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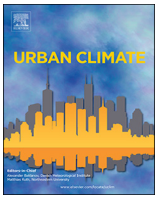

Neighborhood-scale sky view factor variations with building density and height: A simulation approach and case study of Boston

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ABSTRACT

This study establishes a relationship between sky view factors (SVF) and building densities and heights in a neighborhood. This research uses simulation to calculate average SVFs of hypothetical neighborhoods with different average height-density combinations, and uses the results to establish mathematical relationships that can be used in lieu of extensive field studies or generic assumptions. The advantage of this model over other methods lies within the fact that this model calculates the SVF for an urban area as opposed to a specific point. Although there are software applications that can calculate the average SVF of a selected area within an existing city, these applications require 3-dimensional shapefiles of the area, whereas the proposed method is free of such requirements and also can be used towards planning purposes for urban areas that do not exist. The method described herein is validated through direct measurement in a case study of Boston, Massachusetts, USA. Drawing on the concept of local climate zones, the estimates are compared with prior research and field measurements. Systematic analysis of impacts of urban morphology on the SVF can reveal how spatial distribution and height of buildings can modify the urban environment through attenuation of solar radiation and shading.

1. Introduction

One aspect of urban geometry that is of direct relevance to understanding urban heat island (UHI) dynamics is measured by the SVF. The SVF is defined as the ratio of the amount of sky visible with obstructions to the amount of sky that is visible without obstruction (Arnfield 2003, Unger 2004, Loughner et al. 2012). It ranges from zero to one, representing totally obstructed sky and open sky, respectively (Oke 1988, Gál et al. 2009, Unger 2009, Chen and Ng 2011, Chen et al. 2012, Zhu et al. 2013). Urban geometric properties that change the SVF affect the microclimate of urban areas mainly through shading and by trapping heat and pollutants. Reflected solar radiation has a greater chance of exiting the urban environment if building density is lower (Wong and Yu 2008) whereas high building density increases chances of absorbing direct and reflected radiation, thus magnifying the UHI effect (Rajagopalan 2009). During early hours, shadow effects produced by high-rise buildings decrease the net radiation of urban canyons, and thus reduce their temperature. At later hours in the day and during night, due to multiple reflections, long-wave radiation gets trapped inside urban canyons, delaying nocturnal cooling, and hence increasing urban temperatures (Barring et al. 1985, Oke et al. 1991, Oke 1993).

The SVF is one of the most studied topics in UHI research because of the implications it has for urban radiation budgets (Barring

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et al. 1985, Eliasson 1996, Upmanis 1999, Postgård 2000, Chapman et al. 2001b). Effects related to sky view alone can produce an UHI with a magnitude of 7 °C, even without considering the effects of anthropogenic heat release and thermal properties of building materials (Oke 1981, Oke et al. 1991, Chapman et al. 2001a, Svensson 2004). Hence, SVF is a critical measure in monitoring and forecasting surface temperatures (Chapman and Thornes 2004) and has implications for public health (Schmalwieser et al. 2010, Webb 2006, Lai et al. 2013), building energy consumption (Ichinose et al. 2008, Sivam and Karuppannan 2012), and landscape planning. For instance, the absorption of direct and reflected radiation by building material raises the building temperature, which intensifies energy consumption for cooling and consequently leads to increased anthropogenic waste heat (Erell et al. 2011, Giridharan et al. 2007, Priyadarsini 2009, Ichinose et al. 2008, Sivam and Karuppannan 2012). Giridharan et al. (2004) found that increasing SVF by 1% reduces the UHI magnitude by 4% in high-rise and high-density urban environments whereas the UHI magnitude increases by 3% in high-rise low-density open structures. At the same time, increasing building height by 110% increases UHI magnitude by 280%. Similarly, decreasing commercial building heights by 8 m and residential building heights by 2.5 m results in up to 0.4 °C increase in daytime temperatures and up to 1.2 °C decrease in nighttime temperatures (Loughner et al. 2012). Yuan and Chen (2011) suggest that controlling site coverage ratio and building height could effectively increase SVF to mitigate UHIs in high-density urban areas without compromising urban development. A more recent study of Yuan et al. (2017) on different areas of Osaka, Japan, also indicates that one of the main indicators of increased UHI is lower SVF due to higher building densities and average height.

