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 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 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.

Key words: Graphics processing units, Heat transfer modeling, Ray tracing, Sustainability, Urban street canyon

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 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

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31 stand alone system, or interoperate with QUIC.

32 In this paper, we focus on the implementation of an efficient graphics pro-
33 cessing unit (GPU) based ray tracing radiative heat transfer module of QES
34 called QESRadiant. Our computational approach builds upon past work from
35 the field of computer graphics that approximates and simulates the trans-
36 port of visual radiation (light). The methods and models of QESRadiant can
37 simulate key radiative transfer mechanisms for user specified wavebands (e.g.,
38 shortwave or longwave radiation) in realistic building-resolving urban domains
39 at a user-specified resolution. Such urban spaces may be made up of hundreds
40 to millions of buildings with unique shapes, sizes, and reflectance/absorption
41 properties. Due to the high efficiency of our methods and throughput power
42 of GPUs, these domains can be simulated on a single consumer-class desktop
43 computer or laptop, with simulation times on the order of seconds to min-
44 utes. While the presence of vegetation is extremely important, this paper will
45 focus on modeling the urban radiation balance without vegetation. Modeling
46 radiation in vegetative urban domains is discussed in Bailey et al. (2014). We
47 validate QESRadiant by recreating a full-scale urban street canyon field study
48 (Eliasson et al., 2006; Offerle et al., 2007). Measured flux densities for various
49 radiation bands are compared to simulated flux densities at several positions
50 within the canyon. Six statistical measurements are used to assess QESRadi-
51 ant’s ability to predict radiative flux densities at several positions in the urban
52 canyon within acceptable error.

53 1.1 *Building-resolving radiation modeling efforts*

54 The methodologies used to simulate radiative transport processes in urban
55 areas have evolved over the years as computational resources have improved.
56 Most of the earlier urban radiation exchange models focused on idealized street
57 canyon geometries to compute shortwave and longwave radiation interactions
58 between two buildings using view factors that could be derived analytically
59 (e.g., Terjung and Louie, 1997; Terjung and O’Rourke, 1980). However, the
60 difficulty of determining analytical view factors increases with complexity of
61 modeled geometry. Due to the rise in computing power, it has become more
62 common to calculate view factors in a statistical or Monte Carlo manner.
63 For small groups of three-dimensional buildings, Kobayashi and Takamura
64 (1994) used a Monte Carlo ray tracing method to simulate outgoing longwave
65 radiation from an array of cubical buildings. Krayenhoff and Voogt (2007) used
66 ray tracing to determine visibility, but computed view factors between surfaces
67 with exact formulae. The presence of urban vegetation presents substantial
68 complexities that should also be accounted for, such as the simplified ray
69 tracing methods of Asawa et al. (2008). In many applications, radiative fluxes
70 are not the end product of the urban modeling system, but rather it is used

71 as an input to other models. For instance, Matzarakis et al. (2006) developed
72 the *RayMan* software which is able to model groups of buildings for thermal
73 comfort applications.

74 The above models all must make compromises in their level of physical de-
75 scription and domain size. In order to simulate city-scales, assumptions of
76 homogeneity must be made at some level. Recently, Yang and Li (2013) have
77 developed a method similar to Krayenhoff and Voogt (2007) that uses ray trac-
78 ing to determine view factors, but then uses the Gebhart method (Gebhart,
79 1971) to handle multiple reflections. Their methodology can simulate hundreds
80 of buildings with multiple reflections using a novel data storage compression
81 scheme. As previously noted, GPUs can be used to accelerate computations,
82 which was illustrated by Takizawa et al. (2006). They did not use a ray tracing
83 sampling approach, but instead used the GPU to assist with radiosity meth-
84 ods for radiation exchange. Other multi-building radiation interaction tools
85 such as the IES-Virtual Environment 6.0.2, ApacheSim/RADIANCE used by
86 Strämann-Andersen and Sattrup (2011) can handle multiple idealized build-
87 ings and include energy use modules. However, they generally offset compu-
88 tational cost by using simplified physical models that do not fully represent
89 vegetation, anisotropic scattering, or local wind transport.

90 1.2 Computer graphics and the simulation of light

91 Computer graphics research over the last several decades has mostly used ras-
92 terization and ray tracing, two techniques for generating visual representations
93 of generalized 3D physical worlds. Rasterization algorithms project geometry
94 onto a camera’s image plane converting the geometry into image pixels. These
95 techniques generally require sophisticated image-based projection methods to
96 compute the effects of reflections or shadows (Fernando et al., 2001; Segal
97 et al., 1992; Williams, 1978). Nonetheless, rasterization techniques have be-
98 come the dominant method for visual image generation in contemporary video
99 games due to the parallel computational support of matrix and vector oper-
100 ations on GPUs. Alternatively, ray tracing algorithms tend to simulate the
101 physical nature of light by performing intersections between light or viewing
102 rays and 3D scene objects to determine visibility, shadows, and the propaga-
103 tion of light energy (Cook et al., 1984; Whitted, 1980). While computation-
104 ally more expensive, ray tracing-based methods more accurately approximate
105 light transport through stochastic sampling mechanisms supporting necessary
106 scattering and absorption transport paths between different surface material
107 types.

108 Ray tracing methods have evolved into sophisticated, realistic image synthe-
109 sis algorithms approximating the light transport equation proposed by Ka-

110 jiya (1986). Kajiya’s equation analogs the radiative transport equation but
111 focuses on the scattering of visible light between all surfaces allowing for dif-
112 ferent surface scattering attributes. Kajiya’s efforts formed the core Monte
113 Carlo ray sampling underpinnings for path tracing (Kajiya, 1986), photon
114 mapping (Jensen, 1996), and other stochastically-based sampling mechanisms
115 that maintain the conservation of energy. Our method utilizes the stochas-
116 tic sampling approaches related to ray tracing algorithms, and applies these
117 techniques to discretized urban domains.

118 1.3 GPU acceleration

119 The use of GPUs for acceleration was chosen over classic cluster and supercom-
120 puting methods for several reasons. Due to consumer demand for sophisticated
121 video game graphics, the performance capability and affordability of GPUs
122 have seen significant growth in the last ten years. Adopting GPU methods
123 allow QES to run on a wide range of consumer-grade desktop machines and
124 benefit from future graphics hardware improvements. Additionally, radiation
125 exchange with ray tracing requires global sum operations for the accumula-
126 tion of energy. In many multi-node distributed frameworks such as Message
127 Passing Interface (MPI Forum, 2015), this requires expensive collective com-
128 munication. This problem is dramatically mitigated on a GPU, in which global
129 memory is resident on the same device as the compute cores.

