ICUC1.1 Invited Paper

URBANIZATION OF METEOROLOGICAL MODELS AND IMPLICATIONS ON SIMULATED HEAT ISLANDS AND AIR QUALITY

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ABSTRACT

In most meteorological models, urban and non-urban areas are treated mostly similarly, e.g., through similar sub-surface, surface, and boundary-layer formulations. No different/additional mechanisms or physics exists to account for urban-specific dynamics and energetics and for their impacts on the planetary boundary layer. However, recent efforts have suggested various modeling approaches to link the different physics of the canopy and urban boundary layers.

This paper briefly reviews the issue of model urbanization. A review of approaches taken to date is presented. The paper then focuses on one such aspect, that is a formulation we propose for improved prediction of urban air temperature fields. Results from applying a modified (urbanized) model to a Northern Georgia domain are discussed with particular emphasis on urban heat island magnitude and related impacts on emissions and ozone production. Application of the modified (urbanized) model produced a larger simulated Atlanta heat island, which then resulted in increased biogenic volatile organic compounds (e.g., isoprene) emissions by 10% and in accelerated photochemical production of ozone by about the same amount.

INTRODUCTION

The concept of model urbanization is not new. A review of linkages between canopy- and boundary-layer models (1) shows that the issue is very much worth addressing, but that it is also complicated. Part of the reason is that the urban boundary layer is more complex than rural or “idealized” ones. The lower atmosphere over an urban environment is non-homogeneous and non-stationary. The planetary boundary layer (PBL) structure is more complex over urban areas than nearby rural ones, as it consists of canopy and roughness sub-layers not found within typical rural atmospheric surface layers (ASLs). The urban canopy layer (UCL) is composed of diverse individual street canyons, while the urban roughness sub-layer is a non-equilibrium transition layer in which vertical momentum, energy, moisture, and pollution fluxes from individual urban canyons blend together.

Problems arise, however, first in the definition, and then in the specification of the characteristics of the boundary-zone roughness sub-layer. In addition, the lower-boundary surface in urban areas is not clearly defined in PBL models. Is it the ground surface; combination of ground, wall, and roof surfaces; displacement height; rooftop levels; or roughness sub-layer bottom, middle, or top? This definition is important, as solutions of the surface energy and moisture balance equations at atmosphere-ground interfaces require determination of momentum, heat, and moisture fluxes assumed invariant with height (via similarity theory) from the surface to the ASL top. This represents a particular challenge in mesoscale modeling.

The most common definition of the lower boundary in urban PBL models uses a flat (zero building height) sand box approach, in which the only differences between urban and non-urban surface grid points are the specified values of the

aerodynamic, thermal, and radiative coefficients in the surface energy and moisture balance equations. Urban structures are thus reduced to urban sand. On the other extreme, is the addition of grid-averaged urban-building topography height values onto natural topography height values. Intermediate approaches for modeling the physical presence of urban structures are thus needed.

Possible linkage mechanisms between the urban UCL and PBL models include parameterizations of UCLs using observations, physical models, and/or numerical models. Parameterizations could be based on building length-to-height ratios, building length-to-street-width ratios, building roof angles, effective urban roughness lengths, and effective urban displacement heights.

The second group of linkages includes one-way up-scale model nesting. Such techniques could include (in order of increasing desirability) use of 1) typical homogeneous-surface land-use grid cells (e.g., urban, suburban, and rural), 2) average urban surface radiative, thermal, and aerodynamic parameters weighed by scalar grid cell fractional land use, 3) average ASL fluxes weighed by scalar grid cell fractional land, and 4) average ASL fluxes weighed according to vector (amount and distribution) grid cell fractional land use.

The third group consists of one way, down-scale linkages, including storage of UCL model results for use as time- and space-varying initial and surface boundary conditions in PBL models, a technique currently used to link mesoscale and synoptic-scale models. A limitation of this approach is that UCL models are currently too computer intensive for application to entire cities and regions. Also, UCL models alone cannot include upper boundary conditions influenced by time and space variations within the urban PBL.

The final group of linkage techniques consist of two way nesting, with a UCL sub-model either over urban sub-areas or entire domains. In theory, two way nesting should provide the best results, but current formulations (applied between synoptic and mesoscale meteorological models) are not problem-free, e.g., up-scale feedback destroys mass consistency within the larger domain .

