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VERIFICATION OF THE INFLUENCE OF URBAN GEOMETRY ON THE NOCTURNAL HEAT ISLAND INTENSITY

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Abstract: Nocturnal heat island formation is a prominent phenomenon in urban planning research and thermal comfort. It is characterized by an increased air temperature from the periphery to the center of the cities and is partly caused by the urban geometry. The phenomenon is a result of the influence of the characteristics of urbanization, which alter the energy balance of the cities. Among surveys in this context, the model proposed by Oke (1981) shows its relevance in the area. Using simulations with reduced models, Oke found that the fraction of visible sky negatively correlated with the heat buildup on the surfaces and increased the air temperature. The relationship between the height of the buildings and the width of the path (H/W ratio, height/width) was used to measure the urban geometry in this previous study. Based on that study, this research verified the role of geometry in the formation of an urban heat island in a Brazilian city, aiming to adapt this model to real urban conditions. The methodological procedures rely on the following steps: a study of a theoretical-numerical base model (Oke model, 1981) and adjustment (validation). Thus, the methodology to be employed included urban data collection, which included urban geometry and air temperature, the application of the Oke model and its adjustment. The results found in this investigation corroborate the study of Oke (1981) and demonstrate that urban geometry effectively contributes to the formation of nocturnal heat islands.

Keywords: Numerical model; urban geometry; heat island; urban canyon.

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INTRODUCTION

One of the most discussed topics of climatic phenomena that arise from urbanization is heat island formation, which is characterized by an increased air temperature, from the periphery to the center of the cities. According to Oke (1981), this phenomenon is typically nocturnal.

Heat island formation is generally considered a problem for cities because it induces many undesirable effects, such as discomfort in people, health problems, the need for more energy consumption and more pollution. Conversely, the presence of vegetation and winds are factors that contribute to easing its development.

In this context, the urban geometry is treated as one of the factors that significantly influence the formation of heat islands. In many studies, this geometry is measured by the ratio of H/W (height/width), which is the height of buildings divided by the width of the path relative to a point. Thus, the higher the dimensions are of the first compared to the second, the higher the values of H/W will be. The influence of this relationship on the urban microclimate was studied by Oke (1981) and Oke (1988).

Oke (1981) verified via experimental simulations with reduced models that the cooling is lowest when the H/W ratio increases. In this study, Oke developed an empirical model to predict intensity of nocturnal heat islands from the H/W ratio on calm and cloudless days.

The Oke model (1981) became a reference in the area for its importance in studies that analyzed the relationship between geometry and the formation of urban heat islands. However, it had some limitations because it was based on experiments with reduced models in the laboratory. In addition, the Oke studies focused on urban climates that differed from those found in the Brazilian territory.

This research aimed to verify the role of geometry in the formation of nocturnal urban heat islands in a Brazilian city by adapting the model developed by Oke to real urban conditions.

URBAN GEOMETRY AND HEAT ISLAND

According to Oke (1987), the urban heat island effect is probably the clearest and the best-documented example of inadvertent climate modification. The exact form and size of this phenomenon varies in time and space as a result of meteorological, location and urban characteristics.

The studies that investigate the “heat island” phenomenon encountered a subject so complex that they inevitably approached only one (or some) of the several aspects that relate to the topic. The heat island is influenced by vegetation of different types/properties of materials, the types of coverage of buildings, the presence of artificial sources of heat and urban geometry, among other factors. Furthermore, it relates strongly to energy consumption and human thermal comfort, justifying the importance of the theme.

Mirzaei & Haghighat (2010) presented a review of the techniques used to study UHI. The treatment of important parameters, including latent, sensible, storage, and anthropogenic heat, in addition to the treatment of radiation, the effect of trees and ponds and boundary conditions to simulate UHI (urban heat island), were also presented. They comment that ensuring similarity between the real case and the prototype in outdoor spaces it sometimes difficult if not impossible. Small-scale modeling is mostly used in UHI studies to verify, calibrate and improve the mathematical models (e.g., turbulence, stratification). However, the similarity between models and prototype is necessary condition to achieve accurate results.

