Artigo Original

DOI:10.5902/2179460X28619

Ciência e Natura, Santa Maria v.40, e26, 2018
Revista do Centro de Ciências Naturais e Exatas - UFSM
ISSN impressa: 0100-8307
ISSN on-line: 2179-460X

CIÊNCIA e NATURA

Recebido: 15/08/2017 Aceito: 19/01/2018

Sky view factor and thermal comfort analysis using hemispheric images from Google Street View and wavelet in an urban ecosystem of the Brazilian Cerrado

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Abstract

This study analysed the sky view factor (SVF) in one of the hottest cities of the Brazilian Cerrado, and its correlation with thermal comfort in two urban sections with different characteristics, as well as the physiological equivalent temperature (PET) and predicted mean vote (PMV) indices. The analyses were complemented by a characterisation in the frequency field for a 12-month cut-off in the same year of relative air temperature and humidity. The study area was located in the central region of Cuiabá, Mato Grosso, due to the presence of regions with high urbanisation indices and small parks; one section was composed of an afforested area, and the other section, varied building types. To obtain the SVF, the Google Street View image database was used, from which fisheye images were reconstructed and the SVF was determined using RayMan software. The PET and PMV indices were determined for the morning, afternoon, and evening, with comfort in the morning and discomfort in the afternoon and evening. Traditional Morlet wavelets were plotted for time series of relative air temperature and humidity during 2015, which qualitatively demonstrated some of the dynamics of these micrometeorological variables for tropical Cerrado climate.

Keywords: Afforestation. Thermal indices. Traditional wavelet.

1 Introduction

In recent history, cities have undergone major changes in their geometry, with ever-higher buildings, rugged and impermeable roofs, and vegetated areas transformed into commercial areas, which has increased pollution and air heating. Together, these elements generate what is referred to as an urban climate. Urban areas are composed of various components, including squares, streets, avenues, and buildings. Buildings are the most characteristic elements of cities, and can form urban canyons where buildings line both sides of a street, especially in the central area of cities.

The emergence of heat islands demonstrates the climatic change caused by human activity in cities. Heat islands are characterised by an excess of heating of the urban atmosphere compared to that of undeveloped surroundings, mainly in the denser and more verticalised areas of a city (OKE, 2006). One parameter used to verify these formations is the sky view factor (SVF), a dimensionless parameter referred to as a configuration or angular factor (SOUZA et al., 2010) that is defined as the percentage of open sky, with values ranging between 0 (total obstruction) and 1 (uninterrupted view) (OKE, 1981, 1987; RUAS, 2001).

Analytical methods for the SVF calculation use equations based on site geometry. Watson and Johnson (1984, 1987) proposed methods based on the azimuth angle, elevation, and angles of neighbouring buildings. Oke (1981) also calculated the SVF based on the geometry of the urban environment based on canyons of infinite length with defined heights and widths. According to Souza et al. (2010), the SVF can be obtained using photographs and images from digital cameras equipped with fisheye lenses. Grimmond et al. (2001) suggested the SVF could be calculated with an analyser (Li-COR LAI 2000) fitted with an optical sensor and fisheye lens. For both methods, data collection, processing, and storage are relatively simple, and it is necessary to work with estimates of the absolute mean error and with sky condition analyses.

As indicated by Lin et al. (2010), high SVF values represent open sites that tend to exhibit higher heat frequencies in summer compared to highly shaded sites. Chen et al. (2012) studied the relationship between the SVF and air temperature, and showed that the SVF, especially the mean value, was inversely correlated to daytime intra-urban temperature differences. These studies demonstrate that the SVF can be used to parameterise the effect of urban geometry. According to Carrasco-Hernandez et al. (2014), the SVF is useful not only for describing canyons but also for modelling and predicting atmospheric conditions on urban micro-scales, which affect energy exchanges, temperature variations, and air circulation phenomena.

Several indices can be used to evaluate comfort in external spaces, including the physiological equivalent temperature (PET) and predicted mean vote (PMV). The PMV, developed by Fanger (1970), consists of a prediction method of thermal analytical comfort based on a human body thermal balance model, which is a function of personal parameters (e.g. physical activities and clothing type) and environmental parameters (e.g. air temperature, mean radiant temperature, relative humidity, and air velocity) (ABREU & LABAKI, 2010; SOTTO, 2016). Höppe et al. (1999) developed the PET thermal comfort indices for external or internal areas based on radiant and air temperature, relative humidity, and wind. Gulyás et al. (2006) in Freiburg, Germany, and Spangenberg et al. (2007) in São Paulo, Brazil, verified the PET and PMV thermal comfort indices in open spaces and observed that afforestation efficiently influenced the microclimate.

Thermal comfort can be considered as one application area of urban climatology, where the atmospheric elements relative to air temperature and humidity directly influence humans. It is also important to analyse the general variation in bioclimatic conditions (MATZARAKIS et al., 1999; ANDRADE, 2005; LABAKI et al., 2013).