Thus to date, the most common approach to “specify” an urban area in a mesoscale meteorological model is through input differentiation of the gridded surface thermo-physical properties, e.g., roughness length, moisture content, density, specific heat, anthropogenic heat, thermal inertia, albedo, and vegetative cover (2,3,4). However, this approach has limitations as seen above. Thus conceptually, some modifications, e.g., urbanization, to PBL models are needed to improve the accuracy of simulating the UBLs. Another reason why PBL-model urbanization may be necessary is the need to more accurately assess the urban meteorological impacts of changes in certain surface properties, e.g., changes in surface albedo, which result from increased urbanization and changes in roofing and paving materials. In some cases, urban albedo may even be intentionally modified to achieve energy efficiency and air quality improvements (4,5). Thus quantifying the effects of inadvertent or intentional changes in albedo is of interest in meteorological modeling of urban areas.

Another issue related to model urbanization is the generation of annual urban weather, i.e., the extrapolation of episodic meteorological simulation results to annual time periods (6). Specifically, one would like to quantify the changes in year-round hourly meteorological parameters of relevance to building energy modeling, e.g., temperature, due to the urban heat island effect or following certain changes in surface properties, such as albedo. Here again, the urbanization of mesoscale models is important.

In the rest of this paper we present one attempt at better characterizing the urban canopy layer's thermal environment through urbanizing a PBL model following a bulk-parameterization approach. This is explained in the following sections and results are presented for the Atlanta GA region.

PROPOSED URBANIZATION SCHEME

As mentioned in the INTRODUCTION, canopy-layer models are available and have been integrated with PBL models. In some cases, these canopy-layer models have been quite detailed (7,8). However, that level of detail is not so useful or amenable to application in mesoscale modeling at which scale it is difficult to find and/or specify all the needed input at such resolution (e.g., building- and street-scale). In addition, all the detail will be lost when averaging at a mesoscale model's grid. Thus unless the application is micrometeorological in scale, there may be little gain in employing sophisticated urbanization schemes in PBL models.

Thus in this case, a bulk approach may be a more appropriate alternative. "Bulk", in this paper, refers to an approach where parameters are quantified and modified as averages at the PBL model's grid resolution. This approach is more feasible because the input data is readily available, e.g., USGS and remotely-sensed data such as AVHRR. Following this perspective, we select the Objective Hysteresis Model, or OHM (9) as a basis for a PBL model urbanization. We also select the CSUMM (2) as the "host" PBL model. The CSUMM was selected only because it was used by the lead author in several earlier studies, but there is no reason to believe that this urbanization scheme would not apply equally well to other models.

In our proposed urbanization approach, the OHM is implemented in CSUMM so that the ground heat flux term of the PBL model's energy balance equation is modified by including OHM's storage heat flux computation. The modification to computed ground heat flux is proportional to the fractional area covered by urban land uses as specified in the model's input for each grid (10). In the rest of this paper, the modified (urbanized) CSUMM will be referred to as UMM (Urbanized Mesoscale Model) as used in an example application to the Atlanta GA region.

MODELING RESULTS FOR THE ATLANTA GA REGION

An inner-nest modeling domain of 60×60 km was used to simulate the northern Georgia region. Metropolitan Atlanta is roughly in the middle of this domain (Figure 1). The grid interval is 2 km and the modeling episode is July 28 through August 1, 1997. Initial conditions were based on observational data from the Georgia Mesonet (11). The domain and modeling approach are described elsewhere (10). Also, a model performance evaluation of UMM, using this Mesonet data, found it to be an improvement over the non-urbanized CSUMM in simulating the Atlanta heat island during this episode (10).

The Atlanta heat island

Because the UMM has an enhanced mechanism for quantifying the storage heat flux in urban areas, based on OHM, it can more accurately simulate an urban heat island (UHI). In the case of Atlanta GA, the simulations with UMM show an increased UHI intensity compared to that simulated with the original CSUMM (10). At 1400 LST, for example, the UHI is larger by 1.7°C; the temperature at the maximum's location increases from 31.3°C in CSUMM to 33°C in UMM (Figure 1). The simulated UHI is more differentiated (larger temperature gradients) in UMM than in the non-urbanized model. Note

that Figure 1 does not show absolute simulated temperatures, but the increase in UHI intensity as a result of using UMM instead of CSUMM. The air temperature discussed here is at 2.5 m above ground level.

