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Thermal bioclimate as a factor in urban and architectural planning in tropical climates—The case of Campinas, Brazil

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Abstract Urban climate studies can provide information necessary for the improvement of conditions of thermal comfort for people in cities in the Tropics. This paper presents thermal bioclimate analysis of a case study in Campinas, Brazil, using air temperature (T_a), mean radiant temperature (T_{mrt}), and Physiologically Equivalent Temperature (PET), which can be used as assessment factors for urban and architectural planning in tropical climate. The meteorological data air temperature, relative humidity, wind speed, and solar radiation for the period 2003 to 2010 were used to calculate T_{mrt} and PET using the RayMan Pro model. Simulations of shade and wind speed variations were performed to quantify changes in thermal bioclimate due to modifications in urban morphology. The results show that solar radiation and wind speed not only influence air temperature, but also more extensive thermal comfort and heat stress as well. Furthermore, the simulations of the variation of wind speed and shade conditions demonstrate that shade can improve thermal comfort situations in terms of PET above 35 °C. The improvement of outdoor thermal comfort is an important step in achieving sustainability of urban spaces and configurations. These results are valuable for architects, planners, and urban designers for the description of conditions and the development of possibilities for improving microclimatic conditions based on urban design and configurations.

Keywords Thermal bioclimate · Physiologically equivalent temperature · RayMan · Urban spaces · Tropical climate, Brazil (Campinas)

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Introduction

Urban sprawl, without consideration of climate-related issues, can progressively reduce the sustainability of outdoor environments, and it is closely related to quality of life in tropical cities. Energy consumption has increased unintentionally at the building level because of climatic modifications, which has led to a remarkable demand on urban energy resources (Oke 1984; McPherson et al. 1989; Akbari and Taha 1992; McPherson and Sacamano 1992; Jauregui 1997; Matzarakis 2001). The motivation for developing a thermally desirable or neutral outdoor environment has implications beyond the requirements of urban design and the design of climate-adjusted buildings. To re-establish thermally acceptable or neutral conditions, both indoors and outdoors, it is important to specify standards of how urban spaces can be structured and arranged according to the existing climate conditions within a region (Givoni 1989, 1991; Alcoforado and Matzarakis 2010).

Several studies on thermal bioclimate in urban areas have reported that urban streets in particular consist of the shared active facets between their building envelope and the open urban canopy. This implies the relation between urban configuration and the physical properties of urban obstacles (buildings and vegetation primarily) and the knowledge that this affects outdoor and indoor environments (Ali-Toudert and Mayer 2007; Emmanuel et al. 2008). Because of urban morphology, the behavior and pattern of wind and solar radiation fluxes are the factors that have the greatest variability and impact on humans (Lin et al. 2010; Herrmann and Matzarakis 2012). Shading and wind can both play important roles in cities and can substantially modify an urban climate, and consequently the thermal bioclimate (Ali-Toudert and Mayer 2007; Lindberg and Grimmond 2011; Herrmann and Matzarakis 2012).

The reduction of evaporation caused by the lack of vegetation and water supply on the one hand, and the increase roughness of buildings in urban areas on the other, are modifications typical in urban design that promote the formation and intensity of heat islands (Oke 1984; Lombardo 1985). The hypothetical “shadow umbrella” for the reduction of solar radiation during the day to lessen the urban heat island can be augmented both by vegetation that enhances shading and by cooling ventilation (Emmanuel 1993). Controlling radiation by vegetation can introduce the possibility of regulation of urban microclimate modification. In addition, it offers the possibility of climate change adaptation (Green 1993; Abreu and Labaki 2010; Matzarakis and Endler 2010). During the day, the modification of the short- and longwave radiation fluxes by vegetation, in combination with wind speed, can cause a reduction of heat stress (Matzarakis and Endler 2010). Conversely, during the night, in a vegetative environment, the emission of longwave radiation is lower; therefore, the thermal bioclimate can be more pronounced in comparison with open spaces (Matzarakis 2001). In urban configurations, the absorption of radiation and heat storage can be factors that have negative effects on the thermal bioclimate, especially during the night (Alcoforado and Matzarakis 2010).

