Theor Appl Climatol
DOI 10.1007/s00704-013-0886-0

ORIGINAL PAPER

Thermal bioclimate in idealized urban street canyons in Campinas, Brazil

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Received: 16 October 2012 / Accepted: 21 March 2013

Abstract Among several urban design parameters, the height-to-width ratio (H/W) and orientation are important parameters strongly affecting thermal conditions in cities. This paper quantifies changes in thermal comfort due to typical urban canyon configurations in Campinas, Brazil, and presents urban guidelines concerning H/W ratios and green spaces to adapt urban climate change. The study focuses on thermal comfort issues of humans in urban areas and performs evaluation in terms of physiologically equivalent temperature (PET), based on long-term data. Meteorological data of air temperature, relative humidity, wind speed and solar radiation over a 7-year period (2003–2010) were used. A 3D street canyon model was designed with RayMan Pro software to simulate the influence of urban configuration on urban thermal climate. The following configurations and setups were used. The model canyon was 500 m in length, with widths 9, 21, and 44 m. Its height varied in steps of 2.5 m, from 5 to 40 m. The canyon could be rotated in steps of 15°. The results show that urban design parameters such as width, height, and orientation modify thermal conditions within street canyons. A north-east–southwest orientation can reduce PET during daytime more than other scenarios. Forestry management and green areas are recommended to promote shade on pedestrian areas and on façades, and to improve bioclimate thermal stress, in particular for H/W ratio less than 0.5. The method and results can be applied by architects and urban planners interested in developing responsive guidelines for urban climate issues.

1 Introduction

The use of climate factors in architectural and urban planning is important for the thermal bioclimate in tropical cities. In general, open spaces integrate building envelopes and open urban canopy (Lin and Matzarakis 2008a, b). Urban obstacles and their orientation can influence thermal radiation consequently, they have an effect in both outdoor and indoor environments (Oke 1982; Givoni 1989; Mills 1999; Herrmann and Matzarakis 2012).

Research on thermal comfort and urban heat islands frequently refers only to case studies and measurement campaigns, which are insufficient to provide long-term information about special conditions in urban areas (Nakamura and Oke 1988; Yoshida et al. 1990). For thermal comfort issues in particular, studies of urban canyons show that radiation exchange in canyon geometry strongly affects the time of magnitude of energy fluxes of individual canyon surfaces. The orientation of urban canyon surfaces and material of facing walls and floors modulate air temperature and physiologically equivalent temperature (PET), which is cooler by day and warmer by night (Nunez and Oke 1977;

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Mills 1993; Santamouris et al. 1999). Shade enhancement from increased height-to-width ratios (H/W) is clearly capable of significant PET reductions, and thus improves outdoor thermal comfort (Emmanuel et al. 2007; Ali-Toudert and Mayer 2007).

In contrast, simulations of typical street canyons based on long-term data can determine the best scenarios in terms of human thermal comfort within urban street canyons. This methodology can be used for global comparison of urban areas in diverse climate regions and latitudes (Herrmann and Matzarakis 2012).

Changes in parameters of urban design and building construction can transform thermal bioclimatic conditions in urban areas if their results on thermal radiation (described in human biometeorology in terms of PET) and wind speed are considered in urban planning or architecture (Lin et al. 2010). Shading pedestrian areas and surrounding surfaces is the primary strategy in mitigating summer heat stress in hot conditions (Ali-Toudert and Mayer 2007). Both field measurement and simulations based on long-term data can be increasingly applied for developing architecture and urban design to adapt to the urban environment.

2 Urban growth in Campinas, Brazil

Urban growth in the city of Campinas, Brazil, especially from 1970 onwards, has changed its urban configuration and consequently urban climate. Flat and open areas were progressively transformed to urban ones and this effects the city's image. These land use changes can be shown by past aerial images (1956, 1996, and 2012) of parts of the district of Barão Geraldo in Campinas (Fig. 1).

The new pattern of urban growth at regional scale is closely related to the development of urban fabrics. Several factors formed this growth pattern, including new transportation networks, supply and communications infrastructure, environmental and urban laws, and others (Mitica Neto 2008).

A new master plan to organize city development was developed in 1991, and revised in 1996 and 2006. In general terms, the present legislation ("Master Plan and Land Use Construction Standards") and land occupation in Campinas places building height into three categories. These are related to the number of aboveground floors, i.e., 1–2 (9 m), 3–6 (21 m), and 6–12 (44 m).

