Revista Brasileira de Climatologia
Brazilian Journal of Climatology

URBAN MORPHOLOGY AND PREDICTION MODELS OF MICROCLIMATIC PHENOMENA IN DRY ATMOSPHERIC CONTEXT

Morfologia urbana e modelos de previsão de fenômenos microclimáticos em contexto atmosférico seco

Morfología urbana y modelos de predicción de fenómenos microclimáticos en contexto de atmósfera seca

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Abstract: The morphological configuration of cities has a direct influence on microclimatic variation. The predominant built composition in certain areas, the high rates of waterproofed surfaces, vegetation scarcity and water surfaces can have a significant impact on the temperature and humidity values on inhabited areas, often exposing the population on unhealthy environments. The aim of this paper is to elaborate a prediction microclimatic model variation of four different Local Climate Zones (LCZ) exposed to a dry atmospheric condition in an altitude tropical region. The method was developed

on three stages, the first one, refers to a collect campaign of temperature and humidity variation in four different urban environments, LCZ D, LCZ 1, LCZ 5 and LCZ 9 in São José do Rio Preto, Brazil. The representative microclimatic behavior of each area of the city in relation to the performance of a dry air mass was recorded. The second stage involved the microclimatic collected data, which were submitted to a statistical analysis with ANOVA tests, serving as the basis for the development of prediction microclimatic models variation for each LCZs. After validating the models, it was verified, in the third stage, the urban area that presented morphological characteristics that allow the occurrence of high temperature waves and reduced indexes of relative humidity. The produced models for predicting urban microclimatic show a very high capacity of representation to estimate the temperature values in different areas of the city, since in all cases values of R exceed 80%. The results showed that the area with LCZ5 presents the longest periods of heat exposure, which should receive more attention from planners in relation to investments in urban green infrastructure.
Keywords: Prediction Microclimatic Model. Local Climate Zones. Urban Heat Island.

Resumo: A configuração morfológica das cidades tem influência direta na variação microclimática. A composição predominantemente construída em determinadas áreas, os altos índices de impermeabilização, a escassez de vegetação e superfícies d'água podem ter um impacto significativo nos valores de temperatura e umidade das áreas habitadas, expondo muitas vezes a população a ambientes insalubres. O objetivo deste trabalho é elaborar um modelo microclimático de previsão da variação de quatro diferentes Zonas Climáticas Locais (*Local Climate Zones*; LCZ) expostas a uma condição atmosférica seca em uma região tropical de altitude. O método foi desenvolvido em três etapas, a primeira, referente a uma campanha de coleta de variação de temperatura e umidade em quatro ambientes urbanos distintos, ou seja, LCZ D, LCZ1, LCZ5 e LCZ9 em São José do Rio Preto, Brasil. Foi registrado o comportamento microclimático representativo de cada área da cidade em relação ao desempenho de uma massa de ar seco. A segunda etapa envolveu os dados microclimáticos coletados, que foram submetidos a uma análise estatística com testes ANOVA, servindo de base para o desenvolvimento de modelos microclimáticos de predição de variação para cada LCZ. Após validação dos modelos, verificou-se, na terceira etapa, a área urbana que apresentou características morfológicas que permitem a ocorrência de ondas de alta temperatura e índices reduzidos de umidade relativa. Os modelos produzidos para previsão microclimática urbana apresentam uma capacidade de representação muito alta para estimar os valores de temperatura em diferentes áreas da cidade, pois em todos os casos os valores de R ultrapassam 80%. Os resultados mostraram que a área com LCZ5 apresenta os maiores períodos de exposição ao calor, o que deve receber mais atenção dos planejadores em relação aos investimentos em infraestrutura verde urbana.
Palavras-chave: Modelo Microclimático de Previsão. Zonas Climáticas Locais. Ilha de Calor Urbano.

Resumen: La configuración morfológica de las ciudades tiene una influencia directa en la variación microclimática. La composición predominantemente edificada en ciertas áreas, los altos índices de superficies impermeabilizadas, la escasez de vegetación y superficies de agua pueden tener un impacto significativo en los valores de temperatura y humedad en las áreas habitadas, exponiendo a menudo a la población a ambientes insalubres. El objetivo de este trabajo es elaborar un modelo microclimático de predicción de la variación de cuatro diferentes Zonas Climáticas Locales (*Local Climate Zones; LCZ*) expuestas a una condición atmosférica seca en una región tropical de altitud. El método fue desarrollado en tres etapas, la primera, se refiere a una campaña de recolección de variación de temperatura y humedad en cuatro ambientes urbanos diferentes, es decir, LCZ D, LCZ1, LCZ5 y LCZ9 en São José do Rio Preto, Brasil. Se registró el comportamiento microclimático representativo de cada zona de la ciudad en relación al comportamiento de una masa de aire seco. La segunda etapa involucró los datos microclimáticos recolectados, los cuales fueron sometidos a un análisis estadístico con pruebas ANOVA, sirviendo como base para el desarrollo de modelos microclimáticos de predicción de variación para cada ZLC. Después de la validación de los modelos, se verificó, en la tercera etapa, la zona urbana que presentó características morfológicas que permiten la ocurrencia de ondas de alta temperatura e índices reducidos de humedad relativa. Los modelos producidos para la predicción del microclima urbano muestran una altísima capacidad de representación para estimar los valores de temperatura en diferentes zonas de la ciudad, ya que en todos los casos los valores de R superan el 80%. Los resultados mostraron que el área con LCZ5 presenta los períodos más largos de exposición al calor, lo que debería recibir más atención por parte de los planificadores en relación con las inversiones en infraestructura verde urbana.

Palabras clave: Predicción Modelo Microclimático. Zonas Climáticas Locales. Isla de Calor Urbano.

Submetido em: 04/03/2022
Aceito para publicação em: 29/07/2022
Publicado em: 19/08/2022

1. INTRODUCTION

The accelerated urbanization and the climatic change in local levels can affect the health of inhabitants, the economy and the environment, necessitating the development of studies concerning to the impact on local atmospheric processes caused by urban surfaces. The development of computational tools as well as high-resolution climate models over the last three decades made possible that several microclimatic effects could be, in an accurate form, spatially reproduced. This progress has been responsible to increase the understanding about the interaction between land, water, atmosphere, and built environment (GARUMA, 2018). According to the same author, climate models should combine with intra-urban environments models to predict the possible impacts of surfaces and urban geometry.