This paper evaluates the background of the urban climate and bioclimate conditions of Campinas, Brazil, and shows the effects of urban morphology modifications in terms of shading and variation of wind speed. The work also analyzes thermal bioclimate conditions based on air temperature (T_a), the Mean Radiant Temperature (T_{mrt}), and the Physiologically Equivalent Temperature (PET). The results will be helpful for urban and architectural planning and urban design issues in tropical climates, in terms of the modification of environmental factors, such as solar radiation and wind speed, and of how these can influence air temperature and the thermal bioclimate in general. The paper is to quantify the appropriate conditions for outdoor thermal comfort can be improved easily by their adjustment and adaptation in urban and architectural planning processes in tropical cities.

Architectural design and urban planning in Brazil

Usually, cities and buildings tend to be planned and designed according to particular climatic and cultural environments (for example, Butti and Perlin 1979; Acharya 1996; Kennedy and Katoshevski 2009).

However, many buildings have been designed without regard to climate and they require significant energy consumption to maintain indoor thermal comfort during both winter and summer seasons. The combined effect of the design of these buildings and the reduction of green areas accelerates the formation of heat islands (Oke 1984; Lombardo 1985; Monteiro and Alucci 2010). The consequences of these rapid transformations are several, heterogeneous, and complex. The urban territory adds new functions, uses, and spaces in dynamic and unexpected ways because of the impulses and pressures of new developments. For example, luxurious residential areas emerge in the middle of depreciated peripheries with a strong social preoccupation and reduce sustainability. Paradoxically, there are clusters of poor housing in areas of risk or other climatically important areas, such as green areas, mountain slopes, and riverbanks, or in urban voids, without consideration of the issues and approaches of thermal comfort (Sobral 2005).

Urban planning and design influence the formation of heat islands because of the urban geometry and thermal properties of built-up surfaces (Oke 1982; Matzarakis 2001). This phenomenon can also be observed in São Paulo, Brazil, based on air temperature in urban spaces (Lombardo 1985; Sobral 2005). From the relationship between air temperature and thermal comfort, it was concluded that São Paulo is more comfortable during the summer period than it is in winter because of the precipitation and the greater coverage of cloud (Sobral 2005). Another study showed the importance of the consideration of local topography, solar and wind orientations and patterns, and the localization and distribution of green areas in urban design (Assis and Frota 1999). Subsequently, the use of trees and green areas has been suggested to mitigate the negative effects of heat islands and to modify and restructure the environment to reach acceptable levels of thermal comfort (Streiling and Matzarakis 2003; Bueno-Bartholomei and Labaki 2003; Abreu and Labaki 2010; Dacanal and Labaki 2011; Abreu-Harbich et al. 2013).

Methodology

Site descriptions

The research was carried out in Campinas, Brazil (22°48′57″S, 47°03′33″W; 640 m elevation). It is one of the largest cities in the country with 1.1 million inhabitants and very high population density: 1,300/km^2 in some areas (BRASIL 2010) (Fig. 1). The climate of Campinas is classified assubtropical (Cwa; Kottek et al. 2006); it is drier in winter with warm to hot rainy summers. The mean annual air temperature is 22.3 °C and annual rainfall is 1,411 mm with the bulk of the rain falling in the months from November to March and drier periods of 30 to 60 days during July and August. The predominant wind direction is southeasterly with an annual mean speed of 1.4 m s^{-1}. Annual sunshine duration is 2,373 h and the mean daily solar radiation is 4.9 kWh m^{-2}.

Weather variations in Campinas are caused by shifts of the regional atmospheric circulation and the diverse topography. It is affected by tropical, equatorial continental, tropical Atlantic (the most common), and polar (especially polar Atlantic) systems, which modify the regional climate (Monteiro 1973; Nunes 1997).

