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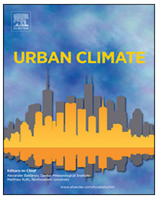

Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies

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ABSTRACT

Microscale atmospheric models are increasingly being used to project the thermal benefits of urban heat mitigation strategies (e.g., tree planting programs or use of high-albedo materials). However, prior to investment in specific mitigation efforts by local governments, it is desirable to test and validate the computational models used to evaluate strategies. While some prior studies have conducted limited evaluations of the ENVI-met microscale climate model for specific case studies, there has been relatively little systematic testing of the model's sensitivity to variations in model input and control parameters. This study builds on the limited foundation of past validation efforts by addressing two questions: (1) is ENVI-met grid independent; and (2) can the model adequately represent the air temperature perturbations associated with heat mitigation strategies? To test grid independence, a "flat" domain is tested with six vertical grid resolutions ranging from 0.75 to 2.0 m. To examine the second question, a control and two mitigation strategy simulations of idealized city blocks are tested. Results show a failure of grid independence in the "flat" domain simulations. Given that the mitigation strategies result in temperature changes that are an order of magnitude larger than the errors introduced by grid dependence for the flat domain, a lack of grid independence itself does not necessarily invalidate the use of ENVI-met for heat mitigation research. However, due to limitations in grid structure of the ENVI-met model, it was not possible to test grid dependence for more complicated simulations involving domains with buildings. Furthermore, it remains unclear whether existing efforts at model validation provide any assurance that the model adequately captures vertical mixing and exchange of heat from the ground to rooftop level. Thus, there remain concerns regarding the usefulness of the model for evaluating heat mitigation strategies, particularly when applied at roof level (e.g. high albedo or vegetated roofs).

1. Introduction

Global climate change coupled with the urban heat island effect continues to be a catalyst for cities to implement measures to reduce air temperature in the urban core (Mills, 2007). These measures collectively mitigate the urban heat island effect and are mechanisms by which policymakers seek to minimize the local effects of climate change. Mitigation strategies can take on a myriad of

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forms (including vegetation, urban canyon adjustments, shade structures, etc.), but in relation to reducing urban air temperatures, one popular approach is the use of highly reflective (high albedo) urban surfaces (Grimmond et al., 2010). The ability to design or modify the built environment to reduce air temperatures during heat waves is important to cities as urbanization and climate change continue to increase air temperatures in urban areas (IEA, 2014; IPCC, 2013).

Vegetative cover has been extensively considered as an urban cooling strategy by planners and microclimate modelers (Ali-Toudert and Mayer, 2007; Lindberg and Grimmond, 2011). While vegetation offers local atmospheric cooling and provision of shade, initial cost, irrigation needs, and maintenance requirements introduce implementation challenges for city planners. Increase in pavement albedo is another commonly considered urban heat mitigation strategy. High albedo paving, however, can be more costly and also introduces concerns about reflected solar radiation (Santamouris, 2013). Mitigation strategies that focus on increasing albedo at the rooftop level are promising in that they have relatively little impact on the current urban form, and can be implemented as part of routine roof replacement with little to no marginal cost (Botham-Myint et al., 2015; Taleghani et al., 2016). Roof albedo modification offers the additional benefit of directly reducing summertime air conditioning loads for modified buildings; however, the effect that roof-level modifications have on near-surface ambient air temperatures is likely less than that achieved by ground-level albedo modification. The challenge for planners and developers is to quantitatively weigh the costs of each of these types of strategies against their likely benefits (Georgescu et al., 2014). While the urban cooling benefits of these mitigation strategies have been tested in computational models, variability in the magnitude of the modeled benefits casts doubt on their accuracy (Santamouris, 2014).

Significant obstacles to the deployment of these mitigation strategies include the cost of city-wide implementation and the general lack of quantitative observational data regarding their performance in reducing air temperatures. Therefore, researchers have turned to computational models to represent the urban built environment and its atmosphere. These models are able to explore the effectiveness of mitigation strategies in a variety of scenarios, such as testing these strategies across entire domains or in smaller, targeted regions of the urban area—which may be a more cost-effective strategy for city planners (Ambrosini et al., 2014; Santamouris, 2014; Taleghani et al., 2014, 2015).