As reported by Ng, (2009); Krüger *et al.*, (2010); Erell *et al.*, (2014); Jihad and Tahiri, (2016), the urban morphological conditions can decisively affect microclimatic parameters, in general. In this way, the formation of Urban Heat Islands (UHI), the energy consumption of buildings and the damage to the sense of comfort, and the population's health, should be foreseen and mitigated (Tsiros, 2010; Krüger, 2017; Salvati *et al.*, 2017).

Several scientific studies have as subject to anticipate, estimate, simulate and measure climatic impacts resulting from changes in natural environment of the cities, which aim to apply evaluation techniques of physical phenomena based on statistical modeling methods of information related to urban climate (Koutroumanou-Kontosi *et al.* 2022, Hollósi *et al.* 2021, Yang *et al.* 2013). Mills *et al.* (2015) also highlight that there is a lack of information on tropical cities in general way, which reinforces the need to register and predict UHI phenomena.

Many representation models and simulations of urban climatic phenomena usually resort to simplifications of environmental and constructive characteristics of the city – as cube-shaped buildings and street canyons – and climatological phenomena, in order to facilitate the systemic investigation (Hebbert, 2014). Physics, mathematics, information science, geography, engineering, urbanism and atmospheric science are interacting to analyze, for example, the consequences for human heat sensation arising from the solar cycle and anthropogenic flows.

These initiatives allow minimizing the quantity of laborious field observation campaigns, partially replacing them with numerical simulations, considering that numerical models enable parametric analysis based on models with field data. One example was the study developed by Ho *et al.* (2014), it demonstrated the ability of a regression model, calibrated with various Landsat scenes and meteorological information in warm summer days, to produce a map of the maximum distribution of the air temperature in Greater Vancouver, Canada. The spatial regression approach has proved to be useful for intra-urban mapping of air temperature variability and easily applicable in other cities.

The processing, standardizing, organization, and dissemination of the large amount of information required to accurate climate-related effects around the world, are still science challenges to face over the next years. Ng *et al.* (2009), Wong *et al.* (2011), Yuan *et al.*, (2011) and Ng *et al.* (2012) mention that although many difficulties in integrating planners and scientists, latent issues of sustainability induce the incorporation of urban climate principles into urban project parameters.

Arnfield (2003) reports that experimental simulations and other mathematical models can make a major contribution to a database formation and in determining of climatic parameters in urban areas. The development of such observing tools facilitates the understanding of complex physical phenomena with the precision required, and thus, minimizes the use of costly equipment and long measurement campaigns.

Gobakisa *et al.* (2011) applied models of artificial neural network and learning paradigms to predict the intensity of Urban Heat Islands (UHI) in Athens, Greece. Based on data of intra-urban temperature and global solar radiation to elaborate different models of advanced training processes of artificial intelligence, the aim of proposal was to evaluate the precision and efficiency of each model. In this way, the models could be applied to evaluate the peak periods of energy consumption during heat waves in summer and to estimate the possibilities of UHI occurrence in certain areas of the city. László & Szegedi (2015) developed a Multiple Linear Regression Model (MLR) that describes the spatial structure and UHI development under favorable synoptic conditions in a town in Ukraine. The results showed that UHI intensity can be estimated in any parts of the town with an accuracy of 0.4°C using the MLR model. The study also points out those surface new parameters should be incorporated into the model, as Sky View Factor (SVF) and Aspect Ratio (H/W).

The magnitude and frequency of UHIs are dependent of several factors, among those, excel the characteristics of the urban surfaces, the geometry of the buildings, the time of the occurrence, the climate, the geographical position of the city and the vegetation. The detection and characterization of phenomena that involve the emergence of UHI necessarily depend on measuring procedures by remote sensing or the variation of temperature and humidity in Urban Canopy Layers. Wong *et al.* (2011) emphasize the frequently application of Computational Fluid Dynamics (CFD) simulations and energy balance models in UHI estimates; nevertheless, the complexity of the urban environment imposes some limitations for the analysis. Prediction models can range from simple three-dimensional representations to complex ones, which aggregate behavioral characteristics of materials, surfaces, and weather forecast models. So that the simulations be as closer as real-scale phenomena, the models must incorporate the largest range as possible of physical parameters related to the urban climate, as anthropogenic heat fluxes.

According to Xu *et al.* (2017), numerical simulations related to research with climate prediction models have also presented more accurate results when morphological information are considered to establish scenarios for climate change (Chen *et al.*, 2011; Salamanca *et al.*, 2011; Wang & Dai, 2015). Therefore, it is fundamental to understand how the morphological characteristics cause impacts to urban climate, considering the dynamic aspects of the construction of the cities, especially in developing countries, which in general, have a great difficulty in keeping urban database updated. In accordance with Mills (2010), the access and the comprehension of data related to the infrastructure of built spaces and about macro, meso and microclimate data provide information and establish a broader understanding of urban dynamics, including economic, social and demographic aspects. So, the climatic vulnerability and the possible detrimental effects of urban space appropriation may be considered in intervention projects on the proposed scale to each study.

Bueno *et al.* (2012) mention that Urban Canopy Models (UCMs) have been developed to represent urbanized areas and to elaborate simulations with urban weather forecasting tools. In general, meteorological information above the Urban Canopy Layer are available through short-term experiments, which limits the UCM application by scientific and professional communities, including construction engineers and urban planners. On the other hand, it is easy to find weather information in climatical data files obtained from measurements in meteorological stations, usually located in open areas outside of the city, for example, at airports.