Fig. 1 Campinas localization

Data

The data were collected at an urban automatic agro-meteorological station using a CR23X data logger (Campbell Scientific Inc.) at the Agronomic Institute of Campinas (IAC) on Santa Elisa Farm (22°54′S; 47°05′W; 669 m elevation). This site is in northern Campinas, 5 km from its center. This station is unaffected by surrounding obstacles and furnishes meteorological data representative of the area. Meteorological data of air temperature, relative humidity, wind speed, and solar radiation from a period of just over 7 years (25.6.2003 to 14.12.2010) were used. Their time resolution was 1 h.

Methods and analyses

The energy balance of the human body (Höppe 1993) is a modern human biometeorological method and allows to derive thermal indices, which is able to describe and quantify the effects of the thermal environment on humans (Mayer 1993; VDI 1998). Hourly meteorological data of air temperature (T_a), air humidity, wind speed, and global radiation were used to calculate the T_{mrt} and the PET. Thus, simulations were done by applying the RayMan model (Matzarakis et al. 2007, 2010), which is able to transfer the global radiation from an area with free horizontal urban structures and estimate the T_{mrt} due to atmospheric influences; first by clouds and then by other meteorological parameters, such as vapor pressure or particles. For the description of real situations in urban areas, different urban configurations are required. The PET results for Campinas during the study period were applied in simulations of wind speed and shade modifications to obtain information about the background thermal bioclimate conditions typical of Campinas.

The following setups were used:

- wind speed reduction of 1.0 m s^{-1},
- wind speed increase of 1.0 m s^{-1} and
- setup of T_{mrt} equal to air temperature (T_a), representing the shade situation.

Results

For the quantification of the background urban climate conditions of Campinas and the frequency distribution on a 10-day basis for the study period, T_a, PET, and T_{mrt} classes have been produced and are presented in Figs. 2, 3 and 4, respectively. These diagrams include frequencies of the classes of temperature intervals based on thresholds in percentages as comfortable, cold, and hot conditions. Values less than 13 °C represent cold conditions, values between 13 and 29 °C are comfortable conditions, values higher than 29 °C are hot conditions, and values higher than 35 °C represent conditions of thermal stress.

Campinas belongs to a warm and cool climate region according to the PET classification (Matzarakis and Mayer 1996) and PET higher than 29 °C represents conditions of thermal discomfort caused by heat.

Figure 2 shows that during winter, T_a considered as cold occurred around 3 % of the time, 90 % of the time it was neutral, and 6.5 % hot. Figure 3 shows that PET considered as cold occurred around 25 % of the time, 55 % of the time it was neutral, and it was above 29 °C for 20 % of the study period and around 20 % of the year. Figure 4 shows that values of T_{mrt} lower than 13 °C occurred for about 40 % of the study period; for 30 % of the study period it was between 13 and 29 °C, and it was above 29 °C for 30 % of the time. The differences between T_a, T_{mrt}, and PET are very high and show the relevance of a separate discussion and description of the results.

Figure 5 shows the mean monthly diurnal variation of PET based on the data of the urban climate station in terms of thermal comfort for the period from 25 June 2003 to 31 December 2010. It can be observed that for daytime hours the values are above 29 °C during the months between September and April.

The mean monthly diurnal variation of PET for the simulations with a wind speed reduction of 1.0 m s^{-1} (Fig. 6), wind speed increase of 1.0 m s^{-1} (Fig. 7), and shade, where T_{mrt} is equal to T_a within the study period (Fig. 8), is presented.

