DEVELOPMENT OF THE INTEGRATED WRF/URBAN MODELING SYSTEM AND ITS APPLICATION TO URBAN ENVIRONMENTAL PROBLEMS


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Abstract

Today’s mesoscale numerical weather models are routinely executed with 1-4km grid spacing and their output are used to drive air quality, transport and dispersion models for urban areas. It is critical for weather models to capture influences of urban forcing on wind, temperature, and humidity in the atmospheric boundary layer structure. To bridge the gaps between traditional mesoscale modeling and microscale modeling, we developed an integrated urban modeling system coupled to the Weather Research and Forecast (WRF) model as a community tool to address urban environmental issues. This urban modeling system consists of different methods to parameterize urban land use, ranging from a simple bulk parameterization to a sophisticated multi-layer urban canopy model that directly interacts with the atmospheric boundary layer. We will describe this modeling system, its application to various metropolitan areas, and evaluation against urban-scale observations. The results demonstrated that representing the urban heat island effects is critical to correctly capture not only differential urban heating, but also wind fields modified by urban areas. High-resolution urban morphology and anthropogenic heating data are important input. We will discuss results using this model as a regional climate-modeling tool to investigate impacts of land-use change in cities on precipitation and regional air quality.

Key words: Urbanization, weather forecast, air pollution, urban climate, and urban hydrology

1. INTRODUCTION

Rapid expansion of urban caused many adverse effects on air quality, energy and water supply/demand, and emergency responses. It is imperative for numerical weather prediction (NWP) models to capture effects of urban forcing on wind, temperature, and humidity in the atmospheric boundary layer structures, so that weather forecast in urban regions and air dispersion and quality models will benefit from improved prediction of the urban meteorological conditions. To bridge the gaps between traditional mesoscale modeling (with 10¹-km grid spacing) and microscale modeling (with 10⁻¹-m grid spacing), we have been developing an integrated urban modeling system coupled to the Weather Research and Forecast (WRF)/Noah land surface model as a community tool to address urban environmental issues and to study urban-atmospheric interactions.

2. INTEGRATED URBAN MODELING SYSTEM IN WRF

The WRF model is a non-hydrostatic, compressible model with mass coordinate system, designed as the next generation NWP model (Skamarock et al., 2005). 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. The Noah land surface model (LSM) (Chen and Dudhia, 2001; Ek et al, 2004) provides surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions to the WRF model and has been implemented in WRF since 2004.

The integrated WRF urban modeling system consists of different methods to parameterize urban land use, a consistent treatment of canopy resistance for both NWP and air-pollution applications, surface biogenic and anthropogenic emissions maps, remote-sensing land-use and characteristics at urban scale, coupling to computational-fluid-dynamic (CFD) or large eddy simulation models (Wyszorrodzki et al., 2009), and a companion urbanized high-resolution land data assimilation system. Currently, there are three ways the effects of urban surface are represented in WRF/Noah: 1) a bulk transfer scheme in which the characteristics of urban surfaces are parameterized in Noah (Liu et al., 2006); 2) a single-layer urban canopy model (SUCM) developed by Kusaka et al. (2001), which takes into account the effects of building geometry on surface energy budgets. This scheme was released in WRF in 2006; and 3) a multi-layer UCM based on Martilli and Rotach (2002), which allows the intereacions of buildings with several layers in the atmospheric boundary layer in WRF. This scheme was released in WRF V 3.1 in April 2009.

3. RECENT APPLICATIONS OF THE WRF/URBAN MODELING SYSTEM
This modeling system was applied to various metropolitan areas (Houston, Oklahoma City, Hong Kong, Tokyo, Salt Lake City, Beijing, Taipei, etc.) and evaluated against urban-scale surface and upper-air observations, which demonstrated that representing the urban heat island effects is critical to correctly capture not only differential heating caused by urban surface heterogeneities, but also mesoscale wind fields modified by urban areas. One challenging issue for developing such urban modeling system is the specification of parameters required by urban models. For this, we have been working with the community to develop a National Urban Database and Access Portal Tool (NUDAPT, Ching et al., 2009), which comprises a number of urban data including traffic, building characteristics, population density, etc. for major cities in the U.S. Some preliminary pre-possessor are developed in ingest these gridded data (at 0.5 and 1 km resolution) into WRF/Noah/Urban coupled model.

