Study of heat islands by orbital data: effects of surface temperature patterns

Michelle A. Cerqueira[*], Bruna K. de L. Santos[**], Diana F. de Freitas[***]

[*]Professor, UFAL-CECA, Rio Largo-AL, acadelino@gmail.com (Corresponding author)
[**]Graduated in Agronomy, UFRPE-UAST, Serra Talhada-PE, bruninhaksantos@hotmail.com
[***]Professor, UFRPE-UAST, Serra Talhada-PE, freitasdf.solos@gmail.com

Abstract

The dynamics of cities have been changing a lot over time. Population growth and increasing urbanization are examples of this. It is noticeable that natural landscapes are changing into artificial landscapes, replacing green areas by completely asphalted ones. These population dynamics directly interfere with the urban climate, modifying it. One of the phenomena caused by the intense urbanization is the Urban Heat Islands (UHI) that happen in the cities, regardless of their size and location. Therefore, this study aimed to evaluate the land surface temperature (LST) in the effects of UHI in the backlands of Pernambuco, located in northeastern Brazil, using remote sensing techniques. For this, the method used consists of a spatial and temporal analysis of the land surface temperature, for which measuring the orbital data of Landsat satellites 5 and 8 were used. The temporal analysis was performed in 10-year gaps (1985, 1995, 2005 and 2016), and the climatic period of data acquisition was the dry period. The results show that, for this study area, LST increased from 1985 until 2016; in 1985 the lowest measured temperature was <25 °C and the lowest temperature in 2016 was around 25-30 °C. The UHI effect is evidenced when comparing data obtained from the surface temperature of urban areas with surface temperature data of green spaces, from which a difference of just over 6 °C is noticeable.
Keywords: remote sensing, surface temperature, orbital images.

1. Introduction

The accelerated and disorganized urban development has caused a series of environmental impacts, as a response to the occupation and anthropic activities on the environment, among which the modification of the urban climate stands out (Nascimento and Oliveira, 2011).

The growing urbanization and therefore the increase of the urban area implies a change in the atmosphere and in land surface temperature (LST). The deforestation and changing of natural landscapes by artificial landscapes, as a result of urbanization, promote a change in the local climate, resulting in temperature variations.

The urban heat islands (UHI) are a phenomenon characterized by the increased temperature in urban areas when compared to surrounding rural areas (Howard, 1818; Oke , 1979; Voogt and Oke, 2003; Voogt 2004; Epa, 2008), the UHI is influenced by reduced vegetation and the properties of urban materials (Voogt, 2004; Epa, 2008). Cities produce UHIs regardless of their location and size, which makes it a problem of global scale.

UHI is normally evaluated through the difference between the air temperature of urban and rural areas using meteorological data; however, this method has a limited spatial coverage (Xiaoma et al., 2013). With the advent of thermal sensors on satellites, there comes the possibility of determining the UHI in low and medium spatial resolution scale.

The present work aims to evaluate the surface temperature (LST) on the effects of Heat Islands (UHI) in the backlands of Pernambuco, by remote sensing techniques, highlighting the green spaces and the urban ecosystem. The remote sensing techniques were validated through *in situ* data.

2. Materials and methods

The studied area was the backlands of Pernambuco, located in the northeast of Brazil, with an area of approximately 32,450 km² and a population of 1,039,733 inhabitants according to IBGE (2017). The caatinga biome is characteristic of the region, featuring a hot and dry climate, with rainfall concentrated in summer and autumn, with precipitation ranging between 500 and 800 mm and unevenly distributed rain over time.

The proposed method implies a spatial and temporal analysis of surface temperature in the backlands of Pernambuco, using orbital data of the satellites Landsat 5 and 8, including the following steps: pre-processing, surface temperature measurement through orbital data and methodology validation through meteorological stations.

The images used in this research were obtained from the website http://glovis.usgs.gov. Table 1 shows the acquisition periods of these images. The chosen climate period for the acquisition was the dry season, due to low rainfall and low incidence of clouds.

The temporal analysis was performed in 10-years gaps, as a composition of images for each 10-years period, since the used sensors do not cover all Brazilian semi-arid region in a single image; because of that, mosaics were generated in order to cover all the studied area.