Both Figs. 6 and 7 show similar levels of thermal comfort during night hours, due to the absence of global radiation. However, during the day, it can be observed that the levels of

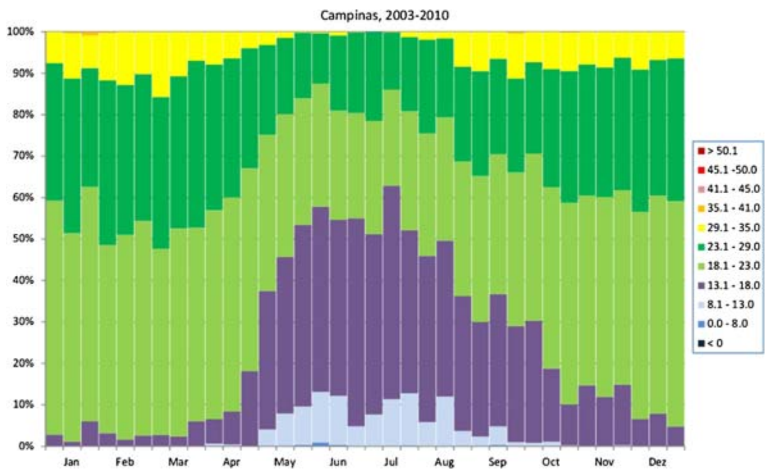

Fig. 2 Frequency distribution of Ta at the urban climate station Campinas for the period 25 June 2003 to 31 December 2010

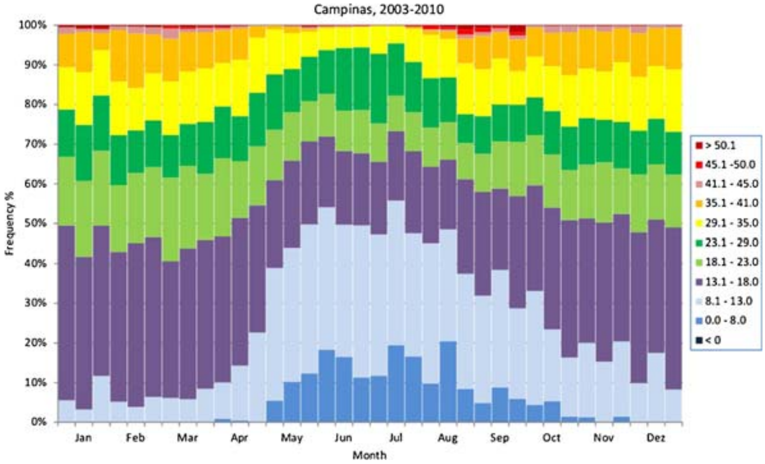

Fig. 3 Frequency distribution of PET at the urban climate station Campinas for the period 25 June 2003 to 31 December 2010

thermal comfort improve because of the increase in wind speed. In other words, if the wind speed increases, the thermal bioclimate conditions can be more comfortable, but if the wind speed decreases, the daytime hours in summer will present a PET above 30 °C. The simulation results confirm that wind speed has an influence on the mitigation of unpleasant thermal conditions.

From Fig. 8, it can be determined that the thermal bioclimate or physiological strain levels during nighttime hours during winter periods are different from those of summer periods. In addition, there was no record of air temperature above 30 °C during daytime hours. This result clearly shows the influence of solar radiation on air temperature in comparison with the diurnal variation of PET within the study period.

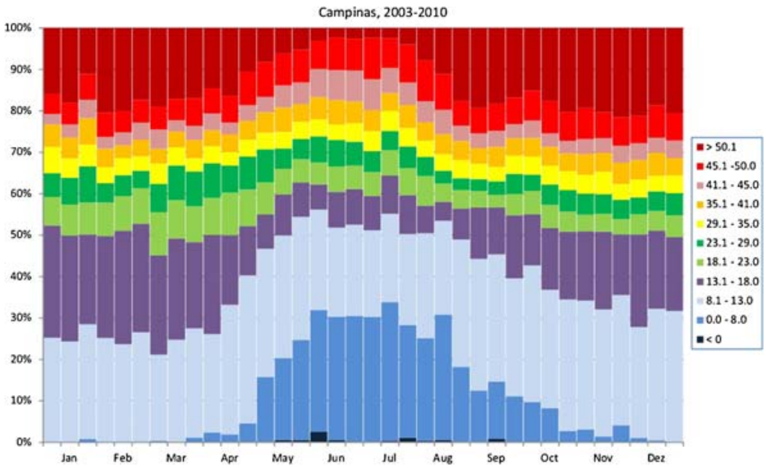

Fig. 4 Frequency distribution of T_{mrt} at the urban climate station Campinas for the period 25 June 2003 to 31 December 2010

