Application of a sensor network to study the energy budget in urban canopies

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Abstract

We adapt a physically-based single-layer urban canopy model (UCM) to study the energy budget in urban areas. The energy budget scheme in this study is similar to the scheme implemented in the WRF-NOAH urban canopy model, but it is decoupled from the Weather Research and Forecasting (WRF) model. Simulations are carried out to quantify the sensitivity of the model to each atmospheric and surface parameter input. To validate and provide accurate inputs to this UCM, several sensing systems are being deployed over the Princeton campus through the Sensor Network Over Princeton (SNOP) project. When the deployment is complete, the measured field data will include: (1) surface and air temperatures, longwave and shortwave radiation, soil moisture and soil heat flux using a wireless sensing network and two standard surface energy budget stations; (2) vertical profile of wind speed and temperature up to 1000 meters using a SODAR/RASS system; and (3) vertical shear stress and heat flux using a scintillometer. The collected data will be used to derive input parameters representative of the campus area, and to test the model predictions.

1. Introduction

According to the United Nations (UN, 2010), more than 50% of world populations currently live in urban areas. This fraction is projected to increase for the foreseeable future. Consequently, urban environmental conditions and infrastructure (e.g. transportation) are becoming increasingly critical to the well-being of the residents in urban area. Examples of adverse environmental impact of dense urbanization include the heat island effect (Oke 1973, 1982) and air pollution in cities.

Unlike flat surfaces or forest canopies, flow in urban canopies is highly localized, inhomogeneous and exhibits more complex patterns. Consequently, modeling and parameterization in urban canopy are more challenging in the sense that they require a much richer parameter space to capture the physics of the flow environment.

The main objectives of this study are: (1) to understand the mechanisms controlling land-atmosphere exchanges in urban areas; (2) to evaluate the current urban canopy model (UCM) implemented in WRF; (3) to improve the parameterization schemes through a distributed sensor network over Princeton campus.

2. Offline WRF-NOAH Urban Canopy Model

Different land use types were conventionally treated as flat surfaces with modified surface parameters (roughness lengths, thermal properties, etc) in climate models. This is an over-simplified approach particularly for urban canopies. Masson (2000) proposed a single-layer energy balance model for urban area, consisting of two surfaces (roof+ground) with systematic parameterization of all surface budgets. The framework was adopted and further developed by Kusaka et al. (2001) and Martilli et al. (2001). Multiple-layer energy balance models with vertical stratification have also been developed (e.g. Kanda et al. 2005) which are more computationally involved. A schematic plot of the turbulent flux resistance network for a single layer model is shown in Fig. 1. The energy budget balance equation involved in the model is given by

$$R_n + Q_F = H + LE + G \quad (1)$$

where R_n is the net radiation, Q_F, H and LE are anthropogenic, sensible, latent heat fluxes respectively, and G is the heat flux conducted to the solid ground or buildings. Note in Fig. 1 that we have partitioned the ground into two categories, viz. impervious (concrete/asphalt) and vegetated surfaces. This additional feature is absent from previous models but is essential for a better representation of suburban areas and cities with significant green spaces. Similar division can be made to the roof as well, if the fraction of green roofs is substantial in the study area. Different parameterization schemes for turbulent fluxes, in particular, latent heat due to evaporation are adopted for different categories.

