A coupled energy and water transport model for urban surfaces

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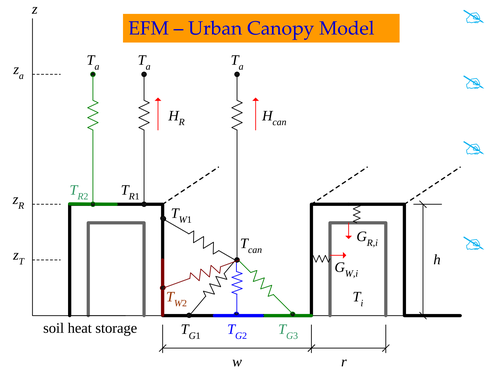
1. Introduction

Urban areas are home to more than half of the world's population. Being humanity's engine of creativity, wealth production and economic growth, rapid urbanization has also emerged as the source of many adverse environmental effects. Problems specific to urban environment include: urban heat island effects, significant emission of greenhouse gases, production of pollutants, etc.

Physically-based urban canopy models (UCM) have proven to be a useful tool to study the surface transport of energy in urban areas. We developed an offline urban parameterization scheme, coupling the transport of energy and water inside urban canopies. It has been tested in detailed numerical/statistical analyses.

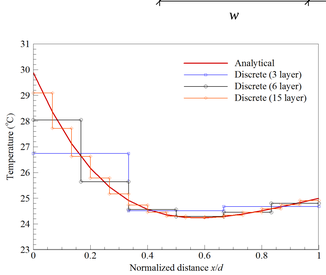
We have been deploying a sensor network consisting of various meteorological stations and sensing instruments over the Princeton University campus, to capture the spatial and temporal variability of meteorological parameters in complex built terrain, through distributed measurements.

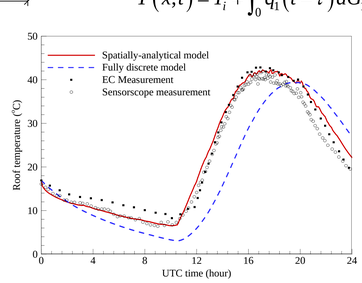
2. A spatially-analytical scheme for surface temperature/soil heat flux

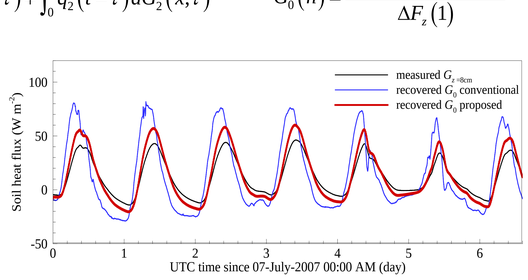


- Buildings are represented as a one-dimensional infinite urban street canyon, similar to the "big-leaf" concept in NOAH land surface model.
- We developed EFM-UCM to include heterogeneous surface types for the ground, walls, and roofs.
- A spatially-analytical algorithm for heat conduction to compute surface temperatures and heat fluxes was implemented to replace the conventional fully discrete model.
- The algorithm can be extended for reconstruction of soil surface heat flux through flux plate measurement, without resorting to the knowledge of soil temperature.

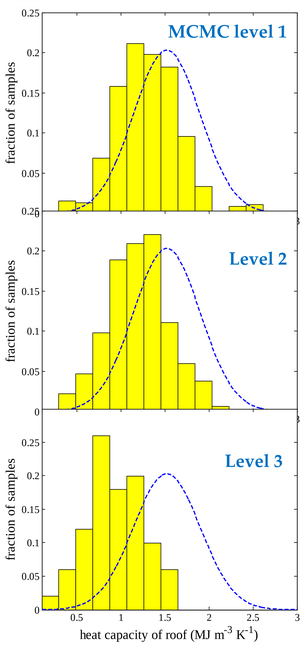
$$T(x,t) = T_i + \int_0^t q_1(t-\tau)\,dG_1(x,\tau) + \int_0^t q_2(t-\tau)\,dG_2(x,\tau) \qquad G_0(n) = \frac{2G_z(n) - G_0 \otimes \Delta F_z}{\Delta F_z(1)}$$