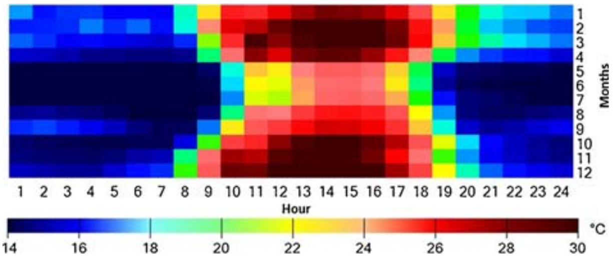

Fig. 5 Mean monthly diurnal variation of PET (°C) based on the data of the urban climate station and for the period 25 June 2003 to 31 December 2010

Table 1 compares the results between the different situations:wind speed below 1.0 m s^{-1}, wind speed above 1.0 m s^{-1}, T_{mrt} equal to T_a, and PET obtained from the annual data of the urban climate station and for the period from 25 June 2003 to 31 December 2010.

It is evident from Table 1 that 44.4 % of PET values were found when the PET is above 25 °C. The highest percentage observed is 75.7 % when T_{mrt} is equal to T_a and the lowest percentage observed is 40.6 % when wind speed is above 1 m s^{-1}. Between 2003 and 2010, 26.8 % of PET is above 30 °C. The highest percentage observed is 34.1 % when T_{mrt} is equal to T_a, and the lowest percentage observed is 21.9 % when wind speed is above 1 m s^{-1}. Similarly, between 2003 and 2010, 16.7 % of PET is above 35 °C. The highest percentage observed is 19.1 % when wind speed is below 1 m s^{-1}, and the lowest percentage observed is 6.3 % when T_{mrt} is equal to T_a. Values of PET above 35 °C are found for 7.8 % of the time. The highest percentage observed is 10.2 % when wind speed is below 1 m s^{-1}, and the lowest percentage observed is 0.1 % when T_{mrt} is equal to T_a.

Discussion

The simulations performed in this study–wind speed reduction of 1.0 m s^{-1}, wind speed increase of 1.0 m s^{-1}, and T_{mrt} equal to T_a, which represents shade situations–show that thermal bioclimate conditions can be affected by modifications of solar radiation fluxes and wind speed. It is observed that above the 25, 30, 35, and 40 °C thresholds, if the wind speed increases, the PET reduces, whereas if the wind speed decreases, the PET increases. In shade situations, if T_{mrt} is equal to T_a, the PET will increase in situations above 25 and 30 °C, and it will reduce in situations above 35 and 40 °C. Shading and wind can both play important roles in cities and can substantially modify the urban climate, and consequently the thermal

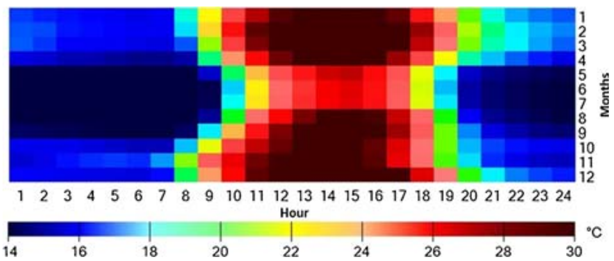

Fig. 6 Mean monthly diurnal variation of PET (°C) if wind T_{mrt} equals T_a based on the data of the urban climate station and for the period 25 June 2003 to 31 December 2010