From these findings, Bueno *et al.* (2014) developed a simple and efficient computational model called Urban Weather Generator (UWG), based on information of meteorological stations, to predict the air temperature variation in Urban Canopy Layers. The model has been improving as it considers information that is more precise. Information pertaining to morphology, configurations of the constructions, distribution in urban space, long-wave radiation, heat exchanges between Urban Boundary Layer and atmosphere, and the effects of the surface roughness in airflow. The calculated temperature data and the data measured by the weather stations network in Singapore and European cities were compared and delivered a satisfactorily performance for all climate conditions. Therefore, can be applied the proposed model by UWG in different climates and urban configurations to estimate the effects of UHI and the demand for energy consumption, as well as it points out ways for considering climatic parameters in the spatial and physical planning of cities.

Considering that, the formation of the cities evolves several aspects not always based on technical and scientific matter. Garuma (2018) reports that to shape a city statistically is important because the composition of the urban fraction depends on the application of different materials that set out the thermal and radiative properties of urban surfaces. In regional studies, it is fundamental to classify the regions with the same building materials, once the morphology of the building and city also depends on cultural issues. Thus, geographic knowledge about the region under investigation is also a crucial point to represent accurately the urban regions in urban climate models.

Nowadays, among the most reverberant initiatives, are the methods proposed by Oke (2006) and Stewart & Oke (2012), both aim to identify the potential of each area to alter the local climate and to characterize the transition between different urban areas. In these cases, the scales are check by dimensions and morphological characteristics that compose an urban landscape. Consequently, it is necessary to describe the properties of urban areas that may affect the atmosphere in relation to structure, surface coverage, urban tissue, and urban metabolism.

In the specific case of classification proposal of the Local Climate Zones (LCZ), Stewart & Oke (2012) studied the landscape for a new climatic classification, particularly for studies in urban areas, which units are determined with physical and cultural characteristics that give to the landscape, properties that can influence the temperature in the Urban Canopy Layer. It is considered that the structure shape affects the local climate by changing the airflows, by the carriage of atmospheric heat and through the net radiation of short and long waves. In turn, surface coverage can modify the albedo, the potential availability of moisture, and the heating and cooling of the soil. Thus, it becomes possible to classify the landscape dividing it into structures with properties nearly homogeneous and generate seventeen classes of similar prototypes under conditions of the natural and constructed environments. Structure, materials, human activities, and uniform surface coverage define the LCZs. They extend horizontally for hundreds of meters and are characterized based on criteria as Sky View Factor, height and width of urban canyons, constructed surface fraction, impermeable surface fraction of the soil, proportion of permeable area of the soil, and roughness of the elements that compose the landscape.

The system was elaborate to standardize the worldwide research in urban climate starting from the urban geometry and common references, according to a certain temperature regime on dry surfaces, with quiet atmosphere, clear nights in areas with mild landscape. Tools of World Urban Data Access Portal (WUDAPT) Ching *et al.*, (2014) and Mills *et al.*, (2015) which elaborate and provide high-resolution databases in relation to the shape of the buildings, vegetation and the land use for urban climate models. Data sets may also include information about anthropogenic heating and population data, depending on the nature of each study.

Thereafter, several studies related to the urban climate have been using the classification method in LCZ to describe and understand its thermodynamic effects on the environments, in order to assist urban design practices. Middel *et al.* (2014) aimed to find effective ways of design and strategies to improve the urban thermal environment using the three-dimensional microclimatic models produced with the aid of ENVI-met software during the summer months. The simulation of air temperature variation was done near the ground for residential neighborhoods in Phoenix, concluding that spatial differences in cooling process are strongly related to solar radiation and local shading patterns.

With the detailed study of different intra-urban climatic environments, it is possible to identify the responsible agents for the dynamic of constructed spaces, to check suggestions and the urban planning with a more technical and scientific basis. The objective of this paper is to elaborate a mathematical model of microclimatic variation forecast of four different LCZs exposed to a dry atmospheric condition, in an altitude tropical area. Such model should be applied as a predictive and identifying tool of microclimatic phenomena in urban environments and consequently, sites which tend more for occurrences of risk areas for human exposure to heat.

2. MATERIALS AND METHODS

The method is separated into three stages, the first one refers to the on-site verification of the temperature and humidity variation in four different configurations of urban environments, that are LCZ D, LCZ 1, LCZ 5 and LCZ 9 in São José do Rio Preto, São Paulo, Brazil.

Was registered the representative microclimatic behavior of each area of the city in accordance with the actions of a warm and dry air mass. For this study, have been used data analysis according to the detection of periods that have been characterized by stable atmospheric behavior, clear sky, weak wind, intense horizontal solar radiation and wind direction varying between northeast and southeast.

The second stage, submitted the collected data to a multivariate statistical analysis, serving as basis for the development of prediction mathematical models of microclimatic variation to each one of the LCZs. After the verification of the model validity, in third stage were indicated urban areas that submitted possible risks of exposure to heat according to their respective morphology.

2.1. Site Characterization

Peel *et al.* (2007) updated the world climate classification map created by Köppen-Geiger and classified São José do Rio Preto as Aw, which corresponds to Altitude Tropical Climate with dry winters and warm and rainy summers. The winter average temperature remains around 18°C and 30° C in the summer. Annual average of relative humidity is around 70% and may reach below than 20% in driest months. The predominance of wind in the São José do Rio Preto region during the winter months occurs in the southeast direction, especially at night.

