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Analysis of thermal bioclimate in various urban configurations in Athens, Greece

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Abstract The present study deals with human thermal comfort, as it is quantified by two well-known human biometeorological indices, Physiologically Equivalent Temperature (PET) and Humidex, in selected urban areas with different tree and building structures. The study took place during July 2003, at Agricultural University of Athens, Greece. Meteorological and environmental measurements were carried out at six sites. The selected sites differ in regard to sky view factor (SVF) values, environmental configuration and green (vegetation) coverage. The results of this study indicate a striking influence of site configuration on human thermal comfort. For example, in an outdoor lawn area surrounded by trees (green atrium) the PET was greater than 41 °C (human perception of "very hot") for 13 % of the measurement time, while in an open building atrium (courtyard) PET was greater than 41 °C for 28 % of the time. In addition, 'comfortable' conditions as PET quantifies formed during 26 % of the measurement time in green atrium but less than 15 % of the time in the building atrium. Especially during daytime the difference between these two sites reached 8.7 °C according to the PET and 4.3 °C according to the Humidex. At sites with low SVF values and dense green coverage the human biometeorological conditions were improved compared to sites with high SVF values and those with buildings nearby. Significant relationships between SVF and biometeorological indices classes were indicated. The PET index better represented human comfort than Humidex.

Keywords Athens · Urban configurations · Thermal bioclimate · RayMan · Physiologically equivalent temperature

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Introduction

It is well known that different urban configurations cause different microclimatic conditions (Stathopoulos et al. 2004; Costa and Araujo 2003; Picot 2004; Clarke and Bach 1971). The configuration may consist of natural (e.g., trees, natural landscape) or artificial obstacles such as buildings (Assimakopoulos et al. 2007; Stathopoulou and Cartalis 2007; Landsberg 1981). Air temperature is not the only environmental parameter that is modified in urban areas; the parameter that is mainly modified is solar radiation (Matzarakis et al. 2007, 2010), and as a consequence local scale alteration to parameters such as air temperature, relative humidity and wind speed may occur (Svensson and Eliasson 2002; Shashua-Bar and Hofmann 2003). These meteorological conditions directly affect human thermal comfort (Nikolopoulou et al. 2001; Matzarakis et al. 1999).

The need for evaluating thermal sensation leads to the concept of a thermal index, a useful tool for describing, designing and assessing thermal comfort. The principle is that factors that influence human response to thermal environment are integrated to provide a single index value (Parsons 1993; Fanger 1972). Empirical indices, like discomfort index, apparent temperature, wind chill index, Humidex or similar ones consider only some of the relevant meteorological parameters and do not account for thermal physiology (Rainham and Smoyer-Tomic 2003; Rubistein et al. 1980). Also, they do not consider all the relevant meteorological parameters, the work activity, the clothing and the personal parameters like height, weight, age and sex (Höppe 1999; Matzarakis et al. 1999). On the other hand, using indices that quantify thermo-physiologically relevant parameters of the human body, like Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET) and OUT_SET* (Outdoor Standard Effective Temperature) is a way to overcome the shortcomings of the empirical indices, because they achieve a generally applicable assessment of the thermal environment by the calculation of the heat balance of the human body (Matzarakis et al. 1999; Fanger 1972). Another thermo-physiological human comfort index, which has been used in North America, is the COMFA model of Brown and Gillespie (Brown and Gillespie 1995; Hartz et al. 2006; Kenny et al. 2009a, b).

In this study, two human biometeorological indices were selected and applied to evaluate the thermal comfort. The first one, Humidex, is a classical empirical thermohygrometrical index. The second is PET (Physiologically Equivalent Temperature) which is a thermal index derived from human energy balance. The study focuses on the influence of site configuration (Sky View Factor, green coverage and shading) on the microclimate and on the thermal comfort under summer conditions. The human biometeorological influence of five site's configuration is compared to conditions associated with an adjacent plane, unobscured site in a highly populated Mediterranean city. The comparison is carried out during July 2003 under calm anticyclonal weather conditions.

Study area and methods

Study area

Athens is located in central Greece (37058′ N, 23043′ E) at a mean altitude of 107 m above sea level on Attika basin. The city's population is 3.130.841 according to 2001 census. The administration district of Athens metropolitan area is about 400 km^2.

Athens belongs to the climatic region Csa according to Köppen climatic classification (Mediterranean, mild humid climate with dry -warm hot- summer). The average daily winter month's (December, January and February) temperature is 9.4 °C, and the daily minimum temperature drops below freezing only twice a year. In the summer months (June, July, August) the average daily temperature is 25.8 °C although the mean daily maximum temperature is more than 31 °C. Annual rainfall is 402 mm and occurs mainly in October and the winter months (Katsoulis 1987).

From a human biometeorological point of view, Athens is a city where high thermal stress conditions may occur, especially during summer months (Matzarakis et al. 1999; Balaras et al. 1993). According to these latest publications, the higher discomfort appears in Athens between July and August (Nastos and Zerefos 2009; Nikolopoulou and Lykoudis 2006).

For the purposes of this study, six outdoor sites were selected. Those sites are located in the Agricultural University of Athens (AUA) campus (37059′ N, 23042′ E, and 36 m altitude) in the western part of Athens metropolitan area (Fig. 1a). The campus is almost 26 ha covered by the buildings for education and research as well as green areas (gardens, experimental crops, arboriculture). The criteria for site selection were site's configuration (the proportion of green coverage and built area, the type of vegetation and the geometry of the nearby obstacles) and the distance between them (Fig. 1b). The proximity allowed us to assume that all sites are under the same meteorological conditions during the study period. The maximum distance between the selected sites is approximately 370 m. More specifically: Site 1 (s1) is located near the automatic meteorological station of Agricultural University of Athens in a planar area free of vegetation and other obstacles like buildings and trees (Table 1). Site 2 (s2) is in the middle of an open atrium of a 10-m-height building constructed of concrete; the atrium shape reduces significantly the sunshine duration at s2. Site 3 (s3) is located inside the AUA botanical garden in a 'green atrium' with ground irrigated grass and the surrounding trees to reach almost 10 m height. Site 4 (s4) is also inside the botanical garden and very close to s3 (20 m). This site's ground coverage is irrigated grass and it is surrounded by high and medium high trees with height varying between 3 and 10 m. The fifth site (s5) is in the middle of the experimental arboricultural field of AUA. Trees over this site are medium height (~3 m) and sparse-linear planted. Finally, site 6 (s6) is in the experimental crop field of AUA. This area is planted during the study period with corn, cotton and wheat.

Bioclimatic indices

For the scope of this study, two human biometeorological indices were used. The first one, Humidex is a simple thermohygrometrical index and the second, PET, is an index that takes into account human energy balance. The reason we choose different type of indices is to compare the sensitivity of those indices under different environmental configurations.