Table 1 - Period of acquisition of images, TM and OLI sensor.

Dates	Sensor	Orbit	Point
26/10/1985	TM	215	65
26/10/1985	TM	215	66
18/11/1985	TM	216	65
18/11/1985	TM	216	66
24/10/1985	TM	217	65
24/10/1985	TM	217	66
07/11/1995	TM	215	65
07/11/1995	TM	215	66
29/10/1995	TM	216	65
29/10/1995	TM	216	66
05/11/1995	TM	217	65
05/11/1995	TM	217	66
02/11/2005	TM	215	65
02/11/2005	TM	215	66
24/10/2005	TM	216	65
24/10/2005	TM	216	66
15/10/2005	TM	217	65
15/10/2005	TM	217	66
15/10/2016	OLI	215	65
15/10/2016	OLI	215	66
06/10/2016	OLI	216	65
06/10/2016	OLI	216	66
29/10/2016	OLI	217	65
29/10/2016	OLI	217	66

Pre-processing of Landsat 5 – TM Images

Images from the TM sensor (*Thematic Mapper*) were rectified according to images from Landsat 8 – OLI, which are available orthorectified. Later the digital numbers (DN's) were converted into reflectance, which is presented in Equations 1 and 2.

$$L_{\lambda,i} = a_i + \frac{b_i - a_i}{255} ND \tag{1}$$

$$\rho_{\lambda i} = \frac{\pi L_{\lambda i}}{k_{\lambda i} \cos Z d_r} \tag{2}$$

Pre-processing of Landsat 8 – OLI Images

The preprocessing step of images from the OLI sensor constituted in the conversion of digital numbers (DN's) of reflectance images, using the Equations 3 and 4.

$$\rho\lambda' = M_\rho Q_{cal} + A_\rho \tag{3}$$

$$\rho\lambda = \frac{\rho\lambda'}{\sin(\theta_{SE})} \tag{4}$$

Where: $\rho\lambda'$ is the value of the planetary reflectance, with solar angular correction; $M\rho$ is the band-specific multiplicative factor (REFLECTANCE_MULT_BAND_x); x is the number of each band; Qcal is the quantified standard product, calibrated for the pixel values; $A\rho$ is the additional value of each band (REFLECTANCE_ADD_BAND_x); x is the number

of each band, $\sin(\theta\_IF)$ is the solar elevation angle. All the mentioned coefficients were obtained by the image metadata.

Extraction of Surface Temperature - LST

The extraction of the temperature in the TM sensor was performed using the SEBAL algorithm, proposed by Allen et al. (2002) according to Equation 5.

$$T = \frac{K_2}{\ln\left(\frac{\varepsilon K_1}{L\lambda}\right) + 1} \tag{5}$$

Where: $K_1 = 607.76$ mWcm^{-2}sr^{-1}μm^{-1}, $K_2 = 1260.56$ K are constant thermal band calibration of Landsat - 5 TM (Allen et al., 2002; Silva et al., 2005). $L\lambda$= radiance and ε = emissivity (Equation 07)

For the extraction of OLI temperature, the equation proposed by Carnahan (1990) and Weng et al. (2004), Equation 6.

$$LST(°C) = \frac{T_B}{1 + \left(\lambda \times \frac{T_B}{\rho}\right) ln\varepsilon} \tag{6}$$

Where: T_B = Brightness temperature in Band 10; λ = wavelength of emitted radiation ($\lambda = 10.8$ μm, the central wavelength of Landsat 8 Band 10); $\rho = h \times c/\sigma$ (1.438×10^{-2} mK), σ = Boltzmann constant (1.38×10^{-23} J/K), h = Planck's constant ($6,626 \times 10^{-34}$Js), and c = speed of light ($2,998 \times 10^{8}$m/s); and ε is the emissivity of the Earth's surface, estimated by Equation 7.

