IMPLEMENTATION OF AN URBAN CANOPY PARAMETERIZATION FOR FINE-SCALE SIMULATIONS

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1. INTRODUCTION

The Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al. 1994) has been modified to include an urban canopy parameterization (UCP) for fine-scale urban simulations (~1-km horizontal grid spacing). The UCP accounts for drag exerted by urban structures, the enhancement of turbulent kinetic energy (TKE) especially near the tops of the buildings, and the modification of the energy budget within the urban canopy (i.e., from the surface to the tops of buildings). This UCP is applied to grid cells in MM5 that have a non-zero fraction of urban land use. This refinement of MM5 is targeted to enable the Community Multiscale Air Quality (CMAQ) Modeling System (Byun and Ching 1999) to capture the details of pollutant spatial distributions in urban areas. Preliminary results will be presented below.

2. URBAN CANOPY PARAMETERIZATION

2.1 *Momentum*

The horizontal components of the momentum equations are modified to account for the area average effect of the sub-grid urban elements following Brown (2000). The modifications are implemented in MM5 via the TKE-based Gayno-Seaman planetary boundary layer (PBL) parameterization scheme (e.g., Shafran et al. 2000). The momentum equations accounting for the urban elements are:

$$\frac{\partial U}{\partial t} = F_U - 0.5 f_{\text{urb}} C_d A(z)\, U \left(U^2 + V^2\right)^{0.5}$$

$$\frac{\partial V}{\partial t} = F_V - 0.5 f_{\text{urb}} C_d A(z)\, V \left(U^2 + V^2\right)^{0.5}$$

$$\frac{\partial \text{TKE}}{\partial t} = F_{TKE} + 0.5 f_{\text{urb}} C_d A(z) \left(U^2 + V^2 + W^2\right)^{1.5}$$

where the Fs are the general forcing terms in each equation; U, V, and W are the wind components; and TKE is the turbulent kinetic energy. In this formulation, it is assumed that the buildings affect the flow but do not take up any volume within the grid cell. C_d is a drag coefficient. The urban fraction of the grid cell is described by f_{urb}. $A(z)$ is the canopy area density, or the surface area of the obstacle (e.g., building) perpendicular to the wind, per unit volume of the urban canopy, expressed in m^{-1}. There are several approaches to describe $A(z)$ (e.g., Uno et al. 1989; Brown 2000) where the function reaches its maximum at the ground level, but vanishes at the top of the obstacles (so the drag term vanishes also at that level). The integral of $A(z)$ from the ground level to the tops of the tallest buildings (H) is λ_f, which corresponds to the ratio of the frontal area to the total surface area of the buildings. In general $A(z)$ is a function of the location within the domain as it depends on building morphology. $A(z)$ can be estimated from λ_f and H assuming some functional form for $A(z)$; here we use a linear function.

To solve the modified momentum equations (the added new term), we follow the analytical solution suggested by Byun and Arya (1986). The TKE equation is solved explicitly. To take proper account of the influence of $A(z)$, the vertical resolution in MM5 is increased in the domain such that several prognostic layers are below H.

2.2 *Energy Budget*

To account for the impact of urban settings on the energy budget, the anthropogenic heat flux is included in the heat equation and not in the surface energy budget (e.g., Chin et al. 2000). The anthropogenic heat flux is set as a function of urban land use subcategory, and it has a temporal weighting function (e.g., Taha 1999). The heat equation also includes the heat contribution of the city canyons following Yamada (1982); the contribution due to rooftops has not yet been implemented. The surface energy balance includes the shadowing/trapping effect of the net radiation reaching the ground in the city canyons modified by extinction of the radiation through the urban canopy using a simple exponential function (e.g., Brown 2000).