130 Typically, programmers create *shaders* (computer graphics functions) to com-
131 pute rendering effects and pixel colors using graphics application program-
132 ming interfaces (APIs) such as OpenGL (Khronos Group, 2015). Many shaders
133 are specifically defined to operate on the GPU using single-precision floating
134 point format. However, there has recently been a trend to adapt GPU-based
135 programming to general purpose computing (GPGPU) (Owens et al., 2007).
136 GPGPU is now represented in numerous scientific fields, such as fluids simu-
137 lation, computational mathematics, and visualization. To facilitate this trend,
138 NVIDIA Corporation (Santa Clara, CA) released a programmable platform
139 called Compute Unified Device Architecture (CUDA) (Nickolls et al., 2008).
140 In CUDA, *kernel* functions are defined to operate in parallel on the GPU and
141 can be applied to a broader range of applications than shaders. Such features
142 that extend capabilities include double precision, dynamic parallelism, and
143 thread communication and synchronization. For more information on scien-
144 tific computing with NVIDIA CUDA, see Luebke (2008).

145 QESRadiant uses GPU accelerated ray tracing to simulate radiative heat
146 transfer. Ray tracing has the feature of being inherently parallelizable in which
147 ray-object intersection tests for different rays are concurrent. However, com-
148 plexities in recursive ray tracing provide a great challenge and limit effective-

ness of GPU-based ray tracing. In 2010, NVIDIA released OptiX, the general purpose GPU ray tracing engine (Parker et al., 2010). Developers are able to create their own ray generation and intersection kernels, as well as define the primary interactions of a ray tracer. OptiX will compile this information and efficiently perform ray-object intersection tests on the GPU using CUDA. QESRadiant relies heavily on the optimizations provided by OptiX. Many of the strategies, program flow, and data containers are specifically designed to interoperate with OptiX.

1.4 Heat transfer modeling

The QESRadiant module is a part of a grid-resolving computational system where each discrete surface has its own energy balance, defined as

$$Q^* = Q_H + Q_E + Q_G. \quad (1)$$

Eq. 1 includes net all-wave radiation Q^* , sensible heat flux Q_H , latent heat flux Q_E , and ground or conductive heat flux Q_G . QUIC EnvSim is modular, so different methods can be used to compute the terms of the surface energy balance equation. However, the focus of this paper is to present QESRadiant’s ability to compute the net all-wave radiative components of Q^* , the driving force of the surface energy balance.

The net all-wave radiation Q^* modeled in this paper is decomposed into short-wave (K) and longwave (L) radiation. Each band is also separated into incident ($\downarrow$) and reflected or emitted ($\uparrow$) counterparts. This equation is defined as

$$Q^* = K^\downarrow - K^\uparrow + L^\downarrow - L^\uparrow. \quad (2)$$

2 Modeling methodology

2.1 Domain representation

Domains in QES attempt to maintain compatibility with the QUIC Dispersion Modeling System, hence buildings and ground geometry are defined according to the needs of QUIC. However, additional urban structures such as vegetation and sensors can be present in a QES domain as well.

Fig. 1. Building and ground surfaces before (a) and after (b) discretization.

176 2.1.1 Buildings

177 Buildings are represented as grid-aligned three-dimensional boxes with posi-
 178 tive, arbitrary dimensions. A building can be made up of several boxes that
 179 can be stacked or placed next to others. The ground is represented by a two-
 180 dimensional horizontal plane. Faces of each box and the ground plane are fur-
 181 ther segmented into smaller two-dimensional planes called patches. Patches of
 182 the ground plane will exist below buildings, but such patches will not emit
 183 longwave radiation. The length, width, and height of a patch may vary, but
 184 must be the same for all patches within the domain (required by QUIC). The
 185 domain in QES can be specified in three ways: an XML document, program-
 186 matically, or a QUIC Project file. QUIC Projects can also be supplemented
 187 with an XML document to specify additional urban structures. A domain can
 188 consist of one to several million patches. Increasing the number of patches
 189 for a domain can potentially increase model accuracy at the expense of also
 190 increasing computational cost.

191 Each patch has multiple physical properties that affect its interaction with the
 192 environment. One such property is albedo (α), which is defined as the ratio
 193 of reflected to incoming radiation and typically depends on the wavelength of
 194 incoming radiation. For the urban environment, we define a total albedo for
 195 the entire shortwave (α_s) and longwave (α_ℓ) spectra. Similarly, each patch is
 196 given a total, hemispherical emissivity value (ϵ), which is defined as the ratio
 197 of emitted radiation flux to the emission flux of a black body. The user has
 198 the option of defining these properties manually, or by assigning it a material
 199 type with predefined values for each material from Santamouris (2013). For
 200 energy to be conserved, the surface emissivity and longwave albedo must sum
 201 to one. QES will automatically verify this in the case of user-specified values.

202 2.1.2 Sensors

203 Virtual sensors are two dimensional planes that gather information about the
 204 simulated environment. Their purpose is to simulate real-world sensors and
 205 diagnostic tools, such as a pyranometer measuring solar irradiance. Unlike

buildings, they can be arbitrarily positioned in the world and be of any unique size. In QESRadiant, a sensor will record (but not augment) radiation that passes through its face in the direction of its normal. Sensors are used to compare simulated radiation fluxes to observed or measured fluxes in the real world. This allows model validation and is used to determine model accuracy in section 3.

2.2 Radiation transport

To simulate the transfer of radiation from one medium to another, rays are emitted from patches, the sun, and the atmosphere with an initial energy. When the ray intersects a patch, fractions of that energy are absorbed, reflected, and scattered. The amount of energy that is absorbed, reflected, or scattered depends on the wavelength of the radiation being simulated, as well as the physical properties of the patch. This process is illustrated as a flowchart in Fig. 2. Total hemispherical radiation flux density is denoted K and L (Wm^{-2}) for shortwave and longwave, respectively. The power or energy rate of an individual ray is E ($Wray^{-1}$), and N number rays are launched.

Single precision floating point format is most often used in QESRadiant when calculating radiation exchange on the GPU. This increases the computational efficiency of kernel execution. However, double-precision floating-point format is used only when necessary for values outside the capability of single precision. This requires a compute capability of 1.3 or higher, which includes nearly all NVIDIA GPUs made after 2009.

