Incorporating Resolved Vegetation in City-Scale Simulations of Urban Micrometeorology and Its Effect on the Energy Balance

Brian N. Bailey
bbailey@eng.utah.edu
M. Overby, R. Stoll, E. R. Pardyjak, P. Willemsen, K. Briggs, and D. Alexander

Department of Mechanical Engineering
University of Utah, Salt Lake City, UT, USA

July 22, 2015
Goals

Want to study impacts of urban vegetation and other green infrastructure on microclimate from tree- to city-scales
Goals

Want to study impacts of urban vegetation and other green infrastructure on microclimate from tree- to city-scales.
Goals

Available methods for such studies:

- Experimental campaigns
- Simulation models
  - Large-scale models (e.g., WRF, "big-leaf")
  - High-resolution micro-scale models
Available methods for such studies:

- Experimental campaigns
- Simulation models
  - Large-scale models (e.g., WRF, "big-leaf")
  - High-resolution micro-scale models
Goals

Available methods for such studies:

• Experimental campaigns
• Simulation models
  • Large-scale models (e.g., WRF, “big-leaf”)
  • High-resolution micro-scale models $$$
Goals

Available methods for such studies:

- Experimental campaigns
- Simulation models
  - Large-scale models (e.g., WRF, “big-leaf”)
  - High-resolution micro-scale models $$$$
Goals

Available methods for such studies:

- Experimental campaigns
- Simulation models
  - Large-scale models (e.g., WRF, “big-leaf”)
  - High-resolution micro-scale models $$$
Goals

Goal

Develop a physically robust energy transport simulation tool that resolves tree- through city-scales that can be used as a research or city planning tool

- Physically robust models
- Near real-time simulation on a desktop computer
Goal

Develop a physically robust energy transport simulation tool that resolves tree- through city-scales that can be used as a research or city planning tool

- Physically robust models
- Near real-time simulation on a desktop computer
Goals

Goal

Develop a physically robust energy transport simulation tool that resolves tree- through city-scales that can be used as a research or city planning tool

- Physically robust models
- Near real-time simulation on a desktop computer
Modeling Framework: Trees

Brian Bailey et al.
bbailey@eng.utah.edu
Volume is described by:

- Leaf area density $a$
- Leaf angle probability distribution $g_L$
Volume is described by:

- Leaf area density $a$
- Leaf angle probability distribution $g_L$
Volume is described by:

- Leaf area density $a$
- Leaf angle probability distribution $g_L$
Volume is described by:

- Leaf area density $a$
- Leaf angle probability distribution $g_L$
Volume is described by:

- Leaf area density $a$
- Leaf angle probability distribution $g_L$
Leaf Energy Balance Equation

\[ R_N = g_H c_p (T_L - T_a) + g_M \lambda \left( \frac{e_s(T_L) - e(T_a)}{p_{atm}} \right) \]

Leaf surface energy balance

- **Radiation**
- **\( R_N \)**
- **\( g_H c_p (T_L - T_a) \)**
- **\( Q_E \): Convection**
- **\( g_M \lambda (\frac{e_s(T_L) - e(T_a)}{p_{atm}}) \)**
- **\( \lambda E \): Latent Cooling**

Iteratively invert to find leaf surface temperature \( T_L \)
Leaf surface energy balance

\[ R_N = g H c_p (T_L - T_a) + g M \lambda \frac{(e_s(T_L) - e(T_a))}{p_{atm}} \]

Radiation

\( Q_E \): Convection

\( \lambda E \): Latent Cooling

Iteratively invert to find leaf surface temperature \( T_L \)
3D radiation model

**a:** Longwave surface emission; **b:** Longwave leaf emission; **c:** Diffuse solar; **d:** Diffuse longwave; **e:** Direct solar
3D radiation model

What happens when a ray hits a volume?

