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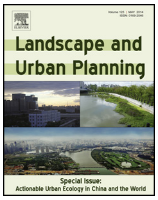

Research Paper

Spatial statistical analysis and simulation of the urban heat island in high-density central cities

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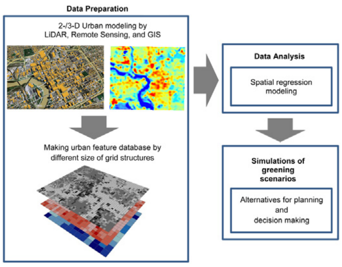
HIGHLIGHTS

- Spatial regression analysis is used to explain the urban heat island (UHI), accounting for spatial autocorrelations.
- Three- and two-dimensional variables are integrated within uniform grids of various scales to model land surface temperatures.
- Solar radiation, open space, vegetation, building rooftops, and water strongly impact land surface temperatures.
- The estimated general spatial model is used to simulate temperature effects of greening scenarios in Columbus, OH.
- The results illustrate the potential of such models to help mitigate the UHI through urban design and land-use policies.

GRAPHICAL ABSTRACT



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ABSTRACT

The urban heat island (UHI) is a mounting problem in built-up areas, leading to increased temperatures, air pollution, and energy consumption. This paper explores the urban determinants of the UHI, using two-dimensional (2-D) and three-dimensional (3-D) urban information as input to spatial statistical models. The research involves: (a) estimating land surface temperatures, using satellite images, (b) developing a 3-D city model with LiDAR data, (c) generating urban parameters with 2-D/3-D geospatial information, and (d) conducting spatial regression analyses. The data are captured over three grids of square cells – 480 m, 240 m, and 120 m – and characterize the center of Columbus, Ohio. The results show that solar radiations, open spaces, vegetation, building roof-top areas, and water strongly impact surface temperatures, and that spatial regressions are necessary to capture neighboring effects. The best regression is obtained with the general spatial model (GSM), which is then used to simulate the temperature effects of different greening scenarios (green roofs, greened parking and vacant lots, vegetation densification) in the center of Columbus. The results demonstrate the potential of such models to mitigate the UHI through design and land-use policies.

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1. Introduction

Projections by the United Nations suggest that 60% of the world's population will reside in urban regions by 2030. The resulting expansion of impervious surfaces is likely to intensify the urban heat island (UHI), whereby temperatures in urban core areas are higher than in surrounding suburban and rural areas. The UHI induces heat stress, tropospheric ozone formation, and resulting health problems. Higher temperatures lead to increased electricity demand for air conditioning, which, in turn, raises power plant pollution and greenhouse gas emissions. In addition, the UHI may increase water temperatures, resulting in water ecosystems impairment. It is clear that mitigating UHI impacts requires comprehensive planning strategies accounting for the effects of urban morphology, infrastructure, and greening, on the UHI. However, a lack of understanding of these effects has been a primary obstacle to implementing such strategies.

The objectives of this paper are to: (1) specify and estimate novel statistical regression models that account for both spatial neighborhood effects and the simultaneous effects of several urban characteristics on land surface temperatures derived from satellite imagery; (2) assess which grid scale used to capture the data yields the statistical model with the best explanatory and predictive power; and (3) use the best regression model to numerically simulate UHI-mitigating strategies in an urban design and planning context. To model the statistical relationship, both two-dimensional (2-D) and three-dimensional (3-D) information is used to represent the complex geometric structure of urban centers, with an application to the urban core of Columbus, OH. Earlier UHI research has primarily used 2-D information, such as land uses delineated with satellite imagery and building ground floor boundaries produced by geographic information systems (GIS). In the case of homogeneous land uses, this data may be sufficient to predict surface temperatures (Carlson & Arthur, 2000). However, 3-D information is necessary to analyze more complex sites, including dense building clusters (Unger, 2006; Unger, Bottyán, Sümeghy, & Gulyás, 2004). LiDAR data are used to generate 3-D urban geometry characteristics. A hierarchy of grids, with cell sizes of 480 m, 240 m, and 120 m, is used to integrate all the data. A spatial regression model capturing neighborhood effects and the relationship between surface temperatures and the geometric characteristics and other factors of the built environment is formulated and estimated for these different grids. The best model is then used to simulate different greening scenarios for the center of Columbus, illustrating its potential for mitigating the UHI.

