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Simulation of the urban heat island effects over the Greater Houston Area with the high resolution WRF/LSM/Urban coupled system

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1. INTRODUCTION

Numerical simulations of urban heat island have been traditionally conducted using mesoscale models with standard slab model or land surface model, and have provided us with essential ideas of the urban weather and climate (e.g., Kusaka et al. 2000). For instance, Liu et al. (2003) applied a the unified Noah land surface model (LSM) with a few urban enhancements in a realtime MM5 operational support system for the 2003 Joint Urban Atmospheric Dispersion Study field experiment. Their realtime forecast results showed that it was able to capture prominent 'urban heat island' effects.

Nevertheless, it is necessary to develop more advanced land surface model considering urban canopy process in order to improve the representation urban heat island influence and hence high-resolution weather forecasts, to understand weather and climate in urban areas, and to correctly estimate energy consumption in urban areas. The Unified Noah-LSM, an advanced land surface/hydrology model, has been recently coupled to the Weather Research and Forecasting (WRF) model (Tewari et al. 2003). In this study, we develop a coupled Noah LSM/Urban-canopy model, based on the single-layer urban canopy model of Kusaka et al. (2001), for the WRF model and present some preliminary test results by applying this coupled system for the Houston urban area.

2. WRF/LSM/URBAN COUPLED SYSTEM

2.1. WRF MODEL

The WRF model is non-hydrostatic, compressible, NWP model with mass coordinate system.

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The basic equations consist of the equations of motion, heat, and moisture, and continuity equation. The WRF has several schemes for each physical process. For example, the WRF has a non-local closure model MRF and a closure model of 1.5 orders by Mellor and Yamada as a PBL scheme, 5-layer soil model and a complicated land surface model with complicated vegetation canopy and hydrological processes as a land surface model, a line-by-line model as a radiation scheme, a simple microphysics with 3 liquid elements by Dudhia and complicated microphysics with 6 liquid elements by Lin as a cloud scheme.

2.2. NOAH LAND SURFACE MODEL

The Noah-LSM provides surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions (Fig. 1) for a coupled atmospheric model. The model is based on the coupling of the diurnally dependent Penman potential evaporation approach, the multilayer soil model, and the primitive canopy model (Chen and Dudhia, 2001). It has single canopy layer and the following prognostic variables: soil moisture and temperature in the soil layers, water stored on the canopy, and snow stored on the ground.

2.3. SINGLE-LAYER URBAN CANOPY MODEL

One basic function of an urban canopy model is to consider the effects of urban geometry on surface energy balance and wind shear for urban regions. Our urban model is based on the urban canopy model developed by Kusaka et al. (2001) and modified by Kusaka and Kimura (2004). The present urban canopy model includes (a) street canyons that are parameterized to represent the urban geometry (Fig. 2), (b) shadowing from buildings and reflection of radiation in the canopy layer (Fig. 3), (c) the canyon orientation and diurnal change of solar azimuth angle, (d) artificial surface consists of eight canyons with different orientation (e) Inoue's model for canopy flows, (f) the multi-layer heat equation for the roof, wall, and road interior temperatures, (g) anthropogenic heating associated with energy consumption by human activities, and (h) a very thin bucket model for hydrological processes.

This urban canopy model estimates both the surface temperatures of, and heat fluxes from the roof, wall, and road; it also calculates the energy and momentum exchange between the urban surface and the atmosphere. The heat fluxes illustrated in the figure 2 are estimated by Monin-Obkhov similarity theory or the Jurges formula used in the architectural field. Net short wave radiation is estimated considering urban geometry (Fig. 3). Net long wave radiations are calculated from the following equation.

$$L_R = \varepsilon_R \left(L^{\downarrow} - \sigma T_R^4 \right),$$

$$L_{W,1} = \varepsilon_W \left(L^{\downarrow} F_{W\to S} + \varepsilon_G \sigma T_G^4 F_{W\to G} + \varepsilon_W \sigma T_W^4 F_{W\to W} - \sigma T_W^4 \right),$$

$$\begin{aligned} L_{W,2} = \varepsilon_W \Big[& (1-\varepsilon_G) L^{\downarrow} F_{G\to S} F_{W\to G} + (1-\varepsilon_G) \varepsilon_W \sigma T_W^4 F_{G\to W} F_{W\to G} \\ & + (1-\varepsilon_W) L^{\downarrow} F_{W\to S} F_{W\to W} + (1-\varepsilon_W) \varepsilon_G \sigma T_G^4 F_{W\to G} F_{W\to W} \\ & + \varepsilon_W (1-\varepsilon_W) \sigma T_W^4 F_{W\to W} F_{W\to W} \Big], \end{aligned}$$

$$L_{G,1} = \varepsilon_G \left[L^{\downarrow} F_{G\to S} + \varepsilon_W \sigma T_W^4 F_{G\to W} - \sigma T_G^4 \right],$$

$$\begin{aligned} L_{G,2} = \varepsilon_G \Big[& (1-\varepsilon_W) L^{\downarrow} F_{W\to S} F_{G\to W} \\ & + (1-\varepsilon_W) \varepsilon_G \sigma T_G{}^4 F_{W\to G} F_{G\to W} + \varepsilon_W (1-\varepsilon_W) \sigma T_W{}^4 F_{W\to W} F_{G\to W} \Big]. \end{aligned}$$