2.2.1 Shortwave transfer

Shortwave radiation is received by patches in three ways. Radiation that reaches the patch directly from the sun is considered *direct* shortwave energy. Energy that has been scattered by the atmosphere and eventually reaches a patch is *diffuse* shortwave energy. Diffuse shortwave is sometimes called *scattered* energy in literature, but we reserve that term for energy that is scattered or reflected by surfaces, the third way a patch can receive shortwave energy. The initialization of direct and diffuse shortwave ray energy rate is defined by its unobstructed flux. The direct solar flux (S_{dr}) and diffuse solar flux (S_{df}) can be assigned values directly (e.g., from measurements) or simulated with a solar flux model. If S_{dr} does come from measurements, it must be weighted by the cosine of the zenith angle. They are considered unobstructed in the sense that the value corresponds to the incoming flux above the urban canopy, not augmented by urban structures.

If measurement values are not available for S_{dr} and S_{df} , they must be simulated

Fig. 2. The primary operations of QESRadiant for a single time step. Radiation is initially emitted from the sun, the atmosphere, and patches in (a). A ray continues to specularly reflect until all energy (E_{ray}) has been absorbed in (c). Scattered energy is emitted separately in (b) where energy may continue to be absorbed, reflected, and scattered. If a rays energy is below a threshold ($\otimes$), all energy is absorbed by the patch.

243 with a model. One such model implemented in QESRadiant is described by
 244 Monteith and Unsworth (2008) and is a cloudless sky radiation model used to
 245 calculate total solar radiation. The model is modified so that the relative air
 246 mass (m) is computed according to Atwater and Ball (1978). To distribute the
 247 energy into diffuse and direct components, the model is also altered based on
 248 measurements by Liu and Jordan (1960), which distinguishes the relationship
 249 between diffuse, direct, and global solar radiative flux density. Currently, this
 250 flux model does not take the turbidity of the atmosphere into account.

251 In Eq. 3 below, τ_m is the molecular extinction coefficient, τ_a is the aerosol
 252 extinction coefficient, θ_s is the solar zenith angle, and S_0 is the solar constant
 253 ($\approx 1367 \text{ Wm}^{-2}$). Both τ_m and τ_a are based off measurements from Liu and
 254 Jordan (1960), but the user may adjust these values if they are known. S_{dr}
 255 and S_{df} may be computed as followed:

$$\begin{aligned} m &= 35/\sqrt{1 + 1224 \cos^2(\theta_s)}, \\ S_{dr} &= S_0 \{\exp[-m(\tau_m + \tau_a)]\} \cos(\theta_s) \quad [\text{Wm}^{-2}], \\ S_{df} &= 0.3S_0 \{1 - \exp[-m(\tau_m + \tau_a)]\} \cos(\theta_s) \quad [\text{Wm}^{-2}]. \end{aligned} \quad (3)$$

256 Direct solar radiation is simulated by launching collimated rays from the sun
 257 toward the ground surface. To accomplish this, the diameter of the entire
 258 domain is determined by computing a bounding sphere of all terrestrial ge-
 259 ometry. This diameter is used to determine the area of the disk that acts as
 260 the emitting plane with a normal parallel to the solar vector. This approach is
 261 illustrated in Fig. 3b. The Blanco-Muriel et al. (2001) model is used for com-
 262 puting the solar position, which reports a higher accuracy compared to many
 263 other models and provides source code. N_{dr} ray origins are distributed across
 264 the surface of the disk in a stratified manner and are randomly displaced a
 265 small amount (jittered) to reduce aliasing effects. Source code for the function
 266 used to sample points on a disk is available in Shirley and Chiu (1997). For a
 267 domain with a diameter d , the amount of energy contained by a direct solar
 268 ray is:

$$E_{s,dr} = \pi d^2 S_{dr} / (4N_{dr}) \quad [\text{W}]. \quad (4)$$

269 Diffuse solar radiation is simulated by uniformly distributing N_{df} rays in a
 270 hemisphere about every ground patch, translating the origin outside the do-
 271 main, then launching them in the direction of the ground patches. This method
 272 is illustrated in Fig. 3a. Additional detail on how a hemisphere is sampled is
 273 presented in section 2.4. This per-ray energy is weighted by the cosine of the
 274 ray zenith angle θ_r . Because the integral of cosine over the hemisphere is equal
 275 to $1/2$, this weighting is multiplied by 2 so that energy is conserved. The diffuse

276 solar energy rate per ray is

$$E_{s,df} = S_{df} 2 \cos(\theta_r) A_p / N_{df} \quad [\text{W}]. \quad (5)$$

277 2.2.2 Longwave transfer

278 To simulate longwave emission, rays are launched from all patches in a hemi-
279 sphere about its surface. The energy rate for each longwave ray emitted from
280 a patch is given by

$$E_\ell = \epsilon \sigma_s T_p^4 2 \cos(\theta_r) A_p / N_\ell \quad [\text{W}]. \quad (6)$$

281 where ϵ is the patch emissivity, σ_s is the Stefan-Boltzmann constant, T_p is the
282 absolute temperature of the patch, A_p is the area of the patch, and N_ℓ is the
283 number of rays launched per patch. When computing Q^* , the total longwave
284 flux emitted from a patch is

$$L^\uparrow = \epsilon \sigma_s T_p^4 \quad [\text{Wm}^{-2}]. \quad (7)$$

285 Longwave radiation can also be scattered by the atmosphere, but is modeled
286 in a way such that the atmosphere is emitting it. This energy is simulated like
287 diffuse shortwave in which rays are distributed in a hemisphere about each
288 ground patch and launched inward. The energy rate per ray emitted by the
289 atmosphere depends on the total diffuse longwave radiative flux density U_{df}
290 and ray zenith angle θ_r . Like S_{df} and S_{dr} , U_{df} can be specified directly from
291 measurements or simulated with a model. One diffuse longwave flux model
292 implemented in QESRadiant is the Yang and Li (2013) model, in which U_{df} is
293 computed from the dew point T_{dp} (in degrees Celsius), dry bulb temperature
294 T_{air} (in Kelvin), sky emissivity ϵ_{sky} , and local hour t (hours past midnight in
295 local time). U_{df} is computed as followed:

$$T_{sky} = T_{air} \sqrt[4]{0.711 + 0.0056 T_{dp} + 0.000073 T_{dp}^2 + 0.013 \cos(15t)} \quad [\text{K}], \quad (8)$$

$$U_{df} = \sigma_s \epsilon_{sky} T_{sky}^4 \quad [\text{Wm}^{-2}].$$

296 Surface weather data sets freely available from MesoWest (Horel et al., 2002)
297 can be automatically loaded by QES to supply T_{dp} and T_{air} for a given time,
298 date, and geographical location. If ϵ_{sky} is not known, QES has an option
299 to compute it from models described in Chen et al. (1995). The amount of
300 longwave energy emitted by the atmosphere per ray is

$$E_{\ell,df} = U_{df} 2 \cos(\theta_r) A_p / N_\ell \quad [\text{W}]. \quad (9)$$

