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Impact of greening on the urban heat island: Seasonal variations and mitigation strategies

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ABSTRACT

Intensive urbanization has led to the depletion of vegetation and its replacement by impervious surfaces, resulting in the accumulation of thermal energy, with urban areas becoming warmer than peripheral areas, a phenomenon known as the Urban Heat Island (UHI). Much of the literature has focused on the relationship between the UHI and urban factors at peak summer times, without considering seasonality effects. There is, however, clear evidence that the UHI varies over the year, with implications for greening mitigation strategies, as green spaces are known to help reduce summer local temperatures, but also reduce exposure to winter cold, thus increasing local winter temperatures. Both effects are likely to generate, in varying extents, benefits in terms of better health and reduced energy usage and pollution emissions. This paper addresses the seasonality of the impacts of building rooftop and façade areas, urban canyons, water bodies, vegetation, and solar radiation, on UHI intensity. In a case study of the central area of Columbus, Ohio, these various 2D and 3D inputs, as well as land surface temperatures estimated with remotely-sensed imagery, are captured within a spatial grid, and used in spatial regression analyses. The estimation results confirm the opposite effects of greenery, measured by the NDVI, on summer and winter temperatures. The estimated models are then used to simulate the seasonal changes in temperatures resulting from a potential urban greening strategy involving green roofs, the greening of parking lots and other vacant spaces, and vegetation densification. The results show that increased greenery reduces temperatures in summer and increases them in winter, thus demonstrating that greening and land-use policies designed to mitigate the UHI must account for seasonal effects to achieve year-long effectiveness.

1. Introduction

Urbanization and the resulting expansion of impervious areas have intensified the urban heat island (UHI), characterized by a temperature differential between central urban areas and surrounding suburban and rural areas. The higher temperatures during the warm season induce health problems for vulnerable populations through heat stress and ozone formation, and increased building energy consumption for air conditioning (Boumans, Philips, Victery, & Fontaine, 2014). It is therefore important to understand the underlying determinants of the UHI in order to develop mitigation strategies and efficiently manage the urban thermal environment.

Much of the previous UHI literature has focused on explaining the UHI spatial pattern at a specific time, generally in summer. The explanatory variables generally include vegetation and other land uses captured in the ground-level two-dimensional (2D) space (Rinner & Hussain, 2011), and three-dimensional (3D) space factors such as building height and volume, sky openness, street canyon, shading, and solar radiation (Chun & Guldmann, 2014).

However, these UHI determinants impact surface temperatures across the year in different ways and at different levels. For instance, green spaces, in particular trees, have been shown to decrease summer temperatures, thus reducing cooling expenditures, but also to provide protection from cold air and wind in winter, thus increasing ambient temperatures, and therefore decreasing heating energy expenditures. These effects will depend on the nature of the green spaces. Deciduous trees provide summer benefits, but their lack of foliage reduces their winter benefits. In contrast, evergreen trees might provide year-round benefits. Therefore, a comprehensive and cost-effective strategy for improving the outdoor thermal environment should encompass all seasons. To implement such a strategy, it is first necessary to understand and measure the time-dependent effects of the critical UHI variables.

The purpose of this paper is to explore the varying contributions of urban features to UHI intensity over the year, using data for the central area of Columbus, Ohio, and spatial regression modeling. Time-varying

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land surface temperatures (LST), solar radiations, and vegetation cover intensity are captured on a bi-monthly basis (February, April, June, August, October, and December), and these variables are combined with time-invariant factors, such as building footprints and façades, sky openness, and water areas. The resulting bi-monthly spatial models are then used to simulate the spatial UHI impacts of a greening scenario.

The remainder of the paper is organized as follows. Section 2 consists in a review of the relevant literature. Section 3 describes the data. The statistical modeling methodology is described in Section 4. The regression estimation results are presented in Section 5. The results of the simulation of a greening scenario are presented in Section 6. Section 7 concludes the paper and outlines areas for further research.

2. Literature review

Research on the UHI has grown exponentially in recent years. A Google Scholar search of the term "urban heat island" returned 48,000 items on September 12, 2017, with 16, 600 items published since 2013. Basic reviews on the physics fundamentals of the UHI, on thermal remote sensing, and on the thermal impacts of urban change can be found in Arnfield (2003), Rizwan, Dennis, and Liu (2008), Mirzaei (2015), and Chapman, Watson, Salazar, Thatcher, and McAlpine (2017). The focus of this short literature review is on the statistical analysis and modeling of the seasonal variations of the UHI. As mentioned earlier, there is a large number of statistical studies of the UHI in daytime and nighttime, but only at a specific time of the year, generally in the summer. Reviews of this literature can be found in Kim and Guldmann (2014), Chun and Guldmann (2014), and Chun and Guhathakurta (2017).

