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INTRODUCTION OF URBAN CANOPY PARAMETERIZATION INTO MM5 TO SIMULATE URBAN METEOROLOGY AT NEIGHBORHOOD SCALE

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1. INTRODUCTION

Since most of the primary atmospheric pollutants are emitted inside the roughness sub-layer (RSL) and consequently the first chemical reactions and dispersion occur in this layer, it is necessary to generate detailed meteorological fields inside the RSL to perform air quality modeling at high spatial resolutions. At neighborhood scale (on order of 1-km horizontal grid spacing), the meteorological fields are strongly influenced by the presence of the vegetation and building morphology of varying complexity, which requires developing more detailed treatment of the influence of canopy structures in the models and using additional morphological databases as input. The assumptions of the roughness approach, used by most of the mesoscale models, are unsatisfactory at this scale. Hence, a detailed urban and rural canopy parameterization (Dupont et al., 2003c), called DA-SM2-U, has been developed inside the Penn State/NCAR Mesoscale Model (MM5) to simulate the meteorological fields within and above the urban and rural canopies. DA-SM2-U uses the drag-force approach to represent the dynamic and turbulent effects of the buildings and vegetation, and a modified version of the soil model SM2-U (Dupont et al., 2003a and b), called SM2-U(3D), to represent the thermodynamic effects of the canopy elements. A first evaluation of DA-SM2-U on the city of Philadelphia (USA) (Dupont et al., 2003c) with a simple urban morphology representation has shown that the model is capable of simulating the important features observed in the urban and rural areas.

The improvement of the urban canopy representation in mesoscale models requires the knowledge of more parameters. These parameters can be divided into three categories: i) the empirical parameters which are deduced from calibration of the models; ii) the "material parameters" which correspond to the physical properties of the surface materials of the canopy elements, they can be easily found in the literature from tables; and iii) the morphological parameters which depend on the structure and on the 3D arrangement of the canopy elements (buildings, vegetation, etc). The morphological parameters are variable from one city to another, and need to be averaged on few 100-m^2 with a vertical resolution of a couple meters to be used at neighborhood scales. Thus, these parameters may be the most difficult parameters to estimate.

Here, the DA-SM2-U version of MM5 is applied to Houston, Texas (USA), in order to study the influence of the morphological parameter resolution on the meteorological fields to know if a detailed resolution of these parameters is required or not for simulating at neighborhood scales. To provide the most accurate representation of these morphological parameters for the entire MM5 computational domain, a Houston GIS Urban Database has been created. This paper gives a brief description of the DA-SM2-U model and of the procedures used to create the morphological parameters on Houston. The first results of the influence study of the representation of the city of Houston on the structure of the urban boundary layer are presented.

2. THE DA-SM2-U VERSION OF MM5

The DA-SM2-U version of MM5 is able to simulate meteorological fields within and above the rural and urban canopy at small mesoscales by using the drag-force approach coupled with the thermodynamic canopy model SM2-U(3D). The drag-force approach transmits directly to the atmosphere the dynamic, thermodynamic and turbulent effects of the canopy elements (vegetation and buildings) by changing the conservation equations of the mesoscale model. The lower level of the computational domain corresponds to the real level of the ground, and additional vertical layers are included within the canopy to allow more detailed meteorological fields within the RSL (see Figure 1). Inside the canopy, the effects of buildings and vegetation are represented by adding i) in the dynamic equation a

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friction force induced by horizontal surfaces of buildings, and a pressure and viscous drag force induced by the presence of buildings and vegetation, ii) in the temperature equation the sensible heat fluxes due to buildings and vegetation, and the anthropogenic heat flux parameterized following Taha (1999), iii) in the specific humidity equation the humidity sources coming from the evapotranspiration of the vegetation and the evaporation of the water intercepted by buildings, and iv) in the turbulent kinetic energy equation a shear production terms induced by horizontal surfaces of buildings, turbulent kinetic energy sources induced by the presence of buildings and vegetation, and buoyant production terms from the sensible heat fluxes emitted by buildings and vegetation. The turbulence length scale has been also modified inside the urban canopy, as proposed by Martilli et al. (2002), by adding a second length scale to consider the vortices induced by the presence of buildings; this modification has been also extended to the vegetation. All of these new terms are volumetric: the volume of buildings is considered in each cell whereas the volume of the vegetation is neglected. The turbulent transport in the vertical is also modified to consider the real volume of air in the cell.