301 2.2.3 Absorption, reflection, and scattering

302 To reduce the memory overhead of QESRadiant, only the total net radiation
 303 of solar energy (K_{net}) on a patch is stored during the simulation. Incoming and
 304 emitted longwave energies are still stored as separate terms since direct access
 305 to these terms is usually needed to determine surface temperatures in land
 306 surface models (LSMs). Therefore, we can rewrite the net radiation equation
 307 modeled by QESRadiant as:

$$Q^* = K_{net} + L^\downarrow - L^\uparrow \quad [\text{Wm}^{-2}]. \quad (10)$$

308 Incoming shortwave and longwave radiation is absorbed, reflected, and scat-
 309 tered by patches. For a ray with an initial energy rate E , waveband λ , and
 310 a patch with albedo α_λ , the amount of energy absorbed from one ray is
 311 $E(1.0 - \alpha_\lambda)$. The sum of absorbed energy for all rays that intersected the
 312 patch (n) is used to compute K_{net} and $L^\downarrow$. That is,

$$K_{net} \approx \frac{1}{A_p} \sum_{i=1}^n E_i(1.0 - \alpha_s) \quad [\text{Wm}^{-2}]. \quad (11)$$

$$L^\downarrow \approx \frac{1}{A_p} \sum_{i=1}^n E_i(1.0 - \alpha_\ell) \quad [\text{Wm}^{-2}]. \quad (12)$$

313 The amount of energy that is scattered and reflected depends on the material
 314 of the patch. This property is determined by a material's specular fraction
 315 (δ_s) and diffuse fraction (δ_d) where $\delta_s + \delta_d = 1$. For example, highly reflective
 316 surfaces like glass or glossy paint would have a high δ_s and low δ_d . Conversely,
 317 soil or gravel would have a much higher δ_d and lower δ_s . The amount of energy
 318 specularly reflected is $E(\alpha_\lambda \delta_s)$ and the amount diffusely scattered is $E(\alpha_\lambda \delta_d)$.
 319 Thus, each patch is able to diffusely scatter and specularly reflect radiation.
 320 This results in a model that is an efficient simplification of a more complicated
 321 bidirectional reflectance distribution function (Roujean et al., 1992). However,
 322 δ_s and δ_d are not defined in literature and are only approximations.

323 If a ray does not intersect a structure and reaches the sky, all of its energy
 324 is absorbed by the atmosphere. Otherwise, a ray will continue to be reflected
 325 and scattered until it no longer carries a significant amount of energy. Once
 326 a ray's energy drops below a predefined threshold ($\otimes$) the rest of the energy
 327 is absorbed by the intersected patch and the ray's life ends. This approach
 328 significantly reduces machine precision errors when dealing with very small
 329 ray energies.

330 For specular reflections, a new ray is launched at the point of intersection. For

331 an incidence angle θ_{inc} , the angle of reflection $\theta_{refl} = \theta_{inc}$ about the surface
 332 normal is used, and the azimuthal angle of direction is unchanged (Fig. 3d).
 333 Scattered energy is isotropic, so new rays are launched in a hemisphere in
 334 the same manner as emitted longwave radiation (Fig. 3c). Unlike specular
 335 reflections, rays are not scattered immediately upon incidence. To reduce the
 336 number of rays required for scattering radiation, the energy that would be
 337 scattered is stored temporarily in memory and is accumulated on a patch
 338 over time. When atmospheric, solar, and thermally-emitted rays have ceased
 339 reflecting specularly, this accumulated *to-be-scattered* energy is emitted at
 340 once and may continue to be absorbed, reflected, and scattered. Eventually all
 341 ray energies will drop below the energy threshold. As a result, the scattering
 342 of radiation requires iterative relaunches of rays until all energy has been
 343 absorbed. In practice, this process nearly always completes in less than ten
 344 iterations.

345 2.3 Sky view factor

346 The sky view factor (SVF) may be defined as the fraction of radiation leaving
 347 a patch that is intercepted by the sky (Johnson and Watson, 1984). SVF is not
 348 explicitly used to model the transfer of radiation within QES. However, due
 349 to its utility in urban modeling it can be simulated with QES as a separate
 350 module called QESViewfactor (see Appendix A). A number of approxima-
 351 tions for the SVF have been proposed (e.g., Kastendeuch, 2013 and references
 352 therein). With our approach, an intersection test is performed whereby rays
 353 are launched outward in a hemisphere about the center of every patch. The
 354 hemisphere is sampled according to section 2.4. If the i^{th} ray reaches the edge
 355 of the domain without intersecting a surface, $\varphi_i = 1$, otherwise $\varphi_i = 0$. The
 356 SVF is then computed by summing the number of rays that did not intersect
 357 a surface, adjusting the value by the cosine of the ray zenith angle θ_i , and
 358 dividing by the total number of rays launched per patch (N_ℓ), that is:

$$F_{sky} \approx \sum_{i=1}^{N_\ell} \frac{2 \cos(\theta_i) \varphi_i}{N_\ell}. \quad (13)$$

359 A similar approach to for computing view factors was introduced by Wallace
 360 et al. (1989) for radiosity calculation. Their methods are similar to Eq. (13)
 361 and show how the differential area to finite area form factor is an adequate
 362 approximation, with enough samples.

Fig. 3. Illustrations of ray launch patterns. In (a), diffuse solar and atmospheric longwave rays are launched toward the center of every ground patch. Their ray origins are positioned outside the domain in a hemisphere about the ground patch. This shows the launch for one such ground patch, while the three other ground patch launches are not shown. In (b), a sphere that encloses the entire domain is used to compute the domain diameter. A disk with a normal parallel to the solar vector is used for simulating direct solar energy, and is determined by this diameter. Ray origins are stratified across the disk and launched toward the buildings and ground. In (c), radiation is scattered diffusely, and new rays are launched in a hemisphere from a patch center. The rays are evenly distributed, but their energies are weighted by the cosine of the zenith angle. In (d), a new ray is launched as an ideal specular reflection.

364 Ray directions are distributed on the hemisphere above a patch by computing
 365 evenly distributed points on a hemisphere about the patch center. The points
 366 on the hemisphere are sampled using a modification of the spiral points algo-
 367 rithm from Saff and Kuijlaars (1997). To obtain a more evenly distributed set
 368 of points, the Golden Ratio $([1 + \sqrt{5}]/2)$ is introduced in the traversal of the
 369 spiral nodes. This function is defined in Appendix B.

