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Examining the impact of urban biophysical composition and neighboring environment on surface urban heat island effect

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Abstract

Due to atmospheric and surface modifications associated with urbanization, surface urban heat island (SUHI) effects have been considered essential in examining urban ecological environments. With remote sensing technologies, numerous land cover type related variables, including spectral indices and land cover fractions, have been applied to estimate land surface temperature (LST), thereby further examining SUHI. This study begins with the reexamination of the commonly used indicators of LST using Landsat Enhanced Thematic Mapper Plus (ETM+) and Landsat Thematic Mapper (TM) images which cover four counties of Wisconsin, United States. Origin of the large variation of LST found in urban areas is then investigated by discriminating soil and impervious surfaces. Except land cover types, neighboring environment is another key factor which may affect LST in urban areas. Thus, a neighboring effect considered method is proposed at the end of the study to better understand the relationship between impervious surfaces fraction (%ISA) and LST by taking the influence of neighboring environment into account. Results indicate that spectral indices have better performance in predicting LST than land cover fractions do within the study area. However, the result remains arguable due to the complexity and uncertainty of spectral mixture analysis. Impervious surfaces are found responsible for the large variation of LST in urban areas, which indicates that impervious surfaces should not be simply considered as a single land cover type has stable negative correlation with LST. Moreover, a better relationship is found between %ISA and LST when neighboring effect is considered, when compared to the traditional method which ignores the neighboring effect.

Keywords: Surface urban heat island; Land surface temperature; Remote sensing; Urban biophysical composition

1. Introduction

Urban heat island (UHI) refers to the phenomenon that apparent higher temperatures are found in urban areas when compared to surrounding rural areas, majorly due to atmospheric and surface modifications associated with urbanization (Voogt and Oke, 2003). Concentrated human activities in urban areas have led to abundant energy emissions, affecting regional climate by altering the energy exchange and heat conductivity (Yuan and Bauer, 2007). Voogt and Oke (2003) divided UHI into three categories: canopy layer heat island (CLHI), boundary layer heat island (BLHI) and surface urban heat island (SUHI). The first two categories can be identified as atmospheric heat island, which is usually described using air temperature records collected by in-situ measurement and records from weather stations, while SUHI are often characterized by land surface temperature (LST) retrieved from airborne and satellite remote sensing imagery.

In the study of SUHI, remote sensing technology has played an important role due to its ability of extracting information for a large geographical area with repetitive coverage. When SUHI is studied using remotely sensed

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data, normalized difference vegetation index (NDVI) has been employed as the main indicator of LST. As it indicates the abundance of green vegetation, a higher NDVI value usually indicates a lower LST value due to evapotranspiration. The relationship between NDVI and LST has been applied to many SUHI related studies. Gallo et al. (1993) analyzed the urban–rural difference of NDVI and LST, and evaluated the impact of urban areas on minimum air temperature. Gallo and Owen (1999) reported that 40% of urban–rural temperature differences can be explained by the differences in NDVI and satellite image derived LST. Lo et al. (1997) analyzed the differences of thermal response of different land cover types between daytime and night, and investigated the relationship between surface radiance and NDVI.

With the development of spectral mixture analysis, land cover fractions were then employed to retrieve LST from remote sensing imagery. Weng et al.(2004) utilized vegetation fraction (%GV) as an indicator of LST in the City of Indianapolis, Indiana, United States. Results demonstrated that LST has a slightly stronger correlation with %GV than NDVI does at all selected scale (30 m, 60 m, 120 m, 240 m, 480 m and 960 m). Yuan and Bauer (2007) calculated mean values of LST for each 1% increment of NDVI and impervious surface fraction (%ISA) for a TM image of Twin Cities, Minnesota, United States. The result indicated that %ISA has better linear relationship with mean LST than NDVI does at all four seasons. Li et al. (2011) also found strong relationship between %ISA and mean LST when investigated the influence of landscape structure on UHI in Shanghai, China. Given the better performance of land cover fractions in the current studies, several issues still exist. First, when %GV is employed as the single indicator of LST, all pixels occupied by non-vegetation land covers have similar values of %GV and are considered to have similar thermal characteristics. However, LST could be unstable even for the same land cover type. Taking soil cover for instance, LST could differ dramatically as the humidity of soil cover changes, even with the same %GV. In other words, different land covers should be discriminated and discussed separately during the process of LST estimation, especially for the areas not dominated by vegetation. Second, when %ISA is applied to study SUHI, the relationship between the mean values of LST and %ISA was examined (Yuan and Bauer, 2007). Urban impervious surfaces, however, represent a collection of materials water cannot infiltrate, and may include a number of specific materials with different thermal characteristics. Mean values of LST may bring a strong statistical relationship with %ISA, but the thermal differences among various impervious surfaces could be ignored. Therefore, it is arguable whether %ISA is a reasonable indicator of LST in urban areas.

In addition to the influence from different land cover types, another key factor could affect LST in urban areas is surrounding environment. For instance, a highway made of asphalt goes through a city which includes downtown, residential area and suburb. Although the road is made of single material, LST may differ dramatically from one segment to another due to the extinct surrounding environment. In downtown, LST of the road is usually higher due to the massive anthropogenic heat emitted by air conditioning systems and vehicles. Meanwhile, temperature above the road may decrease because of the surrounding forests in suburban area. Therefore, in order to accurately estimate LST in urban areas, influence of surrounding environment should be considered. Currently, however, SUHI studies with remote sensing imagery are carried out by treating each pixel as a standalone object and ignore the possible influence among neighboring pixels which could affect LST. The lack of neighboring information may lead to a biased estimation of LST. A neighboring effect considered method is urged for the quantitative estimation of LST.

In order to address the aforementioned issues, the performance of spectral indices (NDVI and NDBI) and land cover fractions (%GV and %ISA) as indicators of LST was examined firstly in our study. Then, we analyzed large LST variation in non-vegetated areas and related it to the influence of surrounding environment on the LST of impervious surfaces. At the end, a neighboring effect considered method was proposed to incorporate the influence from surrounding environment into the estimation of LST.

The remainder of this paper is organized as follows. Next section introduces the study area and data. Section 3 introduces the methods applied to this study. Results and discussion are detailed in Sections 4 and 5 respectively. This paper concludes in Section 6.

2. Study area and data

Four counties, Milwaukee, Waukesha, Washington and Ozaukee, located in Wisconsin, United States were selected as the study area (Fig. 1). These four counties cover a geographic area of 3784 km^2 with a population of 1.6 million (U.S. Census Bureau, 2010). The average population and household number have increased by 3.5% and 7.0% annually since 1980 (Southeastern Wisconsin Regional Planning Commission (SEWRPC), 2010; U.S. Census Bureau, 2010). Moreover, according to the analyses based on historical socio-economic data, this trend will continue in the next several decades (SEWRPC, 2004a, b). There are various land use/land cover types within the study area, including industrial, transportation, residential, commercial, agricultural, water bodies and open lands such as forest, wetland and barren land (SEWRPC, 2000). As the major urbanized area of Wisconsin, the City of Milwaukee has more than 60% of the total population of the study area.

In order to examine the SUHI effect within the study area, several requirements must be satisfied, including: (1) the availability of high spatial resolution imagery; (2) the need of thermal image for LST retrieval; (3) as little cloud cover over the study area as possible; and (4) multiple images for time series analysis. Thus, a Landsat ETM+