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Research paper

The urban heat island in Rio de Janeiro, Brazil, in the last 30 years using remote sensing data

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ABSTRACT

The aim of this work is to study urban heat island (UHI) in Metropolitan Area of Rio de Janeiro (MARJ) based on the analysis of land-surface temperature (LST) and land-use patterns retrieved from Landsat-5/Thematic Mapper (TM), Landsat-7/Enhanced Thematic Mapper Plus (ETM+) and Landsat-8/Operational Land Imager (OLI) and Thermal Infrared Sensors (TIRS) data covering a 32-year period between 1984 and 2015. LST temporal evolution is assessed by comparing the average LST composites for 1984–1999 and 2000–2015 where the parametric Student *t*-test was conducted at 5% significance level to map the pixels where LST for the more recent period is statistically significantly greater than the previous one. The non-parametric Mann-Whitney-Wilcoxon rank sum test has also confirmed at the same 5% significance level that the more recent period (2000–2015) has higher LST values. UHI intensity between "urban" and "rural/urban low density" ("vegetation") areas for 1984–1999 and 2000–2015 was established and confirmed by both parametric and non-parametric tests at 1% significance level as 3.3 °C (5.1 °C) and 4.4 °C (7.1 °C), respectively. LST has statistically significantly (p-value < 0.01) increased over time in two of three land cover classes ("urban" and "urban low density"), respectively by 1.9 °C and 0.9 °C, except in "vegetation" class. A spatial analysis was also performed to identify the urban pixels within MARJ where UHI is more intense by subtracting the LST of these pixels from the LST mean value of "vegetation" land-use class.

1. Introduction

The 21 st century is the first "urban century", according to United Nations Development Programme. More than half the world's population (54%) currently lives in urban areas and projections made in 2014 (United Nations, 2014) suggest nearly two-thirds (one-third) will live in urban (rural) areas. In addition, United Nations (2014) predicts the number of megacities will increase from 28 in 2011–41 in 2030. In recent years much attention has been paid to the development of megacities due to its size and major problems they face, as well as almost all megacities are located in developing countries where urban growth rate is above the world average (United Nations, 2014). Accordingly, monitoring urban areas is important to understand its influence in different environmental parameters (Imhoff et al., 2010) and in weather and climate (Trenberth et al., 2007). In fact, urban construction materials have different thermal capacities and conductivities; the buildings geometry and their arrangements can trap radiation and pollutants, and create a roughness surface influencing airflow and dispersion; engineering structures could remove surface water and change the natural drainage networks and the natural topography, hence changing the flow regimes and humidity. The net effect is a profound change in radiative, thermal, aerodynamic and moisture of the pre-existing surface features, resulting in changes in the natural balance of energy, mass, and momentum.

The urban heat island (UHI) formation, the most usual terminology for urban heating, is one of the most well-known forms of anthropogenic climate modification at the local level. It presents implications for human comfort and health, urban air pollution, energy management and urban planning. As pointed out by Imhoff et al. (2010), UHI phenomenon is associated with changes in surface, where drainage system quickly removes most of the rainwater on impervious materials. Accordingly, only a small portion of the net radiation is used for evaporation (latent heat flux) and most available radiation is used to warm land surface and air directly above (sensible heat flux). On the other

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hand, a great fraction of the net radiation is used to evaporate water at moist surfaces in rural areas (e.g., lakes, rivers, soil, and vegetation) (Bretz et al., 1998; Taha, 1997; Arnfield, 2003). The thermal properties of the construction materials enable a faster heat transfer also contributing to increasing the temperature contrast between urban and non-urban areas. The spatial pattern contour of the isotherms forming one or several island features explains the UHI terminology. The isotherms distribution depends on the urban area configuration, but it is usually characterized by a strong thermal gradient in the urban-rural boundary, followed by a gradual rise in temperature toward the city core. The above description characterizes the classical UHI where the city center or downtown establish your core. However, several hot cores over the urban area may occur in large heterogeneous metropolitan areas forming a different pattern.

UHI phenomenon may be evaluated by comparing the air temperature in urban and rural environments based on automatic and conventional weather stations (e.g., Oke, 1976) and also by land-surface temperature (LST), usually obtained with thermal infrared (TIR) remote sensing data (Li et al., 2012; Chen and Yu, 2016). In situ air temperature data have the advantage of a high temporal resolution and historical time series, but have a low spatial resolution. On the other hand, remote sensing LST data have in general a low temporal resolution, but a high spatial distribution and is more easily related to surface conditions (Owen et al., 1998; Voogt and Oke, 2003; Imhoff et al., 2010). In fact, it is possible to retrieve biophysical land-surface characteristics and to describe urban environment materials based on remote sensing data. Consequently, remote sensing has potential to improve understanding the UHI phenomenon and its effects, and several studies have been assessed UHI using LST retrievals (e.g., Rao, 1972; Carlson et al., 1977; Matson et al., 1978; Gallo et al., 1995; Carnahan and Larson, 1990; Voogt and Oke, 2003; Weng and Quattrochi, 2006; Cheval et al., 2009; Li et al., 2011; Sobrino et al., 2012; Rhinane et al., 2012; Lucena et al., 2013).