370 After the hemisphere has been sampled, the ray directions are rotated by
 371 a random azimuthal angle between 0 and 2π . This random number is the
 372 same for each ray of the same hemisphere, but will differ from other sampled
 373 hemispheres. This reduces the effects of aliasing, in which unrealistic patterns
 374 may be introduced due to uniform sampling.

375 3 Model validation

376 This model has been both verified and validated according to definitions set
 377 by the American Institute of Aeronautics and Astronautics (?). Verification
 378 is not included in this paper for brevity, but includes several tests to ensure
 379 the models perform as expected in ideal domains. Specifically, it has been
 380 verified that energy is conserved, that simulated view factors between neigh-
 381 boring surfaces compare well to an analytical solution, and that a completely
 382 exposed patch or sensor receives the correct amount of energy emitted by the
 383 sun/atmosphere.

Six statistical measures were used to validate the models of QESRadiant. These include the refined index of agreement (IA) from Willmott et al. (2012), coefficient of determination (R^2), fractional bias (FB), model bias (MB), normalized mean square error (NMSE), and mean error (ME). For an observed or measured data set X , a predicted or simulated data set Y , the average of a data set $\overline{X}$, and the number of elements in a data set n , these measures are computed as followed:

$$A = \sum_{i=1}^n (|Y - X|), \quad B = 2 \sum_{i=1}^n (|X - \overline{X}|),$$

$$IA = \begin{cases} 1 - A/B & \text{if } A \leq B, \\ B/A - 1 & \text{if } A > B. \end{cases} \quad (14)$$

$$R^2 = [\sum_{i=1}^n (X_i - \overline{X})^2 - \sum_{i=1}^n (X_i - Y_i)^2] / \sum_{i=1}^n (X_i - \overline{X})^2. \quad (15)$$

$$FB = 2\overline{(Y - X)}/(\overline{X} + \overline{Y}). \quad (16)$$

$$MB = \overline{(Y - X)} \quad [\text{Wm}^{-2}]. \quad (17)$$

$$NMSE = \overline{[(X - Y)^2]}/(\overline{X} \times \overline{Y}). \quad (18)$$

$$ME = \sqrt{\overline{(X - Y)^2}} \quad [\text{Wm}^{-2}]. \quad (19)$$

384 IA is an index value designed for measuring model performance and is a more
 385 robust measure of model agreement than R^2 . It is dimensionless and bounded
 386 by -1.0 and 1.0. R^2 is a measure of how well the variance is explained by the
 387 model, and values less than 0 are set to 0. R^2 will then take on values over the
 388 range: $0 \leq R^2 \leq 1$. For both IA and R^2 , a higher value typically indicates a
 389 better model predictor. The fractional bias is the model bias normalized by the
 390 average of the model and observation. FB will have a value of $-2 \leq FB \leq 2$,
 391 with zero being a perfect score (no model bias). For positive values of X and
 392 Y , $FB > 0$ and $MB > 0$ indicates model over-prediction, while $FB < 0$ and
 393 $MB < 0$ indicates model under-prediction. NMSE is the average squared error
 394 of the model normalized by the average of the model and observation.

395 3.1 Urban street canyon model validation

396 Street canyons represent important and well-studied prototypical elements of
 397 cities and their microclimates. An urban street canyon can be described as
 398 a street or pathway that is bordered by opposing walls. The surfaces within
 399 the canyon have less exposure to the sky (smaller SVF) and retain more heat
 400 than their open terrain counterparts. Studies have found that urban canyon
 401 geometries affect surface energy balance fluxes (Nunez and Oke, 1977). Thus,
 402 to validate QESRadiant we recreate an idealization of the Gothenburg street
 403 canyon study (Eliasson et al., 2006; Offerle et al., 2007) during which extensive
 404 measurements of wind, temperature, and radiation quantities were measured
 405 at different locations within a street canyon for over a year. Specifically, we
 406 compare QESRadiant's simulated shortwave and longwave radiation flux den-
 407 sities at various points within the 3D street canyon.

3.1.1 Domain

The original field experiment was conducted in Gothenburg, Sweden ($57^{\circ}42'$ N, $11^{\circ}58'$ E). Virtual sensors described in section 2.1.2 and shown in Fig. 5 were positioned in the canyon according to radiometer positions described in Eliasson et al. (2006). Because virtual sensors only record values in one direction, two directionally-opposing sensors were used for each radiometer to record incoming and outgoing shortwave and longwave fluxes. A QES-generated top down visualization of the canyon is shown in Fig. 4. In addition to illustrating its virtual representation, Fig. 4 also shows sky view factor and shortwave radiation visualization capabilities.

Due to the limitations imposed by QES for urban domains, certain concessions were made when modeling the geometry of the canyon. These stem from the requirement that buildings in QES cannot be rotated and must be discretized into grid aligned patches. First, the real urban canyon is not precisely oriented North to South or East to West. To accommodate this, after the solar azimuth is computed by QES for the given time and date, it is increased by an additional 20 degrees. Since this validation experiment is only simulating radiation transfer, the solar direction is the only component affected by the canyon's non-cardinal aligned orientation. Second, the rooftop of the buildings that make up the canyon walls are slanted in the real world. To approximate this, patches were stacked on the simulated rooftop in a stair-step like pattern (see Fig. 5). Further, minor geometry details of such as specific brickwork, ledges, street lamps, overhead cables, and other small obstructions were not modeled.

The patch materials of the simulated canyon were varied in attempt to accurately recreate the real canyon. All patches were squares with sides of length

Fig. 4. Contour plots illustrating (left) sky view factor and (right) shortwave radiation for the simulated urban canyon in Gothenburg, Sweden using QUIC EnvSim.

0.5 m, thus the height and width of the canyon was rounded to the nearest 0.5 m. Because the specific physical properties of the building surfaces were not known, they were assigned the following: $\alpha_s=0.3$, $\alpha_\ell=0$, and $\epsilon=1$. Eliasson et al. (2006) describe the canyon walls as 25% windows, but information on exact location and size of the windows was not available. Thus, we considered the entire wall to be a diffuse material ($\delta_d=1$, $\delta_s=0$).