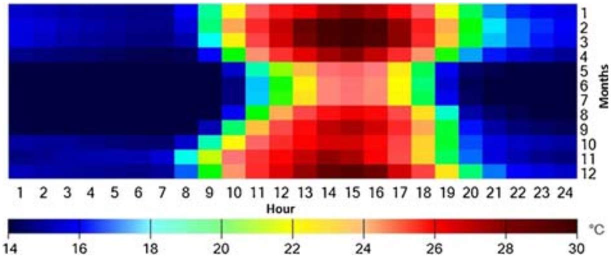

Fig. 7 Mean monthly diurnal variation of PET (°C) if wind speed increases in 1.0 m s^{-1} based on the data of the urban climate station and for the period 25 June 2003 to 31 December 2010

bioclimate (Emmanuel 2005; Ali-Toudert and Mayer 2007; Lindberg and Grimmond 2011; Herrmann and Matzarakis 2012; Abreu-Harbich et al. 2013).

When comparing frequencies of T_a, PET, and T_{mrt}, it can be observed that frequencies of T_a provide an indicator of the outdoor thermal environment. However, the frequencies of PET reveal more information about thermal conditions, because 20 % of daily PET temperature frequencies are above 30 °C during the year.

Other studies have applied only T_a as an indicator of thermal comfort in tropical cities (Sobral 2005). By using PET instead of T_a, our results reveal a different pattern. Although the summer in the Campinas region is mostly rainy and cloudy, this is not sufficient to make it thermally comfortable because there are also high air temperatures during this period. This can be explained further by the energy balance of the human body (Höppe 1993), which is used to deduce the thermal indices and describe the effects of the thermal environment on humans (Mayer 1993; VDI 1998). The variation of air temperature, relative humidity, wind speed, and solar radiation can modify the results and this should be considered.

Nevertheless, it is evident that solar radiation contributes to high PET during the year. Several studies (VDI 1998; Shashua-Bar et al. 2006; Matzarakis et al. 2007, 2010) have indicated that during an extreme situation, i.e., heat waves or very hot conditions, the biggest influence can occur because of the radiation field and wind conditions. Our findings confirm the results observed by Lin et al. (2010).

The present study shows the simulation of the variation of wind speed and shade conditions of Campinas, Brazil, where thermal comfort can be improved by shade in conditions above 35 °C and by a wind speed increase in conditions above 25 °C. People in tropical regions prefer to stay in the shade during hot daytime hours. The relation between the number of people and the thermal environment demonstrates that as air temperature (or other thermal environmental indices) in temperate regions increases, the number of people using public

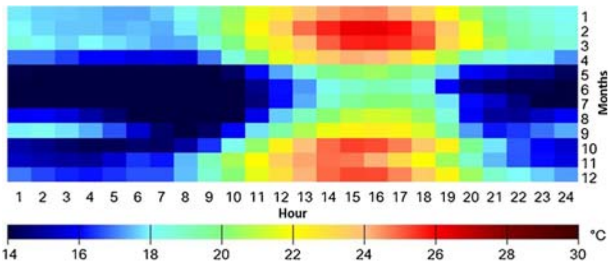

Fig. 8 Mean monthly diurnal variation of PET (°C) if wind speed decreases in 1.0 m s^{-1} based on the data of the urban climate station and for the period 25 June 2003 to 31 December 2010

Table 1 Annual percentages of thresholds based on PET for the period from 25 June 2003 to 31 December 2010

	PET >25°	PET >30°	PET >35°	PET >40°
v−1 m s^{-1}	49.3 %	29.0 %	19.1 %	10.2 %
v+1 m s^{-1}	40.6 %	21.9 %	11.4 %	3.1 %
$T_{mrt} = T_a$	75.7 %	34.1 %	6.3 %	0.1 %
PET original	44.4 %	26.8 %	16.7 %	7.8 %

spaces increases (Nikolopoulou et al. 2001; Thorsson et al. 2004, 2007; Eliasson et al. 2007). Conversely, studies in hot-humid regions indicate that during the cool season, the number of people visiting public squares (Lin 2009) increases as the thermal index value rises. However, the number of people who frequently visit public squares in the hot season decreases as the thermal index increases (Lin 2009).