The SM2-U(3D) model estimates the heat and humidity fluxes emitted by the canopy elements at different levels within the canopy, it corresponds to an extended version of the soil model SM2-U (Dupont et al., 2003a) to the drag-force approach. DA-SM2-U is thus a multi-layer canopy and soil model with few layers of a couple meters within the canopy depending on the mesh of the mesoscale model domain, and three layers within the ground: a surface soil layer for the natural surfaces, a root zone layer, and a deep soil layer. This simple discretization of the ground allows the model to estimate the soil humidity available for the evapotranspiration with a good compromise between the computational time and the accuracy of the water budget evaluation. The sub-grid variability is introduced in DA-SM2-U by considering eight surface types in each canopy grid cell. The total heat flux for a canopy grid cell is thus determined by the average of individual heat fluxes calculated for each surface type, weighted by the fraction areas within the cell.

3. HOUSTON APPLICATION

Our study focuses here on simulating the meteorology on Houston-Galveston area, Texas, during the August 25 - September 1, 2000, period which includes a portion of the Texas 2000 Air Quality Study field program, characterized by high temperatures and dry conditions favorable for the production of ozone. MM5 Version 3 Release 4 has been run by Nielson-Gammon (2001) for this period in a one-way nested including four nested MM5 computational domains of 108-, 36-, 12-, and 4-km horizontal grid spacing. This last 4-km simulation is used here as boundary conditions by the DA-SM2-U version of MM5 to simulate meteorological fields at 1-km horizontal grid spacing (Figure 2).

To provide the most accurate representation of the morphological parameters for the entire MM5 computational domain on Houston, a GIS Urban Database has been created. This database includes multiple surface topography and surface cover digital datasets including land use, bare earth elevation, full-feature digital elevation model, roadway locations, and others.

The land use/land cover (LULC) dataset selected to provide base level information in the MM5 computational domain is the standard LULC dataset available from the U.S. Geological Survey (USGS). The USGS LULC dataset was compared against the National Land Cover Dataset (NLCD) and a site-specific dataset produced by the City of Houston (COH). Both the NLCD and COH datasets were based on more recent information (1990s versus 1970s), but the COH dataset did not cover the entire MM5 modeling domain and the NLCD dataset did not have sufficient urban land use types to attain the level of detail desired. Therefore, the USGS was selected for this study. High-resolution aerial photos from 2000 were used to modify the land use type to correspond to more recent conditions for 1653 km^2 section of central Harris County (Harris A in Figure 2), which includes the downtown core area and the ship channel industrial district.

The final USGS LULC dataset was classified according to the level II classification scheme described by Anderson et al. (1976), including 38 categories with 7 urban categories. Comparison of the original USGS LULC dataset with the modified dataset indicates that the amount of urban land use increases substantially, while the amount of cropland and pasture decreases about the same amount because the area has urbanized significantly during the 20+ years since the USGS dataset was completed. The LULC dataset provided a means to (1) estimate several surface properties including fractions of land cover types with each 1-km^2 grid cell and (2) extrapolate parameters from areas with sufficient data to accurately compute the values to areas within the

MM5 modeling domain that did not have sufficient data to compute parameter values.

The base earth elevation and the elevation of the top of canopy elements (vegetation, buildings and other structures) were determined from the airborne LIDAR (Light Detection and Ranging) dataset obtained from TerraPoint LLC. LIDAR technology produces x, y, z representation of topography via airborne lasers. Data products are created as even distribution of data points in evenly-spaced grids. The LIDAR dataset covered the Harris County area (Harris A + B in Figure 2) with 1-m and 5-m horizontal grid cell spacing and a horizontal accuracy of 15 to 20 cm RMSE and a vertical accuracy of 5 to 10 cm RMSE. The canopy data product was derived by subtracting the bare-earth elevation dataset (Digital Terrain M – DTM) from the non-ground data layer using the ArcView map calculator. To distinguish the buildings from the vegetation in the canopy data product, a building footprint dataset has been created. A building footprint dataset was obtained from the COH and updated using the same high-resolution aerial photos used to update the land use. Primary updates required were the addition of buildings in areas where the aerial photo indicated recent development or redevelopment, and the deletion of buildings in areas where the aerial photo indicated that buildings did not exist. The original COH building dataset within the 1653-km^2 Harris A area included 523,920 building footprints while the modified building dataset contains 664,861 building footprints. The following parameters used by DA-SM2-U have been calculated using the integrated building, vegetation, and land use datasets at 1-km^2 horizontal resolution and 1-m vertical resolution for 3D parameters for the entire Harris A area:

- Mean building height
- Building plan area density,
- Vegetation plan area density
- Building rooftop area density
- Vegetation top area density
- Building frontal area density
- Vegetation frontal area density
- Wall-to-plan area ratio
- Building height-to-width ratio

Following parameter computation in the Harris A region the values were correlated to the underlying land use type using area-weighted averages. The average values for each parameter for each land use type were then extrapolated to each 1-km^2 grid cell in the MM5 modeling domain using an area-weighting scheme based on land use fraction with the grid cell.

In addition to the parameters listed above, numerous other parameters describing building and vegetation morphology and surface cover properties were also computed. See Burian et al. (2003) for a summary of the parameter values and a detailed description of the calculation methods.

4 Influence of the city representation

As shown in the last section, the process of morphological parameters is complex and costly, it is thus necessary to know if a detailed resolution of these parameters is required or not for simulating at neighborhood scales. Hence, two simulations are performed on one day (August 31); they are referenced as “detailed city” and “average city” cases. For the average city case, the morphological parameters of the entire computational domain are deduced from their average values per land use type estimated in Harris A, whereas for the detailed city case, the morphological parameters in Harris A are calculated individually for each grid cell without considering the land use information. Thus, the morphological parameters between the two cases are different only in Harris A.

The Figure 3 compares the average surface temperature (Ts) between the detailed and average city cases at 4 p.m. and 12 a.m. At 4 p.m., Ts is the highest on the South and West sides of the city, corresponding to dry soil with small vegetation. The cooler surface of the city can be explain by the shadowing effect and by the presence of high vegetation, especially in the residential areas. Ts of the detail city is much more spatially heterogeneous (spatial variation: ~10 K) than the one of the average city (~3 K) because the average representation of the city smoothes the morphological parameter values (not shown here). As expected the surface temperature differences between the two cases occur only on the urban part (Harris A). At midnight, Ts of the city is higher than the one of the rural areas (urban heat island), the urban surfaces releasing the heat stored during the day. The urban surface temperature differences between the two cases represent only few degrees, and the same degree of Ts spatial heterogeneity is observed.

Hence, the detailed representation of a city in atmospheric models increases the city heterogeneities which accentuates the spatial heterogeneities of the surface temperatures, especially during the day. The surface temperature heterogeneity accentuates the mixing inside the planetary boundary layer (PBL) by increasing the values of the turbulent kinetic energy (not shown here), and thus increases the PBL height (Figure 4). The differences of PBL height between the two cases can reach 300 m.

Disclaimer. This paper has been reviewed in accordance with United States Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

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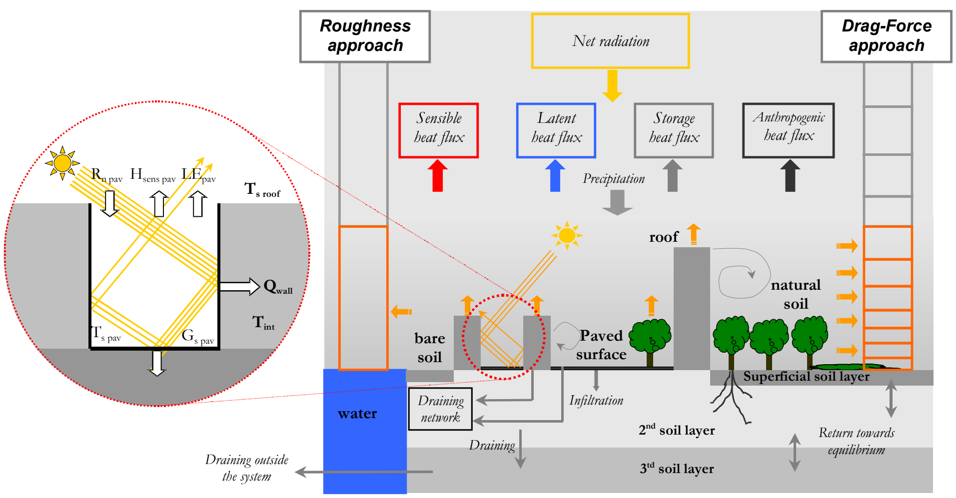

Figure 1. Scheme of the new MM5 canopy parameterization, DA-SM2-U, using the drag-force approach with the soil model SM2-U(3D), compared with the roughness approach.