According to Cadima (2000), Santos & Teixeira (2001), the thermal study of external urban areas is relevant to the valorisation of the variabilities that occur, taking an adaptive approach of individual variables to the thermal environment, which is extremely spatially and temporally variable. Thus, the application of the traditional Morlet wavelet mathematical transformation as a frequency-domain analysis technique has been used in micrometeorological variables studies to verify trends and seasonal variations (TORRENCE & COMPO, 1998; ADDISON, 2017).

For example, air temperature and relative humidity in urban environments cover different spatiotemporal scales, making it necessary to use statistical analyses that enable the understanding of repetitive patterns. Thus, time series analyses using wavelet transform include different dimensions of time, scale, and energy intensity to identify behavioural patterns as a qualitative tool for studying urban dynamics (TORRENCE & COMPO, 1998; FENG & LIANG, 2015). Torrence & Webster (1998) analysed the transformed wavelets tool and determined that when values are assumed without analysing their meaning more deeply, there is a risk of false interpretation, modifying the energy profile and some of the dynamics of the microclimate.

Therefore, in this study, the Google Street View image database was used to obtain fisheye images of two urban areas in the Cerrado of Mato Grosso, Brazil with the aim of calculating the SVF using an alternative and low-cost method to analyse urban surfaces, while verifying their power spectra through traditional Morlet wavelets.

2 Methodology

2.1 Study Area

Cuiabá, the capital of Mato Grosso, Brazil, is located in the geodesic centre of South America and is a hub for various economic activities. It has an area of 3,224.68 km², of which 254.57 km² (7.89 %) is urban and 2,970.11 km² (92.1 %) is rural. It is located between the geographic coordinates of 15°10’S–15°50’S and 54°50’W–58°10’W at an altitude of 165 m above sea level, and is located in the geomorphologic province known as the Cuiabana Depression. According to the last demographic census (IBGE, 2015; LEÃO, 2007), it has 551,350 inhabitants (Figure 1).

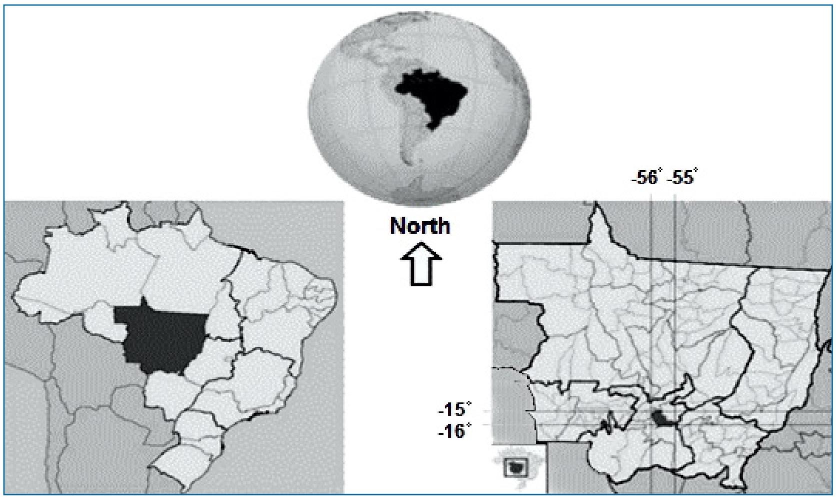

Figure 1 - Location of the city of Cuiabá, Mato Grosso, Brazil
Source: Callejas (2012)

The Cuiabano Cerrado climate is classified as Aw (i.e. tropical semi-humid) under the Koppen’s Climatic Classification, with four to five dry months (May–September) and daily temperature maximums of 30–36°C. It has two well-defined seasons, dry (autumn and winter) and rainy (spring and summer). It has an average annual precipitation index of 1,500 mm and average monthly temperature of 22–32°C (MAITELLI, 2005; CALLEJAS, 2012). The hot, dry period extends from June to September, although some years experience more pronounced periods. The air humidity can sometimes drop to minimums of 18–40%.

In this region, the predominant wind direction is north and northwest for much of the year, and south during winter. Geologically, Cuiabá is situated in a geographic depression, resulting in extremely low mean wind frequencies and speeds. According to Curado (2011), Cox (2008), Luz (2013), the vegetation cover of Cuiabá is composed of remnants of Cerrado, Cerradão, riparian forests around the rivers, and exotic vegetation.

2.2 Image collection and SVF, PET, and PMV calculations

According to Matzarakis & Mayer (2000), afforestation contributes significantly to improving the thermal comfort of urban environments, as it attenuates incident solar radiation Carlson (2006). Other elements also interfere with thermal quality, such as the presence of permeable areas, type of buildings in the surrounding area, and the construction materials used. While vegetation absorbs and transforms heat, built surfaces retain this heat and transmit it back. Thus, shaded areas with permeable spaces tend to be cooler than areas with high concentrations of buildings and pavement (SANTAMOURIS, 2001; KUWABARA et al., 2002; ANDRADE, 2003; CHENET et al., 2004; RIBEIRO, 2016), and two areas, a vegetated and built up area, were considered in this study.

