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Monitoring surface urban heat island formation in a tropical mountain city using Landsat data (1987–2015)

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ABSTRACT

Since it was first described about two centuries ago and due to its adverse impacts on urban ecological environment and the overall livability of cities, the urban heat island (UHI) phenomenon has been, and still is, an important research topic across various fields of study. However, UHI studies on cities in mountain regions are still lacking. This study aims to contribute to this endeavor by monitoring and examining the formation of surface UHI (SUHI) in a tropical mountain city of Southeast Asia –Baguio City, the summer capital of the Philippines– using Landsat data (1987–2015). Based on mean surface temperature difference between impervious surface (IS) and green space (GS1), SUHI intensity (SUHII) in the study area increased from 2.7 °C in 1987 to 3.4 °C in 2015. Between an urban zone (>86% impervious) and a rural zone (<10% impervious) along the urban-rural gradient, it increased from 4.0 °C in 1987 to 8.2 °C in 2015. These results are consistent with the rapid urbanization of the area over the same period, which resulted in a rapid expansion of impervious surfaces and substantial loss of green spaces. Together with landscape composition variables (e.g. fraction of IS), topographic variables (e.g. hillshade) can help explain a significant amount of spatial variations in surface temperature in the area (R^2 = 0.56–0.85) ($p < 0.001$). The relative importance of the 'fraction of IS' variable also increased, indicating that its unique explanatory and predictive power concerning the spatial variations of surface temperature increases as the city size becomes bigger and SUHI gets more intense. Overall, these results indicate that the cool temperature of the study area being situated in a mountain region did not hinder the formation of SUHI. Thus, the formation and effects of UHIs, including possible mitigation and adaptation measures, should be considered in landscape planning for the sustainable urban development of the area.

1. Introduction

Urban heat island (UHI) is a phenomenon whereby urban regions experience warmer temperatures than their surrounding rural areas (Howard, 1818; Voogt, 2004; EPA, 2008). Since it was first described about two centuries ago (Howard, 1818) and due to its adverse impacts on urban ecological environment and the overall livability of cities, the UHI phenomenon has been, and still is, an important research topic across various fields of study (Estoque et al., 2017). And as we enter the urban era of the Anthropocene (Crutzen, 2002; Seto and Reenberg, 2014), this phenomenon is expected to gain more recognition, not only from research and academic communities, but also from landscape and urban planning and policy making bodies.

UHI is classified into two types, namely surface UHIs, which are measured based on land surface temperature (LST), and atmospheric UHIs, which are measured based on air temperature and are often classified into canopy layer and boundary layer UHIs (EPA, 2008). This study focuses on surface UHI, hereafter referred to as SUHI, which is typically present day and night, but tends to be strongest during the day due to the radiation from the sun (EPA, 2008).

Although local climate changes caused by UHIs differ fundamentally from global climate changes (GCCs) caused by increases in the sun's intensity or greenhouse gas concentrations (e.g. in terms of scale and mechanisms), their impacts are often similar (EPA, 2008). For instance, UHIs and global warming due to GCCs can both increase energy consumption and greenhouse gasses emissions, and affect air and water quality, as well as human

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health and thermal comfort (Voogt, 2004; EPA, 2008). Thus, addressing the issues of UHIs can also help mitigate the impacts of GCCs and increase adaptive capacities at the local level (EPA, 2008). Such efforts can also contribute to the sustainable development goals, particularly on 'climate action' and 'sustainable cities and communities' (UN, 2015).

Generally, the formation of UHIs can be regarded asa ne gative 'by-product' or impact of urbanization. More specifically, the formation of UHI is influenced by landscape changes due to urban development in which open lands and green spaces are converted into built-up lands or impervious surfaces (e.g. buildings, roads, etc.) and by the resulting anthropogenic heat (Voogt, 2004; EPA, 2008; Estoque et al., 2017). Thus, landscape compositions such as fractions of impervious surface and green space, which, in most cases, are determined from remote sensing data, have been important inputs to the study of UHI formations (Weng et al., 2004; Buyantuyev and Wu, 2010; Myint et al., 2010, 2013; Xu et al., 2013; Estoque et al., 2017).

Before the advancement of thermal infrared remote sensing in recent decades, the use of *in situ* air temperature data was common in UHI studies. Although this approach has important advantages, e.g. high temporal resolution and long data record, it also has limitations, e.g. poor spatial resolution (Hung et al., 2006). Thermal infrared remote sensing data, on the other hand, while they have lower temporal resolutions, have wider spatial coverage. Remote sensing data are also cost-effective. In general, the development of thermal infrared remote sensing provides opportunities and enables scientists to characterize the spatial and temporal structures of surface temperatures (Voogt and Oke, 2003; Hung et al., 2006; Weng, 2009; Li et al., 2013), and this is indeed an important advancement in the field.