Several studies have attempted to measure the influence of urban geometry on the urban climate. To this end, models or software are often used to simulate real and hypothetical scenarios, which mainly focus on the different situations of urban density. In this context, the urban geometry is commonly represented by the relationship between height and width of the path (H/W) and the sky view factor (SVF).

Because the nocturnal urban heat island results from the difference between urban and rural cooling, Oke (1981) used physical scale models in their experiments. The urban and rural surfaces were simulated by the radioactive passive cooling of these environments after sunset on a calm and cloudless night.

These physical models were built from wood in a cubic polyethylene chamber with dimensions of 0.5 x 0.5 x 0.5 m (**Fig. 1**). The blocks used to simulate the buildings were formed out of wood or concrete at different times of the experiment.

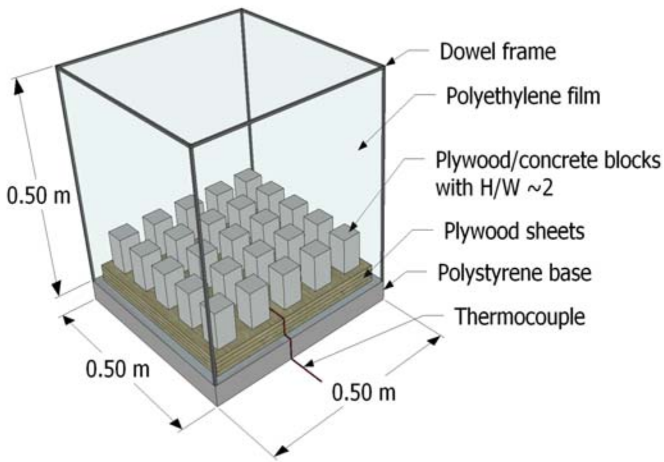

Fig. 1 The “urban” model with its base of support and protection insulation of polyethylene. A thermocouple is situated on the ground in the center of the canyon of the model.
Source: adapted from Oke (1981).

To simulate the difference in urban-rural cooling time, the models were initially at an ambient temperature of ~20ºC and immersed in a cold chamber with an air temperature of ~8ºC. The H/W proportions considered in experiments were of 0.25, 0.5, 1, 2, 3 and 4. The influence of wind, water, vegetation or other materials different of those simulated was not taken into account. The model specifically emphasizes the influence of the geometry on the formation of urban heat islands. The surface temperature of the floor of the canyon was measured with a thermocouple placed in the center of the canyon and avoiding the intersection.

Therefore, the Oke model (1981) was based on a physical formulation whose equations are presented in this work. Geometry considerations led to the development of a simple empirical model (**Eq. 1**) that can predict the maximum intensity of heat islands in a location.

$$\Delta T_{u-r\,(\max)} = 7{,}45 + 3{,}97\ \ln(H/W) \qquad (1)$$

where $\Delta T_{u-r\,(\max)}$ = heat island intensity (ºC) and H/W ratio = ratio of the height of buildings to the width of the path relative to a point.

The ratio H/W was also used by Oliveira Panão *et al.* (2009) to analyze the thermal conductance of the canyon, which quantifies the heat emitted by the street, and to improve the understanding of this integration.

According to Memon *et al.* (2010) and Marciotto *et al.* (2010), the H/W ratio impacts the surface and air temperature and, hence, the energy flow of urban canyons.

Souza *et al.* (2003) developed a subroutine to calculate, visualize and quantify the SVF named 3DSkyView, which was developed on the platform ArcView 3.2. Because ArcView migrated to ArcGIS (currently version 10), this subroutine is being updated by the authors to answer a few questions raised by Matzarakis & Matuschek (2009) with regard to the limitation of the model in ArcView 3.2. With ArcGIS 10, the new capabilities can improve the modeling of surfaces.

