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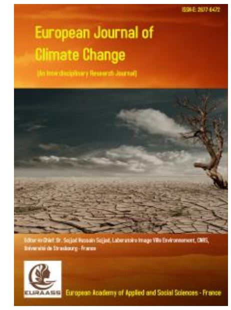

Research Article

Spatial variability and frequency of surface heat island in a small Brazilian city with continental tropical climate

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Abstract

Land surface temperature (LST) is one variable in the earth-atmosphere interactive system. Temperatures are naturally high in tropical environments under continental influence. In Brazil, the problem of high temperature is intensified by the urbanization process, which is characterized by vegetation removal, concentration of buildings, and the use of building materials unfavorable to the climate in the tropics. Therefore, in this article, we analyze the spatial variability and the frequency of the surface temperature during the dry and rainy seasons in Penápolis, a small population city in the countryside of São Paulo State. The analysis was performed by establishing the relationship between the normalized vegetation index (NDVI) and the surface temperature in order to contribute to urban planning. The adopted procedure used 10 images from satellite Landsat 8, Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) for the year 2018. The results showed that the surface urban heat island has significant seasonal variations that are directly associated with the rainfall regime of the region. The intensity was not elevated during the year, and the highest magnitudes occurred in the summer, which is a hot and rainy season. In the winter, being the dry season, the magnitudes were lower. The frequency of heat island intensity taken from 10 points of the images is related to construction density, building materials, and the vegetation cover index. These results are important to understanding the generation of heat in the city and proposing planning measures for the use and coverage of urban land.

Keywords: Urban climate, Surface heat island, Vegetation, Land use, Landsat 8.

1. Introduction

Land surface temperature (LST) is one variable in the earth-atmosphere interactive system that is subject to human influences and provides an understanding of the urban climate. It modulates the ambient air temperature of the lower layers of the urban atmosphere, helps to determine the internal climates of buildings, and affects energy exchanges that influence the comfort level of city dwellers

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(Voogt & Oke, 2003). Surface temperature reflects the energy balance of various surfaces due to differences in their material properties including geometric, radiative, moisture, and aerodynamic properties. Variability in these properties contributes to greater variability of surface temperature compared to air temperature. Therefore, changes in the energy balance at the surface results in changes in LST (Oke et al., 2017).

Studies of LST in cities led to discovery of the surface urban heat island (UHI_{Surf}). This phenomenon was revealed through the use of remote sensing including aircraft-based thermal cameras and radar. The great advantage of remote sensing is its ability to allow visualization of temperatures over large areas. However, it is only possible to obtain a panoramic view of surface temperatures, as some surfaces are hidden (Oke et al., 2017).

The first UHI_{Surf} identified in Brazil was the city of São Paulo using a National Oceanic and Atmospheric Administration (NOAA) sensor with a spatial resolution of 1.1 Km. The study revealed higher temperatures in the urbanized area, but lacked detail due to its low spatial resolution that did not allow identification of intraurban differences in LST (Lombardo, 1985). The launch of new satellites with better spatial resolutions encouraged research in other cities, so that the LST of medium (Andrade et. al., 2007; Barbosa e Vecchia, 2009; Amorim et al., 2009; PolizeL, 2009; Amorim and Monteiro, 2011) and small cities (Dorigon e Amorim, 2013; Ugeda Junior, 2013; Ortiz e Amorim, 2013; Amorim, 2017b) was studied. Results of these studies have revealed some patterns of higher temperatures, generally associated with high building density, certain building materials, and exposed soils. However, synoptic situations in the days before the image capture directly interfered in the urban-rural thermal difference.

Therefore, like other types of urban heat islands, the surface heat island is also identified by comparing the city surface with its rural surroundings (Oke *et al*., 2017). Thus, more recent Brazilian studies have analyzed the intensity of UHI_{Surf} in order to aid in comparison between cities and in the identification of patterns in the continental tropical environment. In addition, few studies of the tropical environment have considered seasonal rainfall variation in tropical climate, which are strongly correlated with the magnitude of UHI_{Surf} (Amorim, 2018).

Therefore, in this article, we analyzed the spatial variability and frequency of LST during the dry and rainy seasons in Penápolis, a small city in the countryside of São Paulo State. The analysis was performed by establishing the relationship between the Normalized Difference Vegetation Index (NDVI) and the LST in order to contribute to urban planning.