The variation of H/W ratio in Campinas is 0.3–2.2, and is linked to the density of built-up area (Fig. 2). The new urban pattern of Campinas produces the urban heat island effect and differences in pedestrian thermal sensation because of the urban configuration and shade trees, as observed by Pezzuto (2007).

The urban canyon, which is a simplified rectangular vertical profile of infinite length, has been widely adopted in urban climatology. The basic structural unit describes a typical urban configuration and quantifies the relationship between urban geometry and thermal comfort (Oke 1973, 1982; Givoni 1989; Mills 1993; Herrmann and Matzarakis 2012; Fröhlich and Matzarakis 2013). The aim of the present study is to quantify the influence of H/W ratio and orientation in a typical urban street canyon of Campinas and to develop urban guidelines concerning H/W ratios and green spaces for adapting urban climate.

3 Methodology

3.1 Study area

The research was performed in Campinas (22°48′57″S, 47°03′33″W; 640 m elevation), in the interior of Brazil. It is one of the largest cities in the country with 1.1 million inhabitants and a very high population density: of 1,300/km^2 in some areas (Ministério do Planejamento, Orçamento e Gestão Brasil 2010).

Weather variations in Campinas are caused by regional atmospheric circulation shifts and diverse topography. There

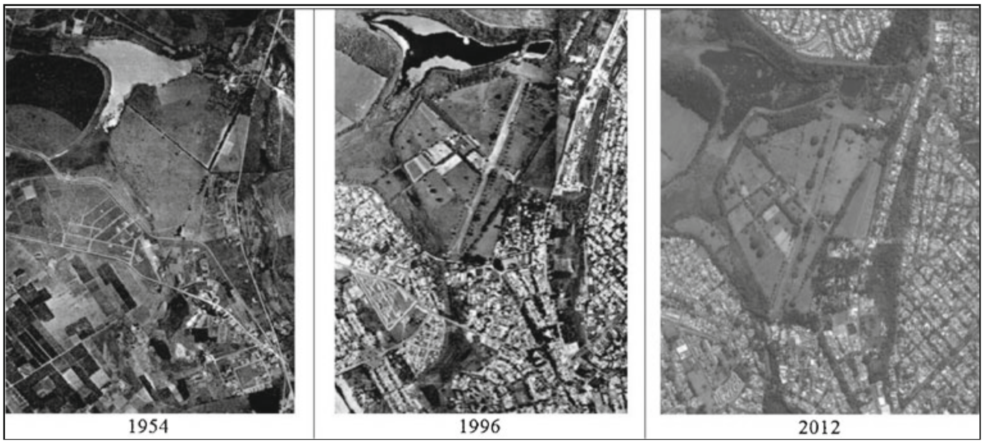

Fig. 1 Land use modifications in Barão Geraldo district of Campinas, with years labeled

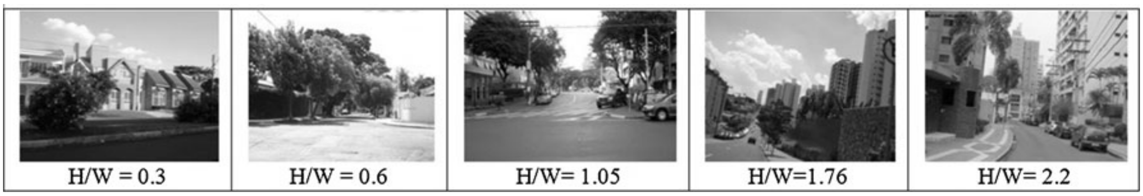

Fig. 2 H/W ratios of certain streets in Campinas

are tropical, equatorial continental, tropical Atlantic (the most common) and polar (especially polar Atlantic) systems, and these modify the regional climate (Monteiro 1973; Nunes 1997).

