the air temperature and for running the analytical model.

3. Empirical findings

Table III summarizes the sites' air temperature values for times 6:00, 12:00, 15:00 and 24:00 for each urban wooded sites (where 15:00 is equal to 14:10 solar time). Table III provides for each site the corresponding values at the Beit-Dagan Meteorological station (located in a rural area). Note that the difference between the site and the meteorological station values is not a correct measure of the trees' cooling effect, since it includes other thermal effects due to differences in wind speed, humidity, ground absorptivity, and urban factors.

The diurnal patterns of air temperature, wind speed, and humidity are shown in Figure 3 for the three urban gardens (Reading garden, Tagore garden and the Tel Aviv University) and for the urban boulevard (Chen Boulevard) and urban street (Iben Gvirol Street).

The air temperature patterns in Table III indicate significant differences between the urban wooded sites and the rural meteorological station at Beit-Dagan, and also

Table III. Daily air temperature values (°C) measured at the studied sites, summer data, Tel Aviv area, Israel.

Site	Time (hour)			
	6:00	12:00	15:00	24:00
Urban Garden				
Reading Garden (Tipuana tipu trees)	24.4	30.8	30.1	25.2
Meteorological station (31/7–1/08/2001)	24.4	30.1	31.1	24.6
Tagore Garden (Ficus retusa trees)	24.0	29.3	29.4	26.0
Meteorological station (15–16/08/2005)	23.6	32.3	32.3	24.5
Tel Aviv University (Date Palm trees*)	24.9	29.8	30.2	26.3
Meteorological station (15–16/08/2005)	23.6	32.3	32.3	24.5
Urban Boulevard				
Chen Boulevard (Ficus retusa trees)	19.5	25.5	24.6	21.2
Iben Gvirol Street	21.5	27.3	27.7	23.4
Meteorological station (03–06/06/1997)	19.4	27.4	26.7	19.4

* The trees are planted over grass.