2.3 *Urban Morphology*

Parameters that are required for the UCP (e.g., H and λ_f) can be extracted from digital imagery (e.g., Ratti et al. 2001) which is commercially available from several vendors for various cities and with different degrees of accuracy and precision. We did not have access to a true urban morphology database for our area of interest, so we modified the MM5 land use database for our domain to have seven subcategories of urban areas adapted from R. Ellefsen (personal communication 2001). These categories crudely represent urban zones such as high-rise, industrial, and urban residential. These urban zones are used to create pseudo-morphology for the region of interest, and the physical characteristics of these areas are used in the UCP. Each of the urban subcategories has a different value for H, λ_f, canyon fraction, and maximum anthropogenic heat flux.

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3. PRELIMINARY RESULTS

The unmodified MM5 was run in a one-way nested mode for several days in July 1995 during which there was a high-ozone episode in the Northeastern U.S. that coincided with a photochemical field study. The MM5 domains included a five-domain configuration (108, 36, 12, 4, and 1.33 km grid spacing). The first four domains were run with 30 vertical layers (about 12 layers in the PBL, and lowest level at 19 m) and physics options appropriate for each resolution. To include the influence of smaller obstacles, the UCP was used on the 1.33-km domain (Figure 1) with 40 layers that included ten new layers in the lowest 100 m (lowest level at 2 m).

Several simulations have been made with the 1.33-km domain to determine the impact of the UCP and the morphology on the simulation. Four 1.33-km simulations are discussed here. The first experiment, *nocan30*, is a 30-layer experiment without the UCP. The second experiment, *nocan40*, is a 40-layer experiment without the UCP. Both *nocan30* and *nocan40* are shown so that the impact of the UCP on the simulation can be evaluated independent of the increase in vertical resolution. Expt. *morph40* includes the UCP with urban morphology. Expt. *homog40* includes the UCP and a homogeneous representation of the city defined by the "average" of the morphology.

Figure 2 is a comparison of the surface (~2-m) temperature for Philadelphia International Airport (PHL) from the four 1.33-km experiments compared to observations for 14 July 1995. Figure 2 shows that the two experiments with the UCP improved the simulated nighttime temperatures by ~2°C and improved the maximum temperatures by ~0.5°C. In the mid-afternoon, the addition of the ten new layers improved the verification, as the 40-layer experiments were superior to *nocan30*. Overall, the diurnal temperature patterns of the simulations with the UCP compare more favorably with observations than the two experiments without the UCP.

As expected for a non-urban location, Millville, New Jersey (MIV), the use of the UCP had little effect on the diurnal pattern of the temperature (not shown). The four simulations are very similar for nighttime temperatures. In addition, the same mid-afternoon impact of the ten new layers occurs at MIV as well as PHL. This suggests that there are no detrimental effects of the UCP on areas beyond the urban core.

Verification statistics were calculated against the National Weather Service standard observation sites shown in Figure 1. Root-mean-square error (RMSE) statistics reflect the nighttime improvements in the temperature in the urban areas in the UCP simulations. Over the 24-h simulation period, the two experiments with the UCP outperformed the two experiments without. Expt. *homog40* has an RMSE of 1.9°C, and the RMSE in *morph40* is 2.0°C. Expt. *nocan30* has an RMSE of 2.2°C, while *nocan40* has an RMSE of 2.4°C. The index of agreement (e.g., Willmott, 1982) for the same period reflects the same ordinal ranking of the experiments and a large separation between the UCP and no-UCP simulations. These statistics tend to show that the use of the UCP generally improves the temperature simulations throughout the domain compared to the "standard" 30-layer configuration, and the improvements are not solely due to the increase in vertical resolution from 30 to 40 layers.

The hourly RMSE comparison for moisture (not shown) indicates that the 40-layer experiments are significantly better than *nocan30*. However, *morph40* verified best of the four experiments (2.11 g/kg), while *homog40* verified third (2.21 g/kg).

