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THIS – Tool for Heat Island Simulation: A GIS extension model to calculate urban heat island intensity based on urban geometry

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ABSTRACT

This paper presents the development of a simulation model, which was incorporated into a Geographic Information System (GIS) in order to calculate the maximum intensity of urban heat islands (UHI_{max}) based on urban geometry data (using a H/W parameter). This tool is called THIS – Tool for Heat Island Simulation. The urban heat island phenomenon is defined by the temperature rise in dense city centers compared with the surrounding countryside. The methodology of this study is based on a theoretical-numerical basis (Oke model), followed by the development of a calculation algorithm incorporated into the GIS platform, which is then adjusted and applied as exemplification. This adjustment was made by calibrating the Oke model for a case study based on two Brazilian cities and different various trends for different roughness length ranges were found. As a consequence, this work has resulted in the automation of an algorithm to obtain maximum intensity values of heat islands based on a simplified model. After finishing the subroutine, the application of the THIS in a simulation of different urban scenarios showed different trends in the UHI_{max} value for the H/W ratio and the roughness length. The UHI_{max} increases when the H/W ratio increases, but the urban canyons with greater roughness (larger areas of facades and more heterogeneous heights, $Z_0 \geq 2.0$) result in UHI_{max} values of approximately two times smaller than canyons with less roughness (homogeneous with highest average areas occupied by buildings, $Z_0 < 2.0$) for the same value as the H/W ratio. Overall, the developed tool has one aim: to simulate the effect of the isolated variable of urban geometry on the maximum intensity of nocturnal heat islands, considering different urban scenarios.

1. Introduction

The worldwide known phenomenon called 'urban heat island' (UHI) is still a concern for the quality of life. Due to the properties and arrangement of their elements, urban centers tend to store more heat and develop higher air temperatures than those found in the outskirts of the city (or surrounding rural areas). For Hamdi (2010) and Mendonça and Monteiro (2003), the growth of UHI due to the increase in urbanization is particularly important for the influence on the estimation of global warming.

Among the factors that influence the intensity of the heat island, urban geometry can be highlighted. Urban geometry interacts with the exchanging radiation between the Earth and Sky by the phenomena of reflection, absorption and thermal storage. The geometric combination of horizontal and vertical intra-urban surfaces is often referred to as 'urban canyon' and generally measured by the height and width (H/W) aspect ratio, the relationship between the average height of the building in an urban canyon and the street width.

Among the analytical studies correlating urban geometry and the formation of heat islands, it is worth highlighting the study conducted by Oke (1981). This author developed an empirically based model for predicting the intensity of nocturnal heat islands based on urban geometry. According to this author, the increase in the H/W ratio corresponds to the decrease in the cooling rate of the urban environment in relation to the rural area. Due to the potentiality of the Oke model, adapting it to a contemporary approach is one of the aims of this paper. Therefore, exploring the model as a computational tool may open up possibilities of urban analysis and make it easier for researchers to use.

Among the computational tools available, Geographic Information Systems (GIS) stand out due to the number of spatial and numerical interactions of geographic objects. In addition to the storage capacity of GIS, they are able to treat and represent tabular data and make it possible to incorporate new techniques and methods into territorial planning.

Associating the issue of urban heat island to the management

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possibilities offered by a GIS, the purpose of this article is to check the influence of urban geometry on the maximum intensity of urban heat islands. Thus, a computational algorithm was developed as an extension of a GIS, by exploiting its potential to analyze and manage geographical data. In order to do this, the following steps were taken: analyze the theoretical-numerical basis (Oke model); develop a calculation algorithm and implement it in the GIS platform; and adjust the tool by simulation testing of urban scenarios.

2. Theoretical basis

This section presents some approaches concerning the relationship between urban geometry and heat islands, as well as some examples of using GIS in urban studies.

2.1. Urban geometry and heat islands

Cities and urban areas change the climate creating various urban microclimates. This is due to a number of complex factors, such as the loss of cooling on vegetated surfaces, increased human activity and heat storage built in urban environments, as well as the effect of the canyon (Levermore & Cheug, 2012).

In microscale climate studies, the geometry of open spaces can be the most important parameter responsible for the variation of the microclimate (Ali-Toudert & Mayer, 2006; Bourbia & Boucheriba, 2010; Oke, 1988; Stewart & Oke, 2012). In this context, urban geometry is usually associated to the formation of urban heat island factors. The geometry variation in urban environments may influence: the increase or decrease in air temperature values when compared to measured data in the outskirts of a city; the speed and direction of winds; and long and short-wave radiation exchanges.

According to Rajagopalan, Lim, and Jamei (2014), the factors affecting the occurrence and intensity of heat islands can be broadly classified into two categories. The first category is the meteorological factors including wind speed and direction, humidity and cloud cover. The second category is basically the product of city design, such as density of built up areas, aspect ratio, sky view factor (SVF) and construction materials.