According to Allen et al. (2002), the emissivity ε can be obtained, for IAF <3, according to Equation 7.

$$\varepsilon = 0,97 + 0,0033.\text{IAF} \tag{7}$$

For Pixels with IAF $\geq 3, \varepsilon = 0.98$, according to Allen et al. (2002). Where the LAI (Leaf Area Index) is defined by the ratio of the leaf area of all vegetation per unit of area used by this vegetation. This index serves as a biomass indicator of each pixel

in the image and it was computed by Equation 8, obtained by Allen et al. (2002).

$$\text{IAF} = -\frac{\ln\left(\frac{0,69 - \text{SAVI}}{0,59}\right)}{0,91} \tag{8}$$

Where: SAVI (*Soil Adjusted Vegetation Index*) is an index that seeks to mitigate the background effects of the soil, given by Equation 09 (Huete, 1987):

$$\text{SAVI} = \frac{(1 + \text{L})(\rho_{IV} - \rho_V)}{(\text{L} + \rho_{IV} + \rho_V)} \tag{9}$$

Where: the L factor is a function of the type of soil, being the most frequent value L=
0.5 (Huete and Warrick, 1990; Accioly et al., 2002; Boegh et al., 2002).

All the steps proposed in this methodology were performed using the software QGIS 2.16.

3. Results and discussion

Land surface temperature (LST) can differ greatly between geographic locations and time periods, whereas the local background climate can vary greatly with space and time (Zhou et al., 2014).

Figure 1 of LST clearly demonstrates an increase in surface temperature between the years of 1985 to 2016. In the year 1985 the surface temperature in the studied area varied between the cities; for example, in the city of Exu, the temperature reached < 25 °C, and in Santa Cruz da Baixa Verde it reached > 40 °C. By observing the map of 1995 we can notice a difference in the western area, which in 1995 reached < 25 °C, differing from 1985, when they reached 25-30 °C. There was a certain homogeneity of temperature in the year 2005, which ranged between 25-35 °C, with temperature increases in some cities and decreases in others, when compared with the year 1995. In the year 2016 there was a temperature increase when compared with the previous years, with temperatures ranging 30 °C to >40 °C. When comparing the years of 1985 and 2016, we can notice that there were significant increases in surface temperature over the past 30 years, when in 1985 the lowest measured temperature was <25 °C, and in 2016 it was around 25-30 °C.
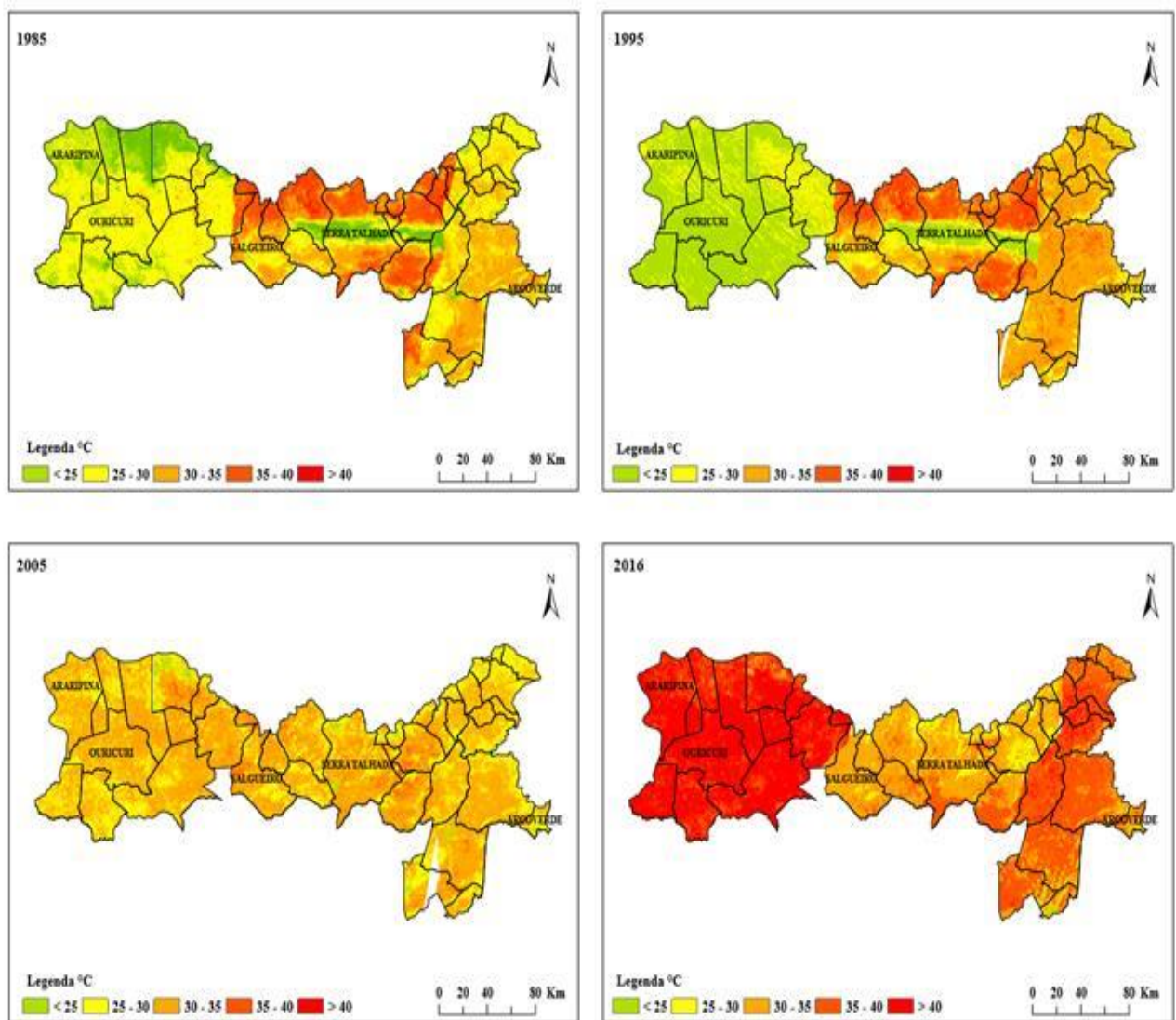
Figure 1 - Spatial and temporal distribution of Surface Temperature for the backlands of Pernambuco.