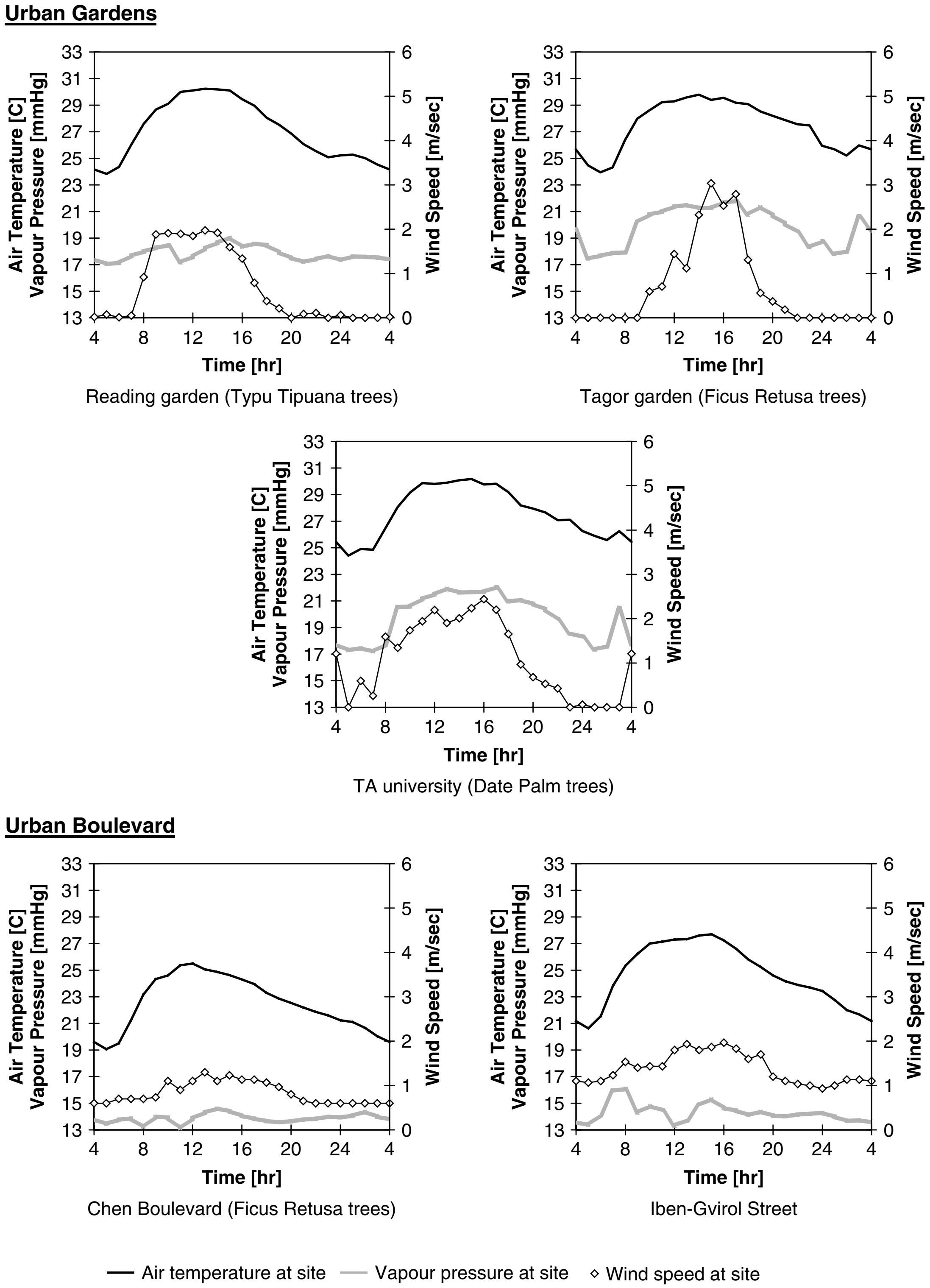


Figure 3. Daily data at the studied sites. Summer data, Tel Aviv area, Israel.

noticeable differences among the sites. The variability among the hourly air temperature values is due to different days of measurements and also to different levels of the variables affecting the site's microclimate. Large differences between the two urban streets were recorded, due to differences in the traffic load and to the fact that Chen Boulevard includes dense broad trees while Iben Gvirol has none.

The quantitative thermal impact on the air temperature variability for each variable is discussed in the analytical analysis.

4. The analytical study

As shown in previous studies (Shashua-Bar and Hoffman 2004; Shashua-Bar *et al.*, 2006), the cooling effect does not depend solely on the tree attributes, but also on the site's specific conditions such as its geometry, the building density of its surrounding buildings, its wind regime, etc. Hence, an interrelationship among the effects of all the variables affecting the site's microclimate. The effect of each variable and its interaction with the urban texture can be studied through simulations using the analytical Green CTTC model. The thermal effect of different trees and urban forms is incorporated in the analytical model through parameterization of their characteristic attributes.

4.1. The Green CTTC model–outline

The Green CTTC model for estimating the diurnal urban air temperature pattern is an extension of the CTTC model (Swaid and Hoffman, 1990/1). The predicted air temperature of the site is calculated through the contribution of the heat received from external sources, mainly the net solar radiation, anthropogenic heat release, and vegetation effects. It comprises design variables and parameters related directly to the physical structure and properties of the built-up complex (mainly, the thermophysical properties of the surfaces and the open space geometry) and to the density and canopy characteristics of shade trees. The levels of these factors can be controlled by the designer, hence, as such, the model is suitable for modelling purposes. Specifically, it can enable the designer to predict the thermal effect of any change in the level of one or more of its control variables. The model does not take into consideration advection effects, thus, its predictions are valid only for calm days, and therefore, not valid on rainy days, stormy days or advection of hot dry winds. It should be noticed that the effect of UHI is more pronounced in calm conditions.

The formulation of the Green CTTC model is given in (Shashua-Bar and Hoffman, 2002; Shashua-Bar *et al.*, 2006). For the convenience of the reader the predicting equation for the cluster's air temperature at time (t) is given here:

$$T(t) = T_0 + \Delta T_{\mathbf{SOLAR}}(t) - \Delta T_{\mathbf{NLWR}}(t) + \Delta T_{\mathbf{AHR}}(t) \tag{1}$$

$T(t)$, is the predicted air temperature at time (t). T_0, is the regional base (or background) temperature that was found to be equal to the mean daily air temperature measured at a rural meteorological station, representative of the non-built-up area near the site in question.

$\Delta T_{\mathbf{SOLAR}}(t)$ is a step function of the penetrated shortwave radiation, using the reciprocal of the CTTC parameter as the attenuating factor. It includes the vegetation effect, expressed as a reduction in the incident solar radiation which is diverted by the trees for the purpose of evapotranspiration and for changes in the plant's heat storage.

The term, $\Delta T_{\mathbf{NLWR}}(t)$, is the contribution of the net outgoing longwave radiation exchange flux-to-air cooling. Like the absorbed solar radiation term, it includes the climatic variables and the effect of control variables but refers to thermal radiation exchange.