Figure 2 - Section 1, Av. Leônidas Mendes (left) and the SVF of Section 1 (right)
Source: Google Earth Pro, 15°34’08.48”S, 56°03’56.70”W

Images of the two study areas were collected from Google Street View. The first area (Section 1) is a segment of 200 m of the Avenida Leônidas Mendes located at the entrance of the Morada do Ouro neighbourhood. This area is considered to be of environmental interest, as it is wooded, and the road separates a small municipal park called Massairo Okamura. In total, 20 images were collected in the first section, which is illustrated in Figure 2.

Section 2 is a 1000-m segment of Avenida Historiador Rubens de Mendonça, which runs through part of the Araes neighbourhood and intersects with Avenida Leônidas Mendes. In this section, 100 images were captured, as illustrated in Figure 3. Both sections are considered to belong to the central area of Cuiabá.

Figure 3 - Section 2, Av. Historian Rubens de Mendonça (left) and the SVF of Section 2 (right).
Source: Google Earth Pro, 15°35’05.58”S, 56°04’29.74”W

The images were treated with the free version of the Paint.net software and imported into Matzarakis’ RayMan software to calculate the SVF and obtain results for the PET and PMV thermal comfort indices.

As per Moreno (2006), the PMV was obtained from environmental (i.e. temperature, relative humidity, mean radiant temperature, and relative air velocity) and personal (i.e. metabolic rate and thermal resistance of clothing) variables to determine the degree of thermal comfort or discomfort of an environment following the thermal sensation scale shown in Table 1.

Table 1 - Thermal sensation scale for PMV

PMV	Thermal sensation
-3	Very cold
-2	Cold
-1	Slight cold sensation
0	Comfortable
+1	Slight heat sensation
+2	Warm
+3	Too hot

Source: adapted from Fanger (1970) and Kulka (2014)

The thermal sensation scale ranges from -3 to +3, and allows for a thermo-environmental evaluation of reduced or elevated temperatures, where thermal comfort lies within the range of -0.5 to +0.5 for cold and hot environments, respectively (OLIVEIRA et al., 2010; MACIEL et al., 2011).

By definition, the PET index has the same value as the air temperature of a standard environment, which provides the same amount of stored heat or the same surface temperature of the human body under the joint action of the environmental variables considered. The internal climate of the standard environment assumes the following values: mean radiant temperature (°C) equal to the air temperature (°C), air velocity equal to 0.1 m/s, water vapour pressure (Pa) equal to 12 hPa, relative air humidity of 50%, and air temperature of 20°C (at ~12 hPa). Nince (2013) compared the calibration of Monteiro’s PET index (2008) for tropical climates (São Paulo), with those of Matzarakis (1999) and Hirashima (2011), as shown in Table 2.

The PMV and PET comfort indices can be calculated using RayMan. This model considers factors that affect the human body, which in turn, if constantly releasing energy, interfere with the body’s rate of heat loss, affecting its sensation of temperature. Thus, factors such as solar radiation, cloudiness, roughness of the urban morphology, and surface energy balance interact with humans (MATZARAKIS et al., 2011).

Table 2 - Comparison of the PET (°C) indices of Monteiro (2008), Matzarakis (1999), and Hirashima (2011)

Thermal sensation	*PET* (*Monteiro*)	*PET* (*Matzarakis*)	*PET* (*Hirashima*)
Very hot	*Above* 43	41	35.5
Heat	31–43	35–41	31–35.5
Not too hot	26–31	23–35	30.5–31
Neutral	18–26	18–23	15.5–30.5
A little cold	12–18	8–18	12–15.5
Cold	4–12	4–8	≤ 12
Very cold	≤ 4	≤ 4	

Source: Nince (2013)

According to Matzarakis and Rutz (2005) and Matzarakis et al. (2000, 2007), the RayMan model is based on German standards and related methodologies, addressing topics such as environmental meteorology, interactions between the surface and atmosphere, and climatic and bi-meteorological analyses of the urban climate. In this context, the human component is considered from two perspectives, human thermal comfort and urban planning. Urban areas generally receive different levels of insolation, so the amounts of energy will differ; because the temporal scale in urban climatology varies with the synoptic scale, and the type of time conditions the spatial variation of the climatic elements in the urban space, the use of soil in the urban environment is the major responsible factor for the variation in climatic elements, in particular on a microclimatic scale. Mathematical tools such as the wavelet transform appear to corroborate with studies of the time series of the air temperature, air relative humidity, and wind, and analyses in the urban climate.