The measurement and monitoring of UHI intensity is central to the study of the UHI phenomenon. UHI intensity, be it based on air temperature or surface temperature, generally refers to the temperature difference between urban and rural areas (Oke, 1982; Arnfield, 2003; Voogt and Oke, 2003; Memon et al., 2009; Hung et al., 2006; Martin-Vide et al., 2015). And because urban and rural areas are both important inputs in determining the magnitude of UHI, the urban-rural gradient approach provides a useful analytical platform (Zhou et al., 2015; Estoque et al., 2017). UHI intensity can also be measured by first classifying the urban landscape into climate zones, followed by an inter-zone comparison (Oke, 2006; Stewart and Oke, 2009).

There is a rich, and still growing, literature concerning UHI studies. For tropical cities, many studies have been done (e.g. Hung et al., 2006; Peng et al., 2012; Alves, 2016; Estoque et al., 2017). Around the world, various city types have also been studied, from small/medium-sized cities to megacities (Oke, 1973; Hung et al., 2006; Peng et al., 2012; Alves, 2016; Alves and Lopes, 2017; Estoque et al., 2017), and from coastal cities (Sakakibara and Owa, 2005; Estoque et al., 2017) to desert cities (Myint et al., 2010; Lazzarini et al., 2013; Bokaie et al., 2016). However, UHI studies on cities in mountain regions are still lacking. Cities in mountain regions, like the hill stations in the tropics (Crossette, 1999; Estoque and Murayama, 2016), have unique environmental characteristics and cool temperature, which are conducive to good living conditions. However, rapid urbanization has also begun taking a toll on the natural environment of some, if not most, of these cities (Crossette, 1999; Estoque and Murayama, 2016).

Hence, the goal of this study is to contribute to the body of knowledge concerning the UHI phenomenon by monitoring and examining the formation of SUHI in a tropical mountain city of Southeast Asia –Baguio City, the summer capital of the Philippines– using Landsat data (1987–2015). Various landscape variables that could potentially help explain the spatial variations of surface temperatures in the area are explored and the implications of the findings in the context of landscape and urban planning, as well as in UHI studies, are discussed.

2. Methodology

2.1. Study area

Baguio City is one of the major hill stations in Southeast Asia and is located in northern Philippines on Luzon Island, approximately 250 km north of Manila, the country's capital city (Fig. 1). It is geographically located within the province of Benguet and serves as the regional center of the Cordillera Administrative Region (CAR), one of the country's 18 regions.

Situated on a 1500 m high plateau in the Cordillera mountain range of Northern Luzon, Baguio City is, on the average, 8 °C cooler than the lowlands (Saldivar-Sali and Einstein, 2007). It is the summer capital of the country. Its average temperature ranges from 15 °C to 23 °C, seldom exceeding 26 °C even during the warmer months (Saldivar-Sali and Einstein, 2007; Estoque and Murayama, 2013a). On average, the coldest month in Baguio City is January, while the hottest month is April. The average annual rainfall in the area is 3914 mm (WWF and BPI, 2014), with August as the wettest month.

The landscape of Baguio City is a mosaic of built-up lands, forests, shrublands, grasslands and scattered small patches of croplands used for vegetable and flower production. The whole study site has a total area of 26,147 ha, covering Baguio City and portions of its adjacent municipalities (Fig. 1b). The elevation of the study area ranges from 363 m to 2094 m, with a mean elevation of 1246 m above sea level. The slope varies from 0° to 71°, with a mean slope of 20°. The climate in the area belongs to the Philippines' Climatic Type I, characterized by two pronounced seasons: a dry season from November to April, and a rainy season from May to October.

2.2. Satellite data used and pre-processing

Landsat images captured in 1987 (December 14; GMT 01:45:33), 2001 (December 12; GMT 02:05:40) and 2015 (December 27; GMT 02:17:09) (http://glovis.usgs.gov/) were used in this study (Fig. 1c). The selection of the images, including their dates of capture and the time-period of the analysis, was influenced by the overall purpose of this study, i.e. to monitor and examine the formation of SUHI in the area. More specifically, the 'oldest' and 'newest' available satellite data for the study area that contain thermal bands for LST retrieval were selected. In the tropical wet regions, including the study area, the availability of satellite data is heavily affected by clouds. So, this was also a major consideration. The inclusion of another time point between the 'oldest' and 'newest' available image data aims to provide a more informed analysis of temporal trends. All the images were acquired in the same month, during the dry season.

Prior to land cover mapping and LST retrieval, all the satellite images were subjected to a set of pre-processing procedures, such as radiometric calibration and atmospheric correction (dark-object subtraction) using the TerrSet software. This whole process of pre-processing resulted in the conversion of the digital number (DN) values of the satellite data into radiometrically calibrated and atmospherically corrected (1) surface reflectance values for the multispectral bands, and (2) at-satellite brightness temperature (T_B) values for the thermal bands expressed in degrees Kelvin.