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Influence of street setbacks on solar reflection and air cooling by reflective streets in urban canyons

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ABSTRACT

The ability of a climate model to accurately simulate the urban cooling effect of raising street albedo may be hampered by unrealistic representations of street geometry in the urban canyon. Even if the climate model is coupled to an urban canyon model (UCM), it is hard to define detailed urban geometries in UCMs. In this study, we relate simulated surface air temperature change to canyon albedo change. Using this relationship, we calculate scaling factors to adjust previously obtained surface air temperature changes that were simulated using generic canyon geometries. The adjusted temperature changes are obtained using a proposed multi-reflection urban canyon albedo model (UCAM), avoiding the need to rerun computationally expensive climate models. The adjusted temperature changes represent those that would be obtained from simulating with city-specific (local) geometries. Local urban geometries are estimated from details of the city's building stock and the city's street design guidelines. As a case study, we calculated average citywide seasonal scaling factors for realistic canyon geometries in Sacramento, California based on street design guidelines and building stock. The average scaling factors are multipliers used to adjust air temperature changes previously simulated by a Weather Research and Forecasting model coupled to an urban canyon model in which streets extended from wall to wall (omitting setbacks, such as sidewalks and yards). Sacramento's scaling factors ranged from 2.70 (summer) to 3.89 (winter), demonstrating the need to consider the actual urban geometry in urban climate studies.

1. Introduction

Mesoscale meteorological models have been developed to predict weather and to simulate regional climates. These tools are used to understand the effects of climate change and urban growth on environmental problems in urban areas, and to develop mitigation and adaptation strategies (Chen et al., 2011). The Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) is an example of such a tool used for these purposes.

Urban canyon models (UCMs) assess the geometry and the thermophysical properties of urban canyons (Best and Grimmond, 2015). UCMs are used to study the influence that urban morphology, surface properties, and energy fluxes have on the local climate. Meteorological models can be coupled to UCMs to better resolve surface-atmosphere interactions in urban areas, and assess near-surface heat islands and their effect on the regional climate (Taha, 1999; Chen et al., 2011). The accuracy of these coupled models depends in part on how accurate the urban morphology can be characterized in the UCM.

The WRF model can be coupled to various UCMs, each with a different level of complexity in the way it defines the urban morphology and resolves surface-atmosphere interactions. The number of parameters to model the influence of urban characteristics on the local climate also varies by UCM. When characterizing vegetative or urban surfaces, WRF defaults to a slab model, which treats the urban geometry as a flat rough surface. A WRF model can also be coupled to the single-layer urban canopy model (SLUCM) developed by Kusaka et al. (2001) and Kusaka and Kimura (2004), or the multi-layer urban canopy model (MLUCM) developed by Martilli et al. (2002). These two models consider the three-dimensional nature of urban canyons, shadowing by canyon walls, and reflection from the canyon surfaces. Wang et al. (2013) developed an even more sophisticated urban model that incorporates vegetation within the urban canopy and can represent each canyon surface (walls, floor, and roof) as a heterogeneous surface made up of different types of sub-surfaces. Their model has been used to enhance the modeling of urban hydrological processes (e.g. those from lawns and green roofs) that affect the urban energy balance (Li et al., 2014; Yang et al., 2015). However,

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its treatment of radiative exchange between facets of the urban canyon (wall, ground, roof, and sky) assumes that all subsurfaces within a facet share the same view factors. For example, if the ground contains a street flanked by setbacks, such as sidewalks or lawns, the sky view factor of each setback would be assumed to be equal to the sky view factor of the street.

Accurately representing the heterogeneous nature of cities in mesoscale models is challenging (Vahmani and Ban-Weiss, 2016). In many urban regions, urban planning data and remotely sensing images are used to create urban maps that classify the urban region into different land-use types. The United States Geological Survey (USGS) National Land Cover Database (NLCD) provides such maps, and describes urban regions with three different land-use categories: low-intensity residential, high-intensity residential, and industrial/commercial (Homer et al., 2015). WRF defines default urban canyon parameters for these three urban land-use categories (Chen et al., 2011); however, the urban canyon parameters can be changed by the user. The canyon geometry used by the model for a particular grid cell is then chosen from the NLCD land-use category that best matches the land cover type of the grid cell. The parameters that describe canyons include geometric dimensions (wall height, street width, and roof width); surface albedos; and thermal surface properties (see Table 1 in Chen et al., 2011). WRF can also be configured to use canyon geometries from the National Urban Database and Access Portal Tool (NUDAPT; Ching et al., 2009), but this database characterizes only a few scattered regions.