Studies of urban thermal fields usually use models and computational tools to provide ease and agility to researchers. According to Oke (1984) and Svensson *et al.* (2002), three types of models can be applied to the climate-related research of urban environments: models with a numerical, physical and empirical basis.

While the applications of physical models are limited by the conditions of scale, the applicability of empirical models is generally restricted to the weather conditions under which they were developed. As a result, numerical models are being widely used and increasingly refined. Moreover, the latter model must always be validated before being applied at different locations. In addition, the interfaces of these models are not always friendly. They can be complex and are constantly being improved; updates are required.

The model developed by Oke (1981) is interpreted as a mathematical model based on an experiment with scale models (physical base) in this research. Because environmental conditions could be controlled, the resulting model is expected to be applicable to real urban environments and not be restricted to any specific location. However, for the purposes of this study, the model needs to be validated prior to its application.

METHODOLOGY

The methodology includes the following steps: applying the Oke model for a city whose urban geometry data were collected and set and the validation of this model based on survey data of air temperature for that same city (**Fig. 2**).

Theoretical-numerical base

The discussed theoretical-numerical basis demonstrates that the H/W ratio is one of the ways to describe the urban geometry and can be related to the development of a nocturnal heat island via simplified modeling of the urban thermal environment.

Thus, the model to be applied corresponds to that proposed by Oke (1981) and described by **Eq. 1**.

Adjust

The model will be applied to simulate a real urban situation for which actual measured data are compared to data simulated by the Oke model. To obtain these actual data, an urban area was selected for this study.

Characterization of data collection points

The city of São José do Rio Preto in the State of São Paulo in Brazil was selected for the surveys. The city of São José do Rio Preto is located at 20º49′12″ºS, 49º22′44″ºO, 443 km away from the capital São

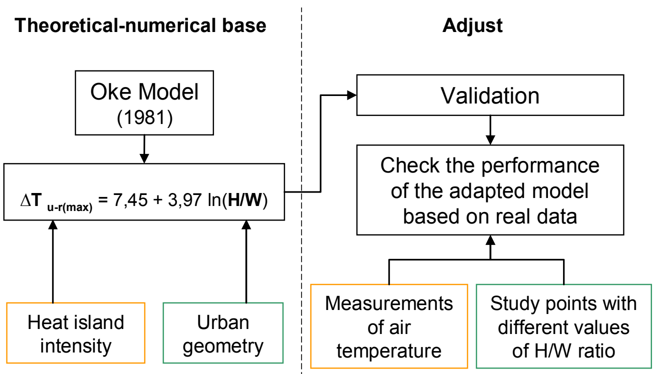

Fig. 2 Scheme or research methodology.

Paulo at an average elevation of 489 meters. Its area is 421.96 km², and it has a population of 408 258 inhabitants (2010, IBGE). This city was selected because it presents urban canyons with different H/W relationships and the urban center has a concentration of vertical buildings.

According to the IBGE, the climate of São José do Rio Preto features approximately 3 dry months per year, classified as type Aw according to Köppen, with a decrease in rainfall during winter and average annual temperature of 23.6ºC. Winters are dry and cold, while simmers are rainy and hot.

For data collection, five points were selected in the central region of the city to provide different values of the H/W. These points were located in the middle of the frontal faces of urban blocks to standardize the estimation of H/W ratios. This estimate considered the measure of the width of the path (W) to be the sum of the measures of the street and the two sidewalks of the canyon. The height of the buildings (H) was estimated to be the average of the buildings closest to the measuring point of the two sides of the street within a radius of 15 meters from the axis of the street. **Table 1** represents the H/W ratios estimated for each measuring point.

Instrumentation for data collection

The rural air temperature data were obtained from the station of the CIIAGRO – Integrated Center of Agrometeorological Information, while the urban air temperatures were measured at the points of collection.