The term, $\Delta T_{\mathbf{AHR}}(t)$, is the anthropogenic effect to air temperature. It includes the effects of man-made nature such as heat release owing to transportation and fuel consumption for domestic use. It is estimated in Wm^{-2} and is added to the absorbed solar radiation at time t.

4.2. Parameterization

The basic characteristics of the three tree species in Table II provide little information as regards the cooling attributes of the trees, as these basic characteristics are specific for each species and state of the tree development, and thus, are too generally stated for analytic purposes. In this study, the attributes affecting the cooling ability are common for any tree species. Six such attributes are chosen as input in the analytical model:

- Tree coverage: The tree coverage is the difference between the values of two attributes: sunny spots under the canopy area and partial tree-shaded area at noon. It is a measure of the canopy size net of sunny spots, relative to the site's ground area.
- Canopy solar absorptivity: A function of the leaf properties, the canopy structure, the canopy solar transmittance, and the soil solar reflection (Monteith and Unsworth, 1995, p 88).
- Canopy solar transmissivity: Average canopy solar transmittance under the tree canopy.
- CTTC: Thermal time constant of the tree canopy. Its reciprocal determines the heating rate of the tree canopy; thus, the higher the time constant, the lower the heating rate.
- Cooling coefficient of tree: That part of solar energy diverted from heating the site to changing of the tree's heat storage and evapotranspiration.

The levels and parameters for the three studied tree species are listed in Table IV. The parameter values of the trees' attributes were estimated by the authors based on measurements conducted by the Department of Geography and Human Environment at Tel Aviv University. The estimation of the two parameter values – thermal time constant and cooling coefficient – follows the methods expressed in (Shashua-Bar and Hoffman, 2002).

Table IV indicates differences in the levels and in the parameter values of the six attributes as estimated in the studied sites, which follows the canopy characteristics of the three tree species. The significant differences occur in the tree coverage (net of sunny spots), canopy solar transmissivity, and the cooling coefficient. The two attributes, the canopy absorptivity and the canopy thermal time constant, as average estimates for a tree canopy, range from about 0.6 to 0.7, and 8 to 9 hours, respectively, showing small differences among the three tree species.

The Ficus tree has a large and dense canopy which is expressed in a small area of sunny spots (5–10%) and a small amount of solar transmittance under its

Table IV. Levels and parameter values of the six attributes of the studied tree species. Summer data, Tel Aviv area, Israel.

Site	Levels		Parameters			
	Sunny spots (%)	Tree coverage (%)	Canopy solar absorptivity	Canopy solar transmissivity	Canopy time[(1)] constant	Cooling coeff. of tree
Tagore Garden (Ficus retusa)	5–10	90	0.60	0.05	9.0	0.60
Reading Garden (Tipuana tipu)	15–20	50	0.60	0.12	7.9	0.50
Tel Aviv University (Date Palm)	30–40	50[(2)]	0.70	0.15	7.6	0.70[(3)]
Chen Boulevard (Ficus retusa)	5–10	70	0.60	0.04	8.0	0.40

(1) Thermal time constant for ground = 8 h, for walls = 6 h.
(2) The grass coverage level (under the Date Palm trees) was 0.80
(3) Cooling coefficient for Date Palm = 0.40, for grass = 0.30

canopy (an average of 5% transmittance). Its massive canopy produces relatively large tree coverage in any open space, and accordingly, leads to a high cooling coefficient of 0.6 in the Tagore Garden due to high heat storage and evaporative energy which reduce the solar energy received by the open space by about 60%. Due to changes in the soil properties and the presence of surrounding built surfaces, the cooling coefficient was found to be lower in the case of the Chen Boulevard (0.4).

The Tipuana tipu tree is characterized by a moderate canopy having more sunny spots (15–20%) and higher solar transmissivity (average of 12%) compared to the Ficus tree. Its cooling coefficient was found to be 0.5 in the Reading Garden, diverting 50% of the received solar energy from heating the site.

The Date Palm tree characteristics are a sparse and narrow canopy, with a considerable percentage of sunny spots (30–40%) and high solar transmissivity (an average of 15%). As opposed to the Ficus and tipu trees, the Date Palm trees can be planted short distances apart in an open space, reaching to a maximum canopy coverage of 50% in the Tel Aviv University site. The Date Palm trees in the studied site were planted over grass. This combination led to the highest cooling coefficient of 0.7. The cooling coefficient of the same grass species, located in the vicinity of the Date Palm site, but fully exposed and without trees, was found to be 0.3, leading to a cooling coefficient of 0.4 for the Date Palm trees.