A variety of computational models are currently available for use in urban microclimate applications (spatial resolution between 1 and 4 m). These models use different approaches to represent the governing flow equations and the urban surface energy balance. Some approaches only consider the radiation budget and ignore the impact of fluid flow through the urban canyon (e.g., RayMan and TEB) (Pigeon et al., 2008; Thorsson et al., 2007). Other models use large eddy simulation (LES) to resolve fluid flow around individual buildings within the urban canyon, in addition to modeling the radiation budget (e.g., TUF-3D) (Krayenhoff et al., 2007). Some urban models use Reynolds Averaged Navier-Stokes (RANS) equations—an approach with reasonable accuracy, but at a lower computational cost than LES (Mirzaei and Haghighat, 2010). Among the RANS modeling approaches, FLUENT, OpenFOAM, and Star-CCM + are sophisticated computational tools, requiring extensive training on the part of the user (Blocken et al., 2007; Botham-Myint et al., 2015; Chen et al., 2009). Other codes, such as ENVI-met and SOLWEIG, are more user-friendly and accessible by less experienced users (Elnabawi et al., 2013; Lindberg and Grimmond, 2011; Samaali et al., 2007)—a characteristic that has both advantages and significant disadvantages.

A literature search of published research using atmospheric microclimate modeling in the urban environment led to 46 search results since 2006. About 30% of these results (14) used or reference ENVI-met explicitly, with RayMan being the next most commonly cited model with 8 results. The general preference for using ENVI-met in these sorts of studies is likely due, in large part, to a balance of sophistication, user-friendliness, and lower computational costs, of the model (Ali-Toudert, 2005; Chow and Brazel, 2012; Roth and Lim, 2017; Singh and Laefer, 2015). An additional reason for the use of ENVI-met is the dynamic coupling of the atmospheric processes with vegetation/soil moisture processes with the model. The search also revealed a general trend toward using spatial resolutions of ~2 m per cell to accommodate for the neighborhood size.

ENVI-met is a Computational Fluid Dynamics (CFD) model that relies on RANS equations to solve for atmospheric flow and heat transfer in urban settings. This model was initially developed by Bruse during his dissertation work in Germany in the late 1990's (Bruse and Fleer, 1998). The model has evolved and transformed into its latest version (v.4), released in the summer of 2016 (www.envi-met.com). The model's user-friendly interface and relatively simple input scheme allows most researchers to be able to run this software with minimal training or expertise. The highly-touted feature of the model is its ability to model complex urban geometries and vegetation while also allowing for energy inputs such as waste heat from vehicles and the effects of water features.

As pointed out by Maggiotto et al. (2014), the majority of literature on the topic of ENVI-met addresses model accuracy and suitability in a rather superficial manner. One important test of model suitability is grid independence testing, which is used to confirm that the discretized model resolution is sufficient such that further refinement of the model grid does not substantially alter model output. However, such testing is lacking in prior investigations involving ENVI-met. Most researchers who seek to evaluate the ENVI-met model use air temperature observations from a limited number of locations in the domain to verify model accuracy (Ali-Toudert, 2005; Emmanuel and Fernando, 2007; Samaali et al., 2007; Yang et al., 2013). Measurements of other atmospheric variables to validate ENVI-met's performance have been collected by some researchers, but were generally not considered in their analysis of ENVI-met model performance (Middel et al., 2014; Ng et al., 2012). The lack of thorough testing of the model's limits and abilities is a serious concern for those attempting to use the software to model prospective changes in the urban surface, such as implementation of urban heat mitigation strategies. Therefore, the present study seeks to fill this knowledge gap by testing the grid independence of ENVI-met to further assess its usefulness for evaluating urban heat mitigation strategies such as increasing albedo of roof and pavement surfaces. First, we explore the historical literature to assess the extent to which ENVI-met has previously been validated. Then, we focus on two questions: (1) is ENVI-met grid independent; and (2) can the model adequately represent the air temperature perturbations associated with heat mitigation strategies?