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Spatial and temporal distribution of urban heat islands

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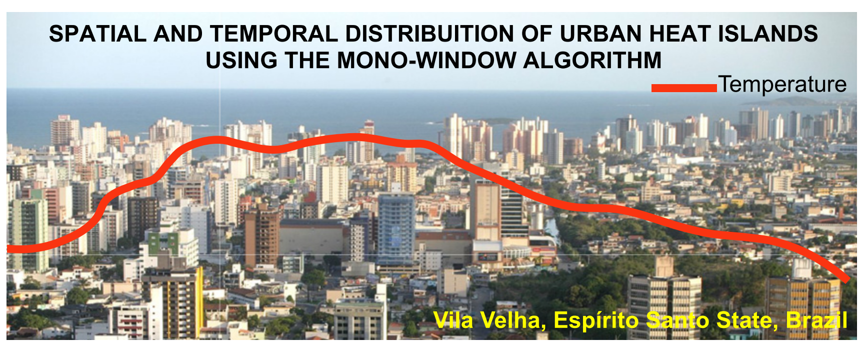
HIGHLIGHTS

- Urbanization resulting in higher radiation absorption, causing the effect of UHI
- Green areas attenuate the effect of UHI, provide thermal comfort.
- Identification of UHI as indicators for urban management and planning
- The methodology applied proved to be appropriate to identify the UHI.

GRAPHICAL ABSTRACT



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ABSTRACT

The formation of an urban heat island (UHI) is one of the most common impacts of the urbanization process. To mitigate the effects of UHI, the planning of urban forests (e.g., creation of parks, forests and afforestation streets) has been the major tool applied in this context. Thus, the aim of this study is to evaluate the spatial and temporal distribution of heat islands in Vila Velha, ES, Brazil using the mono-window algorithm. The study followed these methodological steps: 1) mapping of urban green areas through a photointerpretation screen; 2) application of the mono-window algorithm to obtain the spatial and temporal patterns of land surface temperature (LST); 3) correlation between LST and the normalized difference vegetation index (NDVI) and normalized difference build-up index (NDBI); 4) application of ecological evaluation index. The results showed that the mean values of LST in urban areas were at least 2.34 to 7.19 °C higher than undeveloped areas. Moreover, the positive correlation between LST and NDBI showed an amplifying effect of the developed areas for UHI, while areas with a predominance of vegetation attenuated the effect of UHI. Urban centers, clustered in some parts of the

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city, received the worst ecological assessment index. Finally, the adoption of measures to guide the urban forest planning within urban centers is necessary to mitigate the effect of heat islands and provide thermal comfort in urban areas.

1. Introduction

The development of society and the accelerated process of urbanization have changed the energy balance, infiltration, stormwater runoff, precipitation, temperature, air quality, storage carbon and local biodiversity, contributing to environmental modification and depreciation of the quality of life (Cheng et al., 2008; Chen et al., 2016; Liu and Zhang, 2011; Oke, 1987; Pickett et al., 2011).

A primary concern about the urbanization process is its effect on local temperature. In this context, one of the most common effects on local temperature is the formation of an urban heat island (UHI), which impacts urban planning and life quality (Chen et al., 2009, 2016; Streutker, 2002).

Urban heat island is the occurrence of higher temperatures in metropolitan areas in comparison to temperatures of suburban and rural areas, which means the higher the urbanization level the more prominent the UHI process (Pickett et al., 2011; Santamouris, 2013).

The effect of UHI is caused by the spatial distribution of land surface temperature (LST), which is controlled by the heat flux on the surface and exacerbated by urbanization (Dousset and Gourmelon, 2003; Sun et al., 2010). Thus, obtaining LST is critical for the analysis of UHI (Liu and Zhang, 2011).

The traditional method for analyzing UHI is based on LST data, measured at local observation points. However, since 1960, with the advent of high-resolution earth monitoring satellites, remote sensing technology has been widely used for LST measurements and obtainment of another UHI basic data (Liu and Zhang, 2011; Lu et al., 2009).

In comparison with the traditional method of meteorological observation, the use of remote sensing techniques have the advantage of high spatial resolution, which enables large-scale research of UHI. In contrast, the traditional method may be not sufficient to represent the entire region under study because of uneven distribution and the limited conditions of local meteorological observations points (Liu and Zhang, 2011).