horizontal leaves
vertical leaves
3D radiation model

Attenuation

horizontal leaves

vertical leaves

Anisotropic attenuation coefficient
3D radiation model

Scattering

Anisotropic scattering phase function

horizontal leaves

vertical leaves

Brian Bailey et al.
bbailey@eng.utah.edu
**3D radiation model**

**Emission**

- horizontal leaves
- vertical leaves

**Anisotropic emission and re-absorption**

Brian Bailey et al.

bbailey@eng.utah.edu
Leaf surface energy balance

\[ R_N = gHc_p(T_L - T_a) + gM\lambda \left( \frac{e_s(T_L) - e(T_a)}{p_{atm}} \right) \]

- **Radiation**
- **\( Q_E \): Convection**
- **\( \lambda E \): Latent Cooling**

**Published Work:**

**Radiation Model**

Leaf surface energy balance

\[ R_N = gHc_p(T_L - T_a) + gM\lambda \frac{(e_s(T_L) - e(T_a))}{p_{atm}} \]

- \( R_N \): Radiation
- \( Q_E \): Convection
- \( \lambda E \): Latent Cooling

Boundary-Layer Conductance for Heat
Boundary-Layer Conductance Model

\( g^*_H(\theta_L) \) from inclined flat plate correlations of:


\[ g^*_H \sim f(Re, Gr, Pr; \theta_L) \]
Boundary-Layer Conductance Model

$g^*_H(\theta_L)$ from inclined flat plate correlations of:


$g^*_H \sim f(Re, Gr, Pr; \theta_L)$

New model for a volume of leaves:

$$g_H = \int_0^{\pi} g^*_H(\theta_L) g_L(\theta_L) d\theta_L$$
Incorporating Resolved Vegetation

Brian Bailey

Goals

Modeling Framework

Results

Future Work

Leaf Energy Balance Equation

Leaf surface energy balance

\[ R_N = g_H c_P (T_L - T_a) + g_M \lambda \frac{(e_s(T_L) - e(T_a))}{p_{atm}} \]

\( R_N \): Radiation

\( Q_E \): Convection

\( \lambda E \): Latent Cooling

Conductance for Moisture
(and Stomatal and Boundary-Layer Conductance)

Brian Bailey et al.
bbailey@eng.utah.edu
Incorporating Resolved Vegetation

Brian Bailey

Goals

Modeling Framework

Results

Future Work

Validation

\[ \text{measured } T_L \text{ [}^\circ\text{C}] \]

\[ \text{modeled } T_L \text{ [}^\circ\text{C}] \]

RMSE = 1.5

\[ R^2 = 0.97 \]

\[ d = 0.99 \]

July 31 19:08

Brian Bailey et al.

bbailey@eng.utah.edu
**Leaf Energy Balance Equation**

Leaf surface energy balance

\[ R_N = g_H c_p (T_L - T_a) + g_M \lambda \left( e_s(T_L) - e(T_a) \right) \]

- **Radiation**
- **\( Q_E \): Convection**
- **\( \lambda E \): Latent Cooling**

**Tree Energy Model**

Ground/Building Surface Energy Balance

\[
R_N - \varepsilon \sigma T^4 =
\]
Net Radiation

\[
g_H (T - T_{air}) + g_M \frac{e_s(T) - e_{air}}{p_{atm}} + Q_G
\]
Sensible Heat  Latent Heat  Conduction

Iteratively invert to find surface temperature \( T \)
Mean Wind Field Model

QUIC-URB: Quick Urban & Industrial Complex
Mass-consistent rapid wind field model

Turbulent Transport

Turbulent Advection-Diffusion Equation

\[
\frac{\partial \theta}{\partial t} + U_j \frac{\partial \theta}{\partial x_j} = \alpha_T \frac{\partial^2 \theta}{\partial x_j^2} + q_i
\]

\(\theta \rightarrow \) temperature or moisture

Eddy-Diffusivity:

\[
\alpha_T = \ell_m^2 \left( 2 \overline{S_{ij}} \overline{S_{ij}} \right)^{1/2} Pr
\]

where

\[
\overline{S}_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)
\]
These physically robust models come with substantial computational cost!