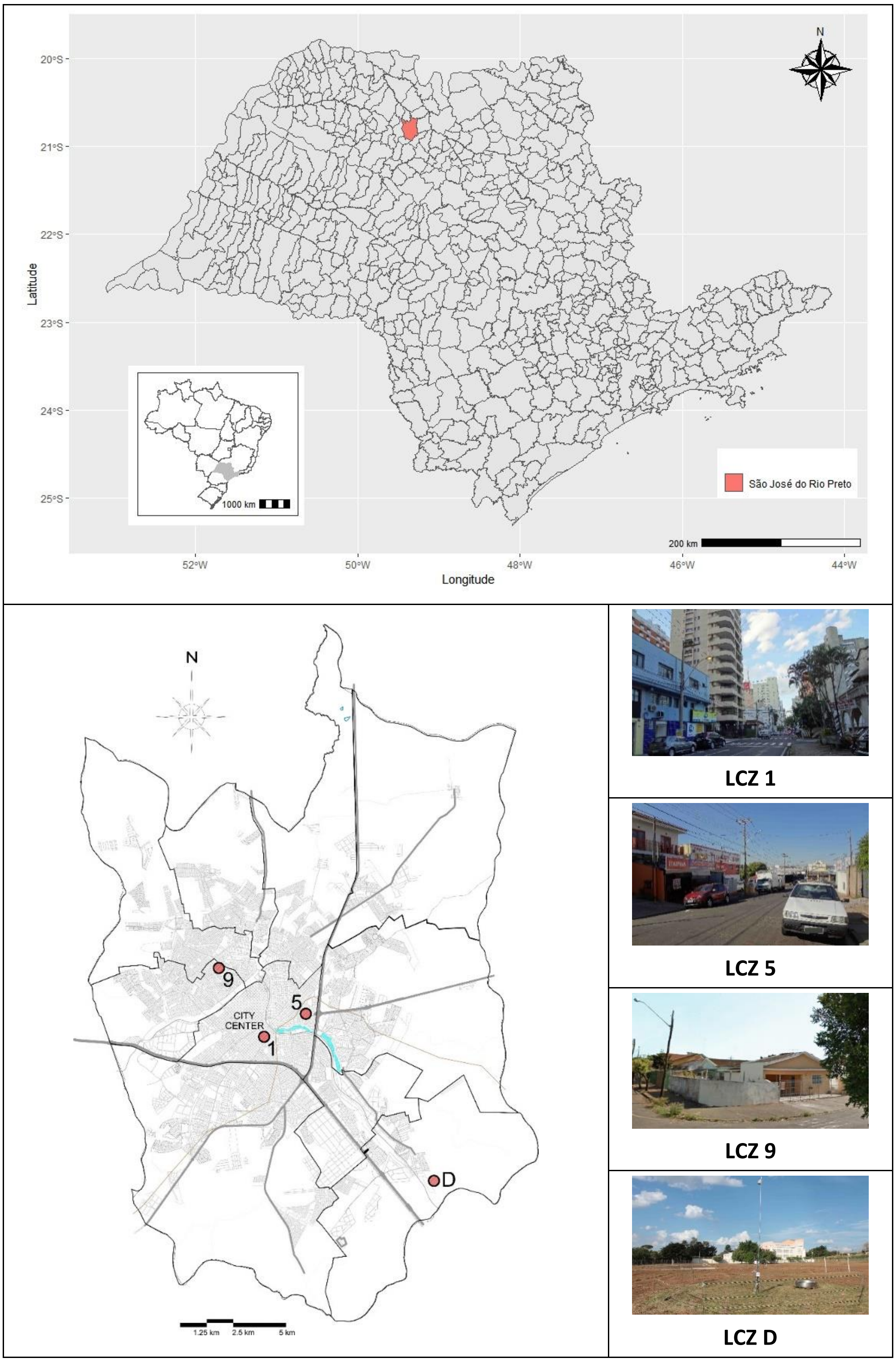
The buildings density and geometry of surrounding canyons, affect the direction of the dominant wind that focuses on the data collection points in the intra-urban network, so it is an important parameter to ensure methodological rigor in microclimatic studies.

The wind coming from the northeast direction is also quite frequent and predominates mainly under dominion of the Atlantic Tropical Mass, what results in stable and dry atmosphere periods throughout the winter (Nimer, 2008). The surface area municipality is 431,32 km² and the relief is relatively smooth, with altitudes varying between 442m and 588m (SJRP, 2022), Figure 1.

The elaboration of the microclimatic prediction model used as reference the thermal behavior of four LCZs during a stable and dry atmosphere period. The classification of each LCZ, based on parameters proposed by Stewart & Oke (2012), in other words, sky view factor (SVF), relationship between height and width of the urban canyon (H/W), built surface, permeable surface, average height of roughness and soil roughness.

To calculate the fraction of each parameter, a study region with a radius of 200m was delimited in relation to the data collection point. The combination between the physical parameters results in the morphology generic description of the urban environment to under consideration.

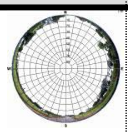
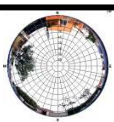
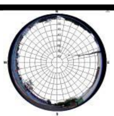
Figure 1 – São José do Rio Preto Site



Source: Adapted from SJRP (2019 e 2022).

SVFs were determined from the generated images by a fisheye lens, coupled to a photographic camera positioned at a height of 1.5m from the ground, vertically aligned upwards. Later, were treated the images in the Rayman 1.2 software, developed by Matzarakis (2009), as recommended by Matzarakis *et al.* (2010), Table 1.

Table 1 – Characteristics of each LCZ studied.

LCZ	SVF	H/W	Built surface	Impermeable surface	Permeable surface	Average height of	Soil roughness (m)	View
LCZ D Low Plants	 **0.80**	0.25	7%	8%	92%	2	0.5	
LCZ 1 Compact high-rise	 **0.35**	4	35.8%	100%	0%	30	0.1	
LCZ 5 Open midrise	 **0.69**	0.4	28%	95.2%	4.8%	5	0.3	
LCZ 9 Sparsely Built	 **0.73**	0.4	13.5%	71%	29%	5	0.2	

Source: Authors (2022).

Between June 9 and July 7 of 2013, the microclimatic behavior of the four urban configurations were monitored, considering the variables of air temperature, relative humidity, solar radiation, direction, and wind speed.

With the HOBO Pro V2 U23-001 sensors, placed inside naturally ventilated PVC shields according to recommendations and specifications of manufacturer, at 3m in height, the data of air temperature and humidity in canopy layer were hourly collected, Figure 2.

In addition, to assist the task of characterize the atmospheric phenomena in macro scale, a Meteorological Station, HOBO, model U30, located at LCZ D with the following components, Figure 2:

Figura 2 – Characteristics of each LCZ.

Figure 2a - Sensor HOBO Pro V2 U23-001

Operation band: -40 ºC to 70 ºC
Precision: 0,2 ºC above 0 ºC till 50 ºC
Resolution: 0,02 ºC a 25 ºC
Response time:
40 min in the moving air 1 m/s

		
Figure 2b – Data logger HOBO U30	**Figure 2c** – Solar Radiation Sensor - precision de ± 10W/m²	**Figure 2d** – Temperature Humidity Sensor – THB-M002. ± 0,2ºC.
		