Higher air temperatures translate to increased precursor emissions and larger photochemical smog formation rates. Is an increase of 1.5°C significant in such modeling? Is it important and worth the effort to urbanize a PBL model for this magnitude of air temperature changes? We answer these questions next and show that it does makes a big difference in terms of temperature-dependent precursor emissions and production of ozone.

Biogenic and anthropogenic emissions

An environmental correction algorithm (12) for computing emissions of isoprene (C_5H_8) and monoterpenes ($C_{10}H_{16}$) is used here to assess the implications of a 1.5°C increase in air temperature on computed biogenic hydrocarbon emissions from vegetation. The algorithm for computation of isoprene emissions has the form:

$$E = E_o \times F_T F_L F_C F_H,$$

$$F_T = [e^{a\,(Ta-c)/R\,Ta\,c}] / [1 + e^{b\,(Ta-d)/R\,Ta\,c}],$$

where E and E_o are the modified and standard emission rates for isoprene, F_T, F_L, F_C, and F_H are correction factors for temperature, light intensity, carbon dioxide concentrations, and humidity, respectively. Ta is air temperature, R is gas constant, and the parameters a, b, c, and d are constants.

We find that within the typical range of absolute air temperatures experienced in Atlanta in summer (~25-37°C), an increase of 1.5°C in air temperature can have a significant impact on increasing isoprene emissions. The increase is about 10% at the solar radiation and humidity levels associated with the modeling episode described earlier. This is significant, especially since isoprene is very reactive. In addition, an increase of 1.5°C has a smaller, but still detectable effect on emissions of anthropogenic volatile organic compounds (e.g., evaporative VOC) and nitrogen oxides (e.g., NOx from power plants and mobile sources). The estimated amount of increase in these anthropogenic precursor emissions is between 1 and 2%.

Ozone formation

A large number of photochemical reactions are temperature dependent. The dependence of these reactions' rate constants is typically given by:

$$C = a\,e^{-E/RT}$$

where a is a constant, E is activation energy, R is gas constant, and T is ambient temperature. Thus as temperature increases, in general, the production of ozone accelerates. This effect is accounted for mainly through the chemistry of peroxyacetyl nitrate (PAN) and is the dominant chemical mechanism. However, one should keep in mind that there is a large number of reactions (some of which have an opposite effect) and that the system of equations is highly nonlinear, e.g., CB-IV mechanism (13). In our modeling of Atlanta, we found that the effects of an urban temperature increase of 1.5°C (directly on photochemistry and indirectly upon temperature-dependent emissions) is an increase in urban averaged ozone concentrations by 10% and of the peak by 5-10 ppbv during the time interval 1400 through 1700 LST in the specified episode. These increases also include the effects of changes in mixing height and winds fields as a result of increased urban air temperatures.

Finally, to give a qualitative assessment of the emission equivalents of these temperature changes, we ran a photochemical model (UAM) 100 times (using different NOx-to-VOC emission ratios) for this episode to generate a peak-ozone isopleth

map (Figure 2). We use this map to "see" the NOx and VOC emissions equivalents that would be needed to achieve an impact on peak ozone concentrations comparable to the impacts of a 1.5°C change in air temperature. The figure suggests that a temperature change of 1.5°C is equivalent to changes of about 8-10% in NOx emissions and 8-10% in VOC emissions. Again, this is a very significant effect, equivalent to the potential impacts of many proposed emission control strategies!

DISCUSSION

This paper presented brief "snapshot" results from an ongoing study by the authors on the effects of the Atlanta urban heat island on meteorological conditions and air quality in the region. The application of the urbanized PBL model (UMM) to the Atlanta modeling domain resulted in a larger simulated UHI. The comparison of UMM's results with observational data is more favorable and suggests improved model performance over CSUMM in simulating the UHI for the selected episode. We also briefly showed that a difference in air temperature of 1-2°C can have significant impacts on biogenic hydrocarbon emissions, such as isoprene, other biogenic and anthropogenic precursor emissions, and the rate of photochemical smog formation. Thus model urbanization is important and worth implementing in PBL models to achieve more reliable results. As shown in this paper, using an urbanized model resulted in significantly different meteorological and air quality conditions. Although this paper presented results for the CSUMM, the general findings and effects should be applicable to other models as well.