Humidex

Humidex is conceptually similar to apparent temperature, also known as the heat index. Like the heat index, Humidex is a measure of thermal discomfort. Humidex is an evolution of 'Humiture' index, employing air temperature and relative humidity. The Atmospheric Environment Service of Canada adopted the new 'Humiture' index, changed the units to degrees Celsius and applied the name 'Humidex' (Tuller 1997).

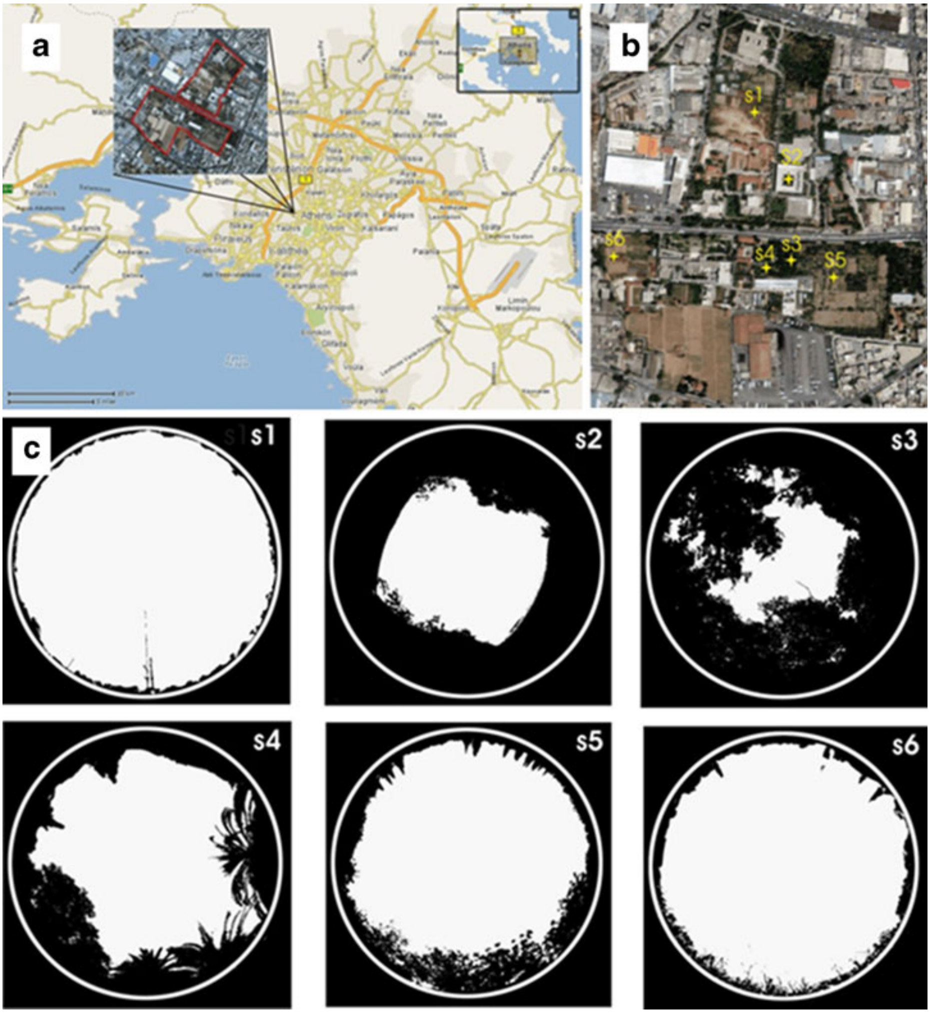

Fig. 1 **a** AUA campus in Athens metropolitan area (**b**) Aerial photography of the selected sites in (**c**) The black and white fish-eye photography were used for SVF calculation at each selected site

Shortly, Humidex is defined as the temperature of relatively dry air (vapour pressure less than 10 hPa), which has the equivalent affect on human comfort as the air with an actual

Table 1 Major characteristics of each selected site configuration

Site	Description	S.V.F	Albedo	Roughness length (z_0)
s1	Meteorological station	1.0	0.35	0.2
s2	Building atrium	0.3	0.20	3.0
s3	Green atrium	0.2	0.20	2.5
s4	Botanical garden	0.5	0.20	2.0
s5	Arboricultural field	0.7	0.15	0.8
s6	Crop field	0.8	0.20	0.3

measured or forecast temperature and humidity. This index is calculated by the following formula:

$$H = Ta + ((5/9)(VP - 10))$$

where H is Humidex (represented in temperature units, °C), Ta is air temperature (°C) and VP is vapour pressure (hPa). This index has been used for human biometeorological studies focused on thermal perception, human health, air pollution, under a wide range of climatic conditions (Tuller 1997; Rainham and Smoyer-Tomic 2003; Conti et al. 2005).

Physiologically equivalent temperature (PET)

PET is a human biometeorological index and can be calculated from the human energy balance model Munich Energy balance Model for Individuals called shortly MEMI. The human energy balance model is an integrated mathematical function that includes all parameters related with human body, clothing, activity, and environmental parameters (Höppe 1993). The fundamental idea in the establishment of PET is the transfer of the actual thermal bioclimate to an equivalent fictitious indoor environment in which the same thermal perception can be expected. Compared to other thermal indices that are also obtained from the human energy balance, such as the predicted mean vote (PMV), PET has the advantage of a widely known unit (°C), which makes results more comprehensible to urban or regional planners (Matzarakis et al. 1999). This index is widely used in many other studies. It is utilized in several types of climates and environmental configurations, like Morocco (Johansson 2006), Portugal (Andrade and Alcoforado 2008; Oliveira and Andrade 2007), Sweden (Svensson and Eliasson 2002), Greece (Charalampopoulos et al. 2006), Germany and elsewhere (e.g. Matzarakis et al. 1999; Gulyás et al. 2006; Lin et al. 2006). The only disadvantage of PET is the requirement of several parameters and the complexity of the needed calculations. In order to minimize these difficulties we can use the special software application RayMan.

RayMan model

For the purposes of this study, we used the RayMan model developed at the Meteorological Institute, University of Freiburg (Matzarakis et al. 2007, 2010). The parameters estimated by RayMan are T_{mrt} and PET. It is well–suited to calculate radiation fluxes, thus all our calculations for T_{mrt} and PET were performed with this model (Matzarakis et al. 2007). This model is frequently used in this type of studies (e.g. Svensson and Eliasson 2002; Charalampopoulos et al. 2006; Thorsson et al. 2004; Lin et al. 2010; Hwang et al. 2011).

The RayMan model, developed according to Guideline 3787 of the German Engineering Society, calculates the radiation flux within environmental configurations on the basis of parameters that include air temperature, humidity, cloud cover, Linke turbidity (a factor that describes the haziness of the atmosphere), day of year, time, albedo of the surrounding surfaces and their solid–angle proportions (Matzarakis et al. 2007; Thorsson et al. 2004). Via the user friendly windows-based interface of RayMan, additional data like height, gender, activity and clothing insulation of the person–subject can be input in order to calculate thermal perception. For the achievement of an accurate environmental configuration description, obstacles, topography and sky view factor are optional inputs of this model. For further information related to the RayMan model, see Matzarakis et al. (2007, 2010) and http://www.urbanclimate.net/rayman/.

