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The integrated WRF/urban modeling system: development, evaluation, and applications to urban environmental problems

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Abstract

To bridge the gaps between traditional mesoscale modeling and microscale modeling, the National Center for Atmospheric Research (NCAR), in collaboration with other agencies and research groups, has developed an integrated urban modeling system coupled to the Weather Research and Forecasting (WRF) model as a community tool to address urban environmental issues. The core of this WRF/urban modeling system consists of: 1) three methods with different degrees of freedom to parameterize urban surface processes, ranging from a simple bulk parameterization to a sophisticated multi-layer urban canopy model with an indoor-outdoor exchange sub-model that directly interacts with the atmospheric boundary layer, 2) coupling to fine-scale Computational Fluid Dynamic (CFD) Reynolds-averaged Navier–Stokes (RANS) and Large-Eddy Simulation (LES) models for Transport and Dispersion (T&D) applications, 3) procedures to incorporate high-resolution urban land-use, building morphology, and anthropogenic heating data using the National Urban Database and Access Portal Tool (NUDAPT), and 4) an urbanized high-resolution land-data assimilation system (u-HRLDAS). This paper provides an overview of this modeling system; addresses the daunting challenges of initializing the coupled WRF/urban model and of specifying the potentially vast number of parameters required to execute the WRF/urban model; explores the model sensitivity to these urban parameters; and evaluates the ability of WRF/urban to capture urban heat islands, complex boundary layer structures aloft, and urban plume T&D for several major metropolitan regions. Recent applications of this modeling system illustrate its promising utility, as a regional climate-modeling tool, to investigate impacts of future urbanization on regional meteorological conditions and on air quality under future climate change scenarios.

1 Introduction

We describe in this paper an international collaborative research and development effort between the National Center for Atmospheric Research (NCAR) and partners with regards to a coupled land surface and urban modeling system for the community Weather Research and Forecasting (WRF) model. The goal of this collaboration is to develop a cross-scale modeling capability that can be used to address a number of emerging environmental issues in urban areas.

Today's changing climate poses two formidable challenges. On one hand, the projected climate change by IPCC (Fourth Assessment Report, 2007) may lead to more frequent occurrences of heat waves, severe weather, and floods. On the other hand, the current trend of population increase and urban expansion is expected to continue. For instance, in 2007 half of the world's population lived in cities, and that proportion is projected to be 60% in 2030 (United Nations, 2007). The combined effect of global climate change and rapid urban growth, accompanied with economic and industrial development, will likely make people living in cities more vulnerable to a number of urban environmental problems, including: extreme weather and climate conditions, sea-level rise, poor public health and air quality, atmospheric transport of accidental or intentional releases of toxic material, and limited water resources. For instance, Nicholls et al. (2007) suggested that by the 2070s, total world population exposed to coastal flooding could grow more than threefold to around 150 million people due to the combined effects of climate change (sea-level rise and increased storminess), atmospheric subsidence, population growth, and urbanization. The total asset exposure could grow even more dramatically, reaching US $35,000 billion by the 2070s. Zhang et al. (2009)

demonstrated that urbanization contributes to a reduction of summer precipitation in Beijing, and that augmenting city green-vegetation coverage would enhance summer rainfall and mitigate the increasing threat of water shortage in Beijing.

It is therefore imperative to understand and project effects of future climate change and urban growth on the above environmental problems and to develop mitigation and adaptation strategies. One valuable tool for this purpose is a cross-scale atmospheric modeling system, which is able to predict/simulate meteorological conditions from regional to building scales and which can be coupled to human-response models. The community WRF model, often executed with a grid spacing of 0.5-1 km, is in a unique position to bridge gaps in traditional mesoscale numerical weather prediction (~10^5 m) and microscale T&D modeling (~ 10^0 m). One key requirement for urban applications is for WRF to accurately capture influences of cities on wind, temperature, and humidity in the atmospheric boundary layer and their collective influences on the atmospheric mesoscale motions.