Figure 2e – Anemometer with 5-degree accuracy and resolution of 1.4 degrees	**Figure 2f** - 6w solar power panel and 6v voltage	**Figure 2g** - Field Assembly Installation

Source: Authors, Adapted from ONSET (2022).

2.2. Statistical Analysis

Regression models were used (Equation 1) based on the analysis of variance (ANOVA). The estimative of temperature (T), and because of the relative humidity (RH), and the solar radiation (SR) for each one of the four investigated areas (LCZ 9, LCZ 5, LCZ 1, LCZ D) was made at the level of 5% of significance; consisting in a useful tool in estimating temperature variation due to the built characteristics of each LCZ.

$$T = \alpha_0 + \alpha_1 \cdot RH + \alpha_2 \cdot SR + \alpha_3 \cdot RH \cdot SR + \varepsilon \quad (1)$$

From Equation 1, αi are the adjusted coefficients by the Ordinary Least Squares (OLS) and ε consists of the random error, with the adjustment quality evaluated by the adjusted coefficient of determination (R^2aj). The ANOVA of the regression model enables to judge if the model and the coefficients are significant. To verify which of the terms (RH, SR, RH · SR) of the model significantly affect the temperature values, was used the Pareto graph.

For each region and during the specified period (9 June to 7 July of 2013 - 28 consecutive days), on average, 673 measurements of each variable were made (i.e., Temperature (T), Relative Humidity (RH) and Solar Radiation (SR)). Those results became basis for the generation of mathematical models.

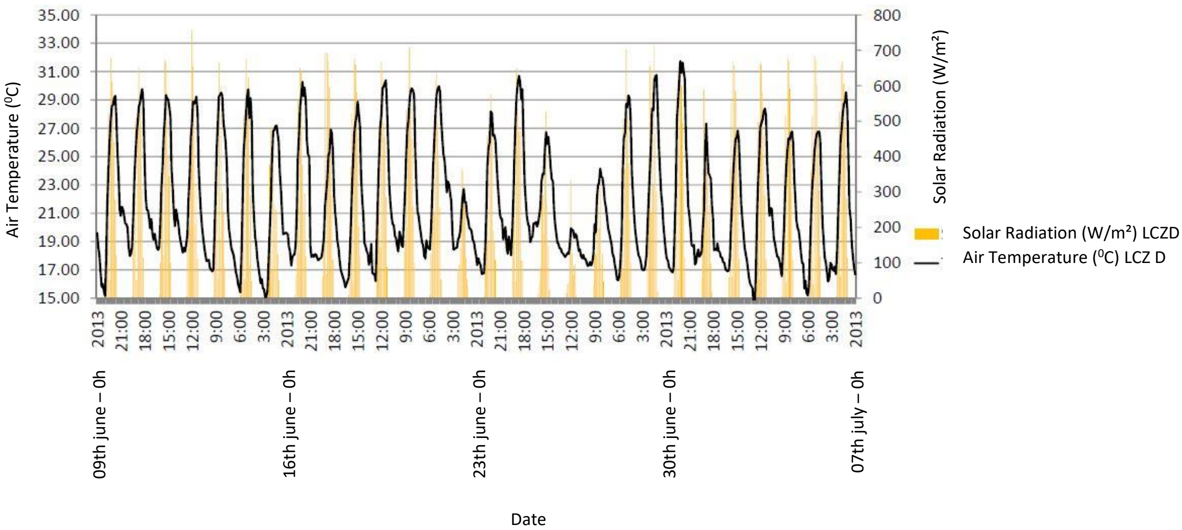
Once the models for each region were found, in sequence, the Tukey test (at level of 5% of significance) was used to evaluate the influence of the region factor (LCZ 9, LCZ 5, LCZ 1, LCZ D) on the temperature values, making possible to evaluate if the regions configurations significantly affect the temperature values. From the Tukey test, A denotes the group with the highest mean value, B as the second highest mean value, and so on. Equal letters entail groups with equivalent statistical means with each other.

3. RESULTS AND DISCUSSION

The 28 days of data collection are characterized by submit several consecutive days with suitable atmospheric characteristics to detect effects of urban climate, such as intense solar radiation with maximum values close to 700W/m^2, low index of relative humidity during the days, wind direction varying between northeast and southeast with maximum speeds below 4.5 m/s.

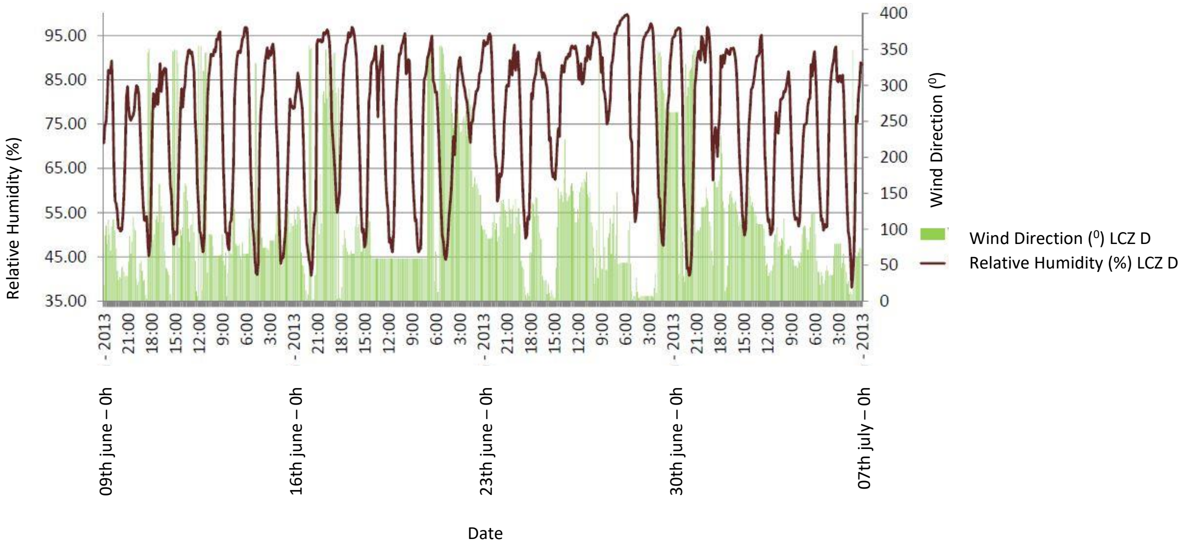
Since there are great possibilities for the UHI occurrence, this period can be used as a sampling for the composition of mathematical models that predict the possible consequences in urban microclimate in other parts of the city starting from the considered variables. The Figures 3 and 4 show the complete variation of air temperature; relative humidity and solar radiation in absolute values measured in LCZ D, and the combination of others LCZs values, in modeling are considered.

