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Assessing the impact of urban expansion to the state of thermal environment of peri-urban areas using indices

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ABSTRACT

In this paper we assess the impact of urban expansion to the thermal environment in peri-urban areas in the urban agglomeration of Athens for the period 1994–2010. Firstly, indices based on the use of earth observation data are used to distinguish urbanized from non-urbanized areas, and define built up features and area evolution at high spatial resolution. The urban expansion of Athens is more pronounced to the north and the west of the city, as well as to the south along the coastline. Secondly, the thermal environment is studied through the estimation of land surface temperature (LST) using Landsat satellite data. Areas, where land cover change has occurred due to urban expansion, show significantly smaller LST differences over the years as compared to a reference area in the urban center; a continuum of similar LST values extends from the city center to the peri-urban areas. This finding is of importance regarding urban climate as a temporal modification of the LST pattern in the peri-urban areas of Athens over the years, may potentially impact energy exchange, local circulation patterns, thermal comfort as well as energy consumption for cooling.

1. Introduction

Population growth and urban expansion have been essential drivers of land use/land cover (LULC) changes and the landscape pattern worldwide (Grimm et al., 2000; Weng, 2007). Due to the growth of urban areas, rural land cover types, such as soil, water, and vegetation, have been replaced with urban materials including asphalt, concrete, and metal (Xu, 2008a). These replacements have profound environmental impacts such as forest degradation, loss of agricultural lands, air, soil and water contamination, increased water use and runoff, and reduced biodiversity (EEA, 2006; Goksel et al., 2006; Santana, 2007; Schneider et al., 2010).

Urban climate is related to urban expansion as LULC changes affect the thermal environment through the modification of surface albedo, thermal emission coefficients and evapotranspiration as well as the enhancement of anthropogenic heat sources (Arnfield, 2003; Voogt and Oke, 2003; Tam et al., 2015). These changes alter the conditions of the near-surface atmosphere over the cities, and have caused several environmental problems, such as the development of urban heat island (UHI). The additional increase of temperatures, resulting from the urban heat island, affects the sustainability of the urban environment and the quality of life of the population, because of the increased energy consumption, the emission of air pollutants and the reduction of human thermal comfort. (Krüger et al., 2013; Boumans et al., 2014; Makido et al., 2012; Wang, 2014; González-Aparicio et al., 2014).

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The assessment and monitoring of urban expansion can be effectively conducted with the use earth observation data. Several researchers (Chrysoulakis et al., 2011; Weng, 2012; Marconcini et al., 2013) have taken advantage of the improved at-sensor spatial resolution (Weng and Quattrochi, 2007), to apply earth observation techniques in order to define the extent and rate of urban expansion. These techniques include some indices that are proposed for the rapid extraction of urbanized areas through the automated mapping of built-up features. The normalized difference built-up index (NDBI) (Zha et al., 2003) and the index based built-up index (IBI) (Xu, 2008b) are based on the spectral response of built-up lands, taken that they have higher reflectance in the middle infrared wavelength range than in the near infrared wavelength range. The main advantage of these indices is that they limit subjective human intervention in the mapping process.

A number of studies have been conducted using earth observation data in order to highlight the magnitude and spatial variability of the surface UHI (Stathopoulou and Cartalis, 2009; Stathopoulou et al., 2009; Senanayake et al., 2013; Hala and Ossman, 2014). These studies provide a spatially continuous view of the thermal environment over large urban areas, thus overcoming the spatial limitations of networks of ground based meteorological stations. In addition, earth observation can effectively depict the thermal environment of urban areas at high temporal resolution. Thus, spatial coverage and temporal repetition are the main advantages of using earth observation in the study of urban climate (Stathopoulou and Cartalis, 2007).

In this study the IBI index is applied to a time-series of Landsat images in order to depict the urban expansion of the city of Athens. Urban areas are defined by all the anthropogenic features, such as rooftops, roads, driveways, sidewalks, and parking lots. Results are correlated with the spatial variation of land surface temperature in order to assess the impact of urban expansion to the state of the thermal environment of the peri-urban areas. Land surface temperature is an important parameter for analyzing the thermal environment as it modulates the air temperature of the lower layer of the atmosphere and is a primary factor in determining surface radiation and energy exchange, the internal climate in cities, and human thermal comfort in the cities.

2. Study area and data

The study area is part of the regional division of Attica where Athens is located. It covers a surface of about 1333 km^2 that includes urban and suburban residential areas, commercial and industrial areas, transport infrastructure, as well as rural areas used for agriculture or covered by natural vegetation and/or bare soil/barren land areas. Athens is a typical Greek city that follows a centralized urban planning system while the outspread of the build-up area can be termed as extensive and continuous, despite the fact that it has recently slowed down due to the economic recession and the decline in the construction sector and in real estate development. The organization of urban space has been non-functional and characterized mainly by high building density, a high degree of land-use mix, the lack of open public spaces in central areas, closed vents to the natural environment of the surrounding countryside and the lack of planned building on the city outskirts (Chorianopoulos et al., 2010; Papamanolis, 2015).

A set of four cloud free Landsat TM images (summer period with similar prevailing weather conditions) were used in this study covering a sixteen years period (1994, 1999, 2005 and 2010) and reflecting spectral resolution in the thermal infrared and spatial resolution of 120 m.

3. Methodology

Pre-processing of the Landsat images was necessary before the extraction of urban areas could be performed. A Landsat orthorectified product was used as reference image to geometrically correct the images, using several ground control points. Following, a relative atmospheric correction method was applied to normalize the multi-temporal images so that the corrected images appear as if obtained under the same atmospheric conditions and with the same sensor. The Ridge Method (Song et al., 2001) was used in this study as it overcomes the difficulty in identifying pseudo-invariant features (PIF's) in the image. The image of the year 1994 was used as reference and all the other images were rescaled accordingly.

The calculation of the IBI index is based on the spectral disparity of the three major land covers (built-up land, vegetation and water) in the bands 2, 3, 4 and 5 of the Landsat TM. Three thematic indices, the normalized built-up index (NDBI) as expressed in Eq. (1), the soil adjusted vegetation index (SAVI) as expressed in Eq. (2) and the modified normalized difference water index (MNDWI) as expressed in Eq. (3) were selected to represent the three components.

$$\mathrm{NDBI} = (\mathrm{TM5} - \mathrm{TM4})/(\mathrm{TM5} + \mathrm{TM4}) \tag{1}$$

$$\mathrm{SAVI} = (\mathrm{TM4} - \mathrm{TM3})(1 + L)/(\mathrm{TM4} + \mathrm{TM3} + L) \tag{2}$$

$$\mathrm{MNDWI} = (\mathrm{TM2} - \mathrm{TM5})/(\mathrm{TM2} + \mathrm{TM5}) \tag{3}$$

where TM2, TM3,TM4 and TM5 are the radiances of band 2, 3, 4 and 5 respectively.

The correction factor L, used in the calculation of SAVI, can take values from 0 to 1. For the region of Attica the exact vegetation percentage is difficult to estimate and a value of $L = 0.5$ was used as it is found to reduce soil noise problems substantially for a wide range of vegetation densities (Huete, 1988). Then, the IBI index was calculated from Eq. (4). The

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