3.1.2 Simulation settings

QESRadiant is able to compute shortwave and longwave atmospheric fluxes as described in sections 2.2.1 and 2.2.2. However, these values were measured by the radiometer that was positioned above the urban canopy (sensor R3). Instead of using models to compute the atmospheric fluxes incident on the canyon, the measured global solar ($K^\downarrow$) was distributed into diffuse and direct components. This was done by first computing S_{df} according to Eq. 3. If the measured global radiation is less than the computed diffuse solar flux (i.e., $K^\downarrow < S_{df}$), then the diffuse radiative flux is set to the measured global radiation ($S_{df} = K^\downarrow$) and the direct solar flux is set to zero ($S_{dr} = 0$). Otherwise S_{df} is used as computed and $S_{dr} = K^\downarrow - S_{df}$. This approach allowed the model to respond to cloud cover in which a reduction of the measured global solar increases the ratio of S_{df} to S_{dr} .

As shown in Fig. 5, five simulated radiometers were compared to the experimental data and are labeled based on their position within the urban canyon. These include: upper center – C4, lower center – C2, eastern lower – E2, and western lower – W2. R3 was used to drive the model inputs. Each sensor measured the incoming and outgoing shortwave and longwave fluxes with respect to the lower center of the canyon.

The temperature of the patches within the canyon wall and ground were also driven with measurements. These temperatures were measured in the study using thermocouples on each wall, and one thermocouple on the ground. In our simulation, the entire ground was set to the temperature recorded by the ground thermocouple. Patch wall temperatures were obtained by linearly interpolating between each of three thermocouples (lower, middle, and upper). All other patches not specified from thermocouple measurements were set to 290 K. The simulation was run from 4 July 2003 through 27 March 2004 with 5 minute time steps. The total number of time steps was nearly 74k.

3.1.3 Validation results

Figures 6 and 7 are scatter plots paired in space and time, comparing flux density of all radiation sensors. No attempt was made to remove cloudy or otherwise imperfect-condition days from the data set.

Fig. 5: A schematic of radiometer and thermocouple locations for the urban canyon test case used in section 3.1. The original study was performed by Eliasson et al. (2006) and Offerle et al. (2007). Radiometer R3 is not shown.

472 An overview of statistical measurements is presented in Table 1. To aid in
 473 interpretation, Fig. 5 shows the orientation of the radiation sensors. Under-
 474 standing the orientation is particularly important for interpreting sensors E2
 475 and W2, which were oriented so that the sensors were parallel to the street
 476 canyon walls.

477 *Sensor sampling strategy validation:*

478 Unobstructed flux values (S_{dr} , S_{df} , and U_{df}) were specified using measurements
 479 from R3. Then, the virtual R3 sensor was used to calculate the simulated
 480 unobstructed flux, which was compared to the true measurement. This test
 481 provides a metric for the effectiveness of our stochastic sampling methodology
 482 since we would expect a perfect correlation if the rays are sufficiently sampled.
 483 Indeed, radiation fluxes at this location showed high IA ($K^\downarrow$: 1.0, $L^\downarrow$: 0.95),
 484 high R^2 ($K^\downarrow$: 1.0, $L^\downarrow$: 0.99), low FB ($K^\downarrow$: -0.03, $L^\downarrow$: 0.0), low MB ($K^\downarrow$: -2.7
 485 Wm^{-2} , $L^\downarrow$: -0.8 Wm^{-2}), low NMSE ($K^\downarrow$: 0.0, $L^\downarrow$: 0.0), and low ME ($K^\downarrow$: 4.7
 486 Wm^{-2} , $L^\downarrow$: 5.1 Wm^{-2}). Results for R3's $K^\uparrow$ and $L^\uparrow$ are not reported, because
 487 without modeling the entire urban area these values are not fully represented
 488 by the model.

489 *Longwave radiation fluxes:*

490 As indicated in Table 1 as well as Fig. 6, simulated longwave radiation dis-
 491 played a strong, linear correlation. C4 $L^\downarrow$ showed the lowest correlation of the
 492 eight longwave sensors with an IA of 0.75, R^2 of 0.76, FB of -0.07, MB of
 493 -19.7 Wm^{-2} , NMSE of 0.01, and ME of 24.8 Wm^{-2} . This is likely due to the
 494 model's inability to adequately represent the complex rooftop geometry. That
 495 is, exposure to atmospheric longwave was less realistic, and rooftop temper-
 496 atures were not driven with measurements. The other sensors had IA values
 497 of ≈ 0.9 , R^2 between 0.93 and 0.97, FB between -0.02 and 0.02, MB between
 498 -6.2 and 6.0 Wm^{-2} , NMSE ≈ 0.0 , and ME between 6.9 and 11.5 Wm^{-2} . This
 499 high correlation indicates that our methodology for the interpolation of the
 500 measured surface temperatures was reasonable and our ray emission strategies
 501 are sufficient.

502 *Shortwave radiation fluxes:*

503 Most $K^\downarrow$ and $K^\uparrow$ sensors showed satisfactory agreement, with an average IA
 504 of 0.79 and average R^2 of 0.56. However, all shortwave scatter plots display
 505 regular over- and under-prediction, resulting in a branch-like separation (see
 506 Figure 7). This behavior may be explained by examining time series plots of
 507 shortwave radiation for three consecutive clear-sky days (Fig. 8) for sensors:
 508 C4 $K^\downarrow$, C2 $K^\downarrow$, and E2 $K^\uparrow$. Figure 8a illustrates how imprecise canyon geom-
 509 etry may cause over-predictions in the morning and evenings at the top of
 510 the canyon (C4 $K^\downarrow$). Figure 8b shows how the predicted shortwave flux at the
 511 inner-center of the canyon (C2 $K^\downarrow$) follows closely to the measured flux. How-

512 ever, the modeled sensor may move between shade and direct solar exposure at
 513 a different time step than the measured sensor, causing over/under-predictions
 514 of several hundred Wm^{-2} . Minor unmodeled obstructions and local geometry
 515 (such as street lamps, wires, brickwork, and small reflective surfaces) are likely
 516 the cause of many over-predictions, especially noticeable in E2 $K^\uparrow$ (Fig. 8c)
 517 which had the lowest R^2 of 0.0. Another noticeable trend is the hysteresis in E2
 518 $K^\downarrow$ (Fig. 7e), also likely caused by imperfect canyon wall geometry offsetting
 519 the time of solar exposure.

520 These results demonstrate how K is highly sensitive to local geometry and
 521 time step. Missing the exact moment a sensor moves between shade and solar
 522 exposure, even by a few minutes or less, may cause significant under-prediction
 523 or over-prediction. Thus, R^2 for radiation fluxes paired in space and time does
 524 not provide the best measure of model correlation. IA, however, is less sensitive
 525 to a missed interval and provides a better measure of model performance.