Analyzing the five municipalities with the largest population in the backlands of Pernambuco (Serra Talhada, Araripina, Arcoverde, Ouricuri and Salgueiro), with estimated populations (in 2016) of 84,970, 83,287, 73,154, 68,236 and 60,117, respectively. We can do an analysis of population growth (Table 2) which implies the urban growth and the increase of the surface temperature.

The population growth causes an expansion of the constructed area, that is, the replacement of natural landscapes by artificial landscapes. Normally, the formation of UHI is primarily caused by changes in the landscape due to urban development, being influenced by the reduced vegetation, resulting in LST.

The city of Ouricuri saw its population decrease from 73,526 in 1991 to 56,733 inhabitants in 2000, with a population reduction and a later demographic growth; in the year 2007, the population in the city reached 63,042 inhabitants. For the same city, the LST map shows a temperature decrease from the year 1985 to 1995. In the year 1985, the

temperature was around 25-30 °C in almost the whole area. In the year 1995, the temperature was around <25 °C, which is evidenced by the coloring difference in the map from one year to another, in the same region.

The city of Serra Talhada went from 72,341 inhabitants in 1991 to 70,162 in 1996, showing a decrease in population growth. In the year 2000, there were 70,912 inhabitants, when the population showed a small growth when compared with the year of 1996, reaching in 2007 a population of 76,198, which evidenced a rapid population growth. By analyzing the LST map, it is possible to observe that from the year 1995 to 2005 there was an increase of the surface temperature; in 1995 it is possible to find areas with < 25 °C temperatures (green color on the map), and in the year 2005 a great part of the city area shows temperatures around 30-35 °C.

In the cities of Araripina, Arcoverde and Salgueiro there was a population growth in recent years, which shows changes in the population dynamics and the urban area. The urban population

dynamics affect urban heat islands because as the size of the city increases, the UHI also increases, and they both often decrease together (Oke, 1979; 1982; Aniello et al., 1995; EPA, 2008).

Table 2 - Population trends by number of inhabitants

Year	Serra Talhada	Araripina	Arcoverde	Ouricuri	Salgueiro
1991	72.341	60.585	55.776	73.526	47.211
1996	70.162	63.719	58.300	57.985	49.164
2000	70.912	70.898	61.600	56.733	51.571
2007	76.198	75.878	64.863	63.042	53.167
2010	79.232	77.302	68.793	64.358	56.629

Source: IBGE (2017).