Figure 3 – Solar Radiation (W/m²) and Temperature (⁰C) on LCZ D



Source: Authors (2022).

Figure 4 – Wind Direction (⁰) and Relative Humidity (%) on LCZ D



Source: Authors (2022).

Table 2 shows the mean ($\overline{x}$), lower (Min) and higher (Max) values of each measured property (T, RH, SR) and the confidence intervals (CI) of average (at level of 95% of confidence) for each one of the four regions that were considered.

Table 2 – Climatic properties results.

Properties	LCZ 9			
	$\overline{x}$	Min	Max	CI
T (°C)	22.46	15.90	31.00	(22.17; 22.74)
RH (%)	71.03	36.00	100.00	(69.80; 72.25)
SR (W/m^2)	136.55	0.60	756.90	(120.57; 152.53)
Properties	**LCZ 5**			
	$\overline{x}$	**Min**	**Max**	**CI**
T (°C)	22.71	16.23	32.07	(22.412; 23.016)
RH (%)	71.28	33.35	100	(70.020; 72.543)
SR (W/m^2)	136.55	0.6	756.9	(120.57; 152.53)
Properties	**LCZ 1**			
	$\overline{x}$	**Min**	**Max**	**CI**
T (°C)	22.61	16.37	30.47	(22.333; 22.886)
RH (%)	72.21	38.53	99.06	(71.076; 73.340)
SR (W/m^2)	136.55	0.6	756.9	(120.57; 152.53)
Properties	**LCZ D**			
	$\overline{x}$	**Min**	**Max**	**CI**
T (°C)	21.68	14.48	31.74	(21.360; 22.003)
RH (%)	76.18	38.1	99.8	(74.946; 77.407)
SR (W/m^2)	136.55	0.6	756.9	(120.57; 152.53)

Source: Authors (2022).

Considering that LCZ 5 has a spatial configuration where sealed areas predominate, few open areas that allow winds activity, scarce vegetation and buildings pattern that promotes a few shaded areas during most of the day, it was possible to record the higher temperatures among all evaluated areas. On the other hand, LCZ 1, although it also presents 100% of sealed areas, the solar radiation does not reach the horizontal surfaces due to the depth of urban canyons and the smaller SVF of the four areas. Thus, there are many shaded areas by the own building's geometry, what induce, in some cases, the formation of canalized urban ventilation and greater possibility of cooling process of urban canopy layer.

Equations 2 to 5 express the regression models obtained for the air temperature estimation for LCZ 9, LCZ 5, LCZ 1 and LCZ D region, respectively. Pareto graphs of each obtained model are presented in Figure 5.

$$T_{LCZ\,9} = 36.227 - 0.19738 \cdot RH + 0.00499 \cdot SR - 0.000051 \cdot RH \cdot SR \qquad [R = 83.80\%] \tag{2}$$

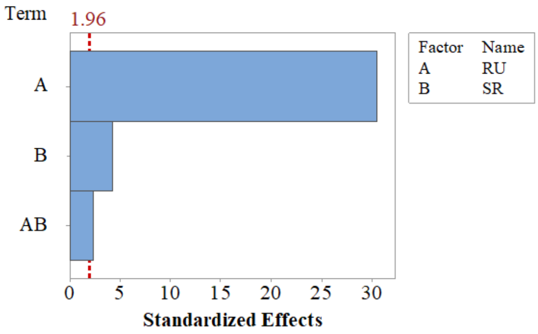
$$T_{LCZ\,5} = 37.561 - 0.21125 \cdot RH + 0.00267 \cdot SR - 0.000020 \cdot RH \cdot SR \qquad [R = 88.19\%] \tag{3}$$

$$T_{LCZ\,1} = 37.877 - 0.21383 \cdot RH + 0.00252 \cdot SR - 0.000021 \cdot RH \cdot SR \qquad [R = 5.81\%] \tag{4}$$

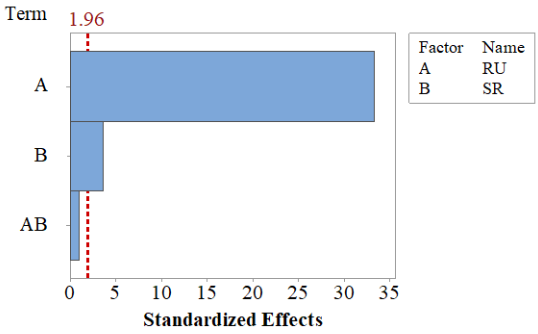
$$T_{LCZ\,D} = 38.620 - 0.22681 \cdot RH + 0.00154 \cdot SR + 0.000016 \cdot RH \cdot SR \qquad [R = 9.76\%] \tag{5}$$

According to the obtained results from Equations 2, 3, 4 and 5, the values of R vary from 83.8% to 89.76%, what shows a very high capacity of representation to estimate the temperature values in different areas of the city, since in all cases values of R exceed 80%.

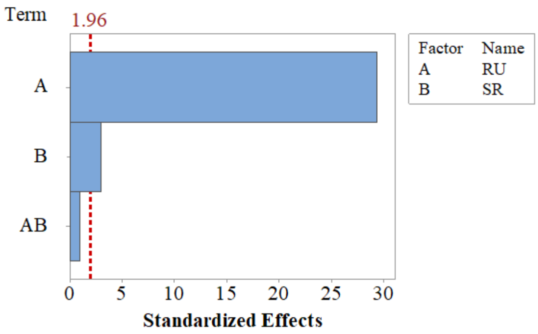
Figure 5 – Pareto graphs for the regression model obtained for the regions LCZ 9 (a), LCZ 5 (b), LCZ 1 (c) e LCZ D (d).