Data

Observed data

To investigate the thermal comfort at each selected site, Hobo Pro (combined sensors and data loggers) were used to carry out measurements every 2 min of air temperature (°C) and relative humidity (%) at 1.5 m height above the ground. The accuracy of the Hobo Pro, in an environment where there are no errors caused by solar or thermal radiation, is ±0.2 °C at 25 °C and±3 % RH over 0 to 50 °C. The Hobos were placed inside mini meteorological shelters, which were painted white to reflect most solar radiation, and their shape allows sufficient natural ventilation. In addition, wind speed (m/s) and global radiation (W/m^2) data from the automatic meteorological station of A.U.A were used. All meteorological data were transformed to 10-minute averages. In addition, since the wind speed data were measured at 3 m above ground level, the wind speed at the reference height of 1.5 m (WS1.5) was calculated according to the following formula (Oke 1987).

$$WS_{1.5} = WS_h(1.5/h)^{\alpha}, \alpha = 0.12_{Zo} + 0.18$$

Here WS_h is the wind speed (m/s) at the height of h, α is an empirical exponent, depending on the surface roughness length. Values of surface roughness length (z_o) we used for this wind speed recalculation are illustrated in Table 1. These values have been estimated according to typical z_o value tables by the related bibliography (Grimmond et al. 1998; Oke 1987; Landsberg 1981). The validation of roughness length values became through simulations via EnviMet model (Bruse and Fleer 1998). Also, in order to estimate radiation budget for T_{mrt} and PET calculation via RayMan, individual albedo values for each selected site (Geiger et al. 1995; Akbari et al. 1992; VDI 1998), as illustrated in Table 1, were used.

Weather

The measurement period lasted a month starting on July 1st, 2003 during anticyclonal conditions. In Table 2 descriptive statistics of major meteorological parameters during the study period are shown. In addition, Fig. 2 shows mean 10-min-average values recorded at the AUA meteorological station. Global radiation values indicate almost continuous sunshine conditions during daytime. The local variation of the global radiation course probably are caused by the high air pollution over the study area or by the presence of clouds. Also, the wind speed course shows clearly calm conditions during July 2003. According to the results in Fig. 2a, wind speed is increased approaching noon and reduces after the sunset. Because relative humidity is an inverse function of air temperature, these variables form a mirror like-shape (Fig. 2b).

Personal data

Human energy balance models, like RayMan, require some inputs related to human morphology and activity. The comfort estimation for this study is directed on a 'typical European male' (35 years old, 1.75 m tall, weight 75 kg). The clothing index of 0.9 clo includes a long sweater and trousers. PET also considers the heat produced by activity (metabolic heat) that is equivalent to 80 W (VDI 1998).

Table 2 Meteorological parameters descriptive statistics during measurement period

Parameter	Average	Minimum	Maximum	St. Deviation
Rainfall (mm)	0.0	0.0	0.0	0.0
Wind speed (m/s)	1.5	0.01	4.9	1.0
Air Temperature (°C)	28.5	19.2	38.4	3.6
Relative Humidity (%)	45.2	13.1	96.1	14.4
Vapour Pressure (hPa)	17.0	8.8	31.0	3.6
Bar. Pressure (hPa)	1008.2	999.6	1013.1	2.5

Site configuration data

For the calculation of the surrounding obstacles, fish-eye photographs (Oke 1987) were inputted in RayMan. Those photographs were adjusted properly in black and white format by this software to calculate the Sky View Factor (Fig. 1c). Details such as building form or tree canopy in the visual hemisphere at measurement sites can be detected. In this study, SVF ranges from 0.2 to 1.0 (Table 1).

Results

Thermal comfort

To evaluate the human thermal comfort conditions among the selected sites, three types of diagrams were used. First, mean values of T_{mrt}, PET, and Humidex were calculated and illustrated on a daily basis (Figs. 3, 4 and 5). Those figures present a brief comparison of the biometeorological conditions formed at each selected site. In addition, integral diagrams (Fig. 6a and b) were used to present the accumulative biometeorological behavior of the studied configurations. Finally, relative frequencies of the PET on a daily basis were used (Figs. 7, 8 and 9). To make the comparison more comprehensive, the relation between SVF and biometeorological indices were determined by regressions and correlations (Fig. 11, Tables 4 and 5). The correlations and regressions between the selected indices and other

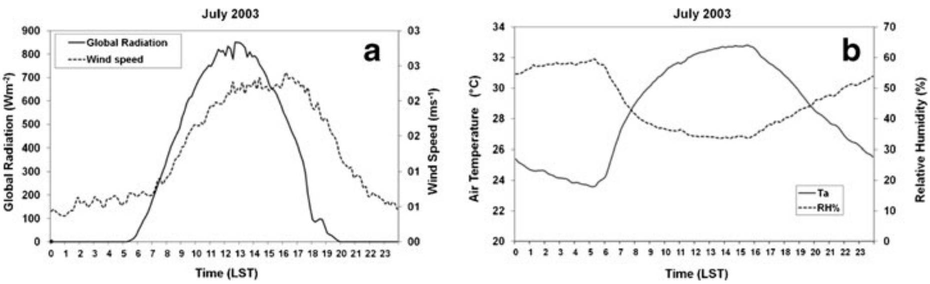

Fig. 2 **a** Mean daily courses of wind speed (m/s) at 3 m and global radiation (W/m^2) during July 2003. **b** Mean daily courses of air temperature at 1.5 m (°C) and relative humidity (%) during July 2003. The measurements were carried out from AUA meteorological station

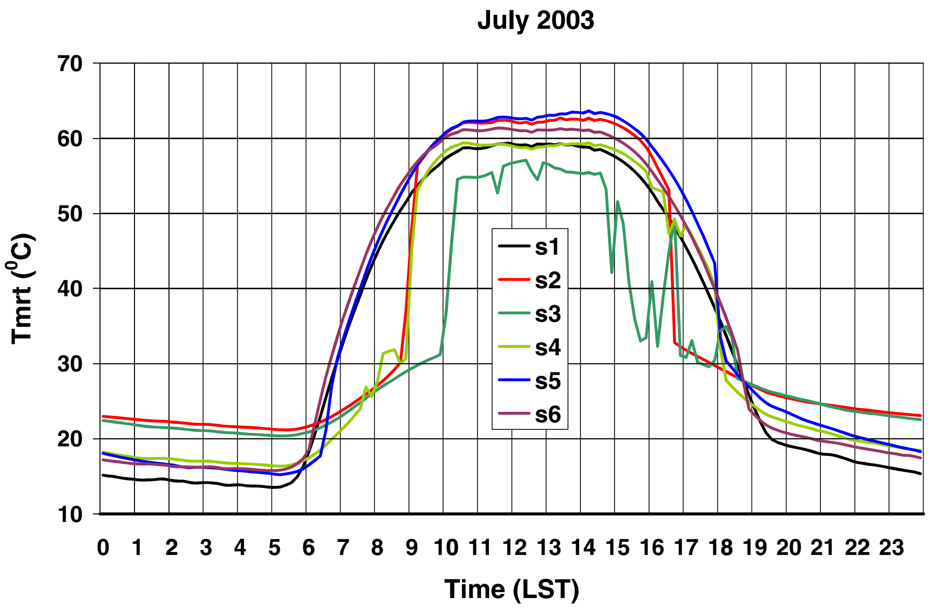

Fig. 3 Mean daily courses of T_{mrt} (°C) during study period

meteorological parameters lead to insufficient results (Hwang et al. 2011; Lin et al. 2010; Gulyás et al. 2006).