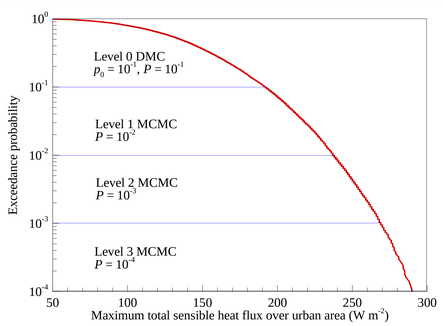




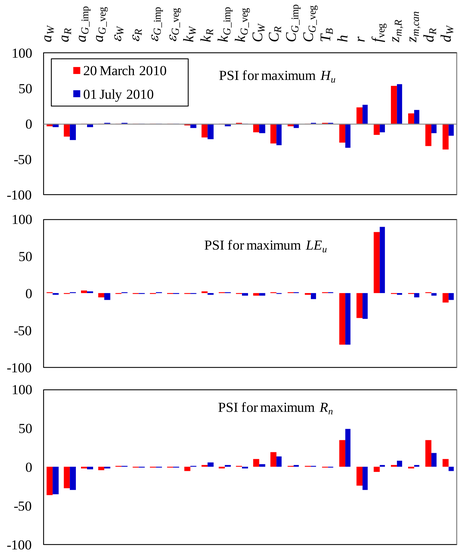


3. Characterization of parameter uncertainties using Markov-Chain Monte Carlo (MCMC)



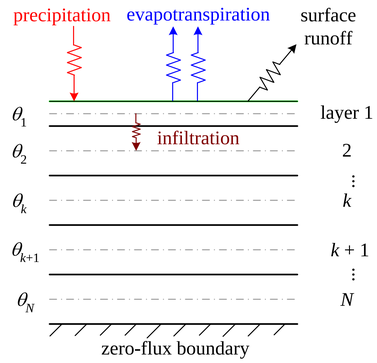


$$\mathrm{PSI} = \frac{1}{N_{level}} \sum_{j=1}^{N_{level}} \frac{E\left[X \middle| Y > y_j\right] - E[X]}{E[X]}$$



- Each uncertain parameter is assigned a PDF (normal or uniform) .
- Define a parameter sensitivity index (PSI) by maximizing monitored outputs and conditional sampling techniques.
- UCM is highly sensitive to urban geometry and building parameters.
- UCM is relatively insensitive to thermal parameters and weather conditions.

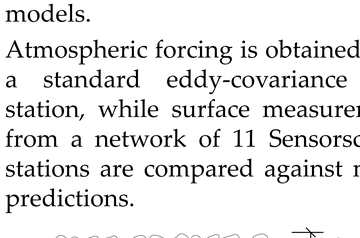
4. Coupled energy and water transport model



$$\frac{\partial \theta_k}{\partial t} = \begin{cases} \frac{1}{d_1}\left[P - ET(\theta_1) - R - Q_{w,1\to 2}\right], & k=1 \\ \frac{1}{d_k}\left[Q_{w,k-1\to k} - Q_{w,k\to k+1}\right], & k>1 \end{cases}$$

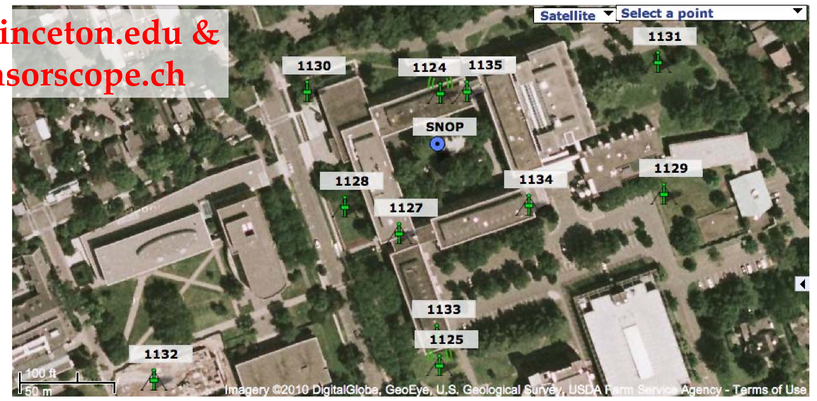
$$Q_{w,k\to k+1} = \bar{D}_{k,k+1}\frac{\theta_k - \theta_{k+1}}{d_k + d_{k+1}} + \bar{K}_{k,k+1}$$