The urban site chosen for a typological study is a typical residential street 27 m wide, commonly found in the centre of Tel Aviv. The urban space factor considered in this study is characterized by its built-up geometry. For a residential street, following the generic model for urban streets (Shashua-Bar *et al.*, 2006), the built-up geometry is parameterized in this study by three geometric relations: the aspect ratio H/W (height to width), the built-up depth ratio $D/L2$ (building depth, D, to the frontal length, $L2$), and the spacing ratio, $L1/L2$ (distance between adjacent buildings $L1$ to the frontal length, $L2$). For all the studied configurations, $W = 27$ m, $L1 = 10$ m, $L2 = 20$ m and $D = 25$ m.

For the studied street of 27 m width with two rows planted, the maximum tree coverage (net of sunny spots) for the Ficus retusa tree is found to be up to 90% of the ground area; for the Tipuana tipu tree, 70%; and for the Date Palm tree, 25% only. These three coverage levels were considered for analysis in this study. Figure 4 demonstrates the three geometric ratios of the studied street and the planting scheme of the maximum coverage of each of the tree species.

4.3. Simulating the air temperature patterns of the sites

The air temperature patterns of the sites were simulated using the Green CTTC model. The purpose was to test

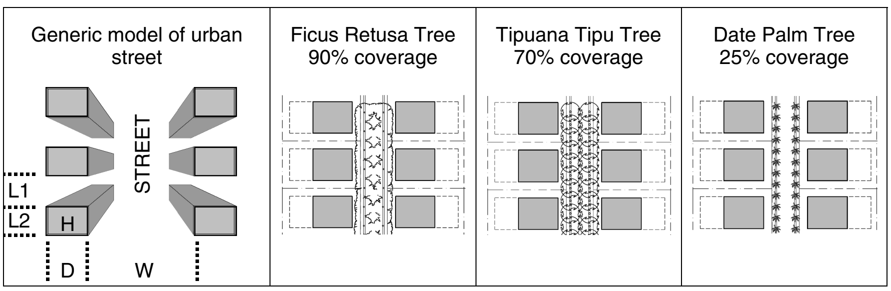


Figure 4. The studied street with maximum coverage of the studied tree species.

Table V. Daily air temperature values measured at the studied sites vs simulated (°C).

Site		Time (hour)			
		6:00	12:00	15:00	24:00
Urban Garden					
Reading Garden	measured	24.4	30.1	30.1	25.2
(Tipuana tipu trees)	simulated	24.5	30.2	30.0	24.6
Tagore Garden	measured	24.0	29.3	29.4	26.0
(Ficus retusa trees)	simulated	24.7	29.2	29.1	26.6
Tel Aviv University	measured	24.9	29.8	30.2	26.3
(Date Palm trees)	simulated	24.2	29.4	30.1	25.9
Urban Boulevard					
Chen Boulevard	measured	19.5	25.5	24.6	21.2
(Ficus retusa trees)	simulated	20.3	24.6	23.7	19.8
Iben Gvirol Street	measured	21.5	27.3	27.7	23.4
(without trees)	simulated	20.9	26.2	25.8	21.2

the validity of the model and the validity of the parameter estimates. In all the validity tests, anthropogenic heat was not taken into account.

The results of the simulations are shown in Table V for the times 6:00, 12:00, 15:00, and 24:00. The diurnal patterns are shown in Figure 5 for the wooded sites and for the urban street, Iben Gvirol, with no trees. The patterns of the three park gardens show a very close fit, indicating a high level of validity.

In the two urban streets, the deviations are systematically positive and large along the whole range of the day pattern. The deviations are about an average of 1 °C for Chen Boulevard, and 1.5 °C for Iben Gvirol Street indicate the anthropogenic effect of vehicular traffic in these two streets. The estimate for the Chen Boulevard during the noon hours is about 2000 passenger cars per hour, and that of Iben Gvirol about 3000, consistent with the deviation values of air temperatures. The simulated estimates for the traffic load in the rush hours are 1.5 °C for the Chen Boulevard and 2.5 °C for the Iben Gvirol Street.

4.4. Estimating the cooling effect of the trees

Estimating the cooling effect as the difference in air temperature between a park garden with trees and a nearby site without trees, yields, in most cases, misleading results. As mentioned earlier, urban factors play an important role in the UCL air formation. In addition, the presence of trees affects the levels of some of the climatic variables such as wind velocity and humidity. In addition, the albedo of trees and of the ground and walls are not the same.