Cool pavements are one of several technologies that can be used to increase urban albedo and to cool cities (HIG, 2016). WRF/urban canyon models can be used to study how increasing the albedo of pavements decreases convective heating of the urban air and thus reduces surface air temperature[1] (Mohegh et al., submitted for publication). However, current urban parameterizations in climate models do not represent canyon geometry in sufficient detail to allow assessment of influence of pavement albedo on air temperature. First, these parameterizations generally define the street extending from wall to wall and do not permit definition of setbacks between the street and the wall. (Setbacks are the portions of the canyon floor, such as sidewalks and front yards, that lie between the street and the canyon wall.) Second, the default street widths defined in these systems may not accurately represent the streets in actual cities. Third, even if urban parameterization in the climate model were sufficiently detailed, is hard to develop data describing realistic urban geometries. Hence, when a WRF/urban canyon model is used to investigate the influence on urban climate of the widespread adoption of "cool" (highly reflective) streets, the results need to be scaled to represent realistic urban geometries.

Cities have a quantifiable relationship between air temperature change and canyon albedo change (Mohegh et al., submitted for publication). Thus, changes in canyon geometry and/or surface albedo alter the canyon albedo, which may in turn affect the air temperature. Assuming other atmospheric parameters like wind flow, vertical and horizontal mixing, and turbulence kinetic energy (TKE) remain constant, the current study relates changes in canyon albedo to changes in air temperature. This permits scaling of climate simulation results to canyon geometries that differ from those modeled. We present a method for estimating factors for scaling air temperature changes obtained from modeling cool streets with a WRF/urban canyon model to those changes expected for more realistic canyons. The advantage of this method is that existing climate model results quantifying the sensitivity of surface air temperature change to changes in canyon or grid cell albedo can be adjusted without re-running the computationally expensive climate model.

Scaling factors are estimated by comparing the change in canyon albedo of the modeled geometry to that of the realistic geometry. Many UCMs have been developed in the last five decades. Since these models generally define surface albedos and thermal surface properties, they can be used to estimate canyon albedo. Let the designation "*N*-reflection" indicate that the model tracks each ray of light through up to *N* reflections from canyon surfaces; any light that strikes a canyon surface after the N^{th} reflection is considered to be absorbed. Terjung and Louie (1973) presented the Urban Shortwave Model with the intention of simulating urban absorption of solar radiation. Their scheme treats the U-shape part of the canyon as an infinite strip having a uniform canyon floor. The work by Terjung and Louie considers the orientation of the canyon and solar position and is a one-reflection model. More recently, Tsangrassoulis and Santamouris (2003) developed a one-reflection canyon albedo model which considers the directional reflectance of windows. The Urban Surface Albedo model developed by Arnfield (1988) was one of the first to consider the multiple reflection effect within an urban canyon. Similar calculations of multiple reflections were also applied in the Albedo Calculation Model developed by Chimklai et al. (2004), and in the urban energy balance models presented by Masson (2000) and by Harman et al. (2004).

All the models mentioned so far treat the canyon floor as a homogeneous surface of uniform albedo, assigning the same albedo to the street and its setbacks (if any). Fortuniak (2008) developed an urban canyon albedo model (UCAM) that slices the floor and walls into small segments and can assign a different albedo to each segment. This lets it apply to some floor segments the street albedo and to other floor segments the setback albedo. The Fortuniak UCAM model can be used for any canyon orientation, and considers multiple reflections between the canyon surfaces.

Although the Fortuniak UCAM could be used to estimate scaling factors, we propose a similar, but simpler model that treats each wall as a uniform surface and tracks up to three reflections. In the proposed UCAM, the canyon floor is composed of a central street and surrounding setbacks. We will show that estimates of canyon albedo calculated with the proposed UCAM agree well with those calculated with the Fortuniak UCAM, especially for canyons with height-to-width ratios less than unity.

This paper summarizes the physics behind the proposed UCAM, then introduces the concept of "canyon transmittance", which can be interpreted as the transmittance of sunlight from canyon ceiling to street to canyon ceiling. We then calculate scaling factors as the ratio of canyon transmittances (transmittance in canyon of interest to that in canyon used in climate model). Scaling factors can be used to adjust air temperature changes obtained from a climate simulation that used generic canyon geometries to what would be obtained from using realistic canyon geometries. Finally, we present a case study that uses details of building stock and street design guidelines to estimate seasonal citywide scaling factors for the city of Sacramento.

2. Theory

2.1. Proposed urban canyon albedo model

The proposed three-reflection UCAM calculates the amount of radiant solar power per unit of canyon length [W/m] (hereafter,

[1] The surface air temperature (hereafter, "air temperature") described here is a diagnostic variable that aims to predict the air temperature two meters above the surface. Due to the complexities of urban terrain and physics parameterizations used in urban models, this variable does not truly represent air temperature at 2 m above the ground (Li et al., 2014). Instead, it can be understood as a diagnostic air temperature near the top of the urban canopy.