Earlier studies of UHI seasonal variations are primarily descriptive. Ackerman (1985), using 20 years of temperature data for two locations in the Chicago metropolitan area, show clear seasonal patterns in urban-rural temperature difference, with peaks in June–September, and that these differences are impacted by winds blowing from Lake Michigan, particularly in summer nights. Kim and Baik (2005), using data for 31 weather stations in Seoul over one year, show that UHI clusters vary in intensity and location over the year, decreasing with wind speed and cloud cover. They also find that the UHI is stronger on weekdays than on weekends, and is influenced by land-use type and anthropogenic heat release. Chow and Roth (2006), using hourly temperature data at 4 weather stations in Singapore over one year, show that canopy-level UHI seasonal variations are related to the extent of green spaces and anthropogenic heat, but not to urban geometry. They also show that higher UHI intensities occur during the monsoon season. Taleghani, Tenpierik, van den Dobbelsteen, and Sailor (2014) study the effects of vegetation and water in summer and winter, using data on courtyards in two university campuses in Portland (OR), USA, and Delft, The Netherlands. They show that the thermal effects of green roofs and courtyards are not significantly different in the two seasons. Oleson, Bonan, Feddema, and Jackson (2011) and Oleson et al. (2015) explore monthly and diurnal climate patterns at the global scale, and measure differences in urban and rural meteorological characteristics with the Community Climate System Model (CCSM) developed by the National Center for Atmospheric Research (NCAR). They find that energy balance and surface characteristics are primary factors in the formation of the UHI. They also propose investigating potential urban heat interactions between neighboring cities.

A more recent stream of studies involves the use of correlation and regression analyses in trying to understand the seasonal variations of the UHI. Hamada and Ohta (2010), using air temperature data over a full year in Nagoya, Japan, compare the UHI in an urban green area, including forest and grassland, with the UHI in the surrounding urban area. The difference in temperature among these two areas turns out larger in the summer than in the winter. They observe a negative correlation between temperature and forest cover, and a cooling effect of the green area reaching 200-300 m into the urban area at night. Cui and de Foy (2012), using both satellite and air temperature data for Mexico City, show that seasonal UHI variations are related to vegetation cover, daytime insolation, and atmospheric stability. Qiao, Tian, and Xiao (2013), using MODIS-derived LST data for April, July, October, and December 2008, and for three functional zones in Beijing, derive regressions between LST and NDVI for the 4 seasons and for both daytime and nighttime. They show that the contributions of forests and croplands to the UHI vary diurnally and seasonally. Haashemi, Weng, Darvishi, and Alavipanah (2016), using MODIS- and Landsat-derived LST data for Teheran over 2 years, show that the correlations of LST with fractional vegetation cover, impervious surfaces, albedo, and elevation, vary seasonally and diurnally. Finally, Yang et al. (2017) regress LST over various measures of green spaces (NDVI, total area, number of patches, and other landscape metrics) measured over the period from April to December 2014. However, they find that green spaces have little effect on the winter urban thermal environment. This result may be due to the fact that no other urban factors (water, impervious surfaces, 3D variables) are considered in this analysis.

Finally, three very recent papers use the technique of land-use regression to investigate more comprehensively UHI seasonality. Kim and Kim (2017) use hourly air temperature (AT) data over 2012–2014 at 28 weather stations in Seoul, Korea. The data are averaged out over the 4 seasons and for both daytime and nighttime. GIS data are used to measure the areas of various land uses within a 1 km radius buffer centered on each station, and 8 regression models (4 seasons, day/night) relating temperatures to land uses are estimated. The results show that residential, commercial, and road land-uses increase temperature, while open space and greenery decrease it. However, the estimated coefficients do not display clear seasonal variations. Park, Ha, and Lee (2017) use AT data for 236 weather stations in Seoul, land-use data within 500 m radius buffers centered on each station, weather data such as wind speed and solar radiation, and 3D variables such as the sky view factor, porosity, and surface roughness, all computed within each buffer. They regress averaged temperatures on the above variables, for each season and for both daytime and nighttime. The results show that the 3D factors have stronger impacts in summer than in winter. Shi, Katzschner, and Ng (2018) use hourly AT data over 2013–2016 for 42 weather stations in Hong Kong. These data are averaged out by season, the whole year, and day and night. Starting with 224 potential predictor variables and using stepwise regression, they produce 10 models with different sets of variables, which makes it impossible to compare them. The fractional vegetation cover, a proxy for green spaces, only appear as significant in the nighttime models for spring and autumn.

In summary, the analysis of the seasonal variations of the UHI has recently grown in sophistication in terms of the explanatory variables considered in regression models. However, clear and consistent patterns in the seasonal effects of these variables, in particular urban green spaces, have yet to emerge. In addition, spatial autocorrelations are not taken into account. Finally, the urban planning and design implications of UHI variability need to be clarified. This paper is an attempt to deal with these issues.

3. Data

3.1. *Study area*

This research focuses on an area of 46.5 km^2 around the Central Business District (CBD) of the city of Columbus, Ohio (Fig. 1). In addition to commercial, office, and governmental buildings, the site also includes parks and residential areas to the south. Water bodies include two rivers, the Olentangy and the Scioto, merging near the CBD, as well as scattered, smaller ponds. Unlike other cities in the Midwest, Columbus has continued to expand in recent years, leading to the construction of many high-rise buildings and impervious surfaces. Kenward, Yawitz, Sanford, and Wang (2014) report that Columbus was ranked eighth among the top ten U.S. cities with the most intense