Here $L^{\downarrow}$ is the downward atmospheric long wave radiation; T_R, T_W, and T_G, are surface temperatures of the roof, wall, and road, respectively. View factors F are computed in the same way as Kusaka et al. (2001). Subscripts W, G, and S denote wall, ground (road), and sky, respectively. For instance, $F_{G\to S}$ means the sky view factor from the road. Subscripts 1 and 2 refer to the absorption of the direct and reflected radiation, respectively. The parameters set by users are summarized in Table 1.

2.4. COUPLING OF WRF, LSM, AND URBAN

The LSM/Urban coupling is realized by using a parameter 'urban percentage' to represent sub-grid scale heterogeneity because the coupled model has two different models to estimate surface fluxes and temperatures from natural and man-made (artificial) surfaces in a grid. Hence, the total grid-scale sensible heat flux, for example, can be estimated as follows:

$$H = A_{NATURAL} \times H_{LSM} + A_{ARTIFICIAL} \times H_{URBAN}$$

Here, H is the total sensible heat flux from a grid to the WRF lowest atmospheric layer, $A_{NATRURAL}$ the area ratio of a natural surface such as grassland, crop, forest, and water, $A_{ARTIFICIAL}$ the area ratio of an artificial surface such as buildings, road, and railway. H_{LSM} is the sensible heat flux from Noah-LSM for natural surfaces, H_{URBAN} the sensible heat flux from Urban Canopy Model for artificial surfaces. Latent heat flux and upward long wave radiation flux from a grid are estimated by the same way.

The surface skin temperature at the grid point is calculated as the averaged value of the 4th power of the temperature on the artificial and natural surfaces weighted by their area.

This parameterization makes coupling easy and allows the results from the canopy model to be compared with those from operational observation, which is carried out above grass-covered open space in cities.

The WRF model receives the surface fluxes and temperature from the LSM/Urban coupled model and gives the atmospheric variables at the lowest atmospheric level as forcing condition for the coupled LSM/Urban model. Thus, the LSM/Urban coupled model is linked with the WRF model through the surface layer process.

3. TEST SIMULATION

We are testing the coupled WRF/Noah-LSM/Urban modeling system for the Houston Urban areas. To correctly represent the heterogeneous urban areas at fine scales, we utilize the USGS National Landuse data set with a new urban Classification System, which divides the urban areas into four categories: 1) open space, 2) low intensity residential, 3) medium intensity residential and 4) high intensity residential with distinctive impervious covers, as shown on Figure 4.

A number of coupled model numerical experiments are being conducted to verify the simulated urban heat island with in-situ observations collected during 2002 HEAT field experiment over Houston, and to test model sensitivity to various urban parameters and model configurations.

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Table 1: Parameters for the single-layer urban canopy model

Parameter	Symbol
Urban type	*Urban type*
Roof level (building height)	z_R
Roof area ratio	A_R
Wall area ratio	A_W
Road area ratio	A_G
Volumetric heat capacity of roof	ρc_R
Volumetric heat capacity of wall	ρc_W
Volumetric heat capacity of road	ρc_G
Thermal conductivity of roof	λ_R
Thermal conductivity of wall	λ_W
Thermal conductivity of road	λ_G
Sub-layer Stanton number	${B_H}^{-1}$
Roughness length	z_0
Roughness length above canyon	z_{0C}
Roughness length above roof	z_{0R}
Zero plane displacement height	d
Roof surface albedo	α_R
Wall surface albedo	α_W
Road surface albedo	α_G
Roof surface emissivity	ε_R
Wall surface emissivity	ε_W
Road surface emissivity	ε_G
Moisture availability of roof	β_R
Moisture availability of road	β_G

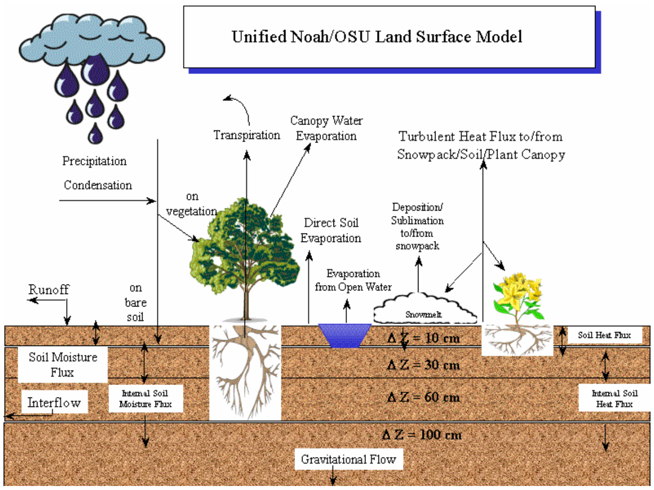

Fig. 1: Schematic of Noah Land Surface Model.