Therefore, we used the Morlet non-orthogonal complex wavelet, which is defined in Eq. (1), where ψ is the wavelet value for a non-dimensionless parameter, w0 is the frequency and gives the number of oscillations within the wavelet itself, and t is the period or time-scale analysis. We considered the Morlet wavelet as a combination of a periodic function with a Gaussian curve displaced along the frequency axis by f0 (centre frequency) of the Gaussian spectrum, which was chosen as the characteristic frequency of the Morlet wavelet. For the traditional Morlet transform in this study, we used the algorithm by Torrence (<http://paos.colorado.edu/research/wavelets>, last accessed 10/27/2016), according to Eq. 2.

$$\psi(t) = \pi^{-0,25} e^{iw_0 t} e^{-1/2t^2}, for w_0 \geq 5 \tag{1}$$

$$TWC(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t)\, \psi\left(\frac{t-b}{a}\right) dt \tag{2}$$

Ehlers (2009) stated that wavelets have moving windows in time–space that dilate or compress to capture low- and high-frequency signals, which aid in the analysis of microclimatic variables. Addison (2017) stated that w0 = 6 can be adopted to satisfy the admissibility condition. Domingues et al., (2016) in turn, reported that, in contrast to sinusoidal functions of infinite extent (long wavelength), wavelets are small waves with an area equal to zero in the graph.

For the PET and PMV index calculations, the variable values were selected to reflect those of July, since this is a critical period in terms of energy density, and Google Street View images were captured for the respective areas during this time.

3 Results and Discussion

We determined differentiated values for the SVF, which is a continuous quantitative variable, for Sections 1 and 2 by performing frequency distributions by classes of values and an exploratory analysis using Statgraphics software. The mean SVFs were affected little by outliers, and values that represented typical elements were identified and their variabilities were quantified.

The histogram plot for Section 1 in Figure 4 shows a downward-facing concavity, indicative of a normal series, with a mean of 0.307, standard deviation of 0.0216564, and frequencies varying gradually on one side and more abruptly on the other. Larger SVF values were not observed in this section, perhaps because afforestation prevented the passage of solar radiation.

The distribution of the data from Section 1 exhibited a slight right-skewed asymmetry, and was slightly leptokurtic (i.e. values were concentrated around the Gaussian distribution peak).

In Section 2, the SVF was affected by variations in urban roughness. In situ observations in this section were suggestive of the formation of two segments with higher (Figure 5 right) and lower (Figure 5 left) building heights. Similar to Section 1, Section 2 exhibited a downward concavity indicative of a normal series, with a mean of 0.425 and standard deviation of 0.0452353, and was influenced by two parameters, one on each side of the distribution (Figure 6).

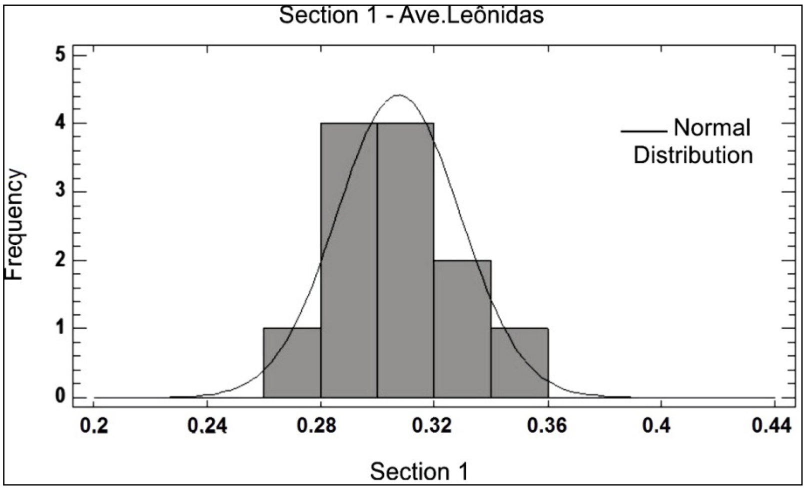

Figure 4 - Histogram of the frequency of SVF values and adhesion tests for Section 1
Source: Created by the authors

Figure 5 - Fisheye images of urban Section 2, showing different roughnesses
Source: Created by the authors

