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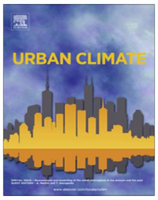

A rapid and scalable radiation transfer model for complex urban domains

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ABSTRACT

An important component of urban microclimate is the radiative heat transfer between the myriad elements that make up the urban fabric. While great progress has been made in developing radiation models for idealized urban spaces, operational simulations of fully resolved city-scale domains remain elusive. As a result, simplifications and assumptions must be made. Such compromises may limit utility, and reveal a need for new, scalable microclimate models. This paper presents a novel, physically-based, building-resolving radiation transfer model (QESRadiant) that utilizes ray tracing techniques accelerated with graphics processing units (GPUs). QESRadiant builds on computer graphics methods, incorporating approaches for global illumination and light transport. Tests show that our methods can rapidly simulate the radiation balance for millions of surfaces with unique shapes and properties using a single consumer-class workstation, requiring times on the order of several minutes. High-resolution (0.5 m) street canyon radiation budgets are validated using field data covering nine months. The results show the model is able to predict radiative fluxes in the canyon with an overall average R^2 of 0.77 and mean error of 14.5 W m^{-2}. Solar radiation was extremely sensitive to geometric obstructions, demonstrating the need for high-quality field experiments that resolve urban details affecting the radiation balance.

1. Introduction

In the past decades, substantial effort has gone into understanding the various mechanisms that contribute to urban climate (Arnfield, 2003; Oke, 1987). While great progress has been made in understanding individual aspects of urban climate, there is still a lack of understanding regarding the interaction of large numbers of different urban elements amongst each other and across scales. Further, there is a dearth of models that include sufficient microscale details that can be used to make place-based decisions and to understand the impacts of these decisions on the larger-scale urban environment (Pataki et al., 2011). There is a critical need for the development of these types of simulation methodologies for designing healthy and efficient cities. One approach involves the parametrization of key physical processes at relatively coarse scales for use within mesoscale weather models (e.g., Grimmond et al., 2010; Martilli et al., 2002; Masson, 2005). An alternative approach toward achieving these goals is to implement a detailed bottom-up representation by resolving the key processes

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Nomenclature

α_λ	albedo/reflectivity for a waveband λ
δ_d	diffuse reflective fraction
δ_s	specular reflective fraction
ϵ	total hemispherical emissivity
ϵ_{sky}	sky emissivity
$\otimes$	ray energy minimum (W)
σ_s	Stefan–Boltzmann constant $\approx 5.6704 \times 10^{-8}$ (W m^{-2} K^{-4})
τ_a	aerosol extinction coefficient
τ_m	molecular extinction coefficient
θ_r	ray zenith angle (rad)
θ_s	solar zenith angle (rad)
A_p	area of a patch (m^2)
d	diameter of the virtual domain (m)
E	individual ray energy rate (W)
K	shortwave radiation flux (W m^{-2})
L	longwave radiation flux (W m^{-2})
m	relative air mass
N_ℓ	number of emitted longwave and scattered rays per patch
N_{df}	number of diffuse atmospheric rays per ground patch
N_{dr}	number of direct solar rays for entire domain
Q^*	net all-wave radiation flux (W m^{-2})
Q_E	latent heat flux (W m^{-2})
Q_G	ground/conductive heat flux (W m^{-2})
Q_H	sensible heat flux (W m^{-2})
S_0	solar constant ≈ 1367 (W m^{-2})
S_{df}	unobstructed diffuse solar flux (W m^{-2})
S_{dr}	unobstructed direct solar flux (W m^{-2})
t	hours past local midnight
T_{air}	dry bulb temperature (K)
T_{dp}	dew point (°C)
T_p	patch temperature (K)
T_{sky}	sky temperature (K)
U_{df}	unobstructed sky longwave diffuse flux (W m^{-2})
FB	fractional bias
IA	refined index of agreement
MB	model bias (W m^{-2})
ME	mean error (W m^{-2})
NMSE	normalized mean square error
R^2	coefficient of determination
SVF	sky view factor

at small scales. With this approach, simulations are designed to resolve urban form details such as buildings and vegetation as well as their complex mass, momentum, and energy transport processes in urban environments.

Our group has been working to develop a building and vegetation resolving system through the GEnUSiS project (Green Environmental Urban Simulations for Sustainability). As part of the project, we are developing a fast modeling system for calculating and visualizing the transfer of heat and moisture in cities for improved design of urban green environments. Such environments include large vegetative spaces, residential gardens, pervious parking lots, green and/or reflective rooftops, and artificial water bodies. This complete modeling system that includes mass, momentum, and heat transfer in urban areas is called QUIC EnvSim (QES). QES builds on the QUIC Dispersion Modeling System (Brown et al., 2013; Pardyjak and Brown, 2001; Singh et al., 2008, 2011) that was designed as a building-resolving tool for rapidly computing wind, turbulence, and concentration fields in cities. QES can be run as a stand alone system, or interoperate with QUIC.

In this paper, we focus on the implementation of an efficient graphics processing unit (GPU) based ray tracing radiative heat transfer module of QES called QESRadiant. Our computational approach builds upon past work from the field of computer graphics that approximates and simulates the transport of visual radiation (light). The methods and models of QESRadiant can simulate key radiative transfer mechanisms for user specified wavebands (e.g., shortwave or longwave radiation) in realistic building-resolving urban domains at a user-specified resolution. Such urban spaces may be made up of hundreds to millions of buildings with unique shapes, sizes, and reflectance/absorption properties. Due to the high efficiency