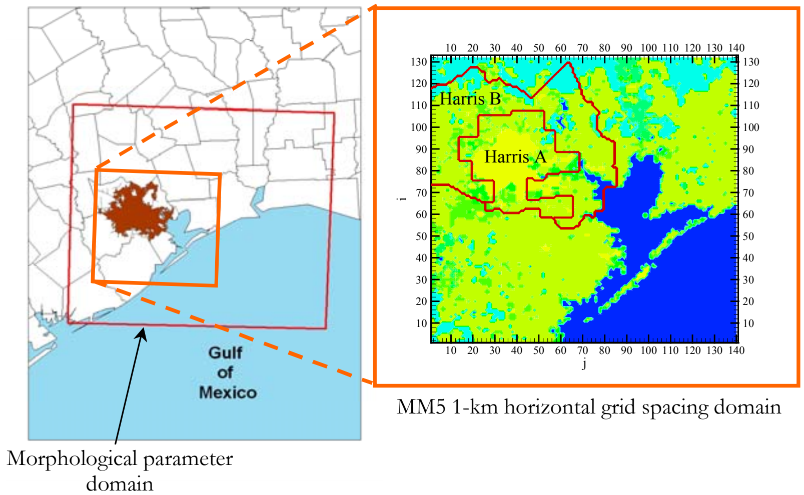

Figure 2. MM5 1-km horizontal grid spacing computation domain on Houston-Galveston area.

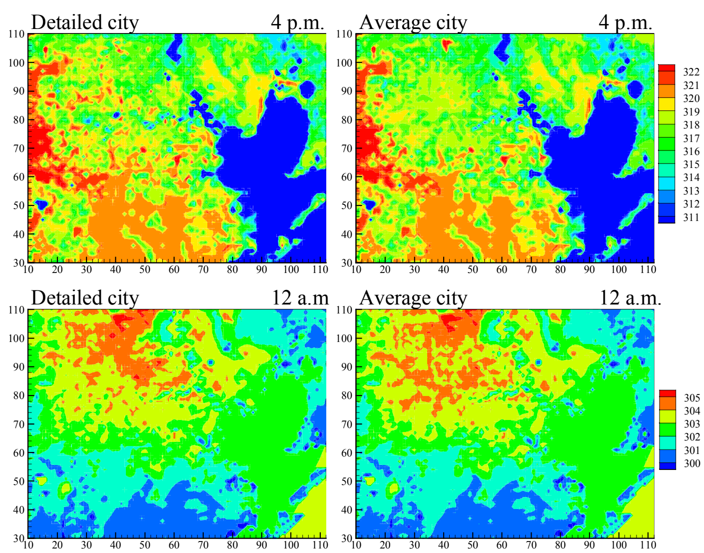

Figure 3. Average surface temperature (K) at 4 p.m. and 12 a.m. for the detailed and average city cases.

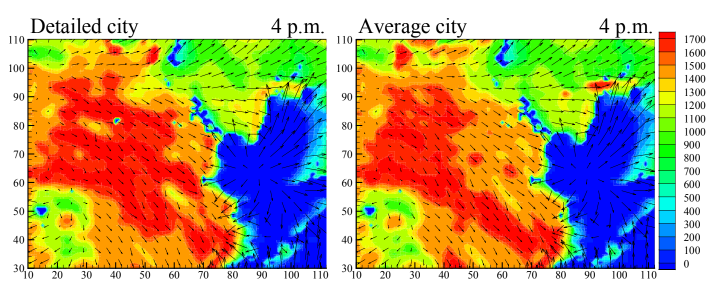

Figure 4. Planetary boundary layer height (m) at 4 p.m. for the detailed and average city cases.