The remainder of the paper is organized as follows. Section 2 consists in a review of the relevant literature. Section 3 describes the study area, data sources, and data processing. Regression models are formulated and estimated in Section 4. The simulations of greening scenarios are presented in Section 5. Section 6 discusses remaining issues and areas for further research. Section 7 concludes the paper.

2. Literature review

There has been an explosive growth in the research literature on the UHI in recent years. Using the search engine Google Scholar and typing in "urban heat island" returns 25,300 distinct journal articles, book chapters, books, working papers, and professional reports, as of October 9, 2013, with 86.5% of these works produced since 2001. Basic reviews of research on the energetic basis of the UHI and on satellite-derived thermal remote sensing of urban areas can be found in Oke (1982), Roth, Oke, and Emery (1989), Voogt and Oke (2003), and Arnfield (2003). There are two streams of modeling research attempting to explain the observed UHI patterns: numerical and statistical. Numerical models involve basic physics equations related to the conservation of mass and energy and the ideal gas law. See Lynn et al. (2009) for an example of such a model used to simulate UHI mitigation strategies. In order to inform the statistical methodology presented here, the focus of this review is on statistical analyses of the UHI.

Previous research shows that vegetated areas have lower surface temperatures than impervious ones (Owen, Carlson, & Gilles, 1998). Oke (1988) reports a 2 °C air temperature difference. Li, Zhao, Miaomiao, and Wang (2010) show that locations further away from a highway are associated with lower surface temperatures. Ca, Asaeda, and Abu (1998) report that the surface temperatures of a grass field in a park are 19 °C lower than those of impervious surfaces. Landsberg and Maisel (1972) were among the first to show that impervious materials lead to a 1–2 °C difference between rural and urban areas.

Yuan and Bauer (2007) find a very strong linear relationship ($R^2 > 0.95$) between mean surface temperature and the percentage of impervious areas. Xiao et al. (2007) also find a high correlation (>0.8) between impervious surfaces and surface temperatures. Trees on impervious surfaces help decrease temperatures by increasing the leaf-air vapor pressure gradient. The transpiration model by Kjelgren and Montague (1998) shows that evaporation from leaves helps decrease urban temperatures.

Remotely sensed imagery has been increasingly used to investigate the effects of 2-D surface characteristics on urban temperatures. Chen, Zhao, Li, and Yin (2006), Katpatal, Kute, and Satapathy (2008), and Amiri, Weng, Alimohammadi, and Alavipanah (2009) generate maps displaying land use/land cover (LU/LC) patterns based on images captured by Landsat Thematic Mapper (TM or ETM+), and find that urban expansion reduces the amount of biomass helping to control surface temperatures. Jenerette et al. (2007) show that surface temperature differences within a city are correlated with the amount of vegetation. Using temporal ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images and LU/LC classification, Kato and Yamaguchi (2007) report that heat storage capability is larger in highly urbanized areas than in sprawling residential areas.

Urban geometry relating to the height and spacing of buildings is another factor for UHI formation. This height-spacing relationship is also called the urban canyon effect, affecting air circulation, wind flow, and thermal energy absorption (Bärring, Mattsson, & Lindqvist, 1985; Bottyán & Unger, 2003; Eliasson, 1996; Oke, 1981, 1988). Dense built-up areas cannot easily release heat energy into the atmosphere, due to the lack of open space resulting from building obstructions. Tall buildings impede wind flows and their cooling effects, and isolate hot air within the canyon. Moreover, when solar energy reaches building surfaces, it is absorbed into the walls. The temperature of the air surrounding these walls is then increased. The sky view factor (SVF) has been widely used to measure the visible sky (Gál, Lindberg, & Unger, 2009; Grimmond, 2007; Unger et al., 2004; Unger, 2009). Grimmond (2007) indicates that reducing SVF increases absorption of solar radiation onto surfaces, decreases terrestrial radiation loss, decreases total turbulent heat transport, and reduces wind speeds, which all directly lead to increased surface temperatures. Unger et al. (2004) found that the difference in mean temperature between the maximum SVF (=1) and a minimum SVF (=0.66) is around 4.4 °C. Gál et al. (2009) show that there is a strong linear and negative relationship between annual mean temperatures and SVF. The size and shape of building structures are prominent features explaining surface temperatures. Giridharan, Ganesan, and Lau (2004) show that areas of dense and tall buildings have 1–1.5 °C higher temperatures (measured at 1.5–2 m above the ground) than other areas.

The shortcomings in previous UHI research are as follows. First, it mostly relies on 2-D information, such as building footprints,