The CIIAGRO is a service provider of IAC – Institute of Agronomy from Campinas, which is a research institute of the Paulista Agency of Technology of Agribusiness from the Secretariat of Agriculture and Supply of São Paulo State, with headquarters in the city of Campinas. The CIIAGRO monitors the agro-meteorological climate and provides support to agricultural activities. Daily weather data are incorporated into the database comprised of 146 localities or collecting points via a web system. The main data entered are the maximum and minimum temperatures of the air and daily precipitation.

This research used data from the automatic station of the CIIAGRO (**Fig. 3**) located at Estr. de Segunda Ordem to Eng. Schimdt, in São José do Rio Preto, at the coordinates of lat. 20º51′12.54″S and long. 49º19′29.84″O.

Table 1. H/W ratio estimation for each measuring point

Measuring point	H/W ratio
1	0.39
2	0.47
3	0.50
4	0.36
5	0.29

The measuring height of this automatic station is approximately 2 meters above the vegetated surface. The temperature and humidity sensor used is a HMP45, by Campbell, whose temperature measurement ranges from -39.2 ºC to 60 ºC, with an accuracy of ± 0.5 ºC (-40 ºC), ± 0.4 ºC (-20 ºC), ± 0.3 ºC (0ºC), ± 0.2 ºC (20 ºC), ± 0.3 ºC (40 ºC) and ± 0.4 ºC (60 ºC) (Rocha *et al.*, 2011).

The equipment used at urban collecting points were date-loggers by HOBO Pro v2, U23-001 model, mark ONSET, with temperature sensors (precision of -40ºC to 70ºC) and humidity (0-100%), both with a 1% error. All equipment was protected from direct sunlight and rain.

The criteria for the installation of equipment considered the following order of priority:

(a) Suitable conditions for the study, away from the influence of vegetation or vertical barriers;
(b) Authorization of resident/merchant for the installation of the equipment on your lot;
(c) Possibility of fastening on poles of the power supply to the batch, 3 meters tall, with south orientation (checked by a compass).

Adjusting the Oke model for data adjustment and validation

The values of the maximum heat island intensity ($\Delta T_{u-r(max)}$) were estimated from the urban geometry of data collecting points using the Oke model (1981) – **Eq. 1** – while considering the scale of the "urban cover layer". The nocturnal heat island was calculated (urban-rural air temperature) for a period of 15 days (from June 9, 2013 to June 23, 2013) in parallel and based on real data measured, which corresponded to 14 nocturnal periods. To this end, only nocturnal values were considered (6:00 pm at 6:00 am) and the maximum value was selected for each day.

Fig 3. Aerial photo of the city of São José do Rio Preto with an indication of the location of the CIIAGRO station (rural) and the area where the measuring points are concentrated (urban).

The data obtained by the Oke model and the real measured data were then compared to the adjustment required for verification and validation.

RESULTS

Nocturnal heat island intensity

Table 2 represents the highest values of the "urban-rural temperature difference" (maximum intensity of heat island) for each day and measured point based on the measurements over the nocturnal period (6:00 pm to 6:00 am).

Table 2. Maximum intensity of heat island of the points measured (from 6:00 pm at 6:00 am, in ºC)

Date	Point 1	Point 2	Point 3	Point 4	Point 5
09.06.2013	3.60	3.80	4.30	3.30	2.70
10.06.2013	3.70	3.90	4.60	3.30	2.50
11.06.2013	4.50	4.60	5.40	4.10	3.20
12.06.2013	4.00	4.90	5.50	4.00	3.50
13.06.2013	4.10	4.10	4.50	3.60	2.70
14.06.2013	4.40	4.90	5.40	4.20	3.40
15.06.2013	2.50	2.10	2.60	2.30	1.90
16.06.2013	1.90	1.70	2.30	2.30	1.90
17.06.2013	3.30	3.30	4.00	2.80	2.30
18.06.2013	4.20	4.40	5.00	3.50	2.90
19.06.2013	3.80	4.90	4.30	3.70	3.00
20.06.2013	3.90	4.20	4.90	3.60	2.70
21.06.2013	3.40	3.20	3.70	3.40	3.10
22.06.2013	2.90	2.70	3.20	2.60	2.30
Maximum values:	4.50	4.90	5.50	4.20	3.50
H/W	0.39	0.47	0.50	0.36	0.29

The highest values for each point did not necessarily occur on the same day. However, this task has allowed the identification of the largest difference between the urban and rural temperatures for each point. These values were compared with the values calculated by the Oke model based on urban geometry (H/W) of each point.