2. Study area

Penápolis lies at 21°26 'south latitude and 50°19' west longitude (Fig. 1), 487 km from the city of São Paulo. The northwest region of São Paulo State, where the municipality is located, was populated by the migratory process known as the "march to the west" encouraged by the coffee culture of 1880 (Ghirardello, 2002). However, it was with the completion of the construction of the Northwest Railroad of Brazil in 1908 that led to the creation of the municipality (Ibge Cidades, 2017).

The urbanization of Latin America is a result of the expansion and development of capitalism, mainly through the process of internationalization of Western industry, which encompasses those peripheral spaces where traditional forms of production developed. In Brazil, this phenomenon manifested itself mainly through the arrival of large multinational, mainly industrial companies, and appropriation of the countryside for capitalist production (Sposito, 1991). Therefore, Brazilian urbanization has its roots in the intense rural-urban migration after 1960, driven by structural challenges such as land concentration, monoculture, and mechanization of agriculture (Scarlato, 2009; Santos, 2009).

In this way, rapid urbanization transformed the landscape through the removal of vegetated cover for the concentration of buildings, waterproofing of the soil, and channeling of streams. In addition, due to the lack of adequate urban planning, use of construction materials that are unsuitable for the climate of the tropics and the suppression of green areas within the cities are used. The configuration of the current urban landscape has resulted in increased surface and atmospheric temperature (Amorim, 2000; Amorim, 2017b)

The climatic regime in which Penápolis is situated is characterized by the transition from tropical to extratropical systems. In a recent study in which Köppen classification was applied to all Brazilian territory based on 208 stations from 1961 to 2015, it was found that the northwest region of São Paulo State is classified as Aw (Dubreuil *et al*., 2017). Therefore, there are well-defined wet and dry seasons: hot and rainy summers and milder, dry winters. These characteristics can be observed in Fig. 2, which shows a hot and rainy period between October and February and a milder, dry period between April and September.

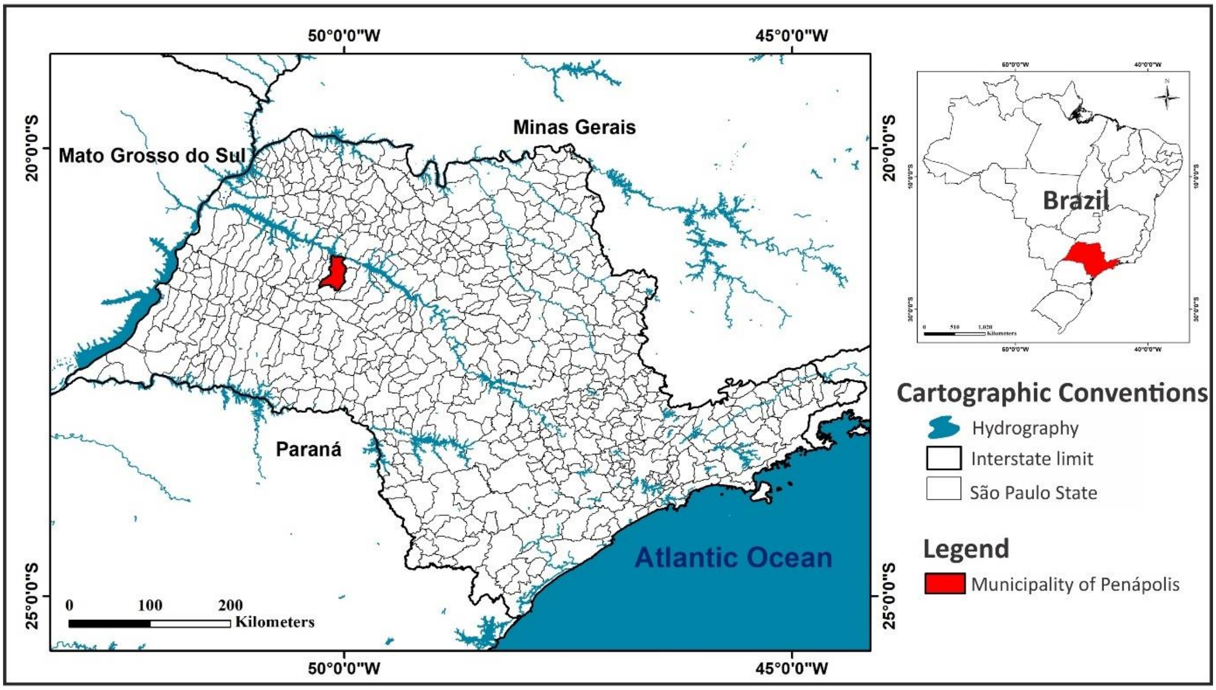

Figure 1: Location of Penápolis in the São Paulo State.