The climate of the city is classified according Köppen–Greiger classification as subtropical (Cwa; Kottek et al. 2006), with less rainfall in winter and rainy summers with warm to hot temperatures. Mean annual air temperature is 22.3 °C and annual rainfall is 1,411 mm. Rain is predominant from November through March, with dry periods of 30–60 days in July and August. The summer period is considered as November through April, with average maximum temperatures between 28.5 and 30.5 °C and minima between 11.3 and 13.8 °C. The warmest month is February, with an average temperature of 24.9 °C, average maximum of 30.0 °C, and minimum of 19.9 °C. The winter season is considered to be June, July and August, with maximum temperatures between 24.8 and 29.1 °C and minima between 11.3 and 13.8 °C. The coldest month is July, with an average temperature of 18.5 °C, an average maximum of 24.8 °C, and a minimum of 11.3 °C. The predominant wind direction is southeast, with a mean annual speed of 1.4 m/s. Annual sunshine duration is 2,373 h, and mean daily solar radiation is 4.9 kWh/m^2.

3.2 Data

Data were obtained from an urban automatic agrometeorological station with CR23X data logger (Campbell Scientific Inc.) at the Agronomic Institute of Campinas 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 not affected by its surroundings obstacles and furnishes meteorological data representative of the areas. The meteorological data are air temperature, relative humidity, wind speed, and solar radiation over a 7-year period (25 June 2003–31 December 2010). Their time resolution was 1 h.

3.3 Methods and analyses

Modern human biometeorological methods use the energy balance of the human body (Höppe 1993) to extract thermal indices for describing effects of the thermal environment on humans (Mayer 1993; VDI 1998). For this purpose, we used hourly values of the aforementioned meteorological data to calculate PET (Mayer and Höppe 1987).

The tridimensional model of urban street canyons was used to analyze urban climate changes caused by modification of urban configuration. We performed simulations using the RayMan model (Matzarakis et al. 2007, 2010a), which transfers global radiation from a free horizon area into urban structures. This model can compute thermal indices (e.g., PET) with less data availability. PET estimation depends on atmospheric influences, primarily clouds and other meteorological variables, such as vapor pressure or particles. Urban morphologies acting as obstacles may also be included. The primary input parameters to RayMan in the present study were air temperature, air humidity, wind speed, and total solar radiation.

To quantify background conditions of Campinas climate, PET was calculated and analyzed in terms of PET classes (Matzarakis and Mayer 1996). Classes of PET for different grades of thermal perception by human beings and their physiological stress—internal heat production of 80 W and heat transfer resistance of clothing of 0.9 clo—were applied in this analysis (Matzarakis et al. 1999).

The following configurations and setups were used. The model canyon was 500 m in length, with widths 9, 21 and 44 m. Its height varied in steps of 2.5 m, from 5 to 40 m. The canyon could be rotated in steps of 15° (Fig. 3). This configuration was built based on current legislation ("Master Plan and Land Use Construction Standards") and land occupation in Campinas.

The results are presented using the Climate Tourism/Transfer Information Scheme (CTIS) software (Matzarakis et al. 2010b). CTIS was developed for the