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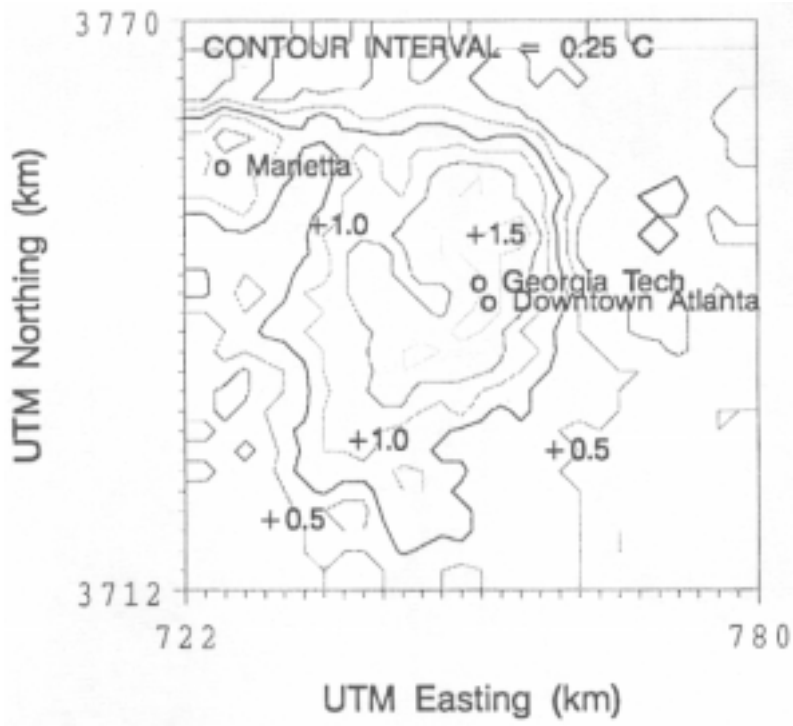

Figure 1. Difference (°C) between the Atlanta UHI simulated with UMM and that simulated with the non-urbanized CSUMM for 1400 LST on August 1. Rural air temperature does not change but urban-rural temperature gradient increases.

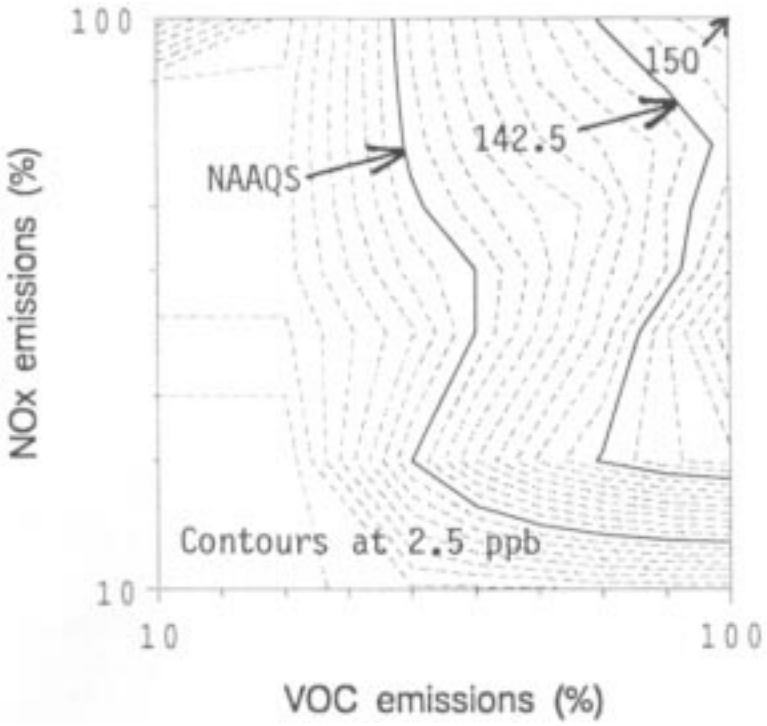

Figure 2. Peak ozone concentration isopleths at 5 PM for Atlanta GA simulated with the Urban Airshed Model (UAM) for the episode July 27- August 1 (1997). The contour interval is 2.5 ppb. The top right corner (100%,100%) represents 150 ppb. The thick line at right is 142.5 ppb and the one at left is the National Standard (120 ppb). The area to the right of 142.5 ppb is equivalent to the effect of 1.5°C.

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