Example of some recent applications of the WRF/Noah/UCM modeling system include:

- Assess impacts of urban heat island (UHI) on boundary layer development and land–sea circulation over northern Taiwan (Lin et al., 2008). It demonstrated that the WRF–Noah–UCM model has significantly improved simulated UHI effect, boundary layer development, and land sea breeze. Sensitivity tests indicate that the anthropogenic heat (AH) plays an important role for the boundary layer development and UHI intensity in the Taipei area, especially during nighttime and early morning. When AH is increased by 100 W m\(^{-2}\) in the model, the average surface temperature could increase nearly 0.3°C in Taipei. Furthermore, the UHI effect also has a significant impact on land sea circulation. It could enhance the sea breeze in the daytime and weaken the land breeze during the nighttime and hence had a significant impact on the air pollution diffusion in northern Taiwan.

- Investigate the formation of horizontal convective rolls (HCRs) in urban areas (Miao and Chen, 2008). Cloud streets organized parallel to the mean boundary-layer wind (a manifestation of HCRs) are seen in the Fengyun-2C satellite imagery around local noon in Beijing. Observed vertical velocity and horizontal wind fields from an urban wind profiler suggest that the time scale for alternating updraft and downdraft in the boundary layer is about 30 min, and the length of the updraft/downdraft is about 9 km. WRF/Noah/UCM simulations show that most HCRs occur in the urban areas with \(\frac{z_i}{L} < 25\) (\(z_i\): the boundary-layer depth, \(L\): the Monin–Obukhov length). Sensitivity tests reveal that HCRs are common in urban boundary layers, while rural areas are more conducive to forming cellular convection; the aspect ratio of HCRs in urban areas is smaller than the typical value over natural landscapes.

- Study the characteristics of UHI and boundary layer structures in Beijing (Miao et al., 2009). The WRF/Noah/SUCM is used to simulate these urban weather features for comparison with observations and to test the sensitivity of model simulations to different urban land use scenarios and urban building structures to investigate the impacts of urbanization on surface weather and boundary layer structures. Results show that the coupled WRF/Noah/UCM modeling system seems to be able to reproduce the following observed features reasonably well: 1) the diurnal variation of UHI intensity; 2) the spatial distribution of UHI in Beijing; 3) the diurnal variation of wind speed and direction, and interactions between mountain–valley circulations and UHI; 4) small-scale boundary layer convective rolls and cells; and 5) the nocturnal boundary layer lower-level jet. The statistical analyses reveal that urban canopy variables (e.g., temperature, wind speed) from WRF/Noah/UCM compare better with surface observations than the conventional variables (e.g., 2-m temperature, 10-m wind speed). Both observations and the model show that the airflow over Beijing is dominated by mountain–valley flows that are modified by urban–rural circulations. Sensitivity tests imply that the presence or absence of urban surfaces significantly impacts the formation of horizontal convective rolls (HCRs), and the details in urban structures seem to have less pronounced but not negligible effects on HCRs.

- Predict impacts of climate and land use change on surface ozone in the Houston, Texas, area (Jiang et al., 2009). To study the effects of climate change under future A1B scenario and land use change on surface ozone (O\(_3\)) in the greater Houston, Texas, area, we applied the Weather Research and Forecasting Model with Chemistry (WRF/Chem) coupled with Noah/SUCM to the Houston area for August of current (2001 – 2003) and future (2051 – 2053) years. Simulation results show that there is generally a 2°C increase in near-surface temperature over much of the modeling domain due to future climate and land use changes. In the urban area, the effect of climate change alone accounts for an increase of 2.6 ppb in daily maximum 8-h O\(_3\) concentrations, and a 62% increase of urban land use area exerts more influence than does climate change. The combined effect of the two factors on O\(_3\) concentrations can be up to 6.2 ppb. The impacts of climate and land use change on O\(_3\) concentrations differ across the various areas of the domain. The increase in extreme O\(_3\) days can be up to 4–5 days in August, in which land use contributes to 2–3 days’ increase. Additional sensitivity experiments show that the effect of future anthropogenic emissions change is on the same order of those induced by climate and land use change on extreme O\(_3\) days.

ACKNOWLEDGMENTS

This work was supported by the NCAR FY07 Director Opportunity Fund and the U.S. DTRA Coastal-urban project.
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