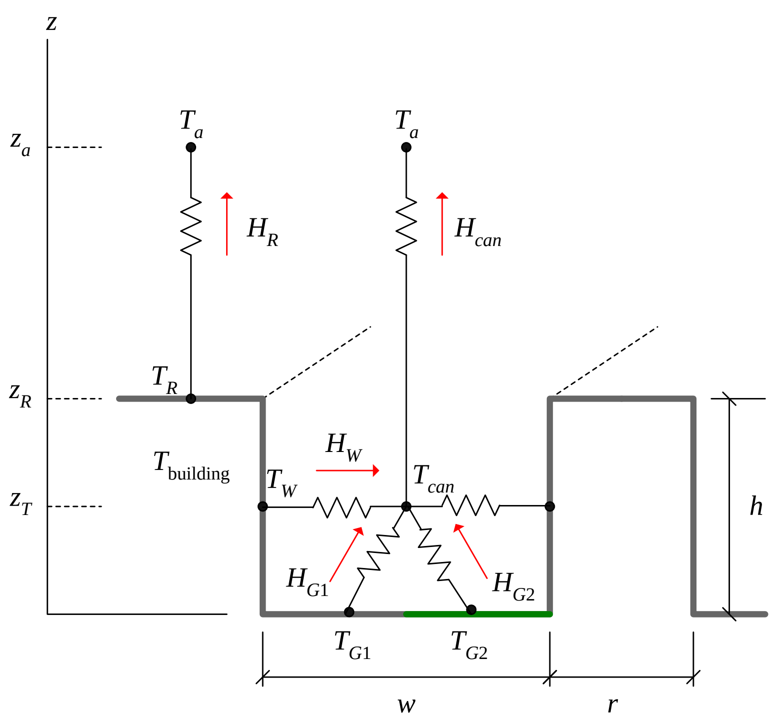

Figure 1: Schematics of turbulence resistance network in single-layer energy balance model

The meteorological (forcing) and surface input parameters required by the UCM are listed in Tables 1 and 2 respectively. We obtain the forcing parameters directly from field measurements. From a preliminary sensitivity analysis, the most critical surface parameters are the thermal properties of solids surfaces (roof, wall and ground).

Table 1: Meteorological parameters for UCM

Meteorological input data	Symbol
Reference height [m]	z_a
Temperature at z_a [K]	T_a
Zonal wind at z_a [m/s]	u_a
Meridional wind at z_a [m/s]	v_a
Specific humifity at z_a [kg/kg]	q_a
Downward direct solar radiation on a horizontal surface [W/m^2]	S_D
Downward diffuse solar radiation on a horizontal surface [W/m^2]	S_Q
Downward longwave radiation on a horizontal surface [W/m^2]	$L^{\downarrow}$
Latitude [rad]	ϕ
Logitude [rad]	λ

Table 2: Canyon dimensions and surface parameters for UCM

Canyon dimensions and surface parameters	Symbol
Roof level (building height) [m]	z_r
Normalized building height [-]	h
Normalized roof width [-]	r
Normalized road width [-]	w
Zero plane displacement height [m]	z_d
Roughness length [m]	z_0
Roof/wall/road surface albedo	$\alpha_R,\ \alpha_W,\ \alpha_G$
Roof/wall/road surface emissivity	$\varepsilon_R,\ \varepsilon_W,\ \varepsilon_G$
Roof/wall/road thermal conductivity [W/mK]	$\kappa_R,\ \kappa_W,\ \kappa_G$
Roof/wall/road heat capacity [J/m^{3}K]	C_R, C_W, C_G
Street canyon orientation [rad]	θ_{can}

3. Sensor Network Over Princeton (SNOP)

Numerous field experimental campaigns have been reported in the meteorological literature. One of the problems associated with most meteorological measurements is the limited coverage both in time and space. SNOP is designed to have a broad coverage by deploying a large array of various sensing systems over a range of sites through continuous measurements. In this project, Princeton campus serves as a test bed resource for the development of environmental sensing systems (the efforts are intimately related to the activities of the Mid-InfraRed Technologies for Health and the Environment, MIRTHE). Instruments that have already been deployed include:

- Two Meteorological/Eddy Covariance (EC) Flux stations: one over a roof top and one over a grass field
- A scintillometer measuring wind drag and vertical heat flux over a street canyon,
- A LIDAR system for monitoring the atmosphere boundary layer,
- Three radiometers for measuring longwave and shortwave radiation,
- IR cameras monitoring wall surface temperature, and
- One disdrometers.

The experimental setup of the eddy covariance station and the scintillometer on the roof top of a building are shown in Figure 2.