In this study, the cooling effect of the trees is estimated as the difference between the site's simulated values with trees to those without trees. Table VI shows the cooling effect of the trees at times 6:00, 12:00, 15:00, and 24:00. The differences among the sites are due mainly to relatively large differences in their net tree coverage levels.

Table VI. Simulated trees cooling effects at the studied sites, (°C).

Tree species	Tree coverage (%)	Time (hour)			
		6:00	12:00	15:00	24:00
Ficus retusa Tree (Tagore Garden)	90	−2.1	−2.5	−3.3	−2.4
Tipuana tipu Tree (Reading Garden)	50	−1.0	−2.0	−2.8	−1.8
Date Palm Tree (Tel Aviv Univ.)	50	−1.7	−1.9	−2.0	−2.1
Ficus retusa Tree (Chen Boulevard)	70	−0.9	−3.0	−3.8	−1.7

4.5. The impact of urban geometry on the cooling effect of trees

The impact of urban geometry on the cooling effect of trees was studied on a typical urban street 27 m wide (wall to wall). Among the three geometric ratios characterizing the generic built form, the aspect ratio (height to width ratio, H/W) was found to have the largest impact. To illustrate the urban impact, only the aspect ratio impact was considered in this study.

Three levels of aspect ratios were considered in the simulations: 0.6 (= 16 m/27 m), 0.8 (= 22 m/27 m), and 1.0 (= 28 m/27 m) corresponding, for this kind of street, to buildings with 4, 6, and 8 floors, respectively. The other two geometric ratios, the depth and spacing ratios, for the 27-m-wide street were held constant at the levels of 1.25 and 0.5 respectively in all the simulations. The simulations were run for a common coverage level of the three tree species, as determined by the smallest maximum coverage level allowed for each tree species. In the 27-m-wide street, taking into account the canopy diameter and the planting distance of the trees, the maximum coverage level (net of sunny spots) was found to be 90% for the Ficus trees, 70% for the tipu trees, and 40% for the Date Palm trees planted in 3 rows, and only 25% for those in 2 rows. The maximum common coverage level allowed for comparison purposes is then 40%, as restricted by the canopy size relative to the street's width. The Date Palm trees considered in the simulations are not planted over grass. Their cooling coefficient is estimated to be about 0.4.

Table VII shows the cooling effects (at 15:00 hours) for the three tree species, all calculated at the same coverage of 40%, net of sunny spots, which is the maximum allowed coverage for the Date Palm trees in a street of 27 m wide (planted in three rows). In this manner, the figures in Table VII can be compared to the cooling ability of the other attributes taken together. For all the three tree species, the effect of increasing the aspect ratio (in this study, by increasing the wall height of the open space) results in reducing the tree cooling effect. Going across the rows, from 4 to 6 building floors, the cooling effect is reduced for all