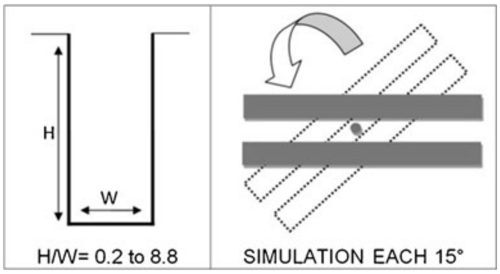

Fig. 3 Street canyon configurations and setups

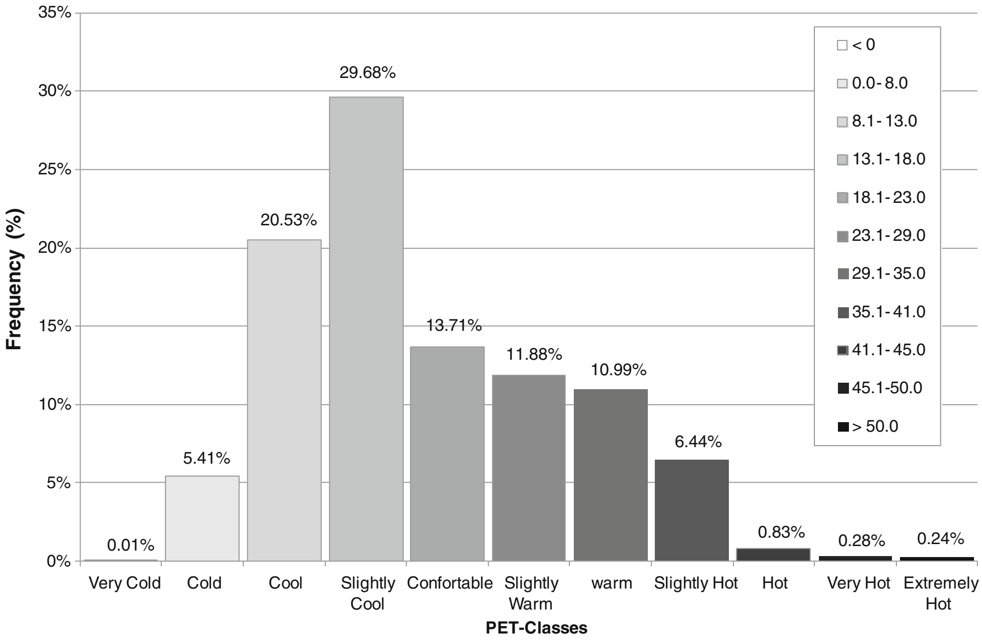

Fig. 4 PET classes for Campinas urban station, for the period 25 June 2003 to 31 December 2010

transfer of climate information for tourism and other purposes, and is applicable here (Matzarakis 2007; Lin and Matzarakis 2008a, b; Zaninovic and Matzarakis 2009). CTIS permits easy visualization of data and results and spatiotemporal comparison.

4 Results

Percentages of PET classes for the period 25 June 2003 to 14 December 2010 were calculated (Fig. 4). Campinas is in a comfortable climate region according to PET classification in which a temperature above 29 °C means a thermal sensation of discomfort for heat stress, especially in daytime hours. Around 19 % of hours in the original dataset from the Campinas urban climate station are in the warm (PET >29 °C), slightly hot (PET >35 °C), hot (PET >41 °C), very hot (PET >45 °C), and extremely hot (PET >50.1 °C) classes. For the same period, frequencies of "neutral" (13–29 °C) are almost 56 %, slightly warm (PET >23 °C) around 12 %, comfortable (PET >18 °C) around 14 %, and slightly cool (PET >13 °C) around 30 %. However, frequencies of

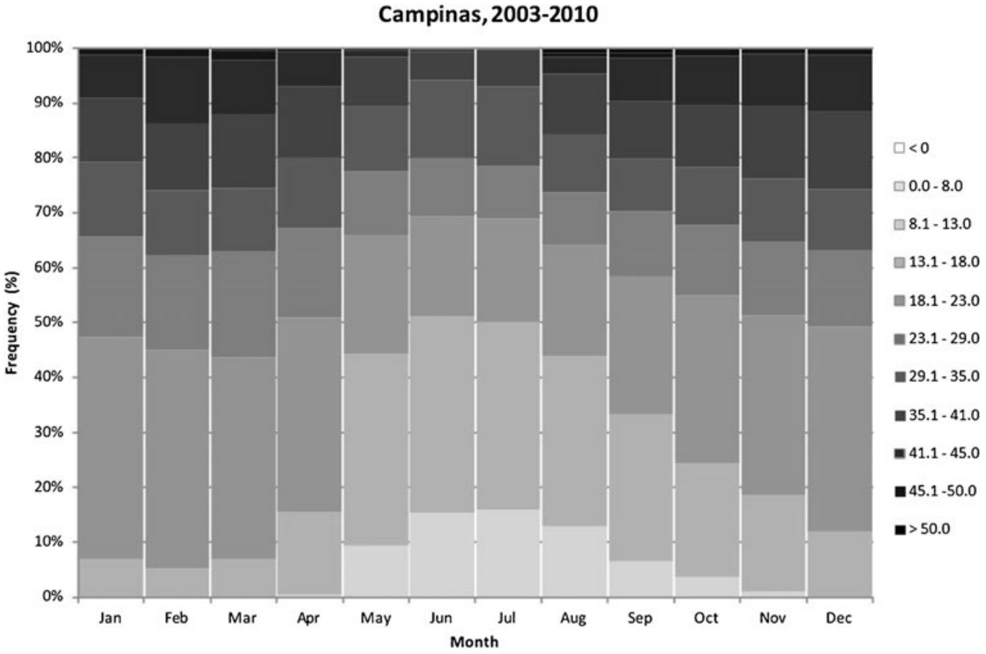

Fig. 5 Monthly frequency distribution of PET at Campinas urban climate station, for the period 25 June 2003 to 31 December 2010