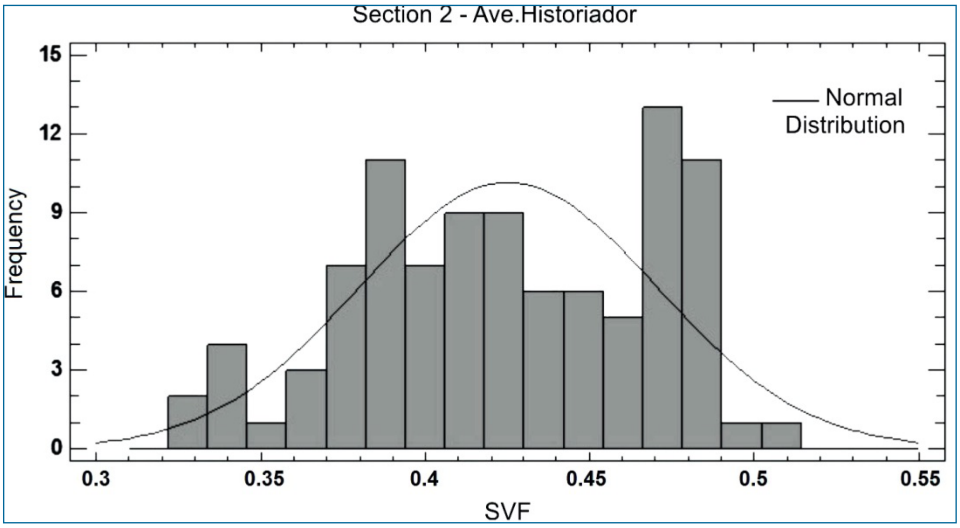

Figure 6 - Histogram of the frequency of SVF values and adhesion tests for Section 2
Source: Created by the authors

Further, the distribution of Section 2 data showed negative kurtosis (i.e. left-skewed asymmetry) and a platykurtic distribution of the Gaussian curve, indicative of SVF values with variations in urban roughness. Thus, both the normalised asymmetry and kurtosis were within the expected range.

Data from both sections demonstrated non-adherence to the exponential distribution and adherence to log-normal and normal distributions. A disadvantage of these graphs is the subjectivity that results from their visual interpretation; thus, non-parametric tests were used to derive more objective results. The Shapiro-Wilk (SW) test is the most powerful test for small samples, as in Section 1, and the Kolmogorov-Smirnov (KS) and SW tests are adequate for cases such as Section 2. These tests can be interpreted as the measurement of the degree of agreement between the data and the null hypothesis of the SVF. The results of the KS and SW tests showed adherence to the tests, and thus acceptance of the normality hypothesis.

In addition, several alternative distributions were tested, the results of which are presented in Table 3. The degree of agreement of the exponential distribution was null for both sections. By mathematical definition, SVF has a log-normal distribution because it is a random variable with a normal distribution, which was corroborated by our results. Table 3 also presents results of the Mann-Whitney and F tests considering the SVF analysis of Sections 1 and 2. The null hypothesis was effectively rejected.

Table 3 - Results for the analysis of means and standard deviation between urban Sections 1 and 2

Statistics	SVF Section 1	SVF Section 2
Average [Standard deviation]	0.307 [0.0216564]	0.425 [0.0452352]
F-test to Compare Standard Deviations	F = 0.229203 P-value = 0.0100249	
Mann-Whitney test to compare medians	W = 1142.0 P-value = 3.2345E-8	

Source: Created by the authors

Figure 7 shows box plots of the Mann-Whitney test results (SOKAL & ROHLF, 1995), which graphically translate the notion of position, dispersion, and asymmetry of the SVF distributions for Sections 1 and 2 as a function of their parameters. There was a statistically significant difference between the medians at the stipulated (95%) confidence level. Therefore, the SVF values for the afforested and unforested areas differed. Lower SVF values represent greater shading on the surface, directly influencing variations in material temperatures and, consequently, air temperature.

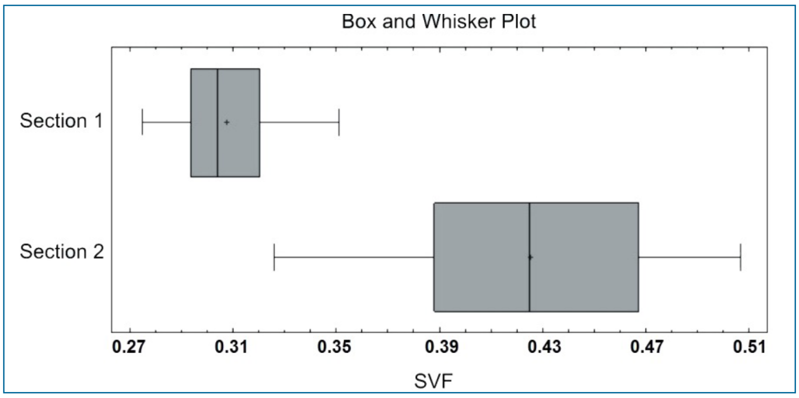

Figure 7 – Box plot for Sections 1 and 2
Source: Created by the authors

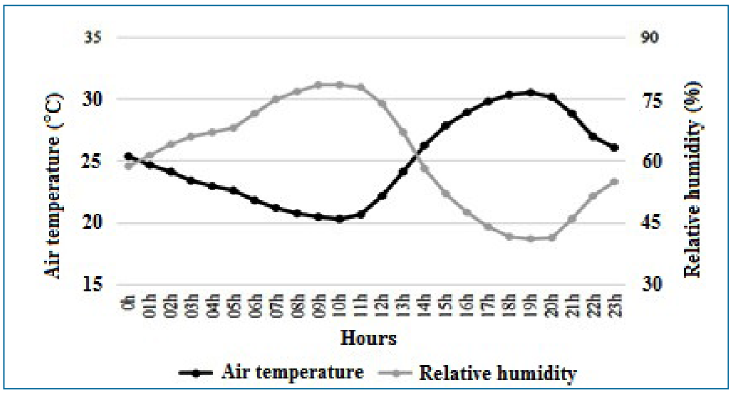

Figure 8 - Average hourly temperature and relative humidity in July 2015
Source: INMET 2012