By making a comparison of the surface temperature of the studied municipalities, for the urban area (Figure 2) and the green areas (Figure 3), it may be noted for example a difference of up to 6.31 °C in Araripina in the year 1985.

The temperature differences in urban areas and green areas are due to the fact that in urban areas the sun rays hit directly on the concrete, which absorbs the heat and releases it in the form of heat waves. Also, in urban areas vehicles emit a lot of gaseous pollutants, buildings are higher and higher, and this prevents the air from circulating properly. As it happens, temperature tends to rise, and this creates urban microclimates, which are spaces with completely different air temperature and humidity from the general environment, caused by the intense urbanization.

Figure 2 - Surface Temperature distribution in an urban area.

The LST analysis (°C) in the urban area of Araripina demonstrates that the municipality has experienced an increase in surface temperature, which in the past ten years increased from 31.02 °C in 2005 to 39.77 °C in 2016 - an increase of 8.75 °C. In the city of Arcoverde, surface temperature varied around 4.33 °C between 2005 and 2016. The variation in Ouricuri was of 6.45 °C from 2005 to 2016, evidencing a temperature increase. The cities of Salgueiro and Serra Talhada presented the lowest variation of surface temperature when all cities analyzed were compared, ranging about 0.55 °C and -0.52 °C, respectively, between 2005 and 2016.

The temperature drops when moving away from urban to greener areas. The benefits that the vegetation offers are the reduction of the impact of the sun rays in the soil, and at the same time the increase of the atmosphere's humidity. Silveira (1999) states that in areas covered by vegetation, air temperatures are generally below their surroundings; this is because the vegetation minimizes radiation

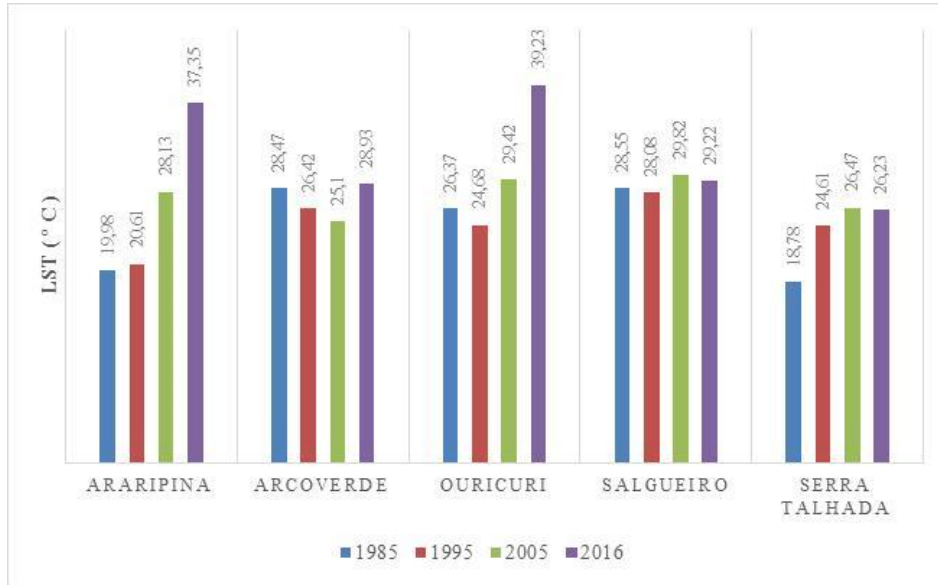absorption and thus reduces heat dissipation by long waves.

Figure 3 - Surface Temperature distribution in green spaces.

The LST in green spaces in Ouricuri and Araripina showed the greatest variations, reaching in 2016 a temperature of 39.23 °C and 37.35 °C, a respective increase of 9.81 °C and 9.22 °C when compared to 2005. In Arcoverde, it ranged around 3.8 °C in recent years; in Salgueiro and Serra Talhada there was a slight variation.