Remarkable progress has been made in the last decade to introduce a new generation of urbanization schemes into atmospheric models such as the Fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5) (Taha, 1999, Taha and Bornstein, 1999, Dupont et al., 2004, Liu et al., 2006, Otte et al., 2004, Taha 2008a,b), WRF model (Chen et al., 2004), UK Met Office operational mesoscale model (Best, 2005), French Meso-NH (Lemonsu and Masson 2002) model, and NCAR global climate model (Oleson et al., 2008). Moreover, fine-scale models, such as computational fluid dynamics models (Coirier et al., 2005) and fast-response urban T&D models (Brown 2004), can explicitly resolve airflows around city buildings. However, these parameterization schemes vary considerably in their degrees of freedom to treat urban processes. An international effort is thus underway to compare these urban models and to evaluate them against site observations (Grimmond et al., 2010). It is, nonetheless, not clear at this stage which degree of complexity of urban modeling should be incorporated in atmospheric models, given that the spatial distribution of urban land-use and building morphology is highly heterogeneous even at urban scales and given the wide range of applications such a model may be used for.

WRF is used for both operations and research in the fields of numerical weather prediction, regional climate, emergency response, air quality (through its companion online chemistry model WRF-Chem, Grell et al., 2005), and regional hydrology and water resources. In WRF-Chem, the computations of meteorology and atmospheric chemistry share the same vertical and horizontal coordinates, surface parameterizations (and hence same urban models), physics parameterization for subgrid-scale transport, vertical mixing schemes, and time steps for transport and vertical mixing. Therefore, our goal is to develop an integrated WRF/urban modeling system to satisfy this wide range of WRF applications. As shown in Fig. 1, the core of this system consists of: 1) a suite of urban parameterization schemes with varying degrees of complexities, 2) the capability of incorporating in-situ and remotely-sensed data of urban land-use, building characteristics, anthropogenic heating, and moisture sources, 3) companion fine-scale atmospheric and urbanized land data assimilation systems, and 4) the ability to couple WRF/urban with fine-scale urban T&D models and chemistry models. It is anticipated that in the future, this modeling system will interact with human response models and be linked to urban decision systems.

In the next section we describe the integrated WRF/urban modeling system. We address the issue of initializing the state variables required to run WRF/urban in Section 3 and the issue of specifying urban parameters and model sensitivity to these parameters in Section 4. Section 5 gives examples of model evaluation and of applying the WRF/urban model to various urbanization problems, and it is followed by a summary in Section 6.

2 Description of the integrated WRF/urban modeling system

2.1 Modeling system overview

The WRF model (Skamarock et al., 2005) is a non-hydrostatic, compressible model with a mass coordinate system. It was designed as a numerical weather prediction model, but can also be applied as a regional climate model. It has a number of options for various physical processes. For example, WRF has a non-local closure planetary boundary layer (PBL) scheme and a 2.5 level PBL scheme based on the Mellor and Yamada scheme (Janjic, 1994). Among its options for land surface models (LSMs), the community Noah LSM has been widely used (e.g., Chen et al., 1996, Chen and Dudhia, 2001, Ek et al., 2003; Leung et al., 2006, Jiang et al., 2008) in weather prediction models; in land data assimilation systems, such as the North America Land Data Assimilation System (Mitchell et al., 2004); and in the community mesoscale MM5 and WRF models.

One basic function of the Noah LSM is to provide surface sensible and latent heat fluxes and surface skin temperature as lower boundary conditions for coupled atmospheric models. It is based on a diurnally-varying Penman potential evaporation approach, a multi-layer soil model, a modestly complex canopy resistance parameterization, surface hydrology, and frozen ground physics (Chen et al. 1996; Chen et al., 1997; Chen and Dudhia 2001; Ek et al. 2003). Prognostic variables in Noah include: liquid water, ice, and temperature in the soil layers; water stored in the vegetation canopy; and snow water equivalent stored on the ground.