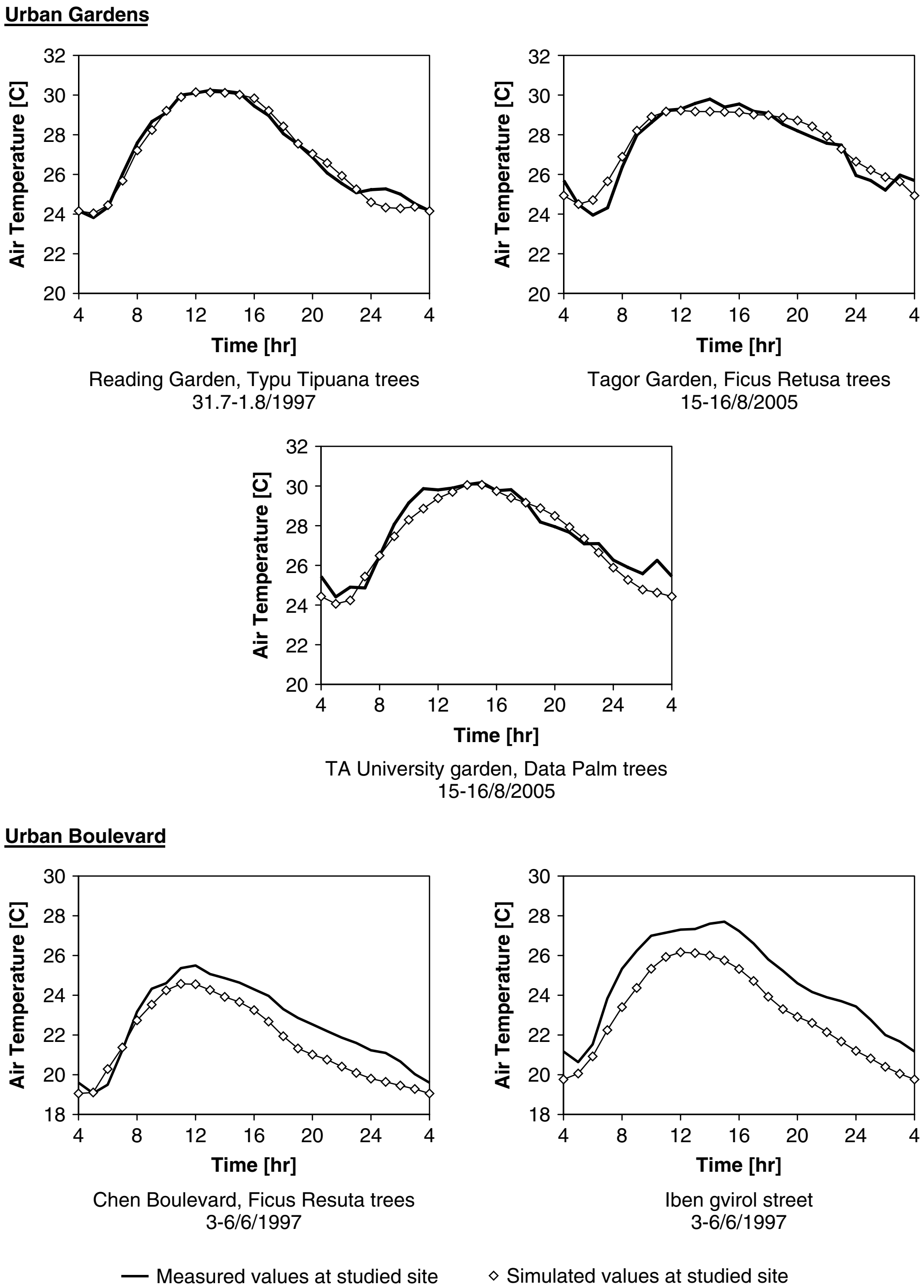


Figure 5. Diurnal air temperature measured at the studied sites vs simulated values (°C).

tree species by 14% (1.32/1.52); going from 4 to 8 building floors, the cooling effect is reduced by 22% (1.19/1.52). Going down the columns in the Table, we find the effect of the three tree species: percentage-wise, the Ficus has 67% (1.52/0.91) more potential than the Date Palm tree, and only 30% more than the tipu tree, and this is found to be so for all the three studied levels of H/W.

The potential of the cooling effect in summer of the three urban tree species in the studied street at 15 : 00 hours, are shown also in Table VII; the diurnal pattern is shown in Figure 6. The trees' cooling effect is estimated by the difference between the studied street planted with the trees compared to the street without trees. The potential cooling effect for each tree species is that calculated at its maximum coverage level of 90, 70, and 25% for the Ficus, tipu, and Date Palm trees (all planted in 2 rows), respectively. In the simulations, the cooling potential of the trees reaches its maximum at 15 : 00 hours. In contrast to the first group of figures in Table VII, where the coverage level is held constant at 40%, the second group of figures in Table show the practical side of selecting the tree species. In this respect, the Ficus and the tipu trees are found to be effective as cooling agents in urban streets, while the Date Palm tree is found to be relatively ineffective.

Table VII. The simulated cooling effect of the three tree species in an urban street (15 : 00 hours), July data, Coastal Mediterranean region, case study: an urban street, 27 m width.

Term of simulation	Species	Tree coverage [%]	Trees potential cooling effect at 15 : 00 [°C]		
			H/W = 0.6	H/W = 0.8	H/W = 1.0
At similar tree coverage	Ficus Retusa Tree	40	−1.5	−1.3	−1.2
	Tipuana Tipu Tree	40	−1.2	−1.0	−0.9
	Date Palm Tree	40	−0.9	−0.8	−0.7
At maximum tree coverage	Ficus Retusa Tree	90	−3.4	−3.0	−2.7
	Tipuana Tipu Tree	70	−2.1	−1.8	−1.6
	Date Palm Tree	25	−0.5	−0.4	−0.4