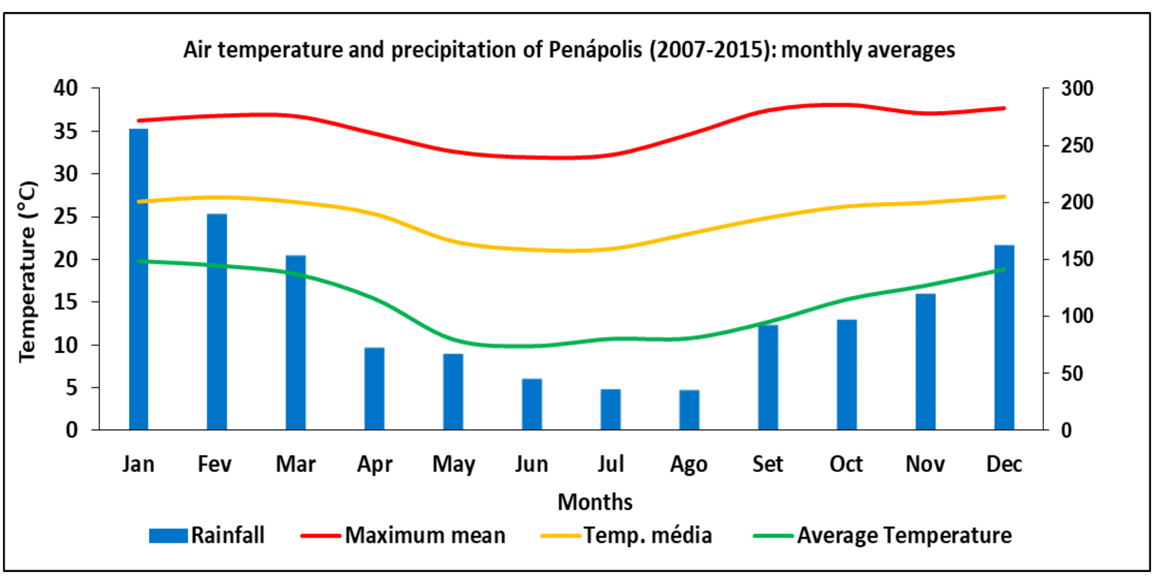

Figure 2: Air temperature and Precipitation in Penápolis among 2007-2018: monthly averages.

As can be observed in Fig. 2, the highest values of maximum air temperature occur in October (38°C), November (37 ° C), and December (37.7°C), and the lowest in June (31.9° C) and July (32.2° C). Minimum temperature has its lowest averages in June (9.8°C) and May (10.6°C), while highest average temperatures occur in December (27.3°C), January (26.7 ° C), and February (27.2 ° C).

On the other hand, precipitation data shows that between October and March, average rainfall values above 150 mm are recorded, with January and February being the rainiest months, at 263 mm and 189 mm, respectively. The variability of precipitation throughout the year is fundamental to understanding the generation and standards of UHI_{Surf} in the tropical environment, as this study addresses.

3. Methodology

This paper used images from Landsat 8 (Land Remote Sensing Satellite). NDVI values were obtained from the Operational Land Imager sensor bands 4 (0.64–0.67μm) and 5 (0.85– 0.88μm), the red and infrared channels, respectively. Both bands have a spatial resolution of 30 meters. For analysis of UHI_{Surf} spatial variability, surface temperature maps were generated using images from the Thermal Infrared Sensor band 10 (10.6–11.19μm) and the thermal infrared channel with its spatial resolution of 100 meters, available with a 30-meter pixel resolution from the United States Geological Survey (USGS). Images from the Landsat series have been widely used in Brazil because of their spatial and temporal resolutions, appropriate for its analysis of the urban climate and free availability.