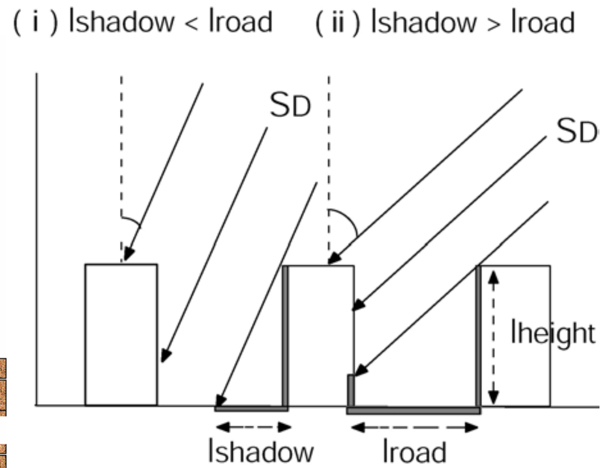

Fig. 3: Radiation in the urban street canyon. l_{shadow} and l_{road} are the length of shading on the road, respectively. l_{height} is the building height.

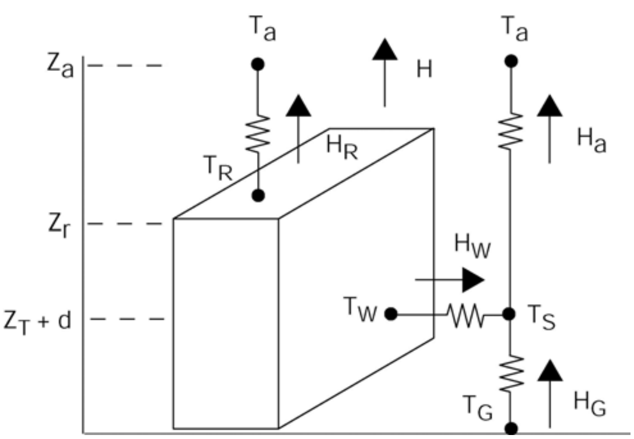

Fig. 2: Schematic of the Urban Canopy Model.
Z_a is the lowest level of the WRF model.
Ta indicates air temperature at the Z_a.
H is the sensible heat flux from the artificial surface. H_R, H_a, H_W, and H_G are the sensible heat fluxes from the roof, canyon, wall, and road, respectively. Z_r is the building height. Z_T and d are the roughness length for heat and zero displacement height, respectively. T_a is the air temperature at Z_a. T_R, T_W, and T_G are surface skin temperature of the roof, wall, and road.

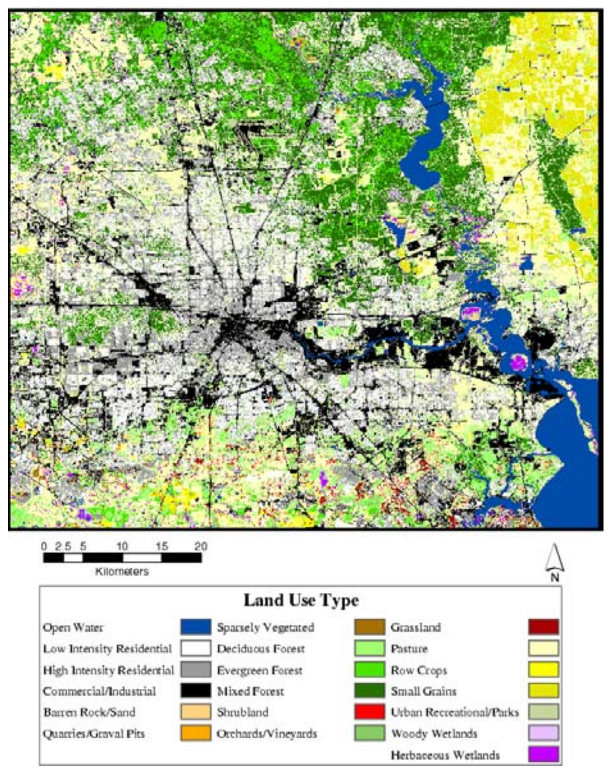

Fig. 4: Land use map for greater Houston area based on 30-m resolution USGS National Landuse data set with a new uraban Classification System horizontal resolution. Base on USGS.