9.11 **UTILIZING THE COUPLED WRF/LSM/URBAN MODELING SYSTEM WITH DETAILED URBAN CLASSIFICATION TO SIMULATE THE URBAN HEAT ISLAND PHENOMENA OVER THE GREATER HOUSTON AREA**

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1. INTRODUCTION

We describe in this paper a research and development effort with regards to developing a coupled land surface and urban canopy model for the Weather Research and Forecast (WRF) model. Subjects to be discussed include the basic description of the coupled system, the important parameters in the urban canopy model, simulations with the coupled system for the Greater Houston area, and its verification against observations obtained from TEXAQS field program.

It is uncommon that some numerical weather prediction (NWP) models run with a grid-spacing of 0.5-1 km for local and regional weather forecasts. At such fine scales, the role of urban landuse in local and regional weather needs to be represented in these models and it is important for NWP models to capture effects of urban on wind, temperature, and humidity in the boundary layer and their influences on the boundary layer depth. Not only these boundary layer weather variables influence people's daily life in the urban region, but also they are important input for air dispersion and quality models, which will benefit from improved prediction of the urban meteorological conditions. Having a consistent treatment of the planetary boundary layer structure and evolution in meteorological and air quality models is imperative.

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Errors in the improper parameterization of urban landuse result in bias in forecasted boundary layer variables and further in predicting the temperature and wind fields.

The spatial distribution of urban landuse (e.g., building height, geometry) is highly heterogeneous even across urban scales. To explicitly solve the motions around an individual building or buildings requires the use of computational fluid dynamics (CFD) models, which are computationally intensive. Hence, in the foreseeable future, NWP models have to parameterize the subgrid-scale urban variability. Even in this context, it is not clear that which degree of complexity of urban landuse treatment should be incorporated in NWP models. For instance, Taha (1999) preferred a simple approach and pointed out that a large amount of detail in complex urban models may be lost when averaging back to a coarse model grid.

In this development effort, we have coupled a single-layer urban canopy model with the Noah LSM, which considers the 2-D geometry of building and roads to represent the radiation trapping and wind shear in the urban canopy (Kusaka et al, 2001; Kusaka and Kimura, 2004). This coupled system was applied to simulate the urban heat island effects for a few selected cases during the 2000 TEXAQS field experiment.

2. REPRESENTING URBAN HEAT ISLAND IN THE COUPLED WRF/LSM/URBAN SYSTEM

2.1. WRF MODEL

The WRF model is a non-hydrostatic, compressible model with mass coordinate system, designed as the next generation NWP model. It has a number of options for various physics processes. For example, the WRF has a non-local closure PBL scheme and a 2.5 level PBL scheme based on Mellor and Yamada scheme. In the recent release of May 2004, none of the land surface models in the WRF V2.0 include a detail urban canopy representation.

2.2. NOAH LAND SURFACE MODEL

The Noah LSM provides surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions (Chen and Dudhia, 2001; Ek et al, 2004). It has single vegetation 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. As released in WRF V2.0, a bulk parameterization for urban landuse has been incorporated in the Noah LSM (Liu et al. 2004, Tewari et al. 2004). It includes: 1) increasing the roughness length from 0.5 m to 0.8 m to represent turbulence generated by roughness elements and drag due to buildings; 2) reducing surface albedo from 0.18 to 0.15 to represent the shortwave radiation trapping in the urban canyons; 3)using a larger volumetric heat capacity of 3.0 J m^{-3} K^{-1} for the urban surface (walls, roofs, and roads) which is usually consisted of concrete or asphalt materials; 4) increasing the value of soil thermal conductivity to 3.24 W m^{-1} K^{-1} to parameterize large heat storage in the urban surface and underlying surfaces, and 5) reducing green vegetation fraction over urban city to decrease evaporation.

2.3. SINGLE-LAYER URBAN CANOPY MODEL

We developed a coupled Noah /Urban-canopy model, based on the single-layer urban canopy model (UCM) of Kusaka et al. (2001). The basic function of an UCM is to take the urban geometry into account in its surface energy budgets and wind shear calculations. Our urban model is based on the urban canopy model developed by Kusaka et al. (2001) and modified by Kusaka and Kimura (2004), which includes: 1) 2-D street canyons that are parameterized to represent the effects of urban geometry on urban canyon heat distribution (Figure 1); 2) shadowing from buildings and reflection of radiation in the canopy layer (Figure 2); 3) the canyon orientation and diurnal cycle of solar azimuth angle, 4) man-made surface consists of eight canyons with different orientation; 5) Inoue's model for canopy flows (Inoue 1963); 6) the multi-layer heat equation for the roof, wall, and road interior temperatures; 7) anthropogenic heating associated with energy consumption by human activities; and 8) a very thin bucket model for evaporation and runoff from road surface.