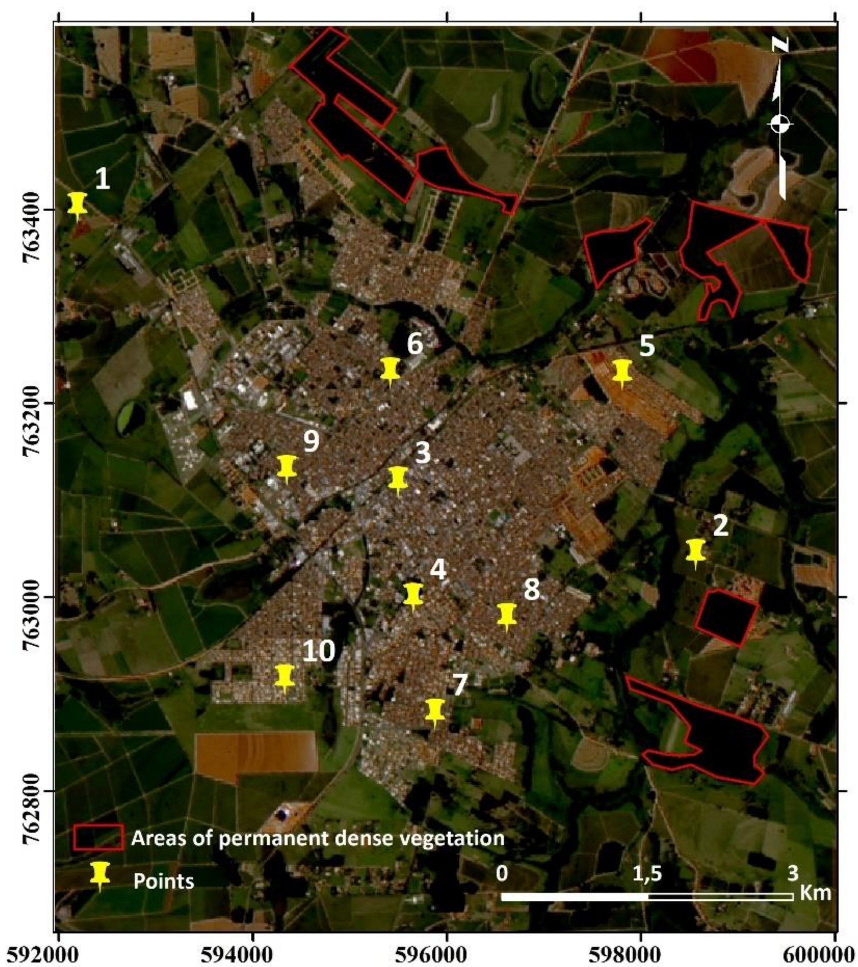

Figure 3: Penápolis: We used the locations of permanent areas of dense vegetation to obtain the average rural temperature and to calculate intensities of UHI_{Surf}. We used point locations to analyze the frequency (%) of UHI_{Surf}.

For conversion of digital numbers in degrees Celsius (°C), and we used the fixed parameters of the satellite sensor, as obtained from the USGS survey site (USGS, 2018). Atmospheric correction of the images was performed using the principles provided by the Atmospheric Correction Parameter Calculator that provides Transmittance, Upwelling, and Downwelling from the local surface data (temperature and humidity). This correction was performed according to the equation of Coll et al. (2010).

Time of image capture in Penápolis is at 10:23 local time (13:21 GMT hour). As the objective was to compare images for an understanding of surface temperature variability in the dry and rainy seasons, the best option was to calculate the intensities of the surface urban heat islands. To calculate the intensities of UHI_{Surf}, we first calculated the average for areas of dense permanent vegetation in the rural surroundings in each image (Fig. 3). This average was considered to be point "0," from which the entire image was subtracted ($\Delta T = u - r$). Fig. 3 shows the points used to extract and calculate the UHI_{Surf} frequency of occurrence.

Defining rural temperature is a challenge (Oke et al., 2017), since it is quite common for the non-urban area to present a similar or greater spatial variability of surface temperature relative to the urban area. In addition, the lower temperature of the zone was not considered in the calculations, because in some images, this corresponded to the surface temperature of water bodies, a fact that is very common in diurnal thermal images and was the case in this study (Oke et al., 2017).

The urban area in the satellite images was delimited by importing and superimposing it on the cartographic base map of the urban network (IBGE, 2010). After surface temperature maps were generated, local meteorological station precipitation data (DAEP, 2018b) was used to analyze precipitation distribution during the 30 days prior to image collection.