The highest temperatures and humidity in July 2015 occurred in the late afternoon and early evening (17:00–20:00 local time) (Figure 8). Climatic data combined with regional studies of surface temperature variation with different land uses and occupations could indicate higher temperatures in sites with intense verticality, high population density, and low vegetation cover (LOMBARDO, 1985; SANTOS, 2012). Found that an increase in the urban network was directly linked to an increase in the mean minimum temperature, with a rise of 0.073°C per year from 1970 to 1992 due to accentuated urban growth during that time.

For the data calculated using the RayMan software for both sections, the PET index table calibrated by Monteiro (2008) and PMV by Fanger (1970) were used, as presented in Tables 2 and 3, respectively. The results indicated that comfortable conditions only occurred in the morning (Figure 9). The highest PET (°C) and PMV values were observed in both sections in the afternoon, with PET values of 31.4°C in Section 1 and 33.56°C in Section 2, equivalent to the thermal perception of heat. Section 2 presented greater warming than Section 1, where the largest difference occurred around 14:00, with a difference of 2.16°C, indicative of the influence of SVF on thermal comfort. Sections 1 and 2 had PMV values of 2.05 and 2.32, respectively, equivalent to a thermal perception of warmth. In the evening, the two sections had similar results, as shown in Figure 9.

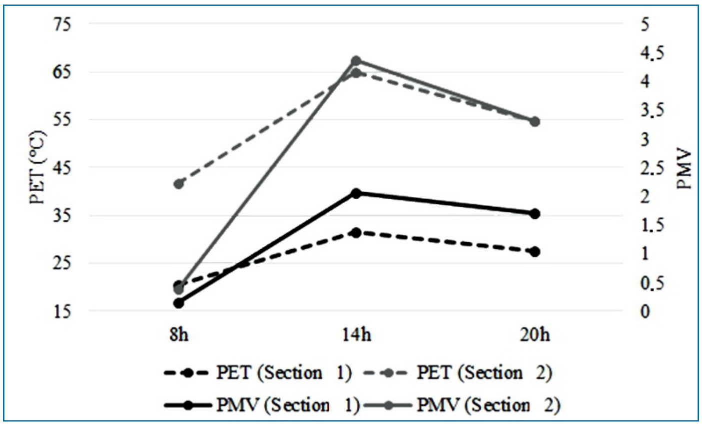

Figure 9 - Thermal comfort indexes (PET and PMV) for Sections 1 and 2
Source: Created by the authors

In recent years, the traditional Morlet wavelet transform technique has been used in time series analyses of micrometeorological and climatic data, allowing the extraction of useful information. The air temperature and air relative humidity data were obtained from the Cuiabá A-901 Station of the National Institute of Meteorology. To complement the Wavelet analysis of air temperature and relative humidity, we also considered wind. The region under study was submitted to the previous wavelet analysis. Thus, when analysing the results of thermal comfort indices for Sections 1 and 2, we also considered the power spectra of air temperature, relative humidity, wind, global solar radiation, and precipitation.

In wavelet analysis, spatial data is complex, and space and time are merged. Each time series are random signals, which, even collected under the same conditions, are different. Figures 10, 11, and 12 show the traditional Morlet wavelets (TWC) for air temperature, air relative humidity, and wind, respectively (GRINSTED et al., 2004; RIVA et al., 2015; YI & CHU, 2012). We considered a) the variability of the series signals, b) the scalogram of the air temperature variable, for example, where the x-axis gives the parameter period and the y-axis gives the parameter scales intensity, c) the global power spectrogram, and d) the annual variable variance, with a white Gaussian noise model with 5% significance level for variance above the dashed line. The colour palette used had a logarithmic distribution, and the significance analysis of coefficient amplitudes verified the boundaries of the spectrum, where the cone of influence indicated the decay of the spectrum in each scale and the background red noise 5% significance level for areas circled in black in the temporal domain (ADDISON, 2017; TORRENCE, 2016; SHINZATO, 2014).