There are several remote sensing datasets used in UHI studies, including NOAA AVHRR (Balling and Brazel, 1988; Sobrino et al., 1991; Streutker, 2002, 2003), Landsat TM/ETM+ (Fu and Weng, 2016; Kim and Guldmann, 2014; Li et al., 2016; Weng et al., 2004), MODIS (Hu and Brunsell, 2013; Pu et al., 2006; Quan et al., 2014; Wan et al., 2002), and ASTER (Liu and Zhang, 2011; Pu et al., 2006). These studies reveal spatial patterns of UHI as well the relationship between UHI and surface coverage, such as vegetation and soil cover (Buyantuyev and Wu, 2010; Weng, 2003; Weng et al., 2004).

Qin et al. (2001) proposed the mono-window algorithm to obtain LST from the thermal band of Landsat Thematic Mapper sensor data. According to Lu et al. (2009), this algorithm provides a simple and highly effective method for obtaining LST, thus facilitating the study and analysis of UHI effects.

The planning of urban forests, including the creation of parks, forests, and afforestation streets, has been one of the main tools identified by researchers of urban environments to mitigate the effects of UHI. The presence of vegetation can generate localized cooling, a phenomenon known as “island of amelioration,” which is the opposite effect of the UHI phenomenon (Dimoudi and Nikolopoulou, 2003; Yu and Hien, 2006; Shashua-bar et al., 2009).

The purpose of this study is to evaluate the spatial and temporal distribution of heat islands in Vila Velha, ES, Brazil using the mono-window algorithm.

2. Material and methods

2.1. Study area

The study was conducted in the municipality of Vila Velha, located on the coast of Espirito Santo state, between latitudes 20° 19′ and 20° 32′ south and longitude 40° 16′ and 40° 28′ west. This municipality is part of the metropolitan area of Greater Vitória (MAGV), along with the municipalities of Vitória, Cariacica, Viana, and Guarapari (Fig. 1). Its total area is 209,965 km^2, with an estimated population of 479,664 inhabitants (IBGE - Instituto Brasileiro de Geografia e Estatística, 2016).

The city of Vila Velha is entirely located in the Atlantic Forest biome (IBGE - Instituto Brasileiro de Geografia e Estatística, 2016), with Aw climate according to Köppen, which means tropical humid with dry winters and hot and rainy summers, annual average temperature around 24.7 °C, and rainfall distributed with greater intensity between the months of October and January (INMET - Instituto Nacional de Meteorologia, 2016).

2.2. Photointerpretation of green areas

This step establish a relationship between the spatial distribution of LST and the Green Areas (GA) of Vila Velha city.

For mapping the GA, we used 26 images from the GeoEye satellite, year 2013, with a 0.41 m spatial resolution, obtained from Google Maps Downloader application.

The software ArcGIS 10.2 was used for preprocessing, enhancement of images, and the photointerpretation procedure, which was performed using screen scanning at the cartographic scale of 1:1000.

The GA were classified only as the free space that met the following prerequisites: composed of tree/shrub; free of buildings or waterproofing covers (at least 70% of the area); and minimally perform ecological, aesthetic, scientific, cultural, and leisure functions.

2.3. Spatial and temporal distribution of UHI

For the spatial distribution of urban heat islands, we acquired 16 images from the Landsat 5 Thematic Mapper (TM) sensor, which are freely on the United States Geological Survey (USGS) website. The images were distributed between the years 2008–2011 (Table S1) in different seasons and had no cloud cover interference.

The meteorological data (air temperature (°C), relative humidity (%), wind speed (m/s) and precipitation (mm) – Table S2) were obtained from the Victoria automatic meteorological station of surface observation (VITORIA-a612) and were provided by the National Institute of Meteorology (INMET).

To obtain the spatial distribution of LST in Vila Velha, ES, the mono-window algorithm was adopted, as proposed by Qin et al. (2001):

$$T_s = \{a_6 \times (1 - C_6 - D_6) + [b_6 \times (1 - C_6 - D_6) + C_6 + D_6] \times T_{sensor} - D_6 \times T_a\}/C_6 \tag{1}$$

The parameters C_6 and D_6 were obtained using Eqs. (2) and (3):

$$C_6 = \varepsilon_6 \times \tau_6 \tag{2}$$

$$D_6 = (1 - \tau_6) \times [1 + (1 - \varepsilon_6) \times \tau_6] \tag{3}$$

where T_s is the LST of the thermal band (TM6) (K), a_6 is constant (67.355351), $b_6$is constant (0.458606), T_{sensor} is the sensor's brightness