For elaboration of the occurrence frequency of UHI_{Surf} intensity, 10 images from the year 2018, captured on days with clear sky, were used. These images were dated 2/24/2018, 03/12/2018, 04/13/2018, 08/08/2018, 06/25/2018, 02/07/2018, 08/28/2018, 10/22/2018, 11/16/2018, and 12/09/2018. For extraction of the surface temperature from these images, 10 points of the intraurban and rural areas were selected (Fig. 3). These were selected based on their variety of density characteristics in terms of buildings, vegetation, building materials, and location within the urban dynamic, since these factors have the greatest impact on surface temperature.

In order to understand the variability of UHI_{Surf} between stations, NDVI was calculated through the ArcGis 10.1 application by calculating the difference between the near infrared and red bands, represented in eq. 1:

$$NDVI = (PIVP – PV) / (PIVP + PV) \quad (1),$$

where PIVP = near infrared, and reflectance PV = reflectance in red.

The values of this operation are contained on a scale between -1 and +1. Areas with values close to -1 reveal the presence of vegetation with water stress or built-up areas, since areas with values close to +1 correspond to more vigorous, dense vegetation. In cases of water bodies, NDVI values tended to be negative (Silva; Galvíncio, 2012). Therefore, with these maps, it was possible to identify vegetation density and spatial distribution in the rural section of Penápolis.

For identification of atmospheric systems, DAEP temperature and precipitation data were used (DAEP, 2018). Relative humidity, wind velocity and direction data were extracted from the automated station of the National Institute of Meteorology (INMET).

4. Results and Discussion

Most UHI_{Surf} studies of the tropical environment have focused on analysis of surface temperature differences relative to urban land use and occupation. This study also sought to establish these relationships while adding seasonal variability of precipitation to the analysis. For this, representative images of the dry and rainy periods were selected, which synthesized the variability of annual precipitation in the study area.

For the rainy season, the image of March 12, 2018 (summer) was selected. On that day, an Atlantic tropical mass was active in the municipality, which supplied high air temperatures and humidity; average temperature of the day was 30.7°C and relative humidity ranged from 35% to 88%. The sky was clear and light winds prevailed over the east and northeast quadrants, attaining a maximum of 1.7 m/s. The dry period was represented by the image of August 28, 2018 (winter), when the municipality was under an Atlantic polar mass. Average diurnal air temperature was 22.8°C, relative humidity ranged between 31% and 81%, and southwesterly prevailing winds reached a maximum of 4.1 m/s.

4.1 The occurrence frequency of UHI_{Surf} intensities (%)

Occurrence frequency of UHI_{Surf} intensity per pixel was extracted from the 10 images from 2018 based on 10 points, of which eight were distributed within the urban area and 2 in the rural area (Fig. 3). Rural points (1 and 2) were those with the highest frequencies of the lowest intensity of UHI_{Surf} (Fig. 4). Point 2 had the highest frequency (60%) at intensities between 1°C and 3°C. On the other hand, point 1 presented a higher frequency (40%) of intensities of 3°C to 5°C and 5°C to 7°C. This result was justified by differences in land use between rural areas, where point 1 in the northwest was characterized by sugarcane crops and pastures while point 2, located to the southwest, was characterized by fruit trees.

Points 3, 4, 5, and 6 demonstrated a higher frequency (40%) of intensities of 3°C to 5°C and 7°C to 9°C. However, it is important to note that among these points, point 4 was the one with the lowest frequency (20%) of intensities of 7°C and 9°C. This was associated with a populated setting, characterized as an open residential area with scattered trees. Point 3 referred to the downtown and points 5 was a compact residential area with bare soil located at the periphery. Point 6 was a compact residential area with scattered trees.

Intensities between 9°C and 11°C had a higher frequency (30%) at points 3, 7, 8, and 9. These points corresponded to the compact residential areas, and were also, with the exception of point 3, points with the highest frequencies of intensities of 11°C to 13°C, especially point 8 (20%). Point 8, located to the southeast of the urban area, was the most superficially heated between the points, which was characterized by the small size of its lots and its high waterproofing rate, since it did not have building-free areas. Heating of point 9 was also associated with these characteristics, but added an absence of tree vegetation and a proximity to an industrial area that has fiber-cement roofs and galvanized steel (zinc).

