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Urban grid forms as a strategy for reducing heat island effects in arid cities

María Belén Sosa*, Erica Norma Correa, María Alicia Cantón

Instituto de Ambiente, Hábitat y Energía (INAHE) – Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) – CCT Mendoza, Argentina

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ABSTRACT

The urban heat island (UHI) modifies the thermal behavior of cities. UHI effects increase the demand for electricity and decreases the livability of outdoor and indoor spaces. This paper seeks to identify forms of urban grids (UGs) that contribute to the reduction of the UHI in Mendoza-Argentina. The microclimates of 10 urban canyons (UCs) were monitored, analyzed and compared during the summertime. This investigation considers the thermal behaviors of open-forested and compact-non forested streetscapes using 4 UG forms. The data were statistically analyzed. The results suggest that the minimum air temperature is related to the combined effects of the neighborhood grid and the UC configuration. However, the maximum and average air temperatures are related to the UC configuration. The multi-azimuthal UG remains cooler. Additionally, the compact-non forested UC was found to be the hottest, which differs from what is known concerning the thermal behavior of UC configurations in the arid zone. When this streetscape is compared to the open-forested UCs, air temperatures differ up to 10.2 °C during the afternoon, 1.7 °C at night, and buildings consume up to 65% more electricity. In summary, creating thermally efficient cities in arid zones requires using the best combination of UG forms and UC design.

1. Introduction

Urban populations have been growing worldwide; presently, half of the world's population resides in urban areas (UN-Habitat, 2016). Consequently, the land area occupied by cities has increased, as has energy consumption. By 2030, global demand for energy is expected to grow by 40–50% (UN-Habitat, 2016).

The process of urban planning is closely related to climate, given that the central purpose of planning is to create an environment suited for humans (Zhao, Fu, Liu, & Fu, 2011). The design and use of the built environment impacts humans at different scales: macro-scale (global warming) and micro-scale (alteration of the urban climate). One of the main alterations of the urban climate is the increase of air temperature, which creates the urban heat island (UHI) phenomenon (Oke, 1982). Research has shown that UHI is primarily caused by the built environment in urban areas in which natural areas are replaced with a high concentration of impervious surfaces that have triggered many environmental issues (Ahmed, Kamruzzaman, Zhu, Shahinoor Rahman, & Keechoo, 2013).

This work focuses on the Mendoza metropolitan area (MMA), which is located in central western Argentina (32°53'S, 68°51'W, 750 m. a. s. l.) in an arid continental climate with low percentages of relative atmospheric humidity and high heliophany. Cities at a global scale usually present one of the two types of streetscapes: compact or open. The compact model has continuous urban development, consisting of tall buildings and narrow streets where the use of urban forestation is absent or scarce. In contrast, the open model—the area studied—has lower buildings with wide and forested streets (Correa, Ruiz, & Cantón, 2010).

Since 2003, the INAHE-CONICET has been studying the urban climate of the MMA with a focus on the magnitude, causes and consequences of the UHI. In arid cities, the UHI is perceived with greater intensity during summertime nights. Previous studies have established some of the impacts caused by this phenomenon: an increase of up to 20% in energy consumption for air conditioning, as well as worsened outdoor thermal comfort conditions (Correa, de Rosa, & Lesino, 2008; Ruiz & Correa, 2014). For example, in the summer of 2014, an intense heat wave caused an increase of air temperature to over 40 °C in the MMA. In response to the heat, air conditioning equipment was used intensively to create indoor thermal comfort. This demand reached record levels of electric energy consumption, with an increase approximately 11.5% between January 2014 and January 2013 (EPRE, 2014).

Many studies suggest that urban planning can influence urban temperature. Jusuf, Wong and Hagen (2007) demonstrate that appropriate planning of land use can mitigate the effects of UHI and improve comfort levels. These points are of interest for developing countries that are undergoing rapid urbanization (Wu, 2014). Shahraki et al. (2011)

* Corresponding author.
E-mail address: msosa@mendoza-conicet.gob.ar (M.B. Sosa).

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estimate that the urban sprawl rate is close to three times the population growth observed for the same period. The results from Minghong and Xiubin (2015) showed that UHI increases with the city growth (i.e., for a city size > 2 km^2, 60% of the UHI variance occurs during the night). Additionally, Stone, Hess and Frumkin (2010) found that the rate of increase in the number of extreme heat events in the most sprawling metropolitan regions was more than double the rate of the observed increase in the most compact metropolitan regions. Finally, Jo, Goleen and Shin (2009) showed higher surface temperatures are linked with a decreased level of vegetation, illustrating the impact of the built environment on urban climate change.

Regarding urban morphology, researchers often focus on urban canyons (UCs). In built environments, UCs usually compose more than a quarter of urbanized areas (Shashua-Bar and Hoffman, 2003); or in some historically planned cities, such as Manhattan or Barcelona, this area is up to 30% of their built surface (UN-Habitat, 2013). Worldwide, there are many studies that discuss strategies of how geometry, materiality and the forestation of UCs can mitigate UHI (Alchapar and Correa, 2015; Lin, Matzarakis, & Hwand, 2011; Ruiz, Sosa, & Cantón, 2015; Sanusi, Johnstone, May, & Livesley, 2016; Shashua-Bar & Hoffman, 2003). However, there is not enough research that considers how planning strategies related to the morphologies of low-density residential neighborhoods can contribute to cooling urban air temperatures. In this sense, Middel, Häb, Brazel, Martin and Guhathakurta (2014) have demonstrated, at the neighborhood scale, that the urban form has a larger impact on daytime temperatures than urban greening. Additionally, Middel, Chhetri and Quay (2015), assessed the combined cooling benefits of trees and cool roofs at this scale. They have demonstrated that a 25% increase of tree canopy in residential neighborhoods resulted in an average decrease of 2.0 °C during the day, whereas cool roofs showed a reduction of only 0.3 °C of air temperature.