What are the options?

- Standard CPU
- Parallel CPU's (e.g., supercomputer)
These physically robust models come with substantial computational cost!

What are the options?

- Standard CPU
These physically robust models come with substantial computational cost!

What are the options?

- Standard CPU
- Parallel CPU’s (e.g., supercomputer)
Computational Expense

Incorporating Resolved Vegetation

Brian Bailey

Goals
Modeling Framework
Results
Future Work

CPU-Based Ray Tracing: NVIDIA OptiX

Brian Bailey et al. bbailey@eng.utah.edu
GPU-Based Ray Tracing: NVIDIA® OptiX™
These physically robust models come with substantial computational cost!

What are the options?

- Standard CPU
- Parallel CPUs (e.g., supercomputer)
- Graphics Processing Units (GPUs)
Test Case

Building the City Geometry:

Salt Lake City, Utah, U.S.A
552 buildings 190,834 discrete patches
City Builder

Adding vegetation:

- 1,812 trees
- Area Fraction: 1.5%
Effect of a (current) park: Washington Square

Incorporating
Resolved
Vegetation

Brian Bailey

Goals
Modeling
Framework
Results
Future Work

Effect of a (current) park:
Washington Square

Brian Bailey et al.
bbailey@eng.utah.edu
Effect of a (current) park: Washington Square

Surface Temperature [°C]

- 14:00 on Oct. 1
- Incoming Air Temperature: 20°C
Effect of a (current) park: Washington Square

Surface Temperature [°C]

Side Note: execution time is on the order of a few minutes
Effect of a (current) park: Washington Square

Wind Field
Effect of a (current) park: Washington Square

Air Temperature [°C] @ 2 m
“What If” Scenarios

What if we vary the number of trees?

No Trees

Double the Trees (Area Fraction: 3%)
“What If” Scenarios

What if we vary the number of trees?

Horizontal average of temperature

Height [m]

Temperature [°C]

mean building height

no trees
normal trees
double trees

Horizontal average of temperature
“What If” Scenarios

What if 10% of rooftops were ‘green’?

![Map of 'green' rooftops](image)

= ‘green’ roof (grass)
“What If” Scenarios

What if 10% of rooftops were ‘green’?
Future Work

Physical Models:
- Full building energy balance
- Regional climate model coupling (WRF)
- Coupling with urban water model (SWMM)

Dissemination:
- User interface
Future Work

Physical Models:
- Full building energy balance
- Regional climate model coupling (WRF)
- Coupling with urban water model (SWMM)

Dissemination:
- User interface
Future Work

Physical Models:

- Full building energy balance
- Regional climate model coupling (WRF)
- Coupling with urban water model (SWMM)

Dissemination:

- User interface
Future Work

Physical Models:
- Full building energy balance
- Regional climate model coupling (WRF)
- Coupling with urban water model (SWMM)

Dissemination:
- User interface
Acknowledgements:

Research Support:

- U.S. National Science Foundation grants IDR CBET-PDM 1134580 and 1133590, and AGS 1255662

Travel Support:

- University of Utah Graduate School
- Global Change & Sustainability Center
Modeling System

**QUIC-EnvSim**

- **QUIC-URB**
  - Wind Field t.k.e.
  - Turbulent Transport Model
    - Air Temp/Moisture
    - Surface Fluxes
  - Surface Energy Balance Model
    - Surface Temperatures
- **Solar Radiation Transport Model**
  - Shortwave Fluxes
- **Longwave Radiation Transport Model**
  - Emitted Radiation

User inputs: geometry, BC’s, & initial guesses

Done: yes
Air Temp. Converged?: yes
Surf. Temp. Converged?: yes
no
no

Brian Bailey et al. bbailey@eng.utah.edu