Since the study was conducted in the dry period, the lowest monthly means for air temperature were obtained in July, a month exhibiting abrupt variations (Figure 10). In this period, thermal inversion occurs due to air masses arriving from the Atlantic. The variance graphs show the red noise levels next to the signals due to abrupt variations in air temperature; the same was observed for relative humidity (Figure 11). For wind (Figure 12), the wavelets indicated low velocities, without abrupt variance variations, since Cuiabá is located in a geomorphologic province known as the Cuiabana Depression, where low-amplitude reliefs predominate. This was confirmed by the temporal domain of the scalogram of wind, with low- and high-frequency components, distributed from days 4 to 32. Thus, the TWC offered a daily frequency of the three variables in all temporal domains, which slightly reached a high frequency for air temperature and wind, according to the spectrograms. Thus, from days 4 to 32, air and wind temperature were in high frequency for temporal domains of days 150 to 400, and from days 4 to 64, relative air humidity exhibited a low frequency. These longer periods are an indication of the seasonality of cerrado microclimates during autumn and winter. Therefore, the use of thermal indices in conjunction with wavelet analysis provides new elements for the study of urban microclimates.

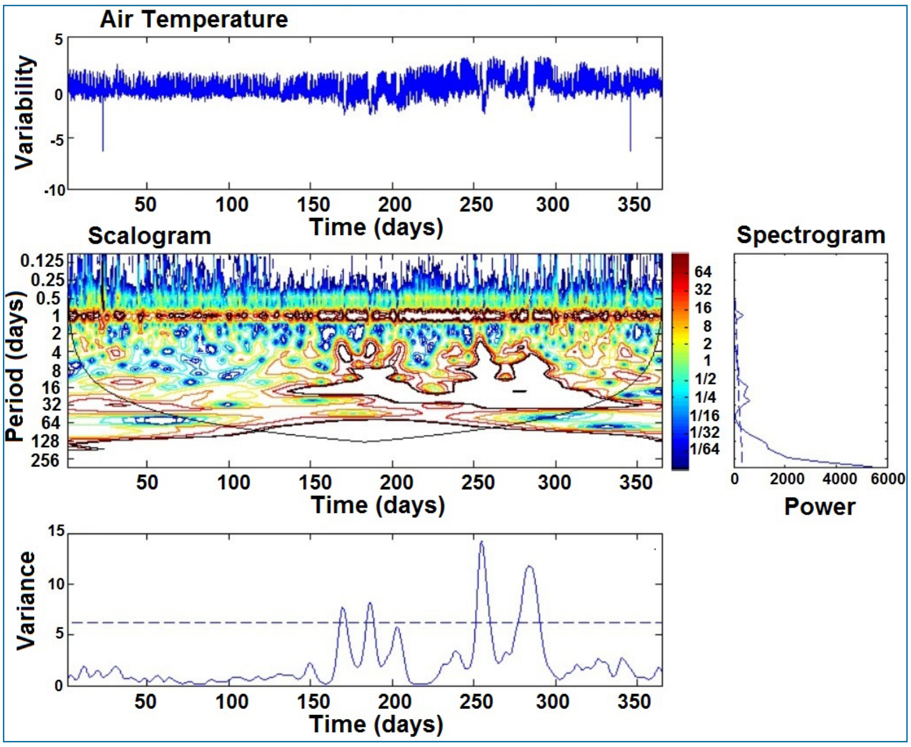

Figure 10 - Traditional Morlet wavelet for air temperature.
Source: Created by the authors

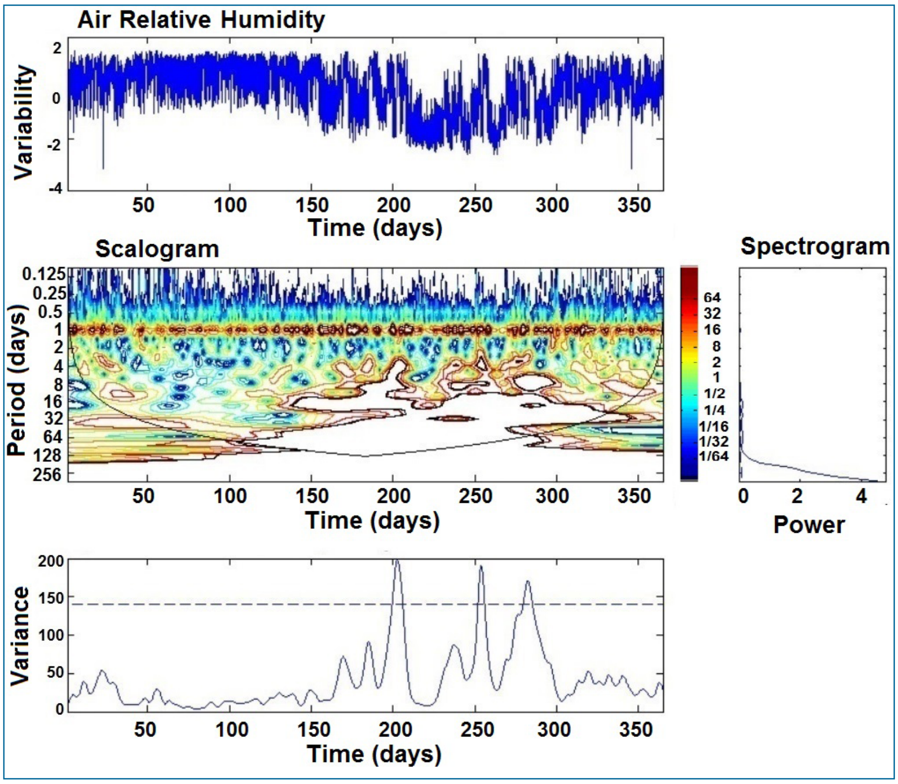

Figure 11 - Traditional Morlet wavelet for relative air humidity
Source: Created by the authors