The management of trees and green areas can promote shade in pedestrian areas and facades and it can modify the microclimate in tropical cities such as Campinas, Brazil. In the city, there are planned neighborhoods with tree-lined streets and green areas, whereas at the same time, dense housing clusters in poorer areas. The urban configuration of "favelas" hampers the planting of trees for shading façades and prevents the movement of wind around the buildings and inside (Sobral 2005). The expansion of streets in cities, the modifications of the geometries of buildings, and fragmented urban areas can reduce green areas (Labaki and Kowaltowski 1998), thus reducing thermal comfort.

Although there are urban areas with trees and other vegetation, urban forestry in different regions of the cities linked to the degree of built-up area and population density (Silva Filho 2004). In Campinas, there are governmental management projects focused on promoting the management of trees in streets and private gardens, but sometimes there is no concern for the benefit to thermal comfort from the microclimate. Some research suggests that plant cover of about 30 % in free flat areas would be suitable for improving the climate and quality of life (Lombardo 1985; Silva Filho 2004); however, this effect on thermal comfort has not been confirmed.

These results suggest that urban and architectural planning in tropical climates, such as Campinas, should be developed with consideration of the thermal bioclimate. The urban configuration of Brazilian cities is typically in a mesh form with long lots comprising buildings and narrow streets and avenues that have been built without regard to the direction of the wind (Labaki and Kowaltowski 1998). Building to a specific width and height can modify urban climate, mainly through radiation fluxes and changes of wind speed and direction (Herrmann and Matzarakis 2012). The existing setup reduces wind speed and makes it difficult for air to circulate in the inner cities, squares, and interiors. Furthermore, the materials used for the facades and roofs of buildings and for the pavement in urban areas can influence heat gains (Oke 1984; Matzarakis 2001). The promotion of ventilation and shading in tropical regions may be of benefit depending on the location of the town, density of buildings, relation between height and width, orientation of the street, and presence of trees along the streets (Givoni 1994; Streiling and Matzarakis 2003; Abreu and Labaki 2010; Lin et al. 2010).

Conclusion

The simulations and calculations based on modern thermal indices (PET) performed in this study show that shading and increased wind speed can substantially improve the thermal bioclimate in tropical cities. In tropical climates, the effect of the "shadow umbrella" can be applied to improve thermal comfort in outdoor environments. It is recommended that in high-density areas, buildings should be deployed strategically depending on the climatic region. Appropriate studies about urban street canyons are needed to evaluate the specific thermal bioclimatic conditions due to width, height, and orientation, the location of a town within a region, and the density of the urban area. The main factor affecting quantitative heat stress is shading, followed by wind speed modifications.

The results of this study suggest that thermal bioclimate characterization in tropical cities can be used directly for adaptation possibilities in the design of urban spaces and architecture, to make the urban climate more comfortable. Urban planning in tropical cities must consider meteorological data, such as air temperature and thermal indices (PET). Thermal bioclimate analyses with data from urban stations fit the RayMan model appropriately and deliver quantitative results. Therefore, urban guidelines concerning the microclimate and urban bioclimate can be adjusted to define and develop possibilities for mitigating the effects of global warming in cities. The inclusion of climate issues in urban guidelines regarding the orientation, widths of paths, and dimensions of buildings, in studies of urban canyons, is necessary for different kinds of climates and urban configurations. In addition, the results produced here and compared with other similar studies for other climates add substantial background information about urban climate and thermal bioclimate. The presented methods and results can be applied by architects and urban planners interested in constructing sustainable cities.

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