Figure 1 Schematic of the Urban Canopy Model. Z_a: height of the lowest model level; T_a: air temperature at Z_a; H: aggregated sensible heat flux; Z_r: building height; Z_T: roughness length for heat; d: zero displacement height. T_R, T_W, and T_G are surface temperature of roof, wall, and road, respectively; and H_R, H_a, H_W, and H_G are sensible heat fluxes from the roof, canyon, wall, and road, respectively.

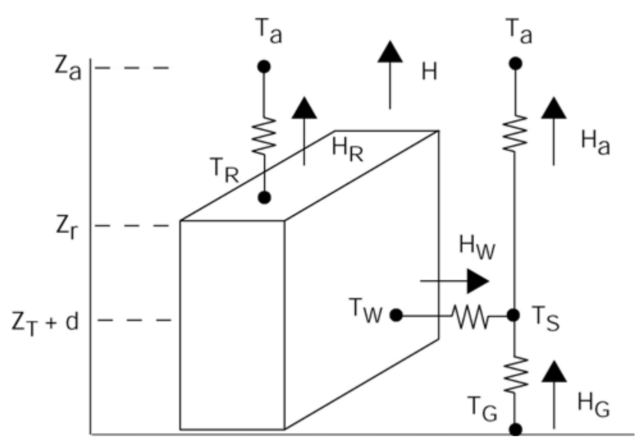
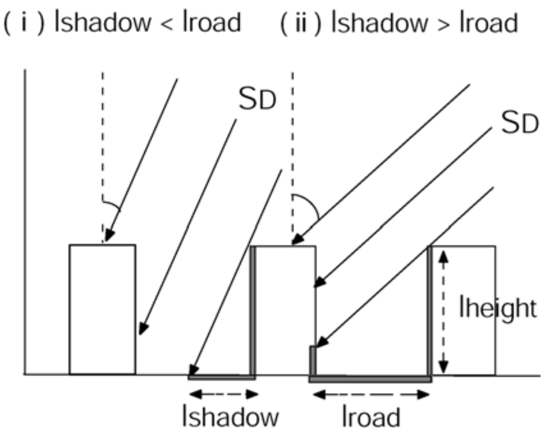


Figure 2: Shortwave downward radiation in the urban street canyon. l_{shadow} and l_{road} are the lengths of shading on the road. l_{height} is the building height.



This urban canopy model takes into account sensible heat fluxes from roof, wall, and road; and then aggregated them into energy and momentum exchange between the urban surface and the atmosphere. Various heat fluxes illustrated on Figure 1 are estimated by the Monin-Obkhov similarity theory or by the Jurges formula used in the architectural field. Surface temperature is calculated from the upward long wave radiation, which is the difference between the net long wave radiation and downward long wave radiation. The net long wave radiations are calculated from the following equation:

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

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

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

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

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

Here $L^{\downarrow}$ is the downward atmospheric long wave radiation. The sky view factors, *F, is* 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 set of parameters required by this UCM is described in Table 1.

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

Parameter	Symbol	Unit
Urban type	*Urban type*	
Roof level (building height)	z_R	[m]
Roof area ratio (Building coverage ratio)	A_R	
Wall area ratio	A_W	
Road area ratio	A_G	
Volumetric heat capacity of roof	ρc_R	[J m^{-3} K^{-1}]
Volumetric heat capacity of wall	ρc_W	[J m^{-3} K^{-1}]
Volumetric heat capacity of road	ρc_G	[J m^{-3} K^{-1}]
Thermal conductivity of roof	λ_R	[W m^{-1} K^{-1}]
Thermal conductivity of wall	λ_W	[W m^{-1} K^{-1}]
Thermal conductivity of road	λ_G	[W m^{-1} K^{-1}]
Sub-layer Stanton number	B_H^{-1}	
Roughness length	z_0	[m]
Roughness length above canyon	z_{0C}	[m]
Roughness length above roof	z_{0R}	[m]
Zero plane displacement height	d	[m]
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

