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Research Paper

Design tool to improve daytime thermal comfort and nighttime cooling of urban canyons

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ABSTRACT

As the urban population increases, the land area occupied by cities has increased at an even higher rate. Given this trend, urban warming has become a global phenomenon that affects outdoor comfort, energy consumption and air quality. Urban climate researchers assess cities' micro-climate behavior in order to be able to propose a suitable urban design. In this sense, urban planners still face a lack of simple tools to evaluate thermal behavior and the comfort conditions of an urban space. This study aims to develop a design tool, which was developed from collected field surveys in a non-forested urban canyon and in 18 representatives of forested ones in Mendoza, Argentina. A linear multivariate thermal comfort model called the COMFA-tool was created and performs well (R^2 = 0.86). The predictive capability of the developed tool was tested. Urban forest variables contribute up to 60% of comfort improvement. The study discusses how confusing it can be to use a solely morphological indicator in forested arid cities (i.e., H/W). Additionally, daytime thermal comfort and nighttime cooling were contrasted. The results presented lead us to think of a compromise solution in terms of designs of urban canyons. We encourage urban planners to use these design tools in order to improve the microclimate behavior of cities.

1. Introduction

In the last several decades, the world has seen an increased gathering of its population in urban areas. This trend is not new, but it is relentless. According to UN-Habitat (2016), in 1990, 43% of the world's population lived in urban areas; by 2015, this had grown to 54%. As the urban population increases, the land area occupied by cities has increased at an even higher rate. It has been projected that by 2030, the urban population of developing countries will double, while the area covered by cites will triple (Angel, Parent, Civco, & Blei, 2011).

One of the best-known urban effects of such development is urban warming, which alters urban climatology, increases the energy consumption of buildings, decreases outdoor thermal comfort in the summer and increases the concentration of air pollutants (Akbari, Davis, Dorsano, Huang, & Winert, 1992; Fujibe, 2009; Grimmond, 2007; Kolokotroni, Ren, Davies, & Mavrogianni, 2012; Wong, Jusuf, & Tan, 2011).

The urban climate is generated from complex phenomena in which many factors are involved. The particular characteristics of each city make it difficult to define effective microclimatic control strategies for all applications. This forces urban planners to confront the problem with a wide margin of uncertainty in the results. For this reason, it is important to understand how cities perform climatically in order to be able to propose an urban design according to the natural resources and the particular features of the cities.

The studies of the microclimatic behavior of cities are based mainly on the following:

(i) Experimental methods associated with the measurement of microclimatic variables. These methods have allowed advances in the knowledge of theoretical models of heat exchange and fluid dynamics between air and urban surfaces (Andrade, Alcoforado, & Oliveira, 2011; Chen et al., 2012; Krüger & Rossi, 2011; Lin, 2009; Mahmoud, 2011; Makaremi, Salleh, Jaafar, & Ghaffarian Hoseini, 2012; Nikolopoulou & Steemers, 2003; Ruiz, Correa Cantaloube, & Cantón, 2015a; Tan, Wong, & Jusuf, 2014; Yahia & Johansson, 2013; Yang, Hou, & Chen, 2011). However, their use and application are limited to the scientific field because they are complex methods that require expensive measurement equipment to acquire the data.
(ii) Computational calculation that models the urban microclimate and thermal comfort. These tools have the advantage of less investment

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of resources with a good degree of adjustment to the measured data. Additionally, simulations allow for the performance of parametric studies and evaluation of hypothetical urban scenarios (Ali-Toudert & Mayer, 2007; Giridharan, Lau, Ganesan, & Givoni, 2007; Mirzaei & Haghighat, 2010). Among the most well-known tools, we can mention RAYMAN (Matzarakis, Rutz, & Mayer, 2007) and ENVI-met Biomet (Bruse, 2016). The use of these tools presents limitations associated with the demand for a large number of input data and difficulties related to requiring high-performance equipment and system operators with a high level of expertise.

Currently, urban planners still face a lack of simple tools to evaluate the thermal behavior and the comfort conditions of a built environment in the pre-design stage. This is why the development of easy-to-use tools would help urban planners to improve the microclimatic conditions of cities.

Based on this background, the objectives of this work are as follows:

- To develop a design tool that can be used by urban planners to evaluate different design alternatives and select the most efficient from the point of view of increasing habitability in cities.
- To contrast the day and night microclimatic behavior of urban canyons by using easy-to-use design tools.