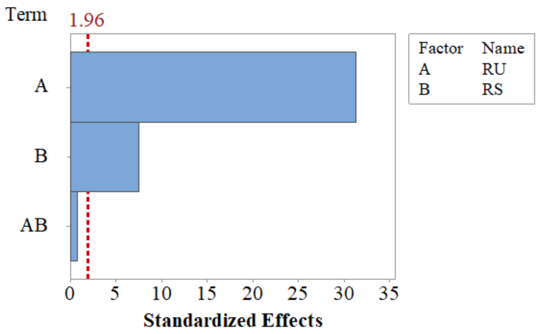
(a)



(b)



(c)

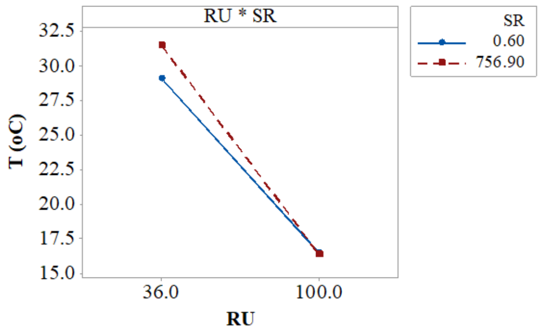


(d)

Source: Authors (2022).

From model of Equation 2, all used terms were considered significant by ANOVA (Figure 5). Increases in RH entail reductions in temperature values, while increases in SR lead to increases in the values of the estimated variable. Because of the interaction effect is significant (RH · SR), this factor stats to impact more in the model than in individual factors. Figure 6 illustrates the interaction graph of these two factors in the temperature estimative for the LCZ 9 region.

Figure 6 – Interaction Graph of the factors (RH · SR) in the estimative of temperature in LCZ 9 region.



Source: Authors (2022).

From Figure 6 to 36% relative humidity (minimum recorded), the temperature for solar radiation of 756.90W/m^2 (maximum recorded) was 8.20% higher than the obtained temperature. For 0.60W/m^2 of solar radiation (minimum registered), and for 100% (maximum recorded), the effect was the inverse, the obtained temperature for 0.60W/m^2 of solar radiation was only 0.70% higher than the temperature for the radiation of 756.90W/m^2.

From Equation 2, 8.02% of the collected data set (T, RH and SR), (54/673) consisted of atypical observations, what resulted in the adjusted determination coefficient value equal to 83.80%, evidencing the good precision of the model. For the LCZ 9 region, the lowest estimated value of the temperature of the air (16.39°C) came from the combination of RH = 100% and SR = 756.90W/m^2, and the highest value (31.50°C) came from the combination of RH = 36.0% and SR = 756.90 W/m^2.

From Equation 3, the individual factors were considered significant by ANOVA in the estimation of temperature values, however, the interaction of factors was considered non-significant (Figure 5b), with the model demonstrating an adjusted determination coefficient equal to 88.19%, what shows accuracy of this adjustment. Because the interaction of the factors (RH · SR) does not be significant, the removal of this term from Equation 3 resulted in Equation 6, whose adjusted determination coefficient is the same of the complete model (Equation 3), that reinforces the small significance of the interaction effect in the air temperature estimation for the LCZ 5 region.

$$T_{LCZ\,5'} = 37.727 - 0.21350 \cdot RH + 0.001504 \cdot SR \qquad [R = 88.19\%] \qquad (6)$$

From Equation 6, increases in RH affect in reductions in local air temperature, while increases in SR provide increases in air temperature. For this adjustment, 6% of the results set (T, RH, and SR) were considered atypical observations. For the LCZ 5 region (Equation 6), the lowest estimated value of air temperature (16.38°C) came from the combination of RH = 100% and SR = 0.60W/m², and the highest value (31.75°C) came from the combination of RH = 33.35% and SR = 756.90 W/m².

These facts elucidate that, as the solar radiation hits the constructed surfaces, the evaporation process increases, and the relative humidity decreases gradually in LCZs. Thus, the dry condition of the acting air mass on territory tends to contribute to the elevation of air temperature and to enhance the possibilities of UHI occurrence.

From LCZ 1, only the factors interaction was considered non-significant, as in the case of the LCZ 5 region model. The exclusion of the factors interaction in Equation 4 results in Equation 7, it should be mentioned that the adjusted determination coefficient remained unchanged (85.81%), what reinforces the small significance of the interaction effect among the factors.

$$T_{LCZ\,1'} = 38.039 - 0.21602 \cdot RH + 0.001238 \cdot SR \qquad [R = 85.81\%] \qquad (7)$$

From Equation 7, just 5.79% of set results (T, RH and RS) were considered as atypical observations. The adjusted determination coefficient of 88.81% shows the good quality of the adjustment also obtained in temperature values estimation for LCZ 1 region.

From Equation 7, increases in RH affect in reductions in local temperature, while increases in SR provide increases in air temperature. The lowest estimated temperature (16.64°C) was derived from combination of RH = 99.06% and SR = 0.60W/m², and the highest value (30.65°C) came from the combination of RH = 38.53% and SR = 756.90W/m².