The T_{mrt} daily courses (Fig. 3) indicate high values reaching almost 65 °C. During the night (22:00 to 06:00 LST) similar values of T_{mrt} were recorded at the six selected sites. Significant differences in the shape of curves are seen after sunrise, especially near noon. At meteorological station (s1), arboricultural field (s5) and crop field (s6) sites, the T_{mrt} course

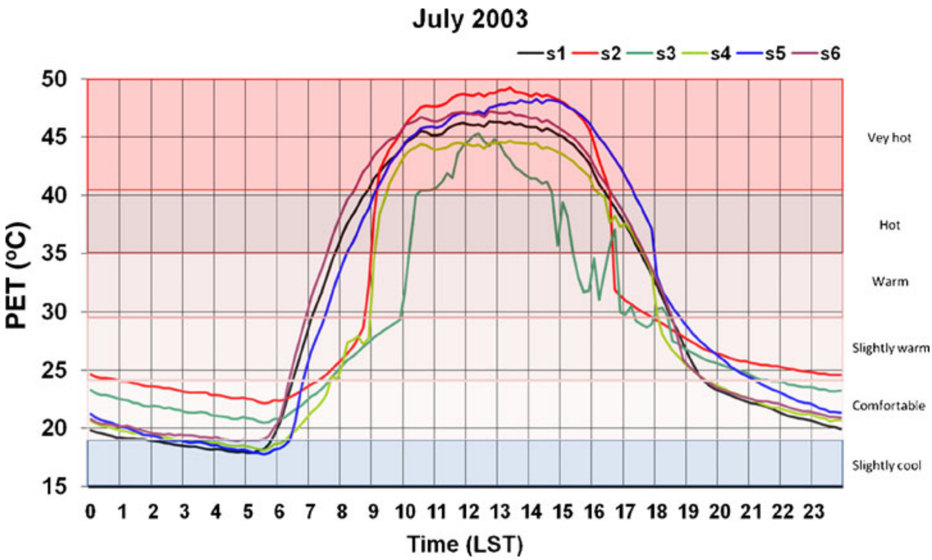

Fig. 4 Mean daily courses of PET (°C) during study period

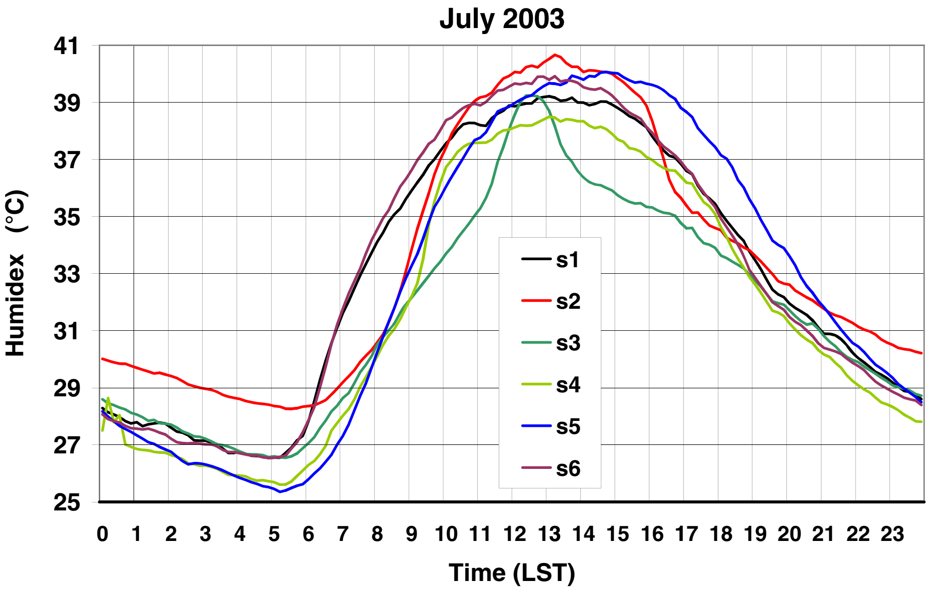

Fig. 5 Mean daily courses of Humidex (°C) during study period

shapes a 'bell' curve caused by the high values of SVF. On the other hand, at building atrium (s2), green atrium (s3) and botanical garden (s4) the T_{mrt} course indicates the strong influence of obstacles existence.

During the study period, very high PET mean values were estimated, reaching 49 °C at s2, the building atrium (Fig. 4). The course shape looks similar to the T_{mrt} curve shape as a consequence of those two parameters correlation. During nighttime (20:00 to 06:00 LST) PET took values within the classes 'Slightly cool' and 'Slightly warm' according to Table 3. On the other hand, during daytime (06:00 to 20:00 LST) PET values were very high, reaching 48 °C and exceeding the lower threshold of the 'Very hot' class. Over almost all of the study period, the higher PET values were estimated at s2 (building atrium) while site s3 (green atrium) had lower PET.

There is less variation in the Humidex values (Fig. 5) in comparison to the corresponding courses of both T_{mrt} and PET, as a consequence of Humidex low sensitivity to radiation budget changes. The maximum value of Humidex was calculated at building atrium (s2), reaching 40.7 °C and the minimum one at arboricultural

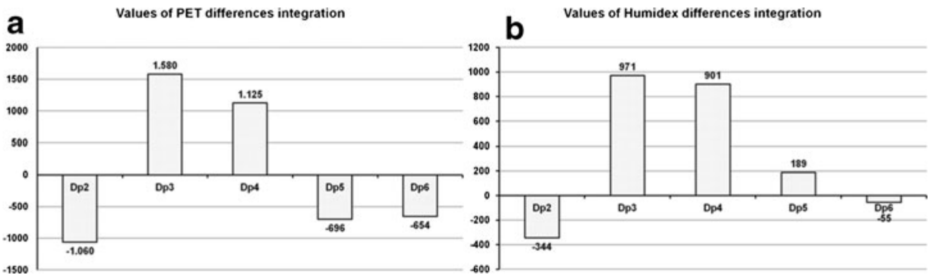

Fig. 6 **a** Differences integral values for PET index. **b** Differences integral values for Humidex index