2. Materials and methods

2.1. Study cases

The Mendoza Metropolitan Area (MMA) is located in central western Argentina (32°53′ S, 68°51′ W, 750 m.750 ma.s.l.). According to the Koppen-Greiger climate classification, it is in an arid continental climate: BWh or BWk depending on the isotherm used (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). It is characterized by cold winters and hot summers, with significant daily and seasonal thermal amplitudes. Winds are moderate and infrequent, the amount and intensity of solar radiation is high, and the average annual rainfall is 198 mm (Gonz & lez Loyarte, Menenti, & Diblasi, 2009). The MMA is considered an oasis city because a major part of the streets are forested.

Nineteen representative urban canyons were selected according to three axes: tree species, street widths and building densities. These characteristics reflect the variety of the prevailing urban features of the MMA. Based on these characteristics, we selected 18 forested urban canyons. The forested canyons had the typical tree species of first and second magnitude. The classification of forest magnitude is based on the end height that a tree reaches 20 years after planting. The first magnitude is for species whose end height exceeds 15 m, such as the London plane tree (*Platanus × hispanica* Mill). The second magnitude is from 8 to 15 m, such as for the European ash (*Fraxinus excelsior* L.). In addition, one urban canyon had no trees. Pictures of the forested urban canyons of Mendoza are shown in Fig. 1. We selected three typical street widths: 16, 20 and 30 m; this derives from the MMA urban regulation policies (Regulatory Law N°4341/1978). In relation to building density, we chose low (buildings from 3 to 6 m in height) and high (buildings from 6 to 24 m in height). All selected urban canyons are oriented East-West to show the greatest difference in temperatures in the summer.

Taking into account the features of the selected cases, we decided to explore different types of variables. The variables selected by category are as follows:

- Urban forest structure: solar permeability (SP), number of trees (NT), trees per meter (T/m), mean tree height (MTH), tree cover (TC) and tree view factor (TVF).
- Urban canyon structure: building volume (BV), compactness (C), urban canyon length (UCL), volume/width (V/W), urban canyon width (UCW), volume/length (V/L), mean building height (MBH), height/width (H/W), building view factor (BVF) and sky view factor (SVF).
- Optical properties of materials: vertical surface albedo (VA) and horizontal surface albedo (HA).
- Microclimate: daytime air temperature (DTair), daytime surface temperature of pavement (DTpav), daytime surface temperature of sidewalk (DTsw), daytime surface temperature of walls (DTwall), solar radiation (SR), relative humidity (RH), wind speed (WS), daytime thermal comfort (COMFA) and nighttime air temperature (NTair).

For more information about the selection and description methodology of the urban variables, see Ruiz, Sosa, Correa Cantaloube, & Cantón, 2015b.

2.2. Thermal monitoring

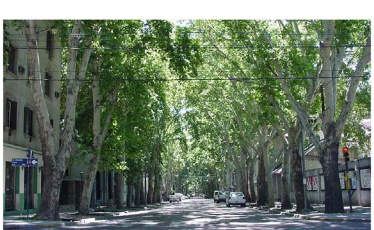
To obtain the values of microclimatic variables, we conducted a measuring campaign from December 17, 2009 to January 26, 2010. The data from this campaign was divided into two periods: daytime (from 9 am to 9 pm) and nighttime (from 9 pm to 9 am). The values of each variable have been averaged for each period. A fixed sensor type H08-003-02 was installed in each urban canyon at 2 m above the ground (Oke, 2004).

In addition, urban canyons were monitored during the daytime between January 8 and January 26, 2010 with a mobile weather station named H21-001. Each urban canyon was divided into four sectors (NE, SE, SO and NO). In each sector, the mobile weather station was moved to a representative point every 15 min. This equipment records air temperature, surface temperature, relative humidity, solar radiation and wind speed data every 15 min. This procedure allowed for the measurement frequency at the same point within the urban canyon to not exceed 1 h.

2.3. SVF Calculation

SVF is one of the most relevant parameters for describing urban structures in complex built environments; i.e., it depends on the morphological and forest urban combinations. There are different methods to obtain the SVF of urban canyons. Digital images acquired from existing urban canyons can be processed with optical software. For hypothetical urban canyon geometries, SVF values can be obtained from simulation software (Bruse, 2009; Chen et al., 2012; Matzarakis et al., 2007; Miguet & Groleau, 2002).

In this study, the SVFs of 19 urban canyons were calculated with "PIXEL DE CIELO", free software. "PIXEL DE CIELO" obtains accurately



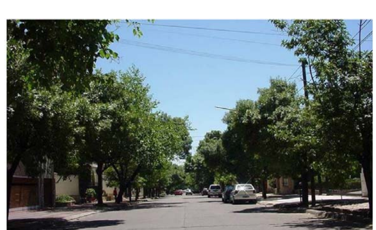


Fig. 1. Forested Urban Canyons of the MMA. (a) Platanus x hispanica and (b) Fraxinus excelsior. Adapted from: Correa, Ruiz, & Cantón, 2010.