The wind speed timeseries for various sites in the domain do not show a clear "winner", potentially due to the more erratic hourly changes in wind speed. However, there is clearly an effect on the wind speed timeseries both in the urban areas (e.g., PNE, not shown) and downstream (e.g., WRI, not shown). The RMSE over the 24-h simulation (not shown) indicates that *morph40* is the best of the experiments (1.32 m s^{-1}). Expt. *homog40* was the worst of the four experiments (1.56 m s^{-1}) for wind speed. The bias (model minus observation) for the same time period (Figure 3) clearly shows that *morph40* is the best of the experiments (-0.31 m s^{-1}), followed by *nocan30* (+0.75 m s^{-1}), *nocan40* (-0.91 m s^{-1}), and *homog40* (-0.96 m s^{-1}). This is consistent with the RMSE scores discussed above. The UCP had very little effect on wind direction in the timeseries and the statistical scores over the same simulation period. Thus the UCP with morphology has a positive impact on the simulations of winds at 1.33-km.

4. CLOSING THOUGHTS

Initial tests with the UCP for simulations on 14 July 1995 show that the UCP at 1.33-km tends to produce the desired effects on the wind, temperature, and TKE fields. The temperature simulations with the UCP tend to be superior to 30-layer and 40-layer simulations without the UCP. In addition, the UCP simulations with pseudo-morphology tend to be superior to the UCP simulations with an "average" homogeneous morphology (i.e., no urban subcategories), particularly for wind speed. Further evaluation of the UCP in MM5 on additional days is underway.

Future plans include expanding the UCP to add the roof energy budget and to use more detailed land use databases and morphology databases so that the urban areas can be more accurately characterized. Also, the UCP will be coupled with a land-surface model and urban soil model.

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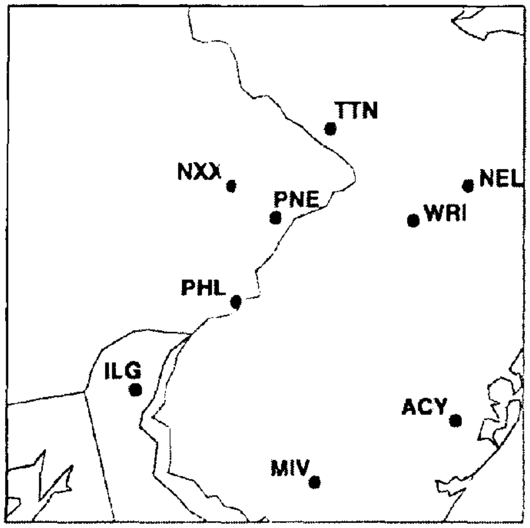

Figure 1. The standard National Weather Service observation sites used for verification on the 1.33-km domain.

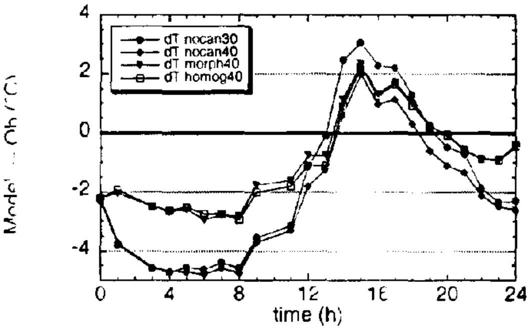

Figure 2. Temperature timeseries (model minus observation) of four 1.33-km experiments compared to observations for Philadelphia International Airport (PHL) for 14 July 1995. Time is in UTC.

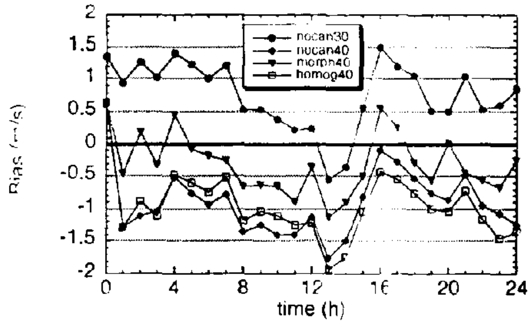

Figure 3. Wind speed bias for four experiments verified against the observation sites shown in Figure 1. Verification is for 14 July 1995. Time is in UTC

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

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