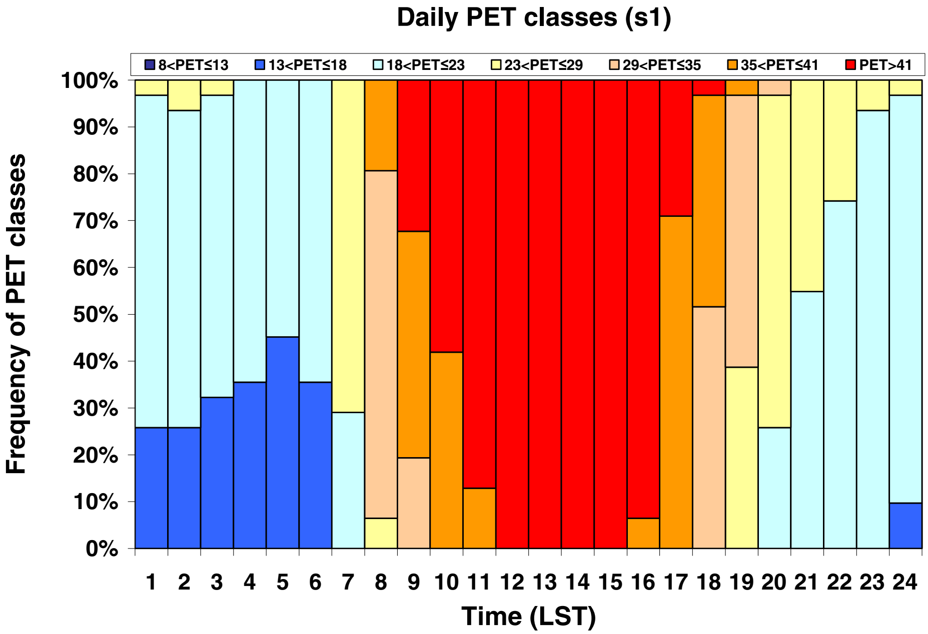

Fig. 7 Time distribution of relative frequencies of PET classes in daily basis, at s1

field (s5), reaching 25.4 °C. Almost all patterns are bell-shaped without remarkable differences. Generally, sites with high green coverage and low SVF, lead to lower Humidex values during the study period.

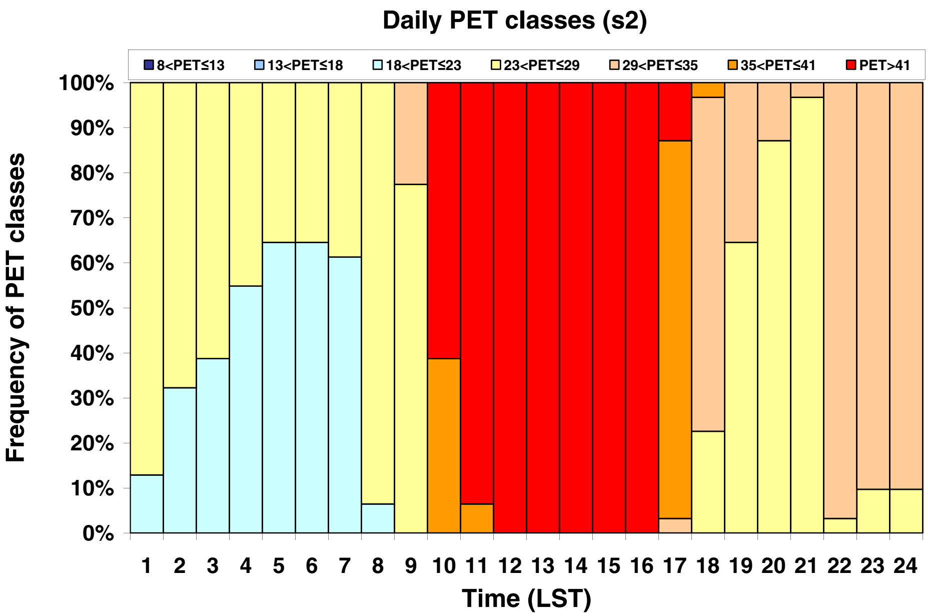

Fig. 8 Time distribution of relative frequencies of PET classes in daily basis, at s2

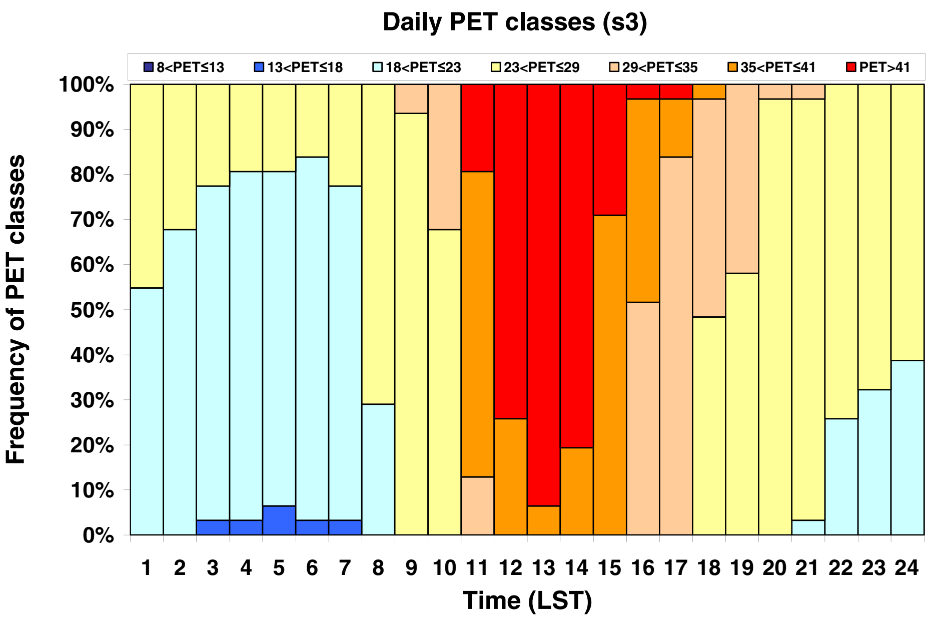

Fig. 9 Time distribution of relative frequencies of PET classes in daily basis, at s3

As mentioned above, s1 is located in an area without obstacles (trees or buildings) so this site can be considered as a place free of anthropogenic activity. All other selected sites may be assumed to be like the AUA meteorological station site (s1) plus obstacles. To quantify the influence of those obstacles on human biometeorological conditions a comparative

Table 3 Ranges of thermal index physiologically equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings, internal heat production 80 W, heat transfer resistance of the clothing: 0.9 clo (Matzarakis and Mayer 1996)

PET	Thermal perception	Grade of physiological stress
	Very cold	Extreme cold stress
4		
	Cold	Strong cold stress
8		
	Cool	Moderate cold stress
13		
	Slightly cool	Slight cold stress
18		
	Comfortable	No thermal stress
23		
	Slightly warm	Slight heat stress
29		
	Warm	Moderate heat stress
35		
	Hot	Strong heat stress
41		
	Very hot	Extreme heat stress

method was used. The integral of differences between s1 and all other sites was calculated on a daily basis. The difference between meteorological station (s1) and building atrium (s2) is symbolized as Dp2, between s1 and green atrium (s3) was symbolized as Dp3, etc. Each integral was calculated using the trapezoidal rule. Positive integral values indicate improved thermal perception at each of the selected site compared to the reference site (s1). This means that the site's configuration leads to improved human biometeorological conditions for the hypothetical person in comparison to the plane—unobstructed site s1. The highest value of the PET integral was calculated for Dp3 (Fig. 6a). Also, a high positive value was calculated for Dp4. On the other hand, a minimum integral value was calculated from the Dp2 curve. As Fig. 6a illustrates, positive integral values were calculated in the case of sites with low SVF along with dense green coverage.