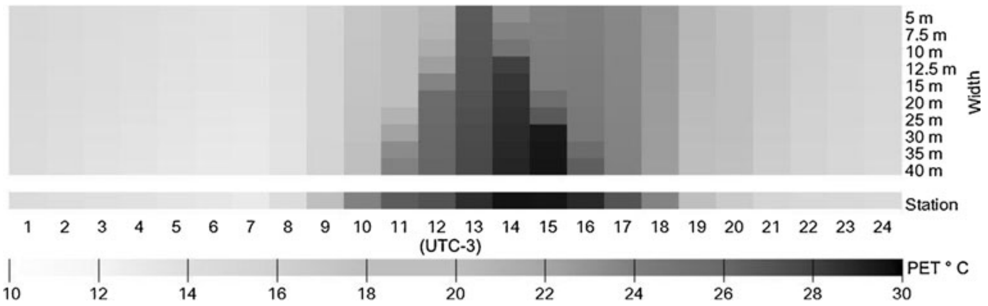

Fig. 6 Diurnal courses of PET (in degree Celcius) for urban canyon with north–south orientation, 21 m height and variable width (5–40 m), based on climate station data from 25 June 2003 to 31 December 2010

"feeling cold" (PET <13 °C) are about 25 %, which include the following thermal sensations: cool (PET >13 °C), cold (PET >8 °C), and very cold (PET >0 °C).

The mean monthly frequency distributions of PET classes were calculated for the same study period (Fig. 5). Heat stress level occurrences in January through March, November and December are greater than 35 % for the warm class (PET >29 °C).

Figures 6 and 7 show the diurnal PET courses for idealized urban canyons in Campinas with north–south and east–west orientations, respectively. Height of the canyon in this case was 21 m, and width from 5 to 40 m. This urban street canyon configuration represents the medium height buildings in Campinas city. PET at the Campinas urban climate station is included in the figures.

From both figures, it is seen that conditions are similar during the night, because of the absence of global radiation. By comparing calculated results of the urban station at different widths (between 5 and 40 m), PET rose 2 °C in the street canyon between 19 and 24 h. During the day, solar radiation effects in the north–south canyon with widths greater than 12.5 m reached maximum values. For the east–west orientation (Fig. 7), temperature increased gradually, and the largest PET values were attained with width approaching 40 m.

Figure 8 presents the diurnal PET course in idealized urban canyons in Campinas with north–south, northwest–southeast, east–west and northeast–southwest directions (the latter is the predominant wind direction in the region). The width of the canyon in this case was 20 m and the height was varied from 9 to 44 m. PET values from the urban station are included in the figure. There were significant differences of temperature during the night, according to the height variation in the canyon. Regarding the various orientations, conditions were dependent on building height, and there was little effect from canyon orientation for width 9 m (H/W=0.45). The east–west and northeast–southwest orientations improved thermal comfort with PET less than 29 °C at width 21 m (H/W=1.05). However, for 44 m width (H/W=2.2), the northeast–southwest orientation produced temperatures in excess of 29 °C.

Figure 9 shows diurnal PET courses with stepwise (15°) rotation in the anticlockwise direction (ACW), for an urban canyon height of 21 m and width of 20 m. This canyon had H/W around 1, which aids result comparison. Orientations of 0° and 180° in Fig. 9 are identical, and are marked north–south (Fig. 6); likewise, east–west is marked 90° (Fig. 7).

North–south (rotation, 0°) and east–west (90°) orientations generated the two extremes at midday, with highest PET for the former and lowest for the latter. The results of rotation in both directions reduced the midday values and shifted the maximum PET toward the morning or evening; overall daytime values decreased. Nighttime conditions were very similar, owing to the lack of total solar radiation, but canyon orientation also affected timing of the first PET increase in the morning.