Finally, the increase of extreme heat events and their consequences of overheating outdoor and indoor air temperatures have significant implications for energy consumption, thermal comfort and the health of city dwellers. Lin et al. (2011) determined that a 1 °C increase in temperature increases peak electricity demands by 2–4% when temperatures exceed 15–20 °C. Further, it was demonstrated that the extended use of air conditioning increases air temperature by 1 °C in hot-dry cities at night (Salamanca, Georgescu, Mahalov, Moustaoui, & Wang, 2014). This temperature increase generates an additional electricity demand for air conditioning causing a vicious cycle that impacts urban sustainability in a negative way (Wong & Siu-Kit, 2013).

2. Objectives

Within this context, the study has the following objectives:

- To analyze and compare the thermal behaviors of urban canyons located in different urban neighborhood grids;
- To evaluate the impact of different forms of urban neighborhood grids on outdoor temperatures to reduce the UHI effect in the MMA;
- To quantify the impact of urban design decisions on energy consumption for cooling the interior of houses within the assessed urban neighborhoods.

3. Methodology

3.1. Study sites: selection criteria and characterization

The MMA comprises 6 districts: Mendoza Capital, Guaymallén, Las Heras, Godoy Cruz, Maipú and Luján, see Fig. 1. In the MMA, 62.8% of the population lives within these districts, and in the past decade, this percentage has increased by 9.4% (INDEC, 2010). The building density of these districts is considered low because it is constituted mostly of single-family detached houses (IPV, 2010). The selection process of the case studies was categorized into three urban levels: urban districts, urban neighborhood grids and urban canyons.

3.1.1. Urban districts

According to the most recent demographic census, the majority of inhabitants live among the three districts that border the Capital: Guaymallén (16%), Las Heras (12%), and Godoy Cruz (11%). However, in the past decade, the population in the Capital (6%) has declined by 1%. This is an indicator of how the city has been expanding its built boundaries.

Defining and measuring urban forms is not a simple task. In this study, we made a graphic survey to characterize the MMA block geometries of the most populated districts. These urban blocks were classified and quantified using AutoCAD software and separated into four types: (i) square, (ii) rectangular oriented North-South, (iii) rectangular oriented East-West and (iv) irregular. The selection of these geometrical classifiers derives from the MMA urban regulation policies (Regulatory law n°4341/1978). Graphic survey results are detailed in Fig. 1, where the blocks are color coded and the percentages of the four types are presented. It should be noted that the blocks in the Capital are not quantified because the most representative form is the square (Stocco, Cantón, & Correa, 2013).

By analyzing the data of Fig. 1, it can be concluded that the most representative block form of Godoy Cruz is the rectangular type in both orientations (31%). Otherwise, in Guaymallén, the most representative block is irregular (48%); and, finally, in Las Heras, irregular blocks are the most representative (33%) followed by the rectangular ones with a North-South orientation (30%).

3.1.2. Urban neighborhood grids

According to Marshall (2005), an urban grid is a set of streets and blocks that constitute an urban area. Particularly for this study, we highlight 4 types of urban grids at the neighborhood level. Based on the most representative block forms from the graphic survey, four neighborhoods were selected:

- For Godoy Cruz, a neighborhood with rectangular blocks is selected. The key characteristic of this case is to have streets with slight orientation changes (Multi-azimuthal grid − Case 1)
- For Guaymallén, a neighborhood with irregular blocks oriented East-West is selected. The defining characteristic of this case are streets with one inlet/outlet (Cul-de-Sac grid − Case 2)
- For Las Heras, a neighborhood with rectangular blocks oriented North-South and East-West is selected (Rectangular grid − Case 3)
- For Capital, a neighborhood with compact-non forested and open-forested urban canyons is selected. The atypical compacted UC has a narrow street (5.5 m) and no trees, while the two adjoining streets are considered as having a typical open-forested configuration (Reticular grid − Case 4)

The selected grids differ in shape and orientation but maintain certain concrete features that can be compared to identify which forms have better thermal behavior. These reliable urban characteristics can be grouped into two categories: (i) environmental (low-density residential areas) and (ii) the characteristics of neighborhood (i.e., percentages of blocks, streets, built-up areas, compactness ratio and average albedos of streets, sidewalks and façades). Fig. 2 shows the values of the indicators used for the characterization of each selected neighborhood.

Additionally, each neighborhood is classified and characterized according to the study of Stewart & Oke (2012), Local Climate Temperature Zones for Urban Studies (LCZ). According to the LCZ classification, three cases (neighborhoods 1, 2 and 3) correspond to the open-low rise class with scattered trees subclass (LCZ 6b). The neighborhood selected in the Capital district has a mixed class because one of the