As Fig. 6b illustrates, Humidex integrals indicate similar accumulative biometeorological behavior at Dp3 and Dp4. Also, a positive but significantly lower integral value was recorded for the case of Dp5. A lower (negative) integral value was recorded from the Dp2 curve.

The relative frequency diagrams may provide useful information on the time-distribution of the biometeorological indices. Diagrams for the three sites representing the higher 'contrast' from the biometeorological point of view will be discussed: Meteorological station (s1) is the 'neutral', building atrium (s2) forms the most aggravating biometeorological conditions and green atrium (s3) forms the most beneficial among the studied sites.

Meteorological station site (s1) indicates the 'normal' frequency distribution of PET versus hour of the day without anthropogenic influence (Fig. 7). This biometeorological behavior is caused only by the meteorological conditions of this area. A wide spread of the class PET >41 °C occurs before and after midday indicating a very hot sensation according to Table 3. During evening and night the dominant class is 18 °C <PET ≤23 °C, which is 'comfortable' thermal perception. Also, during nighttime and early morning, class 8 °C <PET ≤13 °C occurs.

The building atrium site (s2) diagram (Fig. 8) indicates higher frequency values of non-pleasant PET classes. The reason is the combined effect of the high air temperatures inside the open atrium during 24 h and the very high T_{mrt} values during midday. This configuration forms 'moderate heat stress' to 'extreme heat stress' PET values, for almost all the study period. The absence of class 13 °C <PET ≤18 °C probably is a consequence of night cooling prevention at this site. Also at this site (s2) the comfort class 18 °C <PET ≤23 °C is 17 % less frequent than in meteorological station (s1). The low value of SVF (0.3) in combination with the presence of buildings causes an increase of the thermal stress. It is obvious that s2 configuration leads to more uncomfortable thermal perception compared to the 'neutral' s1 configuration.

In contrast to the building atrium (s2), at the green atrium site (s3) the most beneficial biometeorological conditions occur (Fig. 9). The relative frequencies diagram indicates a narrow-spread of class PET >41 °C close to midday (Fig. 9). The dominant class in this case is 23 °C <PET ≤29 °C, which gives a thermal perception of 'slightly warm' according to Table 3, while the relative frequency distribution indicates a tendency for improved biometeorological conditions in comparison to s1. Also the hypothetical person who remains in the building atrium (s2) is under "very hot" conditions for 15 % more time compared to the green atrium (s3). In addition, this configuration, with low SVF and dense vegetation, is suitable for thermal stress reduction under the specific meteorological conditions.

A summary of PET results for each selected site indicating the differences of PET classes distribution is shown in Fig. 10. At building atrium (s2), a reduction of the relative frequencies for the 'cooler' classes (such as 'slightly cool' and 'comfortable) occurred, while for ‘warmer’ classes such as ‘very hot’ (15 % higher than green atrium) and ‘warm’ (6 % higher than green atrium), an increase occured. On the other hand, sites with dense vegetation combined with low SVF values (green atrium and botanical garden), present higher frequencies of ‘cooler’ PET classes and lower ‘warmer’ PET classes.

To evaluate the influence of SVF on human thermal comfort, correlation matrices of SVF vs PET and Humidex class frequencies were calculated and they are presented in Tables 4 and 5. According to the correlation coefficient, PET frequencies are strongly correlated with SVF values, especially during daytime. For values of PET >30 °C the correlation coefficient reaches 0.93 while for PET >35 °C this coefficient is calculated to be 0.87. A high value of this coefficient, but non—significant at $p<0.05$ level, was calculated for PET >41 °C. During the nocturnal period, a strong negative correlation between SVF and PET >20 °C was calculated.

In the Humidex case, low values of correlation coefficients were calculated, because this index does not take into account the radiation budget. Figure 11 shows the linear regression resulted among PET >30 °C class and SVF values. The high value of R^2 (0.85) and the form of this scatter-plot indicate a striking linear function among SVF and this PET class frequency.

Discussion

The results of the comparison between reference site (s1) and the other five selected sites indicate the influence of the environmental setting on human thermal comfort (Shashua-Bar and Hofmann 2003; Johansson 2006; Priyadarsini et al. 2008). The rougher the surroundings the more striking is the influence of the environmental configuration on the thermal stress. The obstacles that form 3D geometry, like buildings and vegetation, affect the incoming

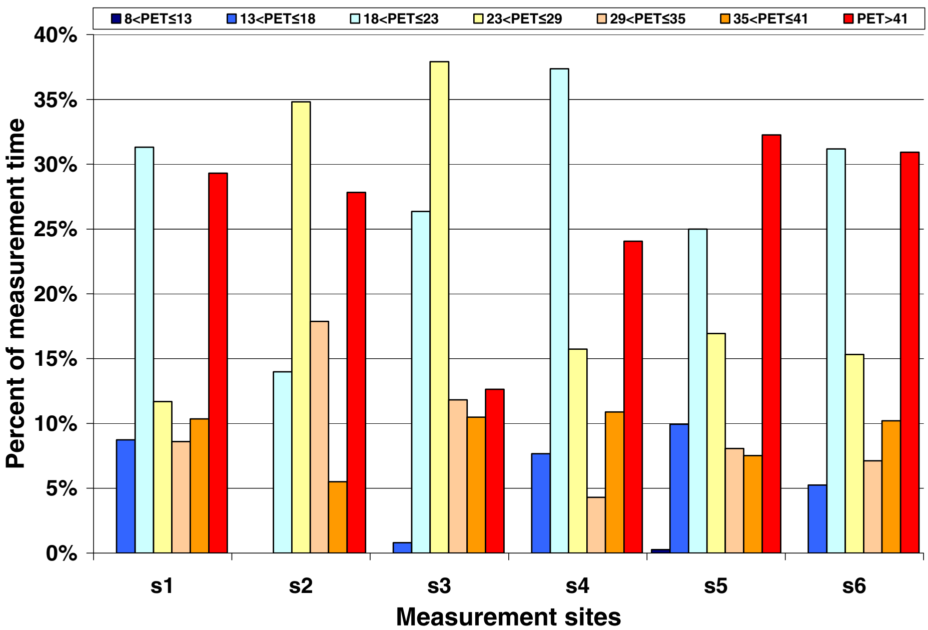

Fig. 10 Relative frequencies of PET classes at measurements site

Table 4 Correlation coefficients (r) between PET class frequencies and SVF values during daytime (06:00–22:00 LST) and nocturnal period (22:00–06:00 LST)