Based on radiation flux estimations and simulation results, some urban guidelines for Campinas were determined (Table 1). There was slight influence of street orientation for H/W up to 0.5. Therefore, forestry management and green areas are recommended to increase shade on pedestrian routes and on façades. For H/W between 0.5 and 1.0, the east–west orientation is recommended, but it is also possible to improve sidewalk spaces with trees. For H/W between 1.0 and 2.0 and street orientation of 45–135°, forestry is recommended for bioclimate control. Finally, for H/W

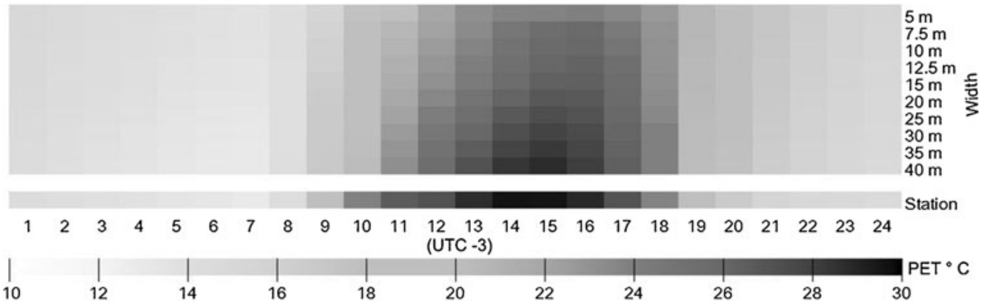

Fig. 7 Diurnal courses of PET (in degree Celcius) for urban canyon with east–west orientation, 21 m height and variable width (5–40 m), based on climate station data from 25 June 2003 to 31 December 2010

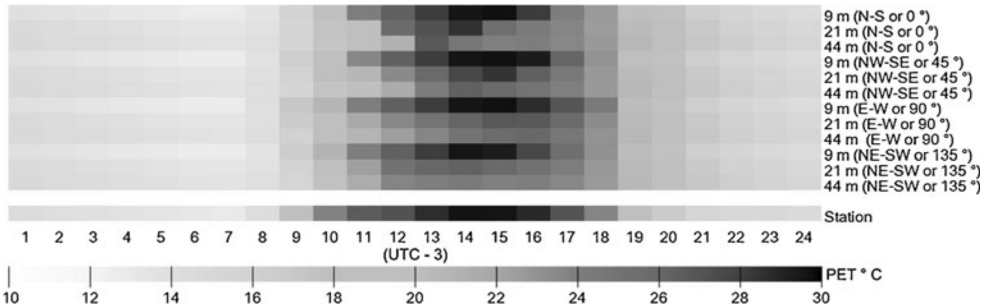

Fig. 8 Diurnal courses of PET (in degree Celcius) for an urban canyon with width 20 m, north–south, northwest–southeast, east–west, and northeast–southwest orientations, and variable height (9, 21, and 44 m); based on climate station data from 25 June 2003 to 31 December 2010

above 2.0, the northeast–southwest orientation is suggested to improve thermal comfort.

5 Discussion

The combined effect of height, width and orientation in street canyons modify PET, which is reduced during daytime; night-time temperatures become warmer than the flat free areas. Our findings confirm results of other research (Nakamura and Oke 1988; Santamouris et al. 1999; Herrmann and Matzarakis 2012; Ali-Toudert and Mayer 2007; Mills 1993).

Total solar radiation at each location and geographic latitude was affected by street orientation and H/W ratio as observed for daytime periods. The results for daytime PET in urban street canyons showed that it increased with H/W decrease, because of the effect of total solar radiation on surfaces. That is, for H/W less than 0.5, buildings cannot shade sidewalks. In this case, urban surfaces are heated more; temperature (air and PET) rise, possibly causing heat discomfort. For H/W around 1, *façades* and sidewalks may be shaded, depending on the orientation. For H/W greater than 2, buildings may shadow *façades* and sidewalks, and temperatures become cooler than those of the urban station. These surfaces may remain cooler during the day but retain heat during the night. Our results confirm those of Emmanuel et al. (2007) and Kakon et al. (2010).

By comparing our results with Herrmann and Matzarakis (2012), we see that the east–west orientation can reduce extreme conditions in Freiburg and Campinas. An H/W ratio up to 1.0 generates higher temperatures in Freiburg than an urban station. For the same ratio range, temperatures in Campinas are cooler than the urban station in which can reduce thermal stress during day hours. Heat conditions as modulated by urban configurations represent useful information for stakeholders to control mild-climate cities such as Freiburg. Likewise, the shading of urban surfaces provides useful knowledge for cooling and managing thermal comfort in tropical cities such as Campinas (Emmanuel et al. 2007; Lin et al. 2010).