In summary, the compact residential areas (points 7, 8, and 9) showed the highest intensities, even warmer than the downtown (point 3). These areas corresponded to popular housing estates whose lots are small and near full occupancy. Through point 9, it was also possible to identify the influence of the materials used on the roofs that caused surface heating. Warming of this point is explained based on American Society for Testing and Materials (ASTM) 1980-98, which indicated that the temperature difference between air and galvanized steel roof is 21.1°C, while the temperature difference between air and fiber cement roof is 10.3°C (PRADO and FERREIRA, 2005).

4.2 The spatial variability of surface heat island in the rainy and dry season

The surface heat island detected in Penápolis has demonstrated seasonal variations in intensity that are directly associated with rainfall variability of the region. Intensity is not the same throughout the year, with the highest values being well-distributed through the 30 days prior to image capture and occurring during the period of heavy rain.

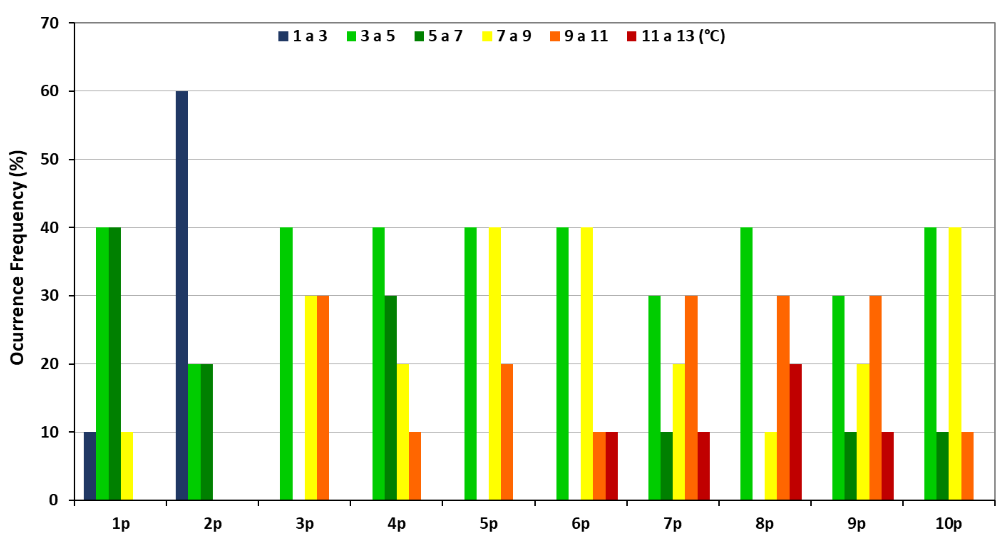

Figure 4: Occurrence frequency (%) of UHI_{Surf} intensities; 10 Images of satellite Landsat 8, from February to December 2018 - 10h22, local time.