Comparing the surface temperature distribution in an urban area with the surface temperature of green areas, it is possible to notice that the temperature in green spaces is always lower. The lack of vegetation in urban areas is one of the causes of climate change in urban areas, whereas the vegetation regulates and improves the climate. In addition, the lack of vegetation reduces the evapotranspiration process and, as a result, there is no evaporative cooling at the site (Pinho and Orgaz, 2000).

It is observed that the temperature difference in Figures 2 and 3 can reach up to 6.31 °C. In the last year, this difference was of 4.42 °C in Arcoverde. These temperature differences in urban spaces and their surrounding green areas show the UHI process, since temperatures in urban areas are increasingly high, and these temperatures are commonly higher than the ones of green areas.

The data of this methodology can be validated by data from weather stations. In the studied area, the city of Arcoverde has a weather station related to the National Institute of Meteorology (INMET), where historical data of the conventional station were gathered, from which daily maximum temperature data for the observed days were extracted (Figure 4).
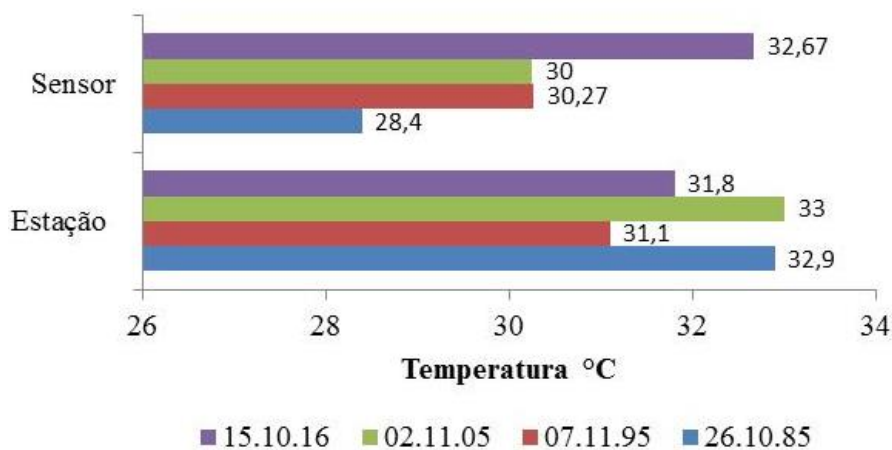

Figure 4 - Temperature Measured by the sensor and at the station of INMET.

It is observed that the measured temperature at the station is higher than the sensor's, except for the October 15th, 2016, with differences of maximum temperature 4.5 °C and minimum 0.83 °C. On average, the surface temperature measured by the sensor and at the station varied 2.3 °C, where the temperature measured at the weather station is the maximum air temperature for that day and the temperature measured by the sensor is on the surface. These results demonstrate that the data are approximate and that they corroborate with those found by Pinheiro et al. (2006) and Galvíncio et al. (2009).

4. Conclusions

The present work evaluated the surface temperature (LST) on the effects of heat islands (UHI) to the backlands of Pernambuco through remote sensing techniques. The results obtained were compared with the population growth, which is linked to urban growth.

Results suggest that, in recent years, the surface temperature of the studied area has increased, and that is due to the fact that cities are in a constant urbanization process. One of the main reasons for urbanization and consequent expansion of the urban area is the population growth.

The urbanization process replaces natural landscapes by artificial landscapes, and that ends up influencing the temperature in these locations. This study provides evidence that the surface temperature in urban areas is higher than in green areas, reaching temperature differences of up to 6.31 °C, which evidences the existence of the heat islands effect.

The evaluation of the surface temperature with satellite images, when compared with the temperature obtained from meteorological stations data, proved to be satisfactory with the advantage of obtaining an analysis on spatial scale. One of the difficulties for the validation of the data obtained through remote sensing was that the region of study has few conventional stations with historical data.

The estimation of the surface temperature with satellite imagery becomes an important tool for obtaining data, as it allows less dependence on meteorological data. There is a shortage of weather data in much of the country and this becomes a limiting factor for carrying out detailed studies about the climate of many regions, especially when they have a big territorial extension.

There is a possibility for future works that contemplate other climatic variables, given that remote sensing can be used for monitoring the hydric stress, surface energy balance, detection of changes in the Earth's surface (e.g. fires), among others.