Time period	Correlation matrix	
	Classification	SVF (r)
Daytime	PET>30 °C	0.93*
	PET>35 °C	0.87*
	PET>41 °C	0.73
Nocturnal	PET>20 °C	−0.83*
	PET>23 °C	−0.69

*Significant at $p<0.05$

radiation during daytime and the outgoing radiation during nocturnal periods. Low SVF values as a consequence of vegetation may improve the thermal comfort under sunny conditions when the hypothetical person is in shadow. On the other hand, low SVF values may hamper the outgoing long-wave radiation, preventing nocturnal cooling and increasing therefore the heat stress (Herbert and Herbert 2002; Eliasson 1996; Masmoudi and Mazouz 2004). The results of this study indicate how human thermal comfort is a consequence not only of SVF but also a consequence of the obstacles material. Sites having similar SVF values like the building atrium (s2) and the green atrium (s3) may present different biometeorological behavior according to both indices (PET and Humidex). The major difference between those two sites is the surrounding material, which in the case of the building atrium (s2) is concrete and in case of the green atrium (s3) is vegetation. The influence of the surrounding material is so strong that s3 forms the best human biometeorological conditions among selected sites, while s2 forms the most stressful. Our results agree with findings from other studies (Lin et al. 2010).

Despite the Humidex advantage of easily obtained input data for its application, the low sensitivity to environmental factors influencing human thermal comfort is a great disadvantage for detailed human biometeorological studies. Despite striking differences among site configuration, the daily courses of Humidex did not indicate differences in human thermal comfort, which the PET values indicated. This is clear because of the substantial differences between the input parameters of the indices (VDI 1998; Conti et al. 2005; Matzarakis et al. 2007).

According to the class frequency figures (Figs. 7, 8 and 9), sites with high SVF form normal 'spreading' of PET classes on a daily basis. On the other hand, sites with high SVF form more variable daily class distributions. When green is the prevailing surrounding material, the appearance of discomfort classes decreases. The opposite results were recorded in the cases of sites having less surrounding green.

Table 5 Correlation coefficients (r) between Humidex class frequencies and SVF values during daytime (06:00–22:00 LST) and nocturnal period (22:00–06:00 LST)

Time period	Correlation matrix	
	Classification	SVF (r)
Daytime	Hum. >27 °C	−0.10
	Hum. >30 °C	0.26
	Hum. >40 °C	0.50
Nocturnal	Hum. >27 °C	−0.15
	Hum. >30 °C	−0.2

Significant at $p<0.05$

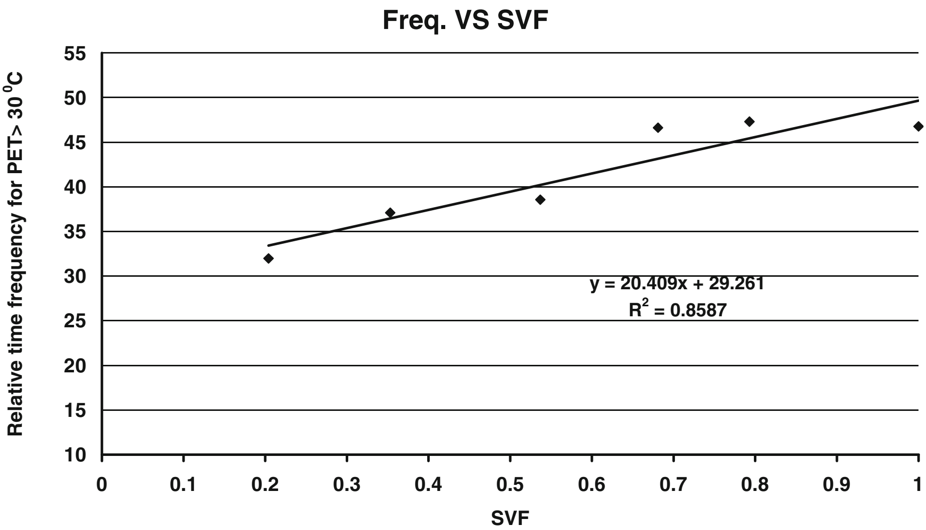

Fig. 11 Linear regression of SVF vs relative time frequency of PET >30 °C class

Finally, PET index frequencies are strongly correlated with SVF values according to the calculated correlation coefficient. Higher values of correlation coefficient were recorded during daytime reaching 0.93 (PET >30 °C) at significance level of 0.05. During the nocturnal period, PET frequencies have strong negative correlation with SVF. In the case of Humidex there is no significant correlation between the index and the SVF (Lin et al. 2010).

In order to quantify the relationship of human thermal comfort with the amount of vegetation, more information about the configuration and type of vegetation is required (Lin et al. 2010; Hwang et al. 2011). In addition, the micro-scale effects of radiation shading can be quantified in order to be helpful for planners (Matzarakis and Endler 2010).

Conclusion

The analysis among the six selected sites suggests that the value of PET shows a strong relation with T_{mrt} value during the study period. T_{mrt} as an expression of radiation fluxes in complex environments is affected by the environmental setting, especially the existence of buildings and trees.

The results of the present study quantify a relationship between human thermal comfort and urban structures configuration. More specifically, under calm weather conditions the Sky View Factor that is formed by the urban structures influences the thermal perception as it is estimated from the results of the application of the selected biometeorological indexes (PET, Humidex). In addition, results indicate that to evaluate accurately the human thermal perception, indices that involve the human energy balance, like PET, are more appropriate than simple indices.

Finally, the results of the study provide useful information and quantitative data for planning, construction and modifying urban structures and their surrounding environment. This is important because of the possibility of adaptation against climate change conditions in cities.

We think that indices which include not all the relevant meteorological parameters for the quantification of thermal bioclimate, do not deliver appropriate results. In urban environments the parameters that have the biggest variation are the radiation fluxes (expressed in terms of T_{mrt}) and wind speed. Both of them but especially the radiation fluxes can be significantly modified by the physical properties of material and morphology of the obstacles (mostly buildings and trees). In the case here we show that radiation fluxes have a substantial influence on thermal bioclimate (Shashua-Bar et al. 2011).