Metropolitan area of Rio de Janeiro (MARJ) is currently going through a complex territorial transformation due to the construction of the Metropolitan Ring Road, Rio de Janeiro Petrochemical Complex (COMPERJ) and Itaguaí Port, one of the largest in the country. Metropolitan Ring Road will facilitate the production flow connecting different federal highways and expanding accessibility to Itaguaí Port and Rio de Janeiro city. Therefore it is expected that different companies are attracted to neighboring towns and along the Metropolitan Ring Road, which will connect the eastern and west end of MARJ.

In addition, the city of Rio de Janeiro and its metropolitan area are part of the megacities group. It is important that MARJ becomes part of a global research network investigating urban environment due to its worldwide exposure. This decade will be decisive for MARJ be promoted to the status of urban environmentally sustainable, starting with Rio + 20 UN Conference on Sustainable Development, which addressed the progress and setbacks of Rio 92, and the sporting events of the 2014 FIFA World Cup Brazil and Rio 2016 Summer Olympic Games, when both stimulate the promotion of sustainable practices and public policy strategies. Thus, it is important to monitor and create a database with information about the MARJ urban environment to collaborate for risk management of this area. In fact, UHI knowledge is fundamental to different areas of Earth sciences such as urban climatology, environmental changes, and human-environment interactions, and is important for planning and management practices. The interest of this work is to study surface UHI in MARJ using remote sensing data.

In this context, the objective of this paper is to 1) map LST between 1984 and 2015 in MARJ; 2) relate LST to land-use patterns; 3) determine the UHI magnitude, and 4) analyze MARJ thermal patterns.

2. Study area

MARJ is located in the southeastern Brazil and includes 21 cities (Fig. 1). Due to its geographical position and historical, economic and political processes, MARJ is now the second pole of population concentration and economic activities of the country. The region has a large amount of sport and socio-cultural activities, specialized supply of goods and services, and a high level of urbanization.

The MARJ urban area pattern spreads from the central city region out in several directions over the metropolis. The total population during the twentieth century displays two well-defined trends: 1) a rise from the 1940s and 2) a stabilization in the 1990s, a pattern observed in the main Brazilian cities during these decades. Patterns of urban and rural population growth show an urban land-use consolidation related to the growth and decline in urban and rural population, respectively. In fact, urban population predominates since the 1940s, with over 1,000,000 people against 351,000 rural inhabitants. This fact reflects the population density growth in agreement with a marked human influence on the landscape. From the 1990s, the urban population has stabilized between 9 and 10 million.

The physical space is marked by distinct physiographic zones: lowlands, massif and hills, bays, ponds and lagoons and it suffers intense transformation, shaped by human social interactions. The lowlands and mountains represented a major challenge to urban growth. The social changes throughout history have resulted in a series of environmental system impacts on the MARJ physical space, such as dismantling hills, drainage of wetlands, rivers canalization, embankments, siltation and disposal of mangroves, lagoons, salt marshes and beaches (Lucena et al., 2013).

The peak precipitation and drought season over MARJ occur during Austral summer and winter, respectively, varying from 130 mm in January to 40 mm in July. Extratropical frontal systems, the South Atlantic Subtropical High (SASH), and the South Atlantic Convergence Zone (SACZ) influence the region as well as the MARJ topography. During Austral summer, extratropical frontal systems reaching MARJ interact with tropical convection resulting from humidity advection from the Amazon region. Extreme events of precipitation are related to SACZ intensification due to the convergence of the moisture from the Amazon region and the moisture transport from SASH (Kodama, 1992, 1993; Grimm, 2003; Coelho et al., 2016). Mean daily temperature vary from 26 °C (February) to 21 °C (July).

3. Method and data

In the following, we describe the data and methodology used to achieve the aims of this research as described in Section 1. A brief overview of the main steps for implementing the adopted methodology is given in the flowchart shown in Fig. 2.

The present study focusses on the analysis of a time series database composed by eighty-two images from Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM +) and Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) onboard Landsat-5, 7 and 8 satellites covering a 32-year period between 1984 and 2015. We constructed this database by selecting images located in the path/row 217/76 (covering MARJ) with cloud coverage less than 10% and corresponding to the morning period (between 09 and 11 h).

Raw images were georeferenced using the polynomial model first degree and nearest neighbor interpolation in SPRING 4.3, a comprehensive GIS and Remote Sensing Image Processing software package developed by Brazilian National Institute for Spatial Research (INPE) (Camara et al., 1996). The Geocover_2003 dataset was the basis for georeferencing, which is a collection of standardized and orthorectified Landsat imagery (TM, and ETM+) covering MARJ region. Both Landsat-5 TM (120 m) and Landsat-7 ETM+ (60 m) band 6 images were resampled to 30 m spatial resolution according to the reflective spectral bands (Li et al., 2017). The Landsat Ground Processing System has resampled the Landsat-8 TIRS bands (100 m) by cubic convolution to 30 m and coregistered with the 30 m OLI spectral bands (Roy et al., 2014). We have separated the Landsat imagery database into two periods, i.e., 1984–1999 and 2000–2015 as shown in Table 1, to allow