This study suggest that shading in street canyons contributes to low PET during hot daytime hours, and that it is mainly affected by width, height and orientation. Shading from both buildings and trees can enhance thermal comfort during summer in tropical cities (Lin et al. 2010). It is known that people in tropical regions prefer to remain in tree shade during the hot daytime. Studies in Campinas showed that solar protection by tree shade contributes to thermal comfort (Dacanal and Labaki 2011; Pezzuto 2007). However, it is necessary to estimate the thermal comfort range of Brazilian residents.

For developing urban guidelines based on thermal comfort, street canyon simulations are required along with a description of the local climate. Other factors such as ventilation, topography, pavement type, and vegetation must be considered to improve thermal comfort. Identification of the climate required for thermal comfort in outdoor and indoor spaces helps architects and urban planners in proper use of urban obstacles. This represents the important step in applying climatological issues to urban design.

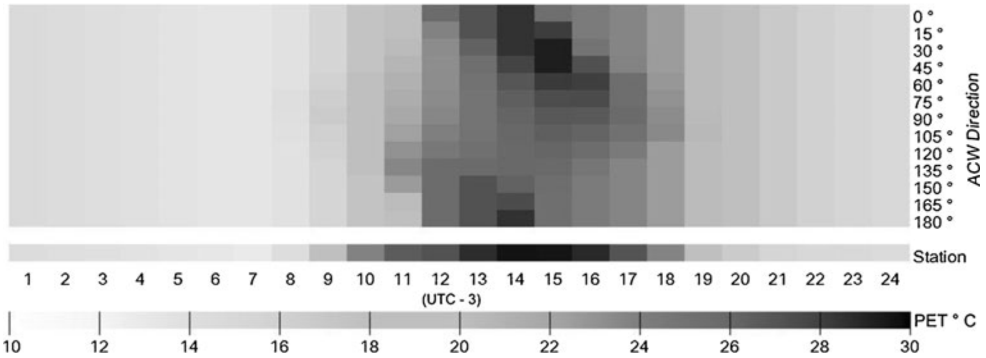

Fig. 9 Diurnal courses of PET (degree Celcius) for stepwise (15°) rotation of urban canyon with height and width 20 m, based on climate station data from 25 June 2003 to 31 December 2010

Table 1 Urban guidelines concerning H/W ratios and green spaces for Campinas

H/W	Urban guidelines
<0.5	The management of forestry and green areas to promote shading on pedestrian ways and façades is recommended.
0.5–1.0	The street can be orientated between 90° and 120°; for the other orientations, it is recommended the management of forestry and green areas.
1.0–2.0	The street can be orientated between 45° and 135°; for the other orientations, it is recommended the management of forestry and green areas.
>2.0	The north–south street orientation is not recommended.

6 Conclusions

Urban design parameters such as width, height and orientation can modify thermal bioclimate conditions within urban street canyons. Here, we quantified PET within typical urban structures, based on simulations using long-term data. This represents a significant approach for evaluating specific thermal bioclimatic conditions in tropical cities, and for development of responsive urban guidelines.

We showed that daytime temperatures can be reduced and nighttime temperatures remain high within urban street canyons in all scenarios, relative to an urban meteorological station. A northeast–southwest orientation can reduce PET during daytime more than with other scenarios. An H/W ratio up to 2 increases shade and improves thermal comfort during daytime more than other ratios. Forestry management and green areas are recommended to augment shade on façades and pedestrian routes and to enhance bioclimate control, particularly for H/W less than 0.5. It is important to combine green areas with H/W ratios to improve thermal sensation in tropical locations, but detailed analyses using field measurements and microclimate simulations are required.

Here, we present a realistic scenario, especially with the comparison of various street configurations with the same input data. This could be an effective method for global comparison of urban areas in different climate regions. The method and results can be applied by architects and urban planners interested in building sustainable cities.

To develop responsive urban guidelines by studying the influence of urban obstacles on microclimate, knowledge of the energy balance of pavement and building materials is necessary. Further, research priorities include the impacts of urban forestry in shading sidewalks and building façades, and wind flows in cities.

Acknowledgments This work was sponsored by the Research Support Foundation of the State of São Paulo (FAPESP), Coordination for the Improvement of Higher Level Personnel (CAPES) and German Academic Exchange Service (DAAD).

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