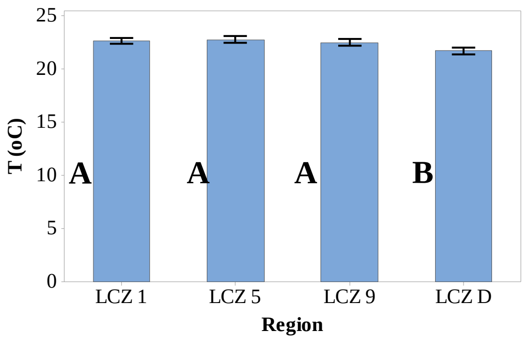
From Equation 5 (LCZ D region), just the interaction of the factors was considered non-significant by ANOVA. The exclusion of the interaction term resulted in Equation 8, which provided the same result of determination coefficient of the complete model (89.76%).

$$T_{LCZ\ D'} = 38.482 - 0.22507 \cdot RH + 0.002523 \cdot RS \qquad [R = 89.76\%] \qquad (8)$$

From Equation 8, increases in RH affect in reductions in local air temperature, while increases on SR provide increases in air temperature. The lowest estimated temperature value (16.02°C) was derived from the combination of RH = 99.80% and SR = 0.60W/m^2, and the highest value (31.82°C) came from the combination of RH = 38.10% and SR = 756.90W/m^2.

The Tukey test (Figure 7) was used to verify the possible differences between Equations 2, 6, 7 and 8, what allows to assess if the regions (LCZ 9, LCZ 5, LCZ 1, LCZ D) influenced significantly on the estimated values of temperature.

Figure 7 – Results of the Tukey test of the region factor (LCZ 9, LCZ 5, LCZ 1, LCZ D) on the estimated temperature values (Equations 2, 6, 7 and 8).



Source: Authors (2022).

From Figure 7, the estimating models of the air temperature of LCZ 9 (Equation 2), LCZ 5 (Equation 6) and LCZ 1 (Equation 7) regions, considered statistically equivalent by Tukey test, entailing that the air temperature estimation of these three regions can be obtained with either of equations 2, 5 or 7. This result indicates that there is no difference of such regions in temperature values, unlike the LCZ D (Equation 8).

Equation 8 gave estimated average values significantly lower than the estimated average values by the equations of the other regions, what entails that the temperature to LCZ D have to be estimate with Equation 8. The larger vegetated surfaces, the lack of buildings and impermeable paved areas are characteristic of LCZ D, what demonstrates the contribution so that the estimated air temperatures be lower than other three evaluated areas.

According to Oke (2006), Middel *et al.* (2014), Mills *et al.* (2015), the strongest intra-urban air temperature variations effect can be found about four hours after sunset. While the natural surface cools quickly, the urban surfaces cool more slowly, for many reasons in which we may highlight as lower SVF, greater heat storage in central areas and lack of vegetation. During the early morning hours, the air temperature over densely built urban tends to be cooler, than that over the natural surface due to overshadowing of surfaces.

4. FINAL CONSIDERATIONS

Among the main contributions of this paper is the creation of prediction models of microclimatic phenomena in tropical areas in warm and dry atmospheric condition based on morphological characteristics of a city. From the thermal behavior of urban environments already implemented, it is possible to estimate the microclimatic effects of a future spatial intervention with a high degree of reliability.

The obtained results from this research enable to conclude that the regression models were significant and applicable to predict impacts in urban climate considering four different spatial configurations according to the classification proposed by Stewart & Oke (2012). The adjusted determination coefficients varied between 83.80% and 89.76%, what shows the high accuracy of the obtained adjustments. The statistical analysis showed equivalence of the models for air temperature estimation between LCZ 9, LCZ 5 and LCZ 1 regions. The same did not occur with the model for LCZ D region, which resulted in average values significantly lower than the estimated average values of air temperature for the other regions.

In all adjustments, increases in relative humidity values resulted in reductions in estimated air temperature values, while increases in solar radiation rates provided increases in air temperature in urban canopy layers. The spatial configuration of LCZ 5, with many sealed areas and sparse vegetation, demonstrated higher air temperatures and lowest relative humidity indexes. Thus, regions with morphological characteristics like LCZ5 may present longer periods of heat exposure and may even represent health risks to the inhabitants. The results of Middel *et al.* (2014) show that advection is important for temperature distribution, and that, spatial differences in cooling process are strongly related to solar radiation, ventilation, and local shading patterns, as well as in the middle of the afternoon, dense urban forms can create freshness islands in Phoenix, USA. In this way, the classification concept in LCZ is useful, not just for studies about distribution and configuration of Urban Heat Island, but also for purposes of planning and design.

Therefore, similar areas to LCZ 5 should receive greater attention from planners regarding to investments in green infrastructure such as urban parks creation, more frequent maintenance of Permanent Preservation Areas around water bodies, and an increase in the number of adjacent arboreal species in promenade. Among the suggestions for new studies is the development of methodologies for mapping urban areas in tropical cities that can estimate the number of inhabitants exposed to extreme climatic conditions, especially in areas with built environment with characteristics that intensify the heat accumulation in urban canopy layers. The improvement of data collection processes from both surface and satellites, should contribute to validate estimation models and improve mitigating actions of the climatic effects obtained through the pressure caused by population growth, changes in use and occupation of the land and air pollution, which sustainability studies, urban resilience and adaptation to climate change are closely related.

The integration of urban spatial planning with microclimatic assessment tools is still a complex challenge, but with a promising future. According to Wong *et al.* (2011) there are four stages to effectively integrate scientific methods with urban planning actions, which include the availability of climate data, the integration of data into three-dimensional city platforms, the application of simulation procedures and thermodynamic effects, and mutual collaboration to provide urban information with the provision of tools to create urban scenarios.

Thus, Garuma (2018) affirms that it is increasingly necessary to strengthen collaboration between climatologists and modelers at local, regional and global levels to facilitate the access to urban climate parameters in definition of strategies to spatial occupation and to determinate the most suitable urban morphology to thermal comfort conditions. Krüger (2017) shows, through ANOVA tests, how and how much local factors affect the perception of the microclimate by open spaces' users, registering representative differences between sites with several indexes of the Sky View Factor in the city of Curitiba, Brazil. These results further reinforce the need for improvement of prediction methods of microclimatic effects in spatial interventions.

In view of this, the assessed regression models contribute to conclude that exists the need to promote equitable distribution of investments in environmental resources and services that enable the minimization of extremes air temperature and increase humidity indexes in dry seasons in José do Rio Preto, São Paulo. Therefore, the results reported until now, should technically support the concepts of urban legislation and mechanisms of control on urban morphology in future spatial interventions, which should favor the improvement of the urban space, and promote the implementation of green infrastructure and buildings consistent with the climate of each city.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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