Here, we mainly focus the urban modeling efforts on coupling different urban canopy models (UCMs) with Noah in WRF. Such coupling is through the parameter urban percentage (or urban fraction, F_{urb}) that represents the proportion of impervious surfaces in the WRF sub-grid scale. For a given WRF grid cell, the Noah model calculates surface fluxes and temperature for vegetated urban areas (trees, parks, etc.) and the UCM provides the fluxes for anthropogenic surfaces. The total grid-scale sensible heat flux, for example, can be estimated as follows:

$$Q_H = F_{veg} \times Q_{H\,veg} + F_{urb} \times Q_{H\,urb}$$

where Q_H is the total sensible heat flux from the surface to the WRF model lowest atmospheric layer, F_{veg} the fractional coverage of natural surfaces, such as grassland, shrubs, crops, and trees in cities, F_{urb} the fractional coverage of impervious surfaces, such as buildings, roads, and railways. $Q_{H\,veg}$ the sensible heat flux from Noah for natural surfaces, and $Q_{H\,urb}$ the sensible heat flux from the UCM for artificial surfaces. Grid-integrated latent heat flux, upward long wave radiation flux, albedo, and emissivity are estimated in the same way. Surface skin temperature is calculated as the averaged value of the artificial and natural surface temperature values, and is subsequently weighted by their areal coverage.

2.2 Bulk urban parameterization

The WRF V2.0 release in 2003 included a bulk urban parameterization in Noah using the following parameter values to represent zero-order effects of urban surfaces (Liu et al., 2006): 1) roughness length of 0.8 m to represent turbulence generated by roughness elements and drag due to buildings; 2) surface albedo of 0.15 to represent shortwave radiation trapping in urban canyons; 3) volumetric heat capacity of 3.0 J m^{-3} K^{-1} for urban surfaces (walls, roofs, and roads), assumed as concrete or asphalt; 4) soil thermal conductivity of 3.24 W m^{-1} K^{-1} to represent the large heat storage in urban buildings and roads; and 5) reduced green-vegetation fraction over urban areas to decrease evaporation. This approach has been successfully employed in real-time weather forecasts (Liu et al., 2006) and to study the impact of urbanization on land-sea breeze circulations (Lo et al., 2007).

2.3 Single-layer urban canopy model

The next level of complexity incorporated uses the single-layer UCM (SLUCM) developed by Kusaka et al. (2001) and Kusaka and Kimura (2004). It assumes infinitely-long street canyons parameterized to represent urban geometry, but recognizes the three dimensional nature of urban surfaces. In a street canyon, shadowing, reflections, and trapping of radiation are considered, and an exponential wind profile is prescribed. Prognostic variables include: surface skin temperatures at the roof, wall, and road (calculated from the surface energy budget) and temperature profiles within roof, wall, and road layers (calculated from the thermal conduction equation). Surface sensible heat fluxes from each facet are calculated using Monin-Obukhov similarity theory and the Jurges formula (Fig. 2). The total sensible heat flux from roof, wall, roads, and the urban canyon is passed to the WRF-Noah model as $Q_{H\,urb}$ (Section 2.1). The total momentum flux is passed back in a similar way. SLUCM calculates canyon drag coefficient and friction velocity using a similarity stability function for momentum. Total friction velocity is then aggregated from urban and non-urban surfaces and passed to WRF boundary layer schemes. Anthropogenic heating and its diurnal variation are considered by adding them to the sensible heat flux from the urban canopy layer. SLUCM has about 20 parameters, as listed in Table 1.