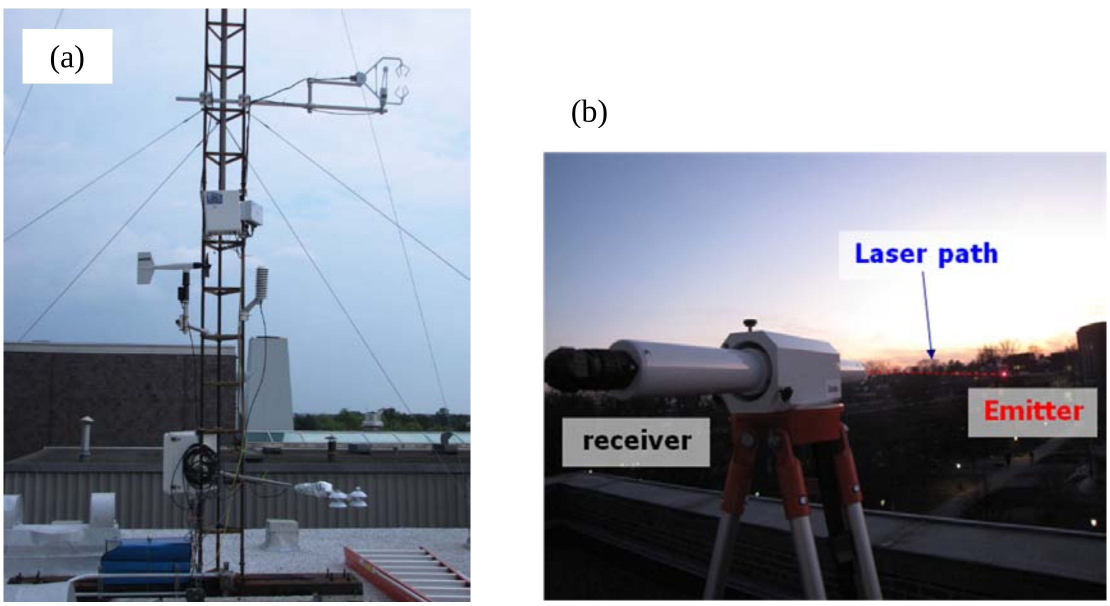

Figure 2: Experimental set up for (a) roof EC station and (b) scintillometer.

In addition, a range of instruments will be added to the network, including

- A distributed wireless network of 12 meteorological stations,

- A SODAR/RASS system measuring vertical profile of wind speed and temperature up to 500m,
- iButtons for temperature and humidity measurements inside buildings.

4. Validation of UCM using SNOP data

We compared the metrological data between the measurements by the roof EC station and the predictions by UCM, for a typical diurnal cycle (14 Aug 2009). The results are plotted in Fig. 3.