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References

Akbari H, Davis S, Dorsano S, Huang J, Winnett S (1992) Cooling our communities. A guidebook on tree planting and light color surfacing. U.S. Environmental Protection Agency, Washington

Andrade H, Alcoforado M-J (2008) Microclimatic variation of thermal comfort in a district of Lisbon (Telheiras) at night. Theor Appl Climatol 92:225–237

Assimakopoulos M, Mihalakakou G, Flocas H (2007) Simulating the thermal behaviour of a building during summer period in the urban environment. Renew Energy 32:1805–1816

Balaras C, Tselepidaki M, Santamouris M, Asimakopoulos D (1993) Calculations and statistical analysis of the environmental cooling power index for Athens, Greece. Energy Convers Manag 34:139–146

Brown RD, Gillespie TJ (1995) Microclimatic landscape design: creating thermal comfort and energy efficiency. John Wiley & Sons, New York

Bruse M, Fleer H (1998) Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. Environ Model Softw 13:373–384

Charalampopoulos I, Kiokakis L, Chronopoulou-Sereli A, Kannavou A (2006) Bioclimatic performance of several sites which differ on their green coverage in Athens, Greece. 6th International Conference on Urban Climate (ICUC-6), Götenborg, Sweden pp 802–805

Clarke J, Bach W (1971) Comparison of the comfort conditions in different urban and suburban microenvironments. Int J Biometeorol 15:41–54

Conti S, Meli P, Minelli G, Solimini R, Toccaceli V, Vichi M, Beltrano C, Perini L (2005) Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. Environ Res 98:390–399

Costa A, Araujo V (2003) Thermal comfort assessment in open spaces: An instrument of urban management for the district of Petrópolis, in the coastal city of Natal/RN, Brazil. Plea 2003—The 20th Conference on Passive and Low Energy Architecture, Santiago—CHILE, 9–12 November 2003

Eliasson I (1996) Urban nocturnal temperatures, street geometry and land use. Atmos Environ 30:379–392

Fanger PO (1972) Thermal comfort. McGraw Hill, New York

Geiger R, Aron R, Todhunter P (1995) The climate near the ground. Rowman & Littlefield Publishers, Oxford

Grimmond S, King T, Roth M, Oke T (1998) Aerodynamic roughness of urban areas derived from wind observations. Bound-Layer Meteorol 89:1–24

Gulyás Á, Unger J, Matzarakis A (2006) Assessment of the microclimatic and human comfort conditions in a complex urban environment: modeling and measurements. Build Environ 41:1713–1722

Hartz DA, Brazel AJ, Heisler GM (2006) A case study in resort climatology of Phoenix, Arizona, USA. Int J Biometeorol 51:73–83

Herbert J, Herbert R (2002) Simulation of the effects of canyon geometry on thermal climate in city canyons. Math Comput Simul 59:243–253

Höppe P (1993) Heat balance modeling. Experientia 49:741–746

Höppe P (1999) The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol 43:71–75

Hwang R-L, Lin T-P, Matzarakis A (2011) Seasonal effects of urban street shading on long-term outdoor thermal comfort. Build Environ 46:863–870

Johansson E (2006) Influence of urban geometry on outdoor thermal comfort in a hot dry climate: a study area in Fez, Morocco. Build Environ 41:1326–1338

Katsoulis B (1987) Indications of change of climate from analysis of air temperature time series in Athens, Greece. Clim Chang 10:67–79

Kenny NA, Warland JS, Brown RD, Gillespie TG (2009a) Part A: assessing the performance of the COMFA outdoor thermal comfort model on subjects performing physical activity. Int J Biometeorol 53:415–428

Kenny NA, Warland JS, Brown RD, Gillespie TG (2009b) Part B: revisions to the COMFA outdoor thermal comfort model for application to subjects performing physical activity. Int J Biometeorol 53:429–441

Landsberg H (1981) The urban climate. Academic, New York

Lin T-R, Matzarakis A, Huang J (2006) Thermal comfort and passive design strategy of bus shelters. 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland

Lin T-R, Matzarakis A, Hwang R-L (2010) Shading effect on long-term outdoor thermal comfort. Build Environ 45:213–221

Masmoudi S, Mazouz S (2004) Relation of geometry, vegetation and thermal comfort around buildings in urban settings, the case of hot arid regions. Energy Build 36:710–719

Matzarakis A, Endler C (2010) Adaptation of thermal bioclimate under climate change conditions—the example of physiologically equivalent temperature in Freiburg, Germany. Int J Biometeorol 54:479–483

Matzarakis A, Mayer H (1996) Another kind of environmental stress: thermal stress. NEWSLETTERS No. 18, 7–10. WHO Colloborating Centre for Air Quality Management and Air Pollution Control

Matzarakis A, Mayer H, Iziomon M (1999) Application of a universal thermal index: physiological equivalent temperature. Int J Biometeorol 43:76–84

Matzarakis A, Rutz F, Mayer H (2007) Modeling radiation fluxes in simple and complex environments—application of the RayMan model. Int J Biometeorol 51:323–334

Matzarakis A, Rutz F, Mayer H (2010) Modelling radiation fluxes in simple and complex environments—basics of the RayMan model. Int J Biometeorol 54:131–139

Nastos P, Zerefos C (2009) Spatial and temporal variability of consecutive dry and wet days in Greece. Atmos Res 94:616–628

Nikolopoulou M, Lykoudis S (2006) Thermal comfort in outdoor urban spaces: analysis across different European countries. Build Environ 41:1455–1470

Nikolopoulou M, Baker N, Steemers K (2001) Thermal comfort in outdoor urban spaces: understanding the human parameter. Sol Energy 70:227–235

Oke T (1987) Boundary layer climates. Routlegde, Cambridge

Oliveira S, Andrade H (2007) An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon. Int J Biometeorol 52:69–84

Parsons K (1993) Human thermal environments. Taylor & Francis, London

Picot X (2004) Thermal comfort in urban spaces: impact of vegetation growth. Case study: Piazza della Scienza, Milan, Italy. Energy Build 36:329–334

Priyadarsini R, Hien W, David C (2008) Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Sol Energy 82:727–745

Rainham D, Smoyer-Tomic K (2003) The role of air pollution in the relationship between a heat stress index and human mortality in Toronto. Environ Res 93:9–19

Rubistein M, Ganor E, Ohring G (1980) Areal distribution of the discomfort index in Israel. Int J Biometeorol 24:315–322

Shashua-Bar L, Hofmann M (2003) Geometry and orientation aspects in passive cooling of canyon streets with trees. Energy Build 35:61–68

Shashua-Bar L, Pearlmutter D, Evyatar E (2011) The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. Int J Climatol 31:1498–1506

Stathopoulos T, Wu H, Zacharias J (2004) Outdoor thermal comfort in an urban climate. Build Environ 39:297–305

Stathopoulou M, Cartalis C (2007) Daytime urban heat island from Landsat ETM + and Corine land cover data: an application to major cities in Greece. Sol Energy 81:358–368

Svensson M, Eliasson I (2002) Diurnal air temperatures in built-up areas in relation to urban planning. Landsc Urban Plan 61:37–54

Thorsson S, Lindqvist M, Lindqvist S (2004) Thermal bioclimatic conditions and patterns of behaviour in an urban park in Götenborg, Sweden. Int J Biometeorol 48:149–156

Tuller S (1997) Climatic controls of the cool human thermal sensation in a summertime onshore wind. Int J Biometeorol 41:26–33

VDI (1998) Methods for the human-biometeorological assessment of climate and air hygiene for urban and regional planning—part I: climate. VDI guideline 3787, Beuth, Berlin