526 *Execution Time:*

527 Hardware specifications are described in Appendix C. The average run time
 528 for a single time step over a diurnal cycle was 4.7 seconds on machine C.2.
 529 The urban canyon test case consisted of 115,736 patches, 1,024 rays were used
 530 per patch hemisphere, and 61.44M rays were used for direct solar radiation.
 531 The number of rays per hemisphere was determined to be sufficient based on
 532 preliminary analysis by ? and unit test verification experiments.

Sensor	IA	R ²	FB	MB (Wm ⁻²)	NMSE	ME (Wm ⁻²)
R3 K [↓]	1.0	1.0	-0.03	-2.7	0.0	4.7
R3 L [↓]	0.95	0.99	0.0	-0.8	0.0	5.1
C4 L [↓]	0.75	0.76	-0.07	-19.7	0.01	24.8
C4 L [↑]	0.89	0.94	-0.01	-3.3	0.0	9.2
C2 L [↓]	0.88	0.93	0.02	6.0	0.0	11.5
C2 L [↑]	0.93	0.97	0.01	1.7	0.0	6.9
E2 L [↓]	0.92	0.96	-0.01	-1.8	0.0	7.9
E2 L [↑]	0.90	0.96	-0.02	-6.2	0.0	8.4
W2 L [↓]	0.91	0.96	-0.01	-3.8	0.0	7.8
W2 L [↑]	0.90	0.96	-0.01	-3.2	0.0	8.1
C4 K [↓]	0.92	0.90	0.19	14.0	0.40	47.9
C4 K [↑]	0.67	0.51	-0.08	-0.5	0.99	5.7
C2 K [↓]	0.86	0.79	0.14	4.9	1.5	43.1
C2 K [↑]	0.71	0.64	-0.37	-1.0	1.6	3.4
E2 K [↓]	0.77	0.37	0.26	1.5	2.8	9.6
E2 K [↑]	0.73	0.0	0.38	4.0	6.8	27.0
W2 K [↓]	0.88	0.86	-0.02	-0.1	0.98	5.3
W2 K [↑]	0.81	0.44	0.32	4.2	3.3	24.0

Table 1

Refined index of agreement (IA), coefficient of determination (R²), fractional bias (FB), model bias (MB), normalized mean square error (NMSE), and mean error (ME) for the urban canyon test case with QESRadiant. Perfect scores for each measure include: IA and R² = 1; FB, MB, NMSE, and ME = 0. Sensor locations and direction of fluxes are shown in the urban canyon schematic (Fig. 5).

Fig. 6. Longwave radiation fluxes for all sensors of the urban canyon test case. The simulated period was 4 July 2003 through 27 March 2004 at 5 minute intervals.

Fig. 7. Shortwave radiation fluxes for all sensors of the urban canyon test case. The simulated period was 4 July 2003 through 27 March 2004 at 5 minute intervals..

Fig. 8. Time series of radiation sensors for the period covering 30 July 2003 – 1 August 2003. Shortwave radiation is highly sensitive to local geometry. Unmodeled obstructions like lamp posts and imprecise rooftop geometry may result in significant over and under-predictions.

533 4 Computational performance

534 It is difficult to compare the computational efficiency of QES to other urban
535 modeling frameworks and systems. Others (e.g., Bruse, 2015; Krayenhoff and
536 Voogt, 2007; Matzarakis et al., 2006) do not report details on simulation run
537 time or hardware portability. Therefore, in this paper, we report simulation
538 run times for all test cases presented, without comparing to other modeling
539 frameworks. These run times are shown in their respective sections (urban
540 canyon test case: section 3.1.3, Salt Lake City SVF case: Appendix A). We
541 also present an experiment to demonstrate the scalability of QESRadiant in
542 section 4.1. While all run time results in this paper are for a single GPU, multi-
543 GPU performance is presented in Overby (2014). All reported run times do
544 not include start up or compilation, but do include memory transfers between
545 the host and device.

546 4.1 Domain scaling and capacity

547 This section attempts to quantify what is meant by the proposition that QES
548 is designed to handle large and complex domains. The following test consists
549 of measuring QESRadiant’s run time for an expanding scene (i.e., domain).
550 For each iteration, new 1 m^3 buildings are added one meter above a ground
551 surface in a checkerboard-like pattern as illustrated in Fig. 9b. While not
552 representative of a real urban layout, it provides a complex domain to stress
553 test the system in which ray launches result in a high number of intersections
554 at different structures. The domain was expanded until an OptiX exception
555 error indicated that the available memory had been exceeded. Run times were
556 recorded along with domain size. The experiment was run on a single device
557 of a GeForce GTX 690 (normally a multi-device GPU, see Appendix C.2).
558 The sample size for diffuse and patch-emitted longwave rays (N_{df} , N_ℓ) was
559 256. Direct ray sample size (N_{dr}) was a function of the number of patches on
560 the ground plane times 256. Instead of setting the latitude, longitude, date,
561 and time, the solar zenith angle was forced to 45 degrees to ensure complex
562 shortwave interaction.

563 QESRadiant was able to run a scene containing over 8.02 million patches
564 in 6 minutes and 10 seconds. After this point, the simulation required more
565 memory than was available on the GPU (2GB). Fig. 9a shows that as the size
566 of the domain increased, run time increased linearly.

(a)

(b)

Fig. 9. Scalability of QESRadiant until hardware limitations are met. In (a), machine C.2 was able to run QES radiant for a domain of over 8 million patches in 6 minutes and 10 seconds. In (b), the test domain continued to expand, adding additional 1 m³ buildings until available GPU memory was exceeded.

5 Summary

QUIC EnvSim is a high performance programmable modeling framework for simulating mass, momentum, and heat transfer in complex urban environments. Modules can be developed within the framework to simulate specific components of the urban microclimate and be combined with other new or existing modules.

This paper introduces the QES module QESRadiant, which computes the transfer of radiation between the ground, buildings, vegetation, and the atmosphere. Buildings are represented as grid-aligned three-dimensional boxes with positive, arbitrary dimensions. A building can be made up of several boxes that can be stacked or placed next to others. The faces of each box are further segmented into smaller two-dimensional planes called patches. QESRadiant simulates longwave and shortwave transfer using the GPU accelerated ray tracing engine NVIDIA OptiX. This is done by emitting rays from patches, vegetation, the sun, and the atmosphere, with an initial energy. When the ray intersects a terrestrial object, fractions of that energy are absorbed, reflected, and scattered. Energy is recorded at every patch within the domain and is used to compute the net radiation component of the surface energy balance.

By leveraging OptiX and CUDA, QESRadiant can model the radiation balance of approximately 8.02 million patches in 6 minutes and 10 seconds (for one time step) on a single desktop workstation with 2GB of GPU memory. Simulation run time linearly increases with domain size. Therefore, as GPUs are allocated

589 more dedicated memory and improve in performance, so will the capabilities
590 of QESRadiant.