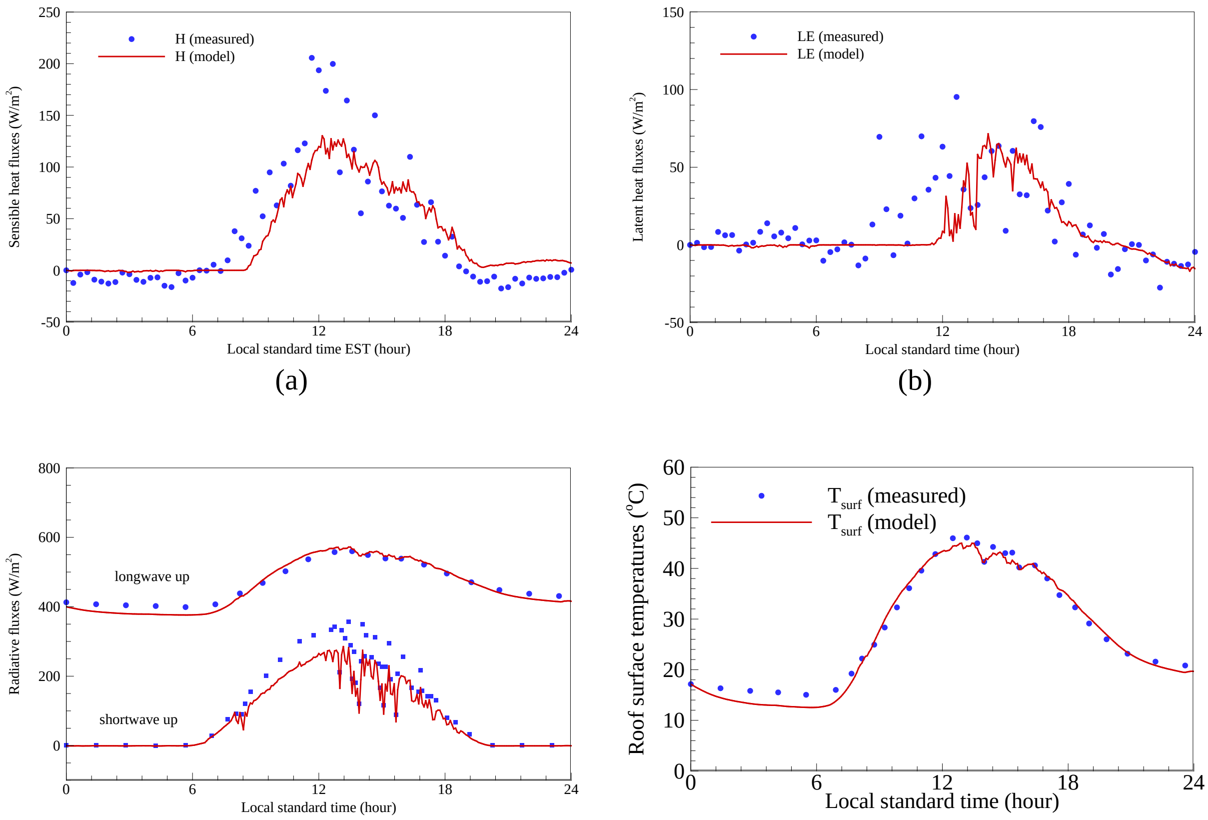

Figure 3: Comparison of model prediction and field measurement: (a) sensible heat; (b) latent heat; (c) upward radiative heat; and (d) surface temperature

From the comparison of turbulent heat fluxes, it is clear that the trend of evolution is well captured by the model, whereas the peak values are underestimated. We conclude that parameterization of eddy diffusivity needs to be further improved. Also the model prediction for sensible heat flux agrees better with measurements than latent heat flux predictions. This is due to the crude parameterization of evaporation, where simplified cases, with impervious (completely dry) and vegetated (completely dry if no rain and saturated during rain) surfaces, are considered. Comparison of upward shortwave and longwave radiation suggested that realistic surface thermal properties, i.e. albedo and emissivity, need to be measured and incorporated into the model, instead of using values from the literature. Figure 3-c for example clearly shows that the albedo used for roof is inadequate since the downwelling shortwave radiation is an input to the model (from measurements) while the upwelling modeled radiation significantly underestimates the measured radiation. For surface temperature, model predictions are in good agreement with measurement data.

5. Concluding remarks

A sensor network consisting of various sensing systems is being deployed over Princeton campus to obtain continuously measured meteorological data with broad spatial coverage. Field measurement data is used to calibrate and improve the current urban canopy parameterization implemented in WRF-NOAH land surface model. More sensing instruments are to be added to the network, including wireless meteorological stations and thermal iButtons. New building parameterization (Kikegawa et al. 2003, Salamanca et al. 2010) are to be incorporated in the UCM to build a more comprehensive energy balance model for urban environments.

Acknowledgement

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References:

[1]. Kanda M, Kawai T, Kanega M, Moriwaki R, Narita K, Hagishima A. A simple energy balance model for regular building arrays. *Boundary-Layer Meteorology* 2005; 116: 423-443.

[2]. Kikegawa Y, Genchi Y, Yoshikado H, Kondo H. Development of a numerical simulation system toward comprehensive assessment of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. *Applied Energy* 2003; 76: 449-466.

[3]. Kusaka H, Kondo H, Kikegawa Y, Kimura F. A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Boundary-Layer Meteorology* 2001; 101: 329-358.

[4]. Martilli A, Clappier A, Rotach MW. An urban surface exchange parameterization for mesoscale models. *Boundary-Layer Meteorology* 2002; 104: 261-304.

[5]. Masson V. A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorology* 2000; 94: 357-397.

[6]. Oke TR. City size and the urban heat island. *Atmospheric Environment* 1973; 7: 769-779.

[7]. Oke TR. The energy basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society* 1982; 108: 1-24.

[8]. Salamanca F, Krpo A, Martilli A, Clappier A. A new building model coupled with an urban canopy parameterization for urban climate simulations – part I. formulation, verification, and sensitivity analysis of the model. *Theoretical and Applied Meteorology* 2010; 99: 331-344.

[9]. United Nations Population Division, *World Urbanization Prospect*, *the 2007 Revision*. Department of Economic and Social Affairs, United Nations Secretariat, New York, 2010.