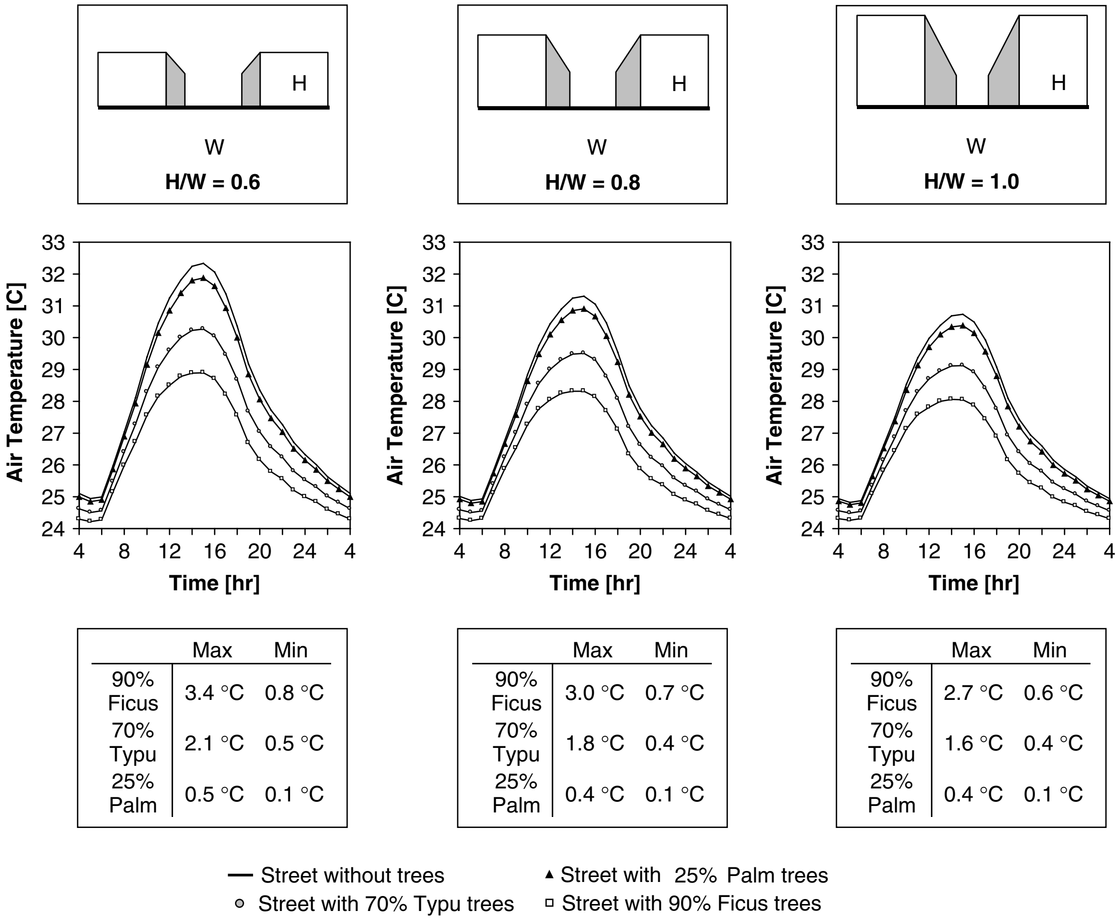


Figure 6. The simulated diurnal cooling effect potential of the three tree species in an urban street, July data, Coastal Mediterranean region.

5. The integrative approach in modelling

In Section 4.5, the impact of changing one control variable, the building density (or number of floors), on the cooling effect of trees is illustrated. It was found that at any level of tree coverage, the cooling effect is not constant, but depends on the level of the other variables in the system. The conclusion is that piecemeal modelling, usually the result reached by empirical analysis, would lead to incorrect conclusions as a result of ignoring the interrelationship and the interaction effects among the system control variables.

The integrative approach of considering all changes simultaneously can be applied using an analytical model correctly formulating the system's mechanism. This approach is illustrated on the Chen Boulevard site. The changes considered from Chen Boulevard's base-levels are:

(a) Raising the building height of Chen Boulevard's open space from 4 floors, the base level, to 6 floors.
(b) Modifying the albedo of walls from 0.5, the base level, to 0.7, that is, a lighter colour for the walls.
(c) Reducing Chen Boulevard's tree coverage from the base level of 70 to 40%, for better ventilation but a warmer microclimate.

DOI: 10.1002/joc

The results of the simulations of the piecemeal modelling and of the integrative approach are shown in Table VIII, in degrees centigrade, relative to the base case (as in a, b, c above) of Chen Boulevard, for the times 6 : 00, 12 : 00, 15 : 00, and 24 : 00. In Table VIII, the piecemeal modelling is expressed as the sum of the separate effects of each modified level (a + b + c), while the integrative modelling is the total effect of the three modified levels simultaneously, and the interaction effect is the difference between these two estimates.