Based on the entire measurement period, the highest rates of heat island intensity occur at night, more specifically between 8:00 pm and 9:00 pm (see examples in **Fig. 4**).

Checking and adjusting the model of Oke

The maximum intensity values of the urban-rural temperature ($\Delta T_{u\text{-}r(max)}$) were calculated based on the data or urban geometry of each collecting point using the Oke model (1981). The calculated values were compared with the corresponding real values (**Table 3**).

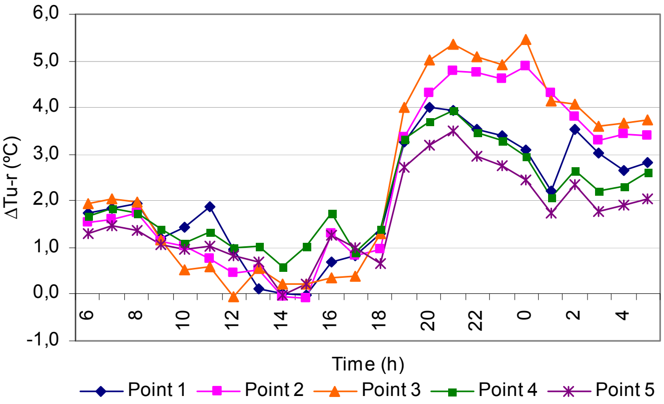

Fig 4. Values of urban-rural difference in temperature (ºC) from 6:00 am (12.06.2013) at 5:00 am (13.06.2013).

Table 3. Maximum intensity of heat island of the points measured (from 6:00 pm at 6:00 am, in ºC)

$\Delta T_{u\text{-}r(max)}$:	OKE model (Eq. 1)	Measured
Point 1	3.67	4.5
Point 2	4.45	4.9
Point 3	4.73	5.5
Point 4	3.34	4.2
Point 5	2.48	3.5

The difference found between the results obtained by the Oke model and the collected data can be explained by the different methodologies in the two experiments. In the first study, the temperature sensor was set on the floor of the center of the canyon of the model because the study was based on experiments with reduced models in the laboratory. In the second study, the temperature sensor was installed in a real urban environment at a height of 3 meters above the ground. In addition, the first study is limited in its capability to simulate a city, and the data from the second study include interference from several variables (e.g. air humidity, winds and different albedo) that were not considered because the intention was to isolate the urban geometry.

However, a significant correlation between these data was noted, which resulted in a high determination coefficient ($R^2 = 0.9686$) seen in **Fig. 5**. This indicates a good fit of the simulated data to the sample of measured data.

Figure 5 suggests that the Oke model can be adapted to the conditions of the city studied according to **Eq. 2**.

$$y = 0.8202x + 1.4574 \quad (2)$$

being:
y = adapted model;
x = result of the Oke model.

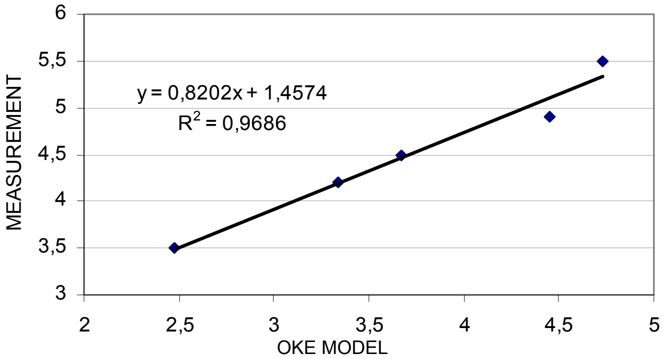

Fig 5. Measuring data × Oke model equation and coefficient of determination (R^2).