Theoretically, the larger the H/W ratio, the smaller the area of visible sky and dissipation of long-wave radiation. Thus, large H/W reduces the cooling rate in urban areas, by reducing the turbulent transport due to the wind and the amount of anthropogenic heat release (Oke, 1987).

In addition to the possible interference on UHI, which the H/W ratio can cause, one of the most significant changes produced by buildings is the air flow changes, usually measured by the roughness length (Z_0). There are various studies linking urban geometry and changes in the wind flow by applying the Z_0 concept (Kanda & Moriizumi, 2009; Millward-Hopkins, Tomlin, Ma, Ingham, & Pourkashanian, 2011; Sugawara & Narita, 2009; Zaki, Hagishima, Tanimoto, & Ikegaya, 2011).

According to Millward-Hopkins et al. (2011), there are two Z_0 parameterization mechanisms that affect the simulation of urban atmospheric environment. One of them is the dynamic effect, i.e. the change in Z_0 causes a variation in the drag force. The other is the thermal effect, i.e. the change in Z_0 can also contribute to the variation of latent and sensible heat exchange.

Studies that attempt to measure the influence of urban geometry on the climate in cities usually use models or computer programs to simulate real and hypothetical scenarios, mainly checking the different situations of urban density. Lately, climate research related to urban environments has used three types of models: numerical, physical and empirically based models (Oke, 1984; Svensson, Eliasson, & Holmer, 2002).

Numerical models are usually designed for any city and simulations under different conditions, but must undergo a validation process before being used. Physical models tend to contribute to the understanding of a particular process or set of conditions for which they are designed to investigate. However, for these models, the most challenging aspect is to obtain thermal mass consistent with the scale. Empirically based models can have high predictive power due to the similarity of the data conditions that are based on their development. They allow for simulations only under the specific conditions measured for which they were developed, thus requiring a long-term basis of field measurements.

While physical model applications are limited by the conditions of scale, empirical model applications are generally restricted to weather conditions under which they were developed. As a result, numerical models are being widely used and increasingly refined.

The Oke model (1981) was developed by comparing results from an experiment with a physical scale model and data observed in the field to analyze the formation of urban heat islands. Based on a series of mathematical deductions, this researcher developed a numerical model of empirical basis. Eq. (1) (with $R^2 = 0.89$) describes the model and has become one of the references in the urban climate literature, as it can isolate the specific role of one of the causes of the heat island, the urban geometry.

$$\Delta T_{u-r(\max)} = 7.45 + 3.97\ln(H/W) \quad (1)$$

where:

$\Delta T_{u-r(max)}$ is the maximum urban heat island;
H is the height of the buildings in the urban canyon;
W is the width of the street in the urban canyon.

Although Oke's model works well in these North American and European cities (with $r^2 = 0.89$ for Eq. (1)), in other cities with different climates, such as Korean and Japanese cities, the model is not able to predict the lower values of UHI intensity (Montávez, González-Rouco, & Valero, 2008), presumably due to the very different thermal admittances of these places (Johnson, Oke, Steyn, Watson, & Voogt, 1991). Moreover, the resulting data from Brazilian cities follow a trend similar to Korean and Japanese cities, as shown in Fig. 1.

The heat island phenomenon has been observed in many cities around the world, predominantly at night. On the other hand, during the day, the urban environment is able to reverse the difference between rural and urban temperatures. The biggest heat island intensities can be observed a few hours after sunset (Oke, 1981). This happens due to the characteristics of the formation of urban areas; they tend to

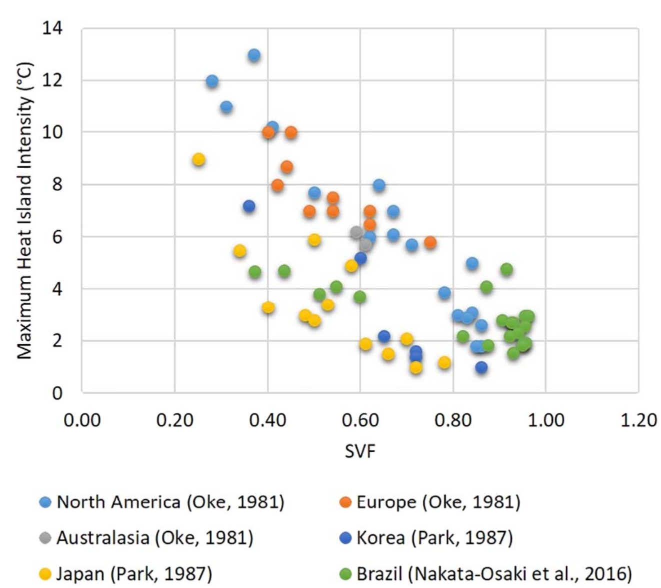

Fig. 1. Relation between the maximum heat island intensity observed in field surveys and the sky view factor of its areas. Adapted from Oke et al. (1991) and from Nakata-Osaki, Souza, and Rodrigues (2016).