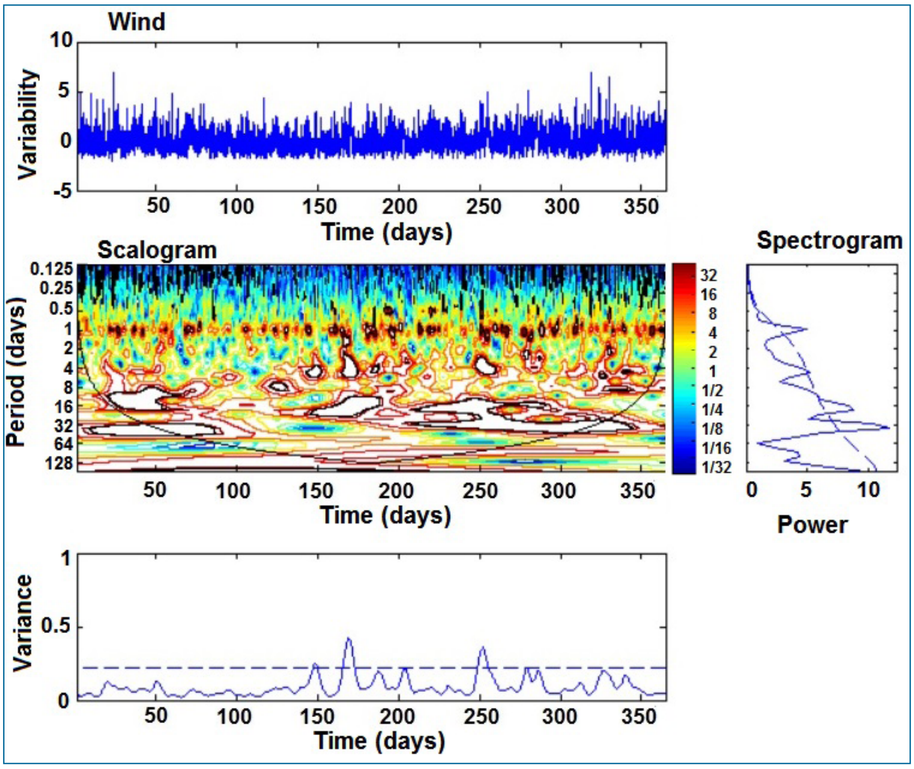

Figure 12 - Traditional Morlet wavelet for wind
Source: Created by the authors

Despite the existing urban planning and studies already conducted in the region, urban development in Cuiabá requires additional attention, because natural areas are being replaced by constructed environments, new waterproof materials are being introduced, and streets, in most cases, have poor afforestation. This situation contributes to the formation of urban canyons and heat islands, and to different insolation in urban microclimates (i.e. microclimates with different amounts of energy), which requires further study using a qualitative temporal framework and multiscale approaches such as Wavelets tools. Thus, analyses of SVF, PET, and PMV should be observed together with local time and climatic parameters in spectral analysis.

4 Conclusions

In this study, we found significant differences in the SVF and in the calculated PET and PMV indices between forested and unforested urban sections. Using RayMan software and correlations of important variables to determine thermal comfort, we confirmed the benefits of shade provided by vegetation, especially in the afternoon, indicating that afforestation is fundamental for improving local environments.

The processes of urbanisation by increasing verticalisation and surface waterproofing of cities favour the formation of urban canyons and heat islands, including in Cuiabá, Brazil. Therefore, the analyses of the SVF variable, as well as PET and PMV, should be observed together with variables of local time and regional climatic parameters. We performed wavelet analyses of the air temperature and air relative humidity series for the year 2015 and qualitatively demonstrated some of the dynamics of these variables in relation to the urban climate in the tropical cerrado.

Analysing the air and surface temperature dynamics in cities, as their interactions with air relative humidity, and wind, as well as precipitation, in the processes of absorption, irradiation, and reflection in cities is complex. Although many studies have been performed, the lack of afforestation in climates that are hot and humid in summer and hot and dry in winter could make urban environments uncomfortable, especially in densely populated cities with a high degree of verticalisation such as Cuiabá, Brazil. Therefore, additional research on Cuiabá is required to study its urban climate, with a focus on afforestation surrounding its road network. This work serves as a foundation for such studies.

Acknowledgements

We thank the Federal Institute of Science and Technology of Mato Grosso for funding and support. We thank the construction department. We thank the Post-Graduation in Environmental Physics of the Federal University of Mato Grosso Dr. José de Souza Nogueira.

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