Including the equation by Oke, the adapted model takes the following form:

$$y = 0.8202 \cdot [7.45+3.97 \cdot \ln(H/W)] + 1.4574 \quad (3)$$

Table 4 presents the values calculated by the adapted model, and **Fig. 6** establishes comparisons between the actual, simulated and adapted values.

Table 5 provides a study of the influence of the urban geometry on the nocturnal heat island by comparing the results obtained with the Oke model to those obtained with the adapted model for several different H/W ratios.

The graph generated from the values in **Table 5** (**Fig. 6**) seems to prove what had been previously stated by Oke (1981): for SVF values > 0.25 (H/W = 2; 1; 0.5; 0.25), the relationships appear to be approximately linear, but for smaller values of SVF (H/W = 3; 4), they are likely curved.

Table 4. Heat island real and adapted values

$\Delta T_{u\text{-}r(max)}$:	Measured	Adjusted model (Eq. 3)
Point 1	4.5	4.51
Point 2	4.9	5.16
Point 3	5.5	5.39
Point 4	4.2	4.23
Point 5	3.5	3.52

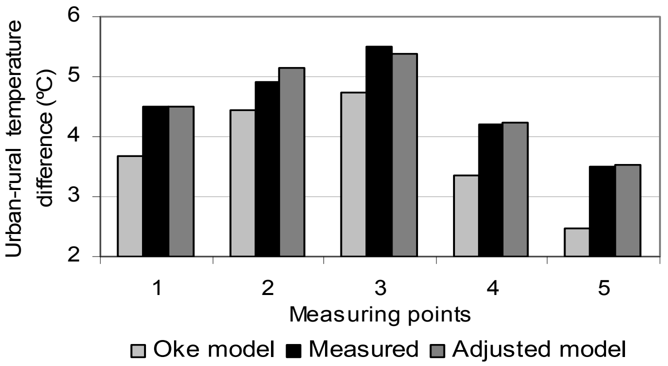

Fig 6. Maximum heat island intensity estimated by the Oke model measured from the collected data and calculated by the adapted model.

Table 5. Maximum intensity of heat island predicted by the Oke model and the fitted model to the specific condition of this study for 6 different values of H/W.

H/W	OKE Model x = 7.45+3.97ln(H/W)	Adjusted Model y = 0.8202x + 1.4574
0.25	1.95	3.07
0.5	4.70	5.36
1	7.45	7.65
2	10.20	9.94
3	11.81	11.28
4	12.95	12.23

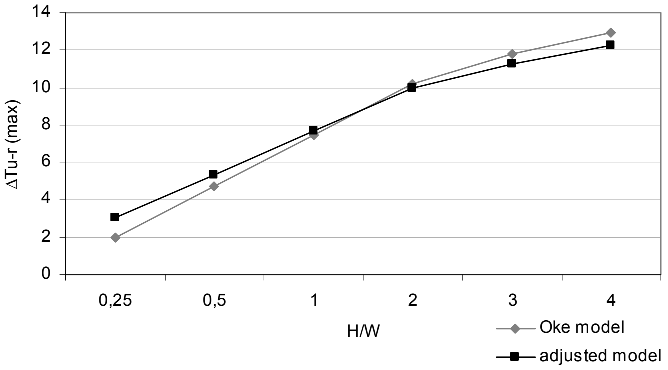

Fig. 6 Maximum heat island intensity estimated by the Oke model and the model adapted to the conditions of the city selected for this study.

CONCLUSIONS

The results obtained in this investigation corroborate the study by Oke (1981), demonstrating that the urban geometry contributes effectively to the process of the formation of a nocturnal heat island.

The actual data measured correlate well with the data simulated by the Oke model, despite the differences in the procedures between the two experiments. The adjusted Oke model appeared to be applicable in real urban areas, specifically in the city that was selected for this study.

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