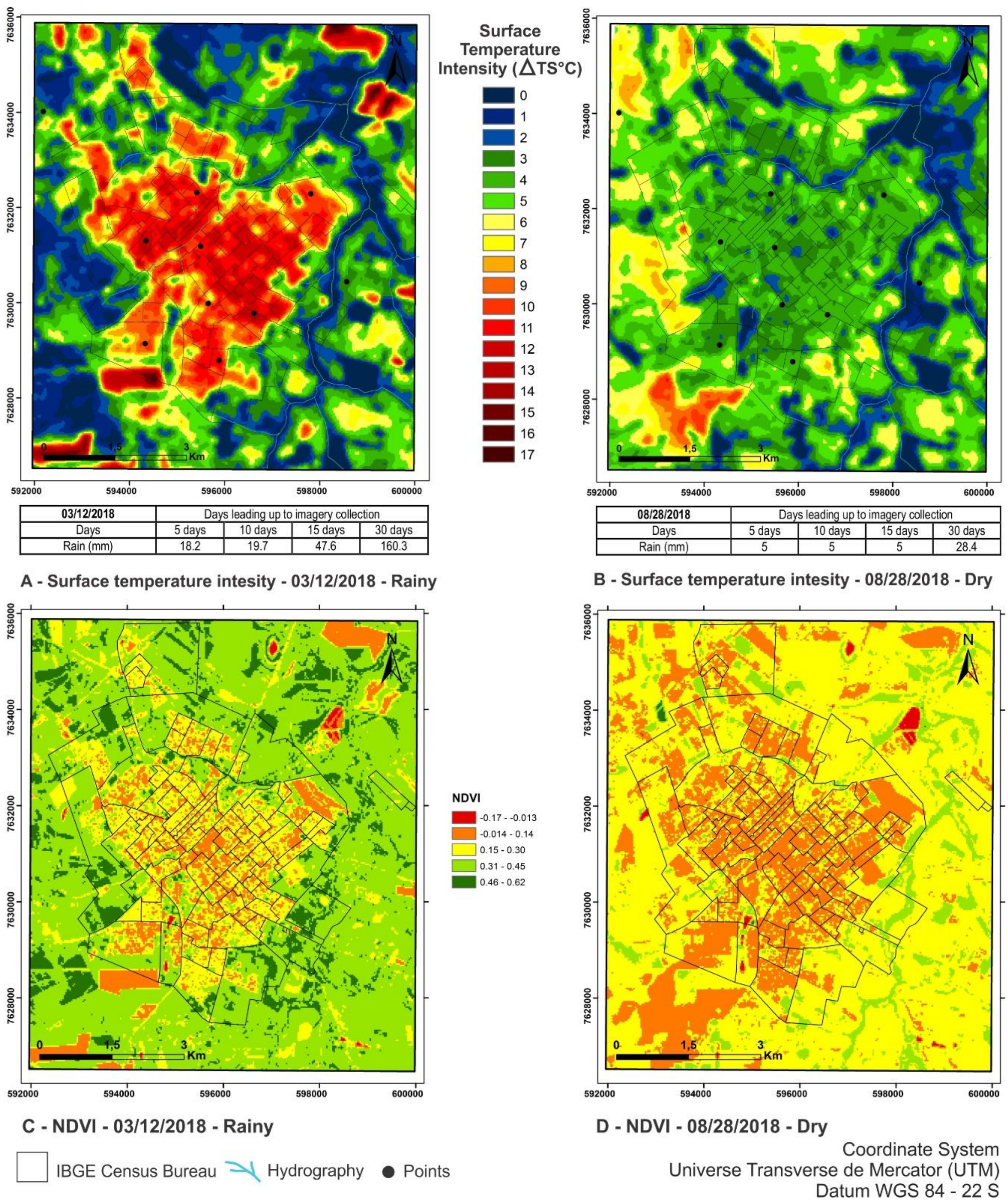

Figure 5: Intensity of UHI_{Surf} (A) and NDVI (C) in rainy and dry periods (B and D).

Figure 5 shows the spatial variation of UHI_{Surf} and NDVI in the rainy and dry seasons and proves the relationship between increased UHI_{Surf} magnitude and vegetative conditions in the nearby rural environment. Image A in Figure 5 represents the rainy season and shows that urban surface temperatures were higher than in rural areas. Absolute surface temperatures ranged between 34°C and 52°C. On March 12, UHI_{Surf} reached a maximum intensity of 14°C, though much of the urban area showed intensities between 10°C and 12°C.

These values were found in areas of high building density and low tree cover. Maximum recorded intensities for this image (17°C) corresponded to the location of exposed soils in the rural area to the north and southwest of the scene.

Image B in Fig. 5 represents the dry period and presents different spatial variability. On that day, the absolute surface temperatures were lower (between 26°C and 39°C). Highest intensity of UHI_{Surf} was of 6°C, but at specific points in the urban area. Much of the urban area showed intensities between 3°C and 4°C. Maximum intensities from this image (11° C) also corresponded to the location of exposed soils to the southwest of the scene. In both analyzed images, images A and C of Figure 5, the lower intensity values remained in forested areas, i.e., dense vegetation, mainly of the tree type.

In the rainy season, urban surface temperatures were about 43°C to 48°C, and ranged from 31°C to 34°C during the dry period. Rural areas showed temperatures between 34°C and 41°C in the rainy season and 27°C and 39°C in the dry season. Comparison of the images with respect to the absolute values revealed that urban surface temperature during the dry period was lower compared to the rainy season, but remained near constant between seasons in the rural areas.