When it comes to the calculation of the SVF, the literature provides many alternatives. Kastendeuch (2013) has used digital elevation models to take into account the slopes and transmittance of objects to compute SVF for any point in an urban environment or natural landscape. In 1999 Ratti and Richens proposed a methodology for calculating SVF by repeatedly casting shadows on 3D building datasets (Ratti and Richens, 1999). Later on in 2001 Brown et al. compared SVF from fisheye photographs of Salt Lake City downtown area with the results of Ratti and Richens' models and found reasonable agreement between the two methods (Brown and Grimmond, 2001). Gál et al. proposed a GIS-based method to calculate SVF using avenue-based 3D datasets of Szeged, Hungary, and compared it to the result of fisheye photographs and found dissimilarities in the results. They argue that the differences are due to the presence of vegetation (Gál et al. 2009). Chen et al. (2012) and Park and Tuller (2014) provide a comprehensive overview of major SVF calculation methods such as:

(1) Geometrical Methods, which are typically based on site surveys to establish building/object heights, and require extensive fieldwork (Oke 1987, Johnson and Watson 1984, Watson and Johnson 1987, Bottyan and Unger 2003),
(2) Fisheye image analyses utilize fisheye lenses that allow a full hemisphere to be viewed and captured at once, but the images require subsequent data processing either manually or through automated image-processing techniques (Steyn 1980, Johnson and Watson 1984, Bradley et al. 2001, Grimmond et al. 2001, Svensson 2004, Chapman et al. 2007, Hämmerle, Gál, Unger, and Matzarakis, 2011),
(3) Three dimensional simulation of terrain and buildings uses computer simulation to map continuous SVF of the urban area. Although it requires computational expertise, this method is less labor intensive than the fisheye lens method (Ratti and Richens 1999, Souza et al. 2003, Gál et al. 2007, 2009, Unger 2009, Chen and Ng 2011, Strømann-Andersen and Sattrup 2011, Lu and Du 2013, Hofierka and Zlocha 2012, Hernández-Carrasco et al. 2015).

There are a number of widely-used computer programs to calculate SVFs, such as the RayMan (Matzarakis and Rutz, 2010), Solweig Urban Climate Group, 2013) and SkyHelios (Matzarakis and Matuschek 2010) models, which are applicable when a 3-dimensional basemap is available. RayMan, performs a stepwise scanning, using the horizon for buildings and their height to calculate the SVF. Solweig, places a hemisphere equipped with light sources over the evaluated point and uses the virtual shadow cast by obstacles for the SVF calculation. SkyHelios, generates virtual fisheye pictures to calculate the SVF in the same way as RayMan (Hämmerle et al. 2011). RayMan and Solweig only calculate the SVF for a *single point* at a time, whereas, SkyHelios also presents the option for calculating *continuous* SVFs of an area. However, using SkyHelios needs a high-resolution digital elevation model as an input, which has its own drawbacks. First, it is not available for every urban area, and second, it does not model the shape of the buildings accurately (Matuschek and Matzarakis, 2010). Because these models require 3D basemaps as inputs, their uses as planning aids are rather limited.

Despite the large body of literature on measuring SVFs, the existing work is either too labor-intensive to be practical or too specific to be generalizable. This paper presents a simple equation to calculate the average SVF of a neighborhood or city based on average height and density of buildings. The added value of this work is in its simplicity to capture continuous SVFs for an area without the prerequisite of a digital elevation model or any complicated data sources, as well as its application in changing an urban setting or calculating SVFs for neighborhoods that are not developed yet. As a consequence, this method will offer more freedom in urban planning procedures.

There are already valuable efforts towards providing practical frameworks to urban planning. In their seminal work, Stewart and Oke (2012) defined local climate zones (LCZs) as the regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale, and they provided estimates of average building height, average density and SVF for each local climate zone. Later, they used numerical models to simulate thermal characteristics of LCZs and found different thermal signatures for each LCZ class which counts as a quantitative support for the LCZ concept (Stewart et al. 2013). Thus, a comparison of our estimates with theirs could provide important information towards validation of either work.

First, this paper presents a three-dimensional simulation-based method Using R (R core team, 2014) to calculate the SVF. Then, the study drives a relationship between average SVF of a neighborhood on the one hand and average building height and density on