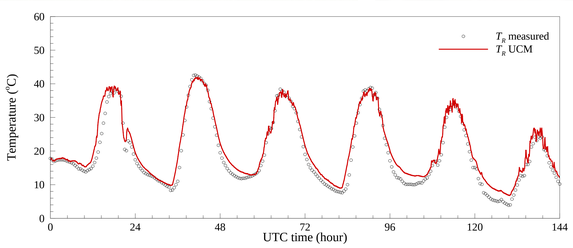
- Physically-based water transport models are implemented for the vegetated and engineered surfaces with water-holding capacity.
- Experimental data obtained from a distributed sensor network over Princeton campus is used to drive and validate the numerical models.
- Atmospheric forcing is obtained from a standard eddy-covariance (EC) station, while surface measurements from a network of 11 Sensorscope® stations are compared against model predictions.

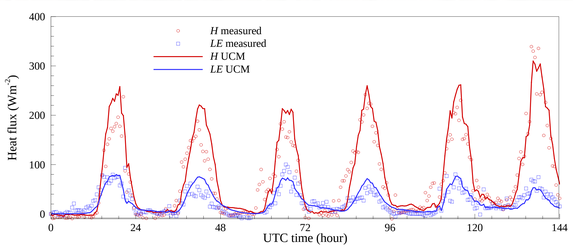


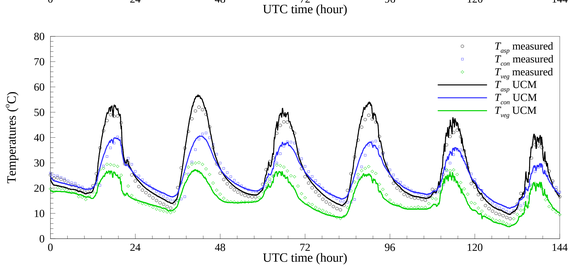
$$\phi_{eng}\frac{\partial \delta_w}{\partial t} = P - E_p - R$$

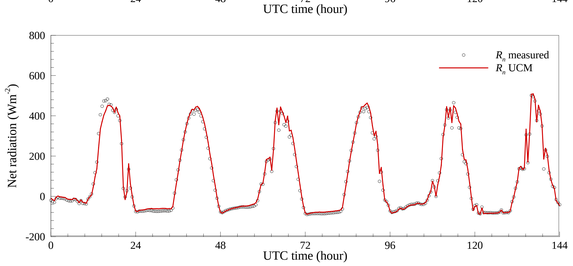
$$\phi_{eng} = \begin{cases} \text{porosity of gravel for roof} \\ \text{1.0 for asphalt/concrete} \end{cases}$$

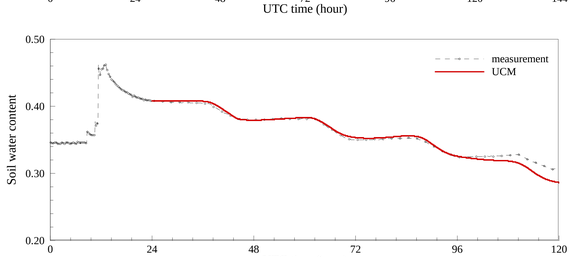












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[1] Wang ZH and Bou-Zeid E (2011) Coupling a hydrological model with physically-based urban canopy schemes. To be submitted to *Quarterly Journal of Royal Meteorological Society*.

[2] Wang ZH and Bou-Zeid E (2011) Comment on "Impact of wave phase difference between soil surface heat flux and soil surface temperature on soil surface energy balance closure" by Z. Gao, R. Horton and H. P. Liu. *Journal of Geophysical Research – Atmosphere*, **accepted**.

[3] Wang ZH, Bou-Zeid E, Au SK and Smith JA (2011) Analyzing the sensitivity of WRF's single-layer urban canopy model to parameter uncertainty using advanced Monte Carlo simulation. *Journal of Applied Meteorology and Climatology*, **tentatively accepted**.

[4] Wang ZH, Bou-Zeid E and Smith JA (2011) A spatially-analytical scheme for surface temperatures and conductive heat fluxes in urban canopy models. *Boundary-Layer Meteorology*, **138(2)**, 171-193.