Therefore, temperatures in the rural area were not particularly low during the dry season (winter) relative to the rainy season (summer). NDVI difference between stations indicated the cause of this pattern. Values between 0.31 to 0.62 in the rainy season (image C) and -0.014 and 0.45 for the dry season (image D) in the rural area showed the highest growth and development of the rural vegetation and, therefore, the decrease in temperatures during the rainy season. On the other hand, diminished vegetative cover in the dry period and the greater amount of exposed soil caused high rural surface temperatures in the dry season. Thus, it was found that the intensity of UHI_{Surf} in Penápolis in the dry season was lower. This reduction was due to reduced warming in the urban areas in the dry season (winter) and the maintenance of warming in rural areas due to vegetation conditions, which were directly related to precipitation variability.

Values of precipitation in the days before image collection were directly related to conditions of the vegetative cover, and, therefore, the intensity of UHI_{Surf}. In the spring and summer, during the hot and rainy season, rural vegetation is healthy due to the high availability of water in the soil and air, which results in lower surface temperatures in these areas, and, consequently, greater differences between urban and rural surface temperature and the increased of intensity of UHI_{Surf}. This is because surfaces with access to water, such as moist soils, have lower surface temperatures due to evaporative cooling (Oke *et al.*, 2017).

However, under low rainfall conditions, during autumn and winter, there is a loss of part of the foliage, and soil exposure, which causes warming of the rural area, reduces the difference between urban and rural temperatures and lowers the intensity of UHI_{Surf}. Dry surfaces tend to absorb more heat, as they do not channel much available energy to the processes of evaporation (Oke *et al.*, 2017). The city is practically impermeable to water, and its structure causes water to quickly drain. This makes for a dry environment and a greater potential for heating compared to the rural area. However, in the dry season, the rural area has a lower energy expenditure for evaporative processes, and thus, increased energy available for heating.

5. Conclusions

Among the results of this study is proof that changes in land use caused by urbanization alter energy balances of surfaces, generating an increase in surface temperatures. Therefore, urban development in Brazil is creating uncomfortable environments in terms of thermal comfort, since it boosts natural heating through, mainly, increased building density, decreased vegetation, and the use of materials inappropriate for the tropical climatic reality. This study also proved that, even in small towns, these changes are already noticeable, as can be observed by the analyzed UHI_{Surf} phenomenon, which has already shown a significant magnitude, especially in the summer (14°C). This paper also sought to contribute to an understanding of the spatial and seasonal variability of UHI_{Surf} in the continental tropical environment.

Frequency analysis (%) of UHI_{Surf} intensities at specific points in the urban and rural areas of Penápolis confirmed that the increase in surface temperature is closely related to land use, especially building density, absence of vegetation, and building materials. Analysis of the spatial distribution of UHI_{Surf} confirmed that, in the tropical continental environment, this phenomenon has significant seasonal variations that are directly associated with the region's rainfall regime. Magnitudes of UHI_{Surf} recorded by satellite images are not constant throughout the year. Intensity is higher during the rainy season and in the presence of verdant rural areas, conditions prevalent in the spring and summer seasons. During the dry period, autumn and winter seasons, intensity decreases due to the lower availability of moisture, leading to exposed soil and the loss of plant mass in rural areas, and, therefore, warming.

Results presented here are similar to those of previous studies of tropical environments with similar rainfall. Weng (2003) identified a similar pattern when analyzing the radiant temperature in Guangzhou (23°08' N and 113°17' E), China from Landsat 7 images. The author noted that during the summer solstice, image from August 29, 1997, the surfaces presented higher temperature variation and the urban and rural areas can easily be distinguished. The same pattern can also be observed in the tropical environment of the South Hemisphere. Amorim (2018), when analysing the city of Presidente Prudente (22°06' S and 51°47' W), identified that during the rainy season (summer solstice – image from January 18, 2016) the difference of surface temperature between the urban and rural area is higher, mainly when the rain is well distributed during the 30 days prior to the images collection. The authors attribute the different patterns of surface temperature to a seasonal variation in solar illumination and the state of vegetation.

It is important to recall that this identified spatial variability refers to the daytime period using Landsat 8 satellite images (13:21 GMT hour/10:22 local time). Nocturnal characteristics of UHI_{Surf} in Brazilian cities of medium and small size are still unknown due to the lack of nighttime satellite images of adequate spatial resolution. Results presented here are important for understanding a mechanism of heat generation in cities and for guiding urban planning, especially regarding land use regulations, maintenance and revitalization of urban vegetation, and the use of materials appropriate for the tropical climate. In this sense, it is believed that urban climate studies being developed in Brazil can contribute significantly to improvements in urban environmental quality.

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