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Meso-urban meteorological and photochemical modeling of heat island mitigation

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ABSTRACT

A fine-resolution, meso-urban meteorological model was updated and applied, using new data and techniques in this study, in driving fine-resolution photochemical simulations to evaluate the air-quality impacts of urban heat island mitigation. The drag-force-based formulation of the model improves the simulation of fine-resolution meteorological and air-pollutant concentration fields in the urban canopy layer. Compared to the meso scale, the meso-urban modeling of heat island mitigation produces larger localized impacts on meteorology and ozone air quality and captures phenomena of interest that are typically not detectable at the coarser scale. These include, for example, cool islands, heat islands, flow convergence associated with heat island circulation, flow divergence at the leading edge of urban areas, and vertical variation in turbulent kinetic energy budget components within the canopy layer in response to vertical changes in densities of buildings and vegetation. They also include fine-resolution features in the simulated ozone concentration field and its response to surface modifications. Model results show that heat island mitigation is effective in reducing local ozone concentrations. This paper presents results from Sacramento, California, as an example using increased urban albedo as the control mechanism. For the region, episodic conditions, and surface modification scenarios examined in this paper, air temperature is decreased by up to 3 °C. Changes in ozone consist overwhelmingly of decreases but can also involve increases with the latter being confined to small areas and short time intervals. While larger reductions in ozone are detected, decreases of up to 5–10 ppb are more representative and the daily maximum 8-h average can be decreased by up to 13%.

1. Introduction

Urban heat island mitigation has been shown to have positive impacts on energy, thermal environmental conditions, and air quality in urban areas (e.g., Taha, 1996, 1997, 2005; Rosenzweig et al., 2006; McPherson et al., 2002; Pomerantz et al., 1997). Simulations with state-of-science meteorological, emissions, and photochemical models (e.g., Taha (2005, 2007) account for positive (beneficial) and negative (inadvertent) impacts of urban heat island mitigation on ozone formation. The net effects in most areas and conditions consist of significant reductions in ground-level ozone.

More recently, new modeling capabilities, newer data, and updated parameterizations, such as model urbanization (Taha, 1999; Taha and Bornstein, 1999; Dupont et al., 2004) have rendered such modeling relatively more accurate by allowing for fine resolution simulations (Taha, 2007, 2008a). This paper presents an application of fine-resolution meteorological fields from an urbanized meteorological model in driving photochemical simulations of urban heat island mitigation in California. Sacramento is presented as an example focusing on the effects of increased urban albedo as the mitigating strategy.

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2. Methodology and approach

This application involves simulations at both meso- and meso-urban (sub-meso) scales. Mesoscale modeling of urban heat islands and mitigation is discussed in Taha (2005, 2008b) and for this type of application, in Taha (2005) including model performance evaluation. Fine-resolution meso-urban meteorological simulations of heat islands with the uMM5 are described in Taha (2008a, 2007). In this paper, the uMM5 is used to drive fine-resolution photochemical simulations of urban areas in California using the CAMx photochemical model. Findings from simulations of the Sacramento region are summarized, and a low-cost approach for generating urban canopy parameters input for the model based on commercially available data, e.g., Google Earth PRO (Taha, 2007) is presented.

2.1. Meteorological models

2.1.1. uMM5

The uMM5 is described in Taha (2008a). The model is based on the urbanized MM5 (DA-SM2-U) of Dupont et al. (2004) which includes a soil model (SM2-U) based on the ISBA force-restore model (Noilhan and Planton, 1989). To accommodate the finer resolutions for which the model is intended, and to more accurately represent phenomena at sub-grid scales and within the canopy layer, the model formulation is modified such that new source/sink terms are added to the conservation relations of the mesoscale model (MM5). The newer parameterizations (UCP) and related input are described in Taha (2008a); Dupont et al. (2004); Dupont and Mestayer (2006); Martilli et al. (2002); Otte et al. (2004), and Taha (2007).

2.1.2. MM5

The mesoscale model used in simulating coarse-grid (non-UCP) domains in this effort is the PSU/NCAR MM5 (Dudhia, 1993; Grell et al., 1994). The MM5 is widely used in conjunction with photochemical regulatory modeling, e.g., Tesche et al. (2001) and Seaman and Stauffer (1996). For specifically simulating the potential impacts of urban surface modification strategies, the MM5 was used by Taha (2005, 2007, 2008b), for example.

2.2. Photochemical model

Here, the Comprehensive Air Quality Model with Extensions (CAMx) (Environ Corp., 2003) is used. CAMx is an Eulerian, 3-dimensional grid, photochemical model that allows simulation and assessment of "one atmosphere", i.e., ozone (gaseous) and particulate matter air pollution, and incorporates several state-of-science capabilities (Yarwood et al., 1996).

2.3. Emission inventories

Episodic emission inventories used in this application are discussed in Taha (2005, 2007). The gridded emission inventories were downscaled from the next coarse-grid domain (4 km) to the finer-resolution nested 1 km photochemical model grid corresponding to the uMM5 domain discussed above. In addition, air-pollutant initial and boundary conditions were also interpolated to the fine grid.

2.4. UCP and morphology data generation and application

In addition to meteorological, emissions, and surface initial and boundary condition data needed as input to the MM5, the uMM5, like its predecessor, the DA-SM2-U of Dupont et al. (2004), requires an additional set of model-specific input parameters, e.g., detailed 3-dimensional morphology (Taha, 2008a; Dupont et al., 2004; Burian et al., 2003). These 2- and 3-dimensional arrays of parameters (Table 1) were developed in this study using an alternate method in-lieu of the more traditional but costly sources of data, e.g., those derived from lidar (Burian et al., 2003). The low-cost alternate method developed in this study relies in part on deriving morphology from Google Earth PRO information (see Section 2.4.1). Furthermore, the parameters in Table 1 are correlated with a region-specific LULC classification scheme (Table 2) which is then used as an extrapolation template to urban areas where no 3-dimensional morphological information exists.

2.4.1. UCP data development

Table 1 summarizes the additional parameters needed in the uMM5. Parameters that are a function of height ($f(z)$) and/or direction (f(direction)) are marked accordingly. While these entries are self-explanatory, Eqs. (1)–(10) in

Table 1
Canopy geometry parameters (UCP) and surface input to uMM5

Parameter/input	Symbol in Eqs. (1)–(10)	$f(z)$	f(direction)
Land-use fraction (see Table 2)			
Pavement land-cover fraction			
Roof cover fraction			
Vegetation cover fraction			
Water fraction			
Building height-to-width ratio (H2W)	λ_h		■
Building wall-to-plan ratio	λ_w		
Impervious surface area/drained		■	
Dominant orientation of streets			■
Mean building height	h_{AW}		
Vegetation canopy mean height	h_{AW}		
Zo and Zd (for grid level)	Z_o, Z_d		■
Building frontal area density (FAD)	A_f	■	■
Building top area density (TAD)	A_t	■	
Building plan area density (PAD)	A_p	■	
Vegetation frontal area density (FAD)	A_f	■	■
Vegetation top area density (TAD)	A_t	■	
Vegetation plan area density (PAD)	A_p	■	
Sky view factor (or derived from H2W)		■	