References

Accioly, L.J.deO., Pachêco. A., Costa, T.C., Lopes, O.F., Oliveira, M.A.J., 2002. Empirical relationship between vegetation structure and TM/LANDSAT data. Revista Brasileira de Engenharia Agrícola e Ambiental 6, 492-498.

Allen, R.G., Tasumi, M., Trezza, R. 2002. Surface SEBAL - Energy Balance Algorithm for Land Idaho Implementation. Advanced Training and Users Manual. Version 1.0.

Aniello, C., Morgan, K., Busbey, A., Newland, L., 1995. Mapping micro-urban heat islands using Landsat TM and a GIS. Computers & Geosciences 21, 965–969.

Boegh, E., Soegaard, H., Thomsem, A., 2002. Evaluating evapotranspiration rates and surface conditions using Landsat TM to estimate atmospheric resistance and surface resistance. Remote Senssing of Enviromental 79, 329-343.

Carnahan, W.H., Larson, R.C., 1990. An analysis of an urban heat sink. Remote Senssing of Enviromental 33, 65-71.

EPA. US Environmental Protection Agency, 2008. Reducing Urban Heat Islands: Compendium of Strategies. US Environmental Protection Agency, Washington.

Galvíncio, J.D., Dantas, L.G., Fernades, J.G., Silva, J.B., Moura, M.S.B., Machado, C., 2009. Análise da temperatura do ar e da superfície no sítio boa felicidade em São José do Sabugi-PB no semi-árido do Brasil. Revista de Geografia 26, 124-141.

Howard, L., 1818. The Climate of London. 1. W. Phillips, London.

Huete, A.R., Jackson. R.D., 1987. Suitability of Spectral Indices for Evaluating Vegetation Characteristics on Arid Rangelands. Remote Sensing of Environment 23, 213–232.

Huete, A.R., Warrick, A.R., 1990. Assessment of vegetation and soil water regimes in partial canopies with optical remotely sensed data. Remote Sensing of Environment 32, 155-167.

IBGE. Instituto Brasileiro de Geografia e Estatística, 2017. Censo Demografico. Disponóvel: www.sidra.ibge.gov.br. Acesso: 5 maio 2017.

Nascimento, D.T.F., Oliveira, I.J., 2011. Análise da evolução do fenômeno de ilhas de calor no munícipio de Goiânia/GO (1986-2010). Boletim Goiano de Geografia 31, 113-127.

Oke, T.R., 1982. The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society 108, 1-24.

Oke, T.R. 1979. Review of Urban Clobatotology. Technical Note. World Meteorological Organization 169, 43.

Pinho, O.S., Orgaz, M.D.M., 2000. The urban heat island in a samll city in coastal Portugal. International Journal of Biometeorology 44, 198−203.

Pinheiro, A.C.T., Mahoney, R., Privette, J.L., Tucker, C.J., 2006. Development of daily long term record of NOAA-14 AVHRR land Surface temperature over Africa. Remote Sensingof Environment 103, 153-164.

Silva, B.B.da, Lopes, G.M., Azevedo, P.V.de, 2005. Balanço de radiação em áreas irrigadas utilizando imagens Landsat 5 TM. Revista Brasileira de Meteorologia 20, 243-252.

Weng, Q., Yang, S., 2004. Managing the adverse thermal effects of urban development in a densely populated Chinese city. Journal of Environmental Management 70, 145−156.

Voogt, A.J., Oke, T.R., 2003. Thermal remote sensing of urban climates. Remote Sensing of Environment. 86, 370-384.

Voogt, J.A., 2004. Urban heat islands: hotter cities. Disponível: www.actionbioscience.org/environment/voogt.html. Acesso: 5 maio 2017.

Xiaoma, L., Zhou, W., Ouyang, Z., 2013. Relationship between land surface temperature and spatial pattern of greenspace: What are the effects of spatial resolution Landscape Urban Plan. 114, 1-8.

Zhou,Y., Yang, G., Wang, S., Wang, L., Wang, F., Liu, X., 2014. A new index for mapping built-up and bare land areas from Landsat-8 OLI data. Remote Sensing Letters 10, 862–871.