It is necessary to estimate heat transfer from the natural surface (parks, recreation areas, etc.) when a grid cell is not fully covered by urban 'artificial' surface. Hence, this UCM is coupled to Noah through a parameter 'urban percentage', U_p , to represent urban sub-grid scale heterogeneity, which can be estimated by fine-scale satellite images. Hence, the aggregated grid-grid-scale sensible heat flux, for example, can be estimated as follows:

$$H = (1 - U_p) \times H_{LSM} + U_p \times H_{UCM}$$

Here, *H* is the total sensible heat flux from an 'urban' grid cell to the atmospheric surface layer, U_p is the area ratio of a man-made urban surface, and (1-U_p) represents natural surface such as grassland, farmland, and trees. H_{LSM} is the sensible heat flux from the Noah LSM for natural surfaces, while H_{URBAN} is the sensible heat flux from UCM for artificial surfaces. Latent heat flux and upward long wave radiation flux from a grid cell are treated in a similar way.

2.4. COUPLING WRF, NOAH LSM, AND URBAN MODELS

The Noah LSM/Urban coupling is realized by using a parameter 'urban percentage' to represent sub-grid scale, so that Noah LSM estimates surface fluxes and temperature from vegetated urban areas (trees, parks, etc) and the UCM provides the above for man-made (artificial) surfaces for a given grid. Hence, the total grid-scale sensible heat flux, for example, can be estimated as follows:

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

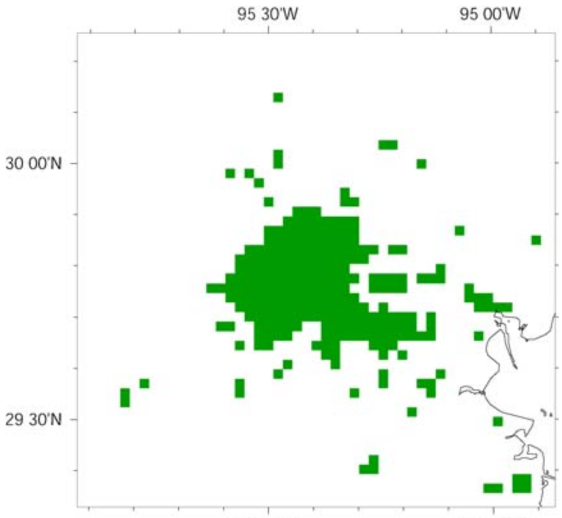
Here, *H* is the total sensible heat flux from a grid to the WRF lowest atmospheric layer, $A_{NATRURAL}$ the area ratio of a natural surface such as grassland, crop, forest, and water, $A_{ARTIFICIAL}$ the area ratio of an artificial surface such as buildings, road, and railway. H_{LSM} is the sensible 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.

2.5. DETAILED REPRESENTING URBAN LANDUSE DISTRIBUTION FOR THE HOUSTON AREA

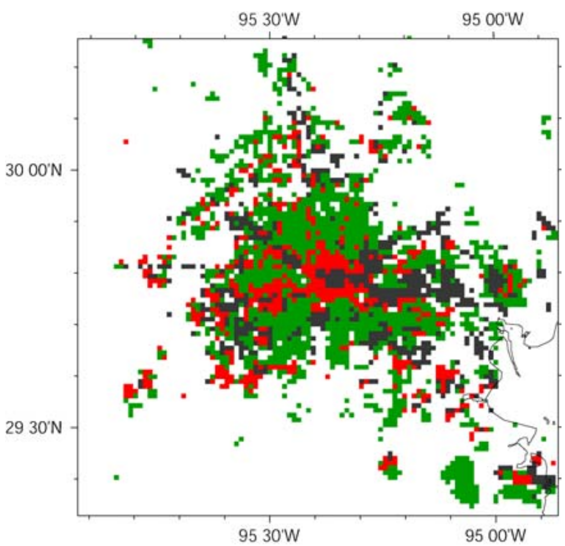
Regardless of the complexity of urban landuse models, the first challenge in NWP urban landuse modeling is to accurately characterize the extent of urban areas. This has to rely on the use of remote sensing data for specifying large urban areas. However, due to the differences in algorithms used to identify urban and rapid growth of urban areas in certain regions, different data sources may reveal different urban coverage. Sometimes, it is therefore necessary to adjust the urban areas using field survey data.