The figures in Table VIII indicate that for any hour of the day, the total thermal effect reached by piecemeal modelling (row A) is smaller than that reached by the integrative solution (row B). The bias is cumulative as the day goes on: from 16% at 6 : 00, 57% at 15 : 00, to a maximum of 129% at night. The bias is the result of the interaction effects resulting from the interrelationship among the system's control variables. The larger the change of the variables' levels, the greater the bias.

6. Summary and conclusions

The study examines the mechanism of microclimate and its significance in urban planning through two components that dominantly affect the city's microclimate – built-up density and urban shade trees. Both components are multivariate in nature, hence, regularity is sought throughout the analysis in order to enable the designer to draw general conclusions and guidelines. The problem is resolved through parameterization of the variables – for vegetation, six basic cooling attributes are used, and for the building density, three built-up geometric ratios were found to fully cover most situations.

Three tree species with different canopy characteristics and canopy coverage levels were studied: Ficus retusa, Tipuana tipu, and Date Palm. These three species of shade trees are dominant in Tel Aviv gardens and streets. The findings were applied to a typical residential street, 27 m wide, with buildings of 4, 6, and 8 floors.

Modelling effects and sensitivity analysis were studied by the piecemeal procedure (one variable modification at a time) and by the integrative procedure (a simultaneous change of all variables). The difference between the two sets of estimates indicates the interaction effect.

Other analytical studies that simulated the vegetation effect within the urban tissue, found different results. According to Emmanuel *et al.* (2007), in a tropical climate, the effect of vegetation is less significant than the effect of the urban geometry and surfaces albedo, while Dimoudi and Nikolopoulou (2003) pointed out that in a Mediterranean climate, vegetation can play an important role depending on the urban geometry. This study contributes to the significance of tree species as a factor that must be considered in estimating their cooling effect within the urban varied morphology.

The main findings are:

- The cooling effect of the trees in summer in a hot humid climate is significant and can reach up to 3–4 degrees of cooling, which is about 50% of the air temperature rise from sunrise to noon hours.
- The potential cooling effect of the tree was found to depend mostly on its canopy coverage level and planting density in the urban street, and little on other species characteristics. This should be considered when selecting tree species for climatic sustainable planning.
- The Date Palm tree in a residential street (27 m wide) was found to be ineffective as a cooling agent.
- A tree's thermal effect is strongly related to the urban street geometry. For any tree coverage level, the cooling effect is not constant: the deeper the open space (high H/W), the smaller the tree cooling effect.
- In urban streets with deep open spaces, the effect of trees on the related microclimate is small. In such cases, trees with small canopy size such as the canopy of the Date Palm, are more suitable than large ones, especially if the deep open space is that of a narrow street width rather than of high flanking walls. Such trees are mostly needed along sidewalks for the benefit of pedestrians, mainly for shading and thermal comfort in the noon hours.
- In the case of urban streets with shallow open spaces, a tree's potential cooling effect can be enhanced by using broad-leaf trees (such as the Ficus and Tipuana tipu tree species) in minimum planting intervals, so that canopies will overlap at maturity.
- Significant interaction thermal effects were found to exist between the vegetation effects and the built-up effects. Piecemeal modelling of the variables led to thermal effects with a significant bias as compared to the integrative modelling. The integrative solution is reached through the use of an analytical model. In this study, the Green CTTC model is found to yield satisfactory results.

Table VIII. Piecemeal vs integrative modelling, (°C). Case study: Chen Boulevard.

Simulated effects	Time (hour)			
	6 : 00	12 : 00	15 : 00	24 : 00
Effect of building density 4* floors to 6 floors	−0.08	−1.38	−1.60	−0.37
Albedo modification from 0.5* to 0.7	−0.18	−0.41	−0.73	−0.34
Tree coverage reduction from 70%* to 40%	−0.05	+1.00	+1.31	+0.54
Sum of modeling effects:				
Piece-meal effect (A)	−0.31	−0.79	−1.02	−0.17
Integrative effect (B)	−0.36	−1.15	−1.60	−0.39
Interaction effect (B-A)	−0.05	−0.36	−0.58	−0.22
Interaction effect in [%] (B/A - 1) × 100	16	46	57	129

* Values of the base case

Acknowledgements

The authors wish to thank to the Israel Ministry of Environmental Protection for financing this research (Grant no. 4-060).

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