591 The models of QESRadiant were validated by simulating a study of an urban
592 street canyon in Gothenburg, Sweden as described by Eliasson et al. (2006)
593 and Offerle et al. (2007). A 3D urban canyon provides an excellent testbed
594 for validation because the surfaces within the canyon have less exposure to
595 the sky and retain more heat throughout the day, affecting the surface energy
596 balance. Radiometers were located at various positions within the canyon, and
597 wall temperatures were driven with measured values from thermocouples. The
598 simulations ran from 4 July 2003 until 27 March 2004 with 5 minute inter-
599 vals for a total of nearly 74k simulations. Six statistical measures were used
600 to gauge model performance: refined index of agreement (IA), coefficient of
601 determination (R^2), fractional bias (FB), model bias (MB), normalized mean
602 square error (NMSE), and mean error (ME). Simulated longwave correlated
603 with observed longwave exceptionally well, with averages IA: 0.88, R^2 : 0.93,
604 |FB|: 0.02, |MB|: 5.7 Wm^{-2} , |NMSE|: 0.0, and ME: 10.6 Wm^{-2} . Measures for
605 shortwave energy appeared to be statistically sensitive to the time step and
606 local geometry. Virtual and measured sensors would go between shade and di-
607 rect solar energy at different times. This is likely due to imprecise building roof
608 geometry and minor obstructions (e.g., street lamps, wires). This occurrence
609 resulted in regular over- and under-predictions, and made R^2 less adequate for
610 illustrating model accuracy. However, IA is not as sensitive to the missed time
611 step and indicated acceptable agreement. Shortwave had averages IA: 0.79,
612 R^2 : 0.56, |FB|: 0.22, |MB|: 3.8 Wm^{-2} , |NMSE|: 2.30, and ME: 20.8 Wm^{-2} .

613 This validation test case elucidated several important points. First, there is
614 a need for high-quality urban experimental data sets like the Gothenburg,
615 Sweden case to test models like QES that can simulate at the half-meter
616 scale. Further, high resolution geometric details and properties of the urban
617 fabric are needed for model validation. Simulating the balance of radiation in
618 urban spaces with ray tracing provides a new level of physical realism, and
619 can aptly be applied to a wide range of domains.

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Appendix A: Salt Lake City sky view factor test case

Sky view factors are an important measurement when analyzing the effects of urban form on the microclimate. In a study by Brown et al. (2001), SVF measurements were recorded throughout downtown Salt Lake City, Utah at various locations. These measurements were calculated from fish-eye photographs taken by an upward pointed camera with a hemispheric lens. The latitude, longitude, and height of the camera placement for a given measurement were recorded in addition to the SVF. The study took place in October, 2000 during the DOE CBNP URBAN field experiment.

To validate the ability of QESViewfactor to simulate SVF, we compare simulated values to measurements from Brown et al. (2001). In Fig. A.1b, each black bordered circle is a camera placement. The inner color of the circle represents measured SVF reported by Brown et al. (2001). In addition to computing SVF, QES can also generate fish-eye views. Figure A.2 shows side-by-side comparisons of QES-generated fish-eye views and photographs by Brown et al. (2001). In the QES-generated image, a blue dot represents a ray that reached the sky, while a black dot indicates it was blocked by a building. The photograph was taken with a digital camera using a Nikon FC-E8 hemispheric lens. Note that fish-eye views are generated by QES for visual comparisons. The method by which Brown et al. (2001) uses to compute SVF is not used. SVFs are calculated in QESViewfactor using the methods defined in section 2.3.

The scatter plot showing correlation can be seen in Fig. A.1a. However, two conditions related to limitations of the building data set cause inaccuracies between the simulated and reported SVFs. First, discrepancies in building geometries are evident, as the data set is not an exact representation of downtown Salt Lake City, Utah. In some cases, entire buildings are missing as illustrated in Fig. A.2b. Second, the absence of vegetation may cause large errors, especially in park or greenspace areas as shown in Fig. A.2c.

Simulating SVFs for Salt Lake City took 0.51 seconds on machine C.2. The domain consisted of 201,647 patches, and 1,024 rays were used per patch hemisphere.

Fig. A.1. Comparison of predicted to measured (Brown et al., 2001) SVF for downtown Salt Lake City, Utah. (a) shows a scatter plot of sky view factor comparisons. Shown measures are index of agreement (IA), fractional bias (FB), and normalized mean square error (NMSE). (b) shows contours of SVF for downtown Salt Lake City, Utah, computed with QES. The inner color of the black bordered circles represents measured SVFs.

(a) SLC fish-eye view at UTM coordinates (425188.45495, 4513267.1181).

(b) SLC fish-eye view at UTM coordinates (424792.42923, 4513116.81619).

(c) SLC fish-eye view at UTM coordinates (424789.07114, 4512691.3084).

Fig. A.2. Comparison of simulated (left) and photographic (right) fish-eye images for Downtown Salt Lake City, Utah. Photographs are used with permission from Brown et al. (2001). Limitations in data sets like approximated building dimensions or missing buildings/vegetation may cause errors in model agreement.

665 Appendix B: Functions and formulae

666 *B.1: Hemispherical ray direction*

667 Points on the hemisphere are sampled using a modification of the spiral points
668 algorithm from Saff and Kuijlaars (1997). The index of the ray is used to
669 compute the direction in 3D space.

```
670  
671 Function hemisphere direction  
672     ray idx is the nth ray of a hemisphere  
673     offset = 1 / samples per hemisphere  
674     y = ray idx * offset - 1 + ( offset / 2 )  
675     r = sqrt( 1 - y*y )  
676     phi = ray_idx * Pi * ( 3 - sqrt(5) )  
677     direction = < cos( phi )*r, y, sin( phi )*r >  
678     rotate to project in direction of patch normal  
679     return direction  
680
```

681 Appendix C: Device specifications

682 *C.1: GeForce GTX Titan*

OS:	Ubuntu 12.04 LTS
RAM:	64 GB RAM
683 CPU:	8-core Intel Xeon E5-2690, 3.00GHz
GPU:	NVIDIA GeForce GTX Titan 6GB GDDR5
Software:	NVIDIA OptiX 3.0.0, CUDA 5.0

OS:	Ubuntu 12.04 LTS
RAM:	16 GB RAM
685 CPU:	4-core Intel i7-3820, 3.60GHz
GPU:	NVIDIA GeForce GTX 690, 2GB GDDR5 per GPU
Software:	NVIDIA OptiX 3.0.1, CUDA 5.0

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