As shown on Figure 3, the urban area for the Greater Houston area adjusted by 30-meter resolution Landsat data (b) is much larger and more realistic than the one based 1994 USGS landuse map (a).

Figure 3. Urban areas over the Houston metropolitan region.



a) Houston urban extent defined by the 1-km USGS landuse map. green: urban



b) Houston urban extent based on the USGS/EPA 30-m Landsat based landuse map. green: low-intensity residential area, red: high-intensity residential area, and black: commercial/industrial.

Note that the USGS National Landuse data set with a new urban Classification System 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. This type of more detailed urban classification (b) is critical for defining urban geometry, hydrologic characteristics, and subgrid-scale natural landuse fraction required by more sophisticated urban canopy models such as the UCM model used in this study.

3. URBAN HEAT ISLAND AND ITS INTERACTIONS WITH SEA-BREEZE FOR THE HOUSTON AREA

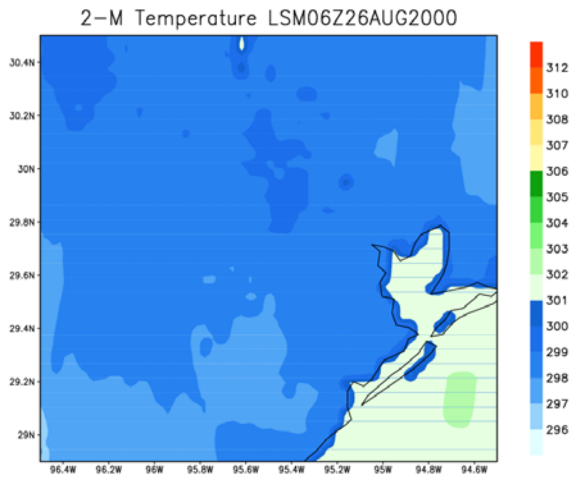
We selected the 25 and 30 August 2000 as our first cases to apply this coupled WRF system. The 25 August case was chosen because it was cloudy ahead of the sea-breeze front followed by clearing in the late afternoon after the front passes. Hence, it represents a potentially interesting case in which the strength of urban heat island can modify the evolution of sea-breeze and impact the air quality in the Houston region. Also there are data collected during the Texas Air Quality Study 2000 (TEXAQS 2000) that we can use to evaluate the model. In the preliminary test presented in this paper, WRF model, with 4-km grid spacing, was run for a 24-hour simulation initialized at 12Z on 25 August and on 30 August, respectively.

The nighttime 2-meter air temperature simulated with UCM is 10 degrees higher than that simulated with the Noah LSM without urban treatment for the urban areas (Figure 4). More interestingly, the simulation with UCM, together with a detailed urban classification map, was able to produce the often observed temperature distribution within an urban heat island. That is: higher temperature is found in high-intensity residential area, because of larger building coverage, is usually higher than that in low-intensity residential areas.

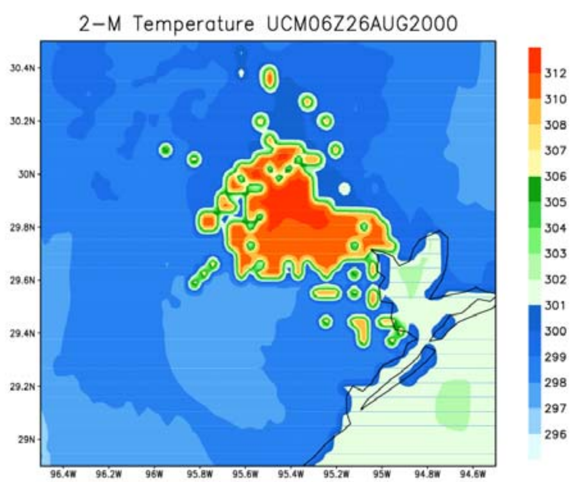
Further investigations reveal that the fine-scale temperature distributions are larger determine by the wall temperature distribution (Figure 5). Presumably, this is because building walls absorb more downward solar radiation due to radiation trapping than roads, and have deeper heat storage layer and large thermal capacity than roofs.

More simulations with higher resolution (2-km grid spacing) are underway to study the sensitivity of various UCM parameters and their influences on urban boundary layer structures. Observations from TEXAQS 2000 are used to evaluate these simulations.

Figure 4. WRF simulated air temperature at 2 meter valid at 06Z 26 August 2000.

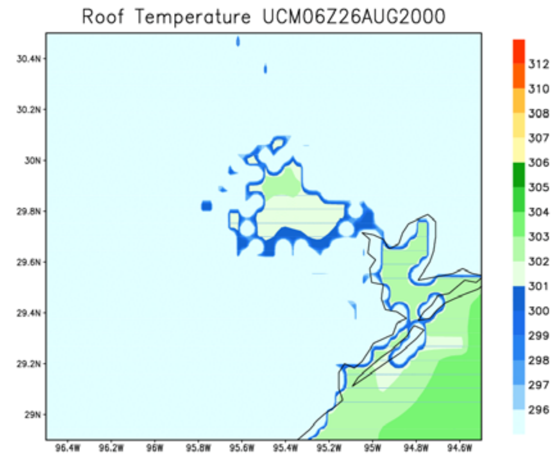


a) Simulation with the Noah LSM without urban treatment.

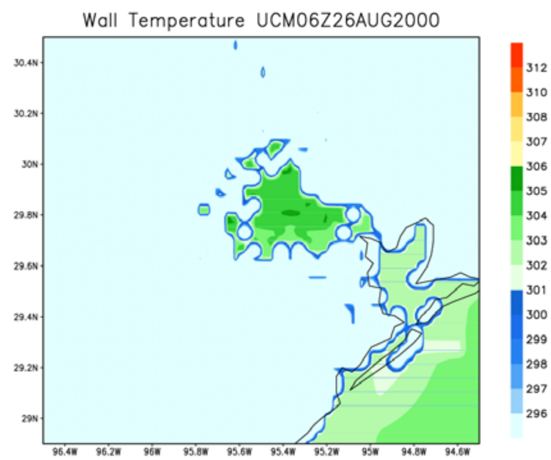


b) Simulation with the Noah LSM coupled with UCM

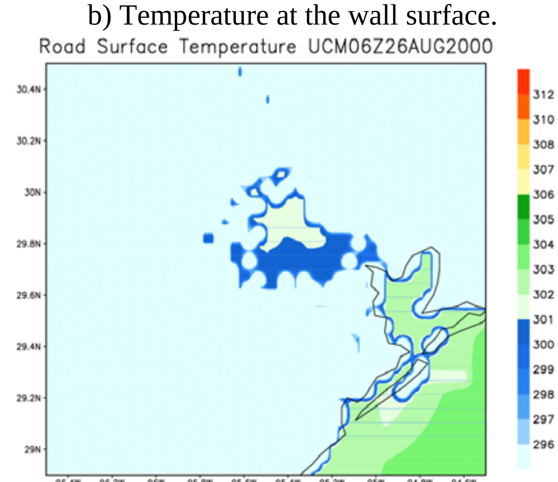
Figure 5. Surface temperature from the urban canopy model valid at 06Z 26 August 2000. Also shown is the sea surface temperature.



a) Temperature at the roof top.



b) Temperature at the wall surface.



c) Temperature at the road surface.

4. SUMMARY

Nowadays NWP models with 0.5-1 km grid spacing have been used for local forecasts, and this type of fine grid spacing is likely to be used for NWP at continental-scale in the near future. Capturing fine-scale influences of urban heat island becomes increasingly important. Described in this paper are recent modeling results that utilized a more complex urban canopy model in WRF with a more detailed description of urban landuse types.

WRF simulations conducted with an UCM and multiple urban landuse types produced some interesting fine-scale atmospheric structures reflecting the underlying thermal characteristics of urban buildings, walls, and roads.

As far as urban canopy models are concerned, the degree to which we can improve the prediction of urban boundary layer structures depends on how well we: 1) understand the statistical characteristics of turbulent transfer of heat/momentum from urban canyon to the atmosphere because of possible gaps in representing scales of motions, 2) characterize the urban landuse at fine-scales, 3) define important parameters in complex UCMs, and 4) initialize the temperature profiles in buildings, walls, and roads. Much of the future improvements will rely on the utilization of new remotely-sensed data and field observation data.

Should these features simulated by the WRF/Noah/UCM are confirmed by observations, this type of coupled models, along with multiple urban types, will be useful to improve longterm (beyond a few hours) urban weather forecasts, which are practically absent in current NWP models. More accurate predication of boundary layer structures in a city and in rural areas will certainly improve our ability to predict air quality and dispersion for important homeland security applications.

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