2.4 Multi-layer urban canopy (BEP) and indoor-outdoor exchange (BEM) models

Unlike the SLUCM (embedded within the first model layer), the multi-layer UCM developed by Martilli et al. (2002), called BEP for Building Effect Parameterization, represents the most sophisticated urban modeling in WRF, and it allows a direct interaction with the PBL

(Fig. 2). BEP recognizes the three-dimensional nature of urban surfaces and the fact that buildings vertically distributes sources and sinks of heat, moisture, and momentum through the whole urban canopy layer, which substantially impacts the thermodynamic structure of the urban roughness sub-layer and hence the lower part of the urban boundary layer. It takes into account effects of vertical (walls) and horizontal (streets and roofs) surfaces on momentum (drag force approach), turbulent kinetic energy, and potential temperature (Fig. 2). The radiation at walls and roads considers shadowing, reflections, and trapping of shortwave and longwave radiation in street canyons. The Noah-BEP model has been coupled with two turbulence schemes: Bougeault and Lacarrere (1989) and Mellor-Yamada-Janjic (Janjic, 1994) in WRF by introducing a source term in the TKE equation within the urban canopy and by modifying turbulent length scales to account for the presence of buildings. As illustrated in Fig. 3, BEP is able to simulate some of the most observed features of the urban atmosphere, such as the nocturnal Urban Heat Island (UHI) and the elevated inversion layer above the city.

To take full advantage of BEP, it is necessary to have high vertical resolution close to the ground (to have more than one model level within the urban canopy). Consequently, this approach is more appropriate for research (when computational demands are not a constraint) than for real-time weather forecasts.

In the standard version of BEP (Martilli et al., 2002), the internal temperature of the buildings is kept constant. To improve estimation of exchanges of energy between the interior of buildings and the outdoor atmosphere, which can be an important component of the urban energy budget, a simple Building Energy Model (BEM, Salamanca and Martilli, 2009) has been developed and linked to BEP. BEM accounts for the: 1) diffusion of heat through the walls, roofs, and floors; 2) radiation exchanged through windows; 3) longwave radiation exchanged between indoor surfaces; 4) generation of heat due to occupants and equipment; and 5) air conditioning, ventilation, and heating. Buildings of several floors can be considered, and the evolution of indoor air temperature and moisture can be estimated for each floor. This allows the impact of energy consumption due to air conditioning to be estimated. The coupled BEP+BEM has been tested offline using the BUBBLE (Basel UrBan Boundary Layer Experiment, Rotach et al., 2005) data. Incorporating building energy in BEP+BEM significantly improves sensible heat-flux calculations over using BEP alone (Fig. 4). The combined BEP+BEM has been recently implemented in WRF, and is currently being tested before its public release in WRF V3.2 in Spring 2010.

2.5 Coupling to fine-scale Transport and Dispersion (T&D) models

Because WRF can parameterize only aggregated effects of urban processes, it is necessary to couple it with finer-scale models for applications down to building-scale problems. One key requirement for fine-scale T&D modeling is to obtain accurate, high-resolution meteorological conditions to drive T&D models. These are often incomplete and inconsistent, due to limited and irregular coverage of meteorological stations within urban areas. To address this limitation, fine-scale building-resolving models, e.g., Eulerian/semi-Lagrangian fluid solver (EULAG) and CFD-Urban, are coupled to WRF to investigate the degree to which the: 1) use of WRF forecasts for initial and boundary conditions can improve T&D simulations through downscaling and 2) feedback, through upscaling, of explicitly resolved turbulence and wind fields from T&D models can improve WRF forecasts in complex urban environments.

In the coupled WRF-EULAG/CFD-Urban models (Fig. 5), WRF generates mesoscale (~1-10 km) atmospheric conditions to provide initial and boundary conditions, through downscaling, for microscale (~1-10 m) EULAG/CFD-Urban simulations. WRF meso-scale simulations are performed usually at 500 m grid spacing. Data from WRF model (i.e., grid structure information, horizontal and vertical velocity components, and thermodynamic fields, such as pressure, temperature, water vapor, as well as turbulence) are saved at appropriate time intervals (usually each 5-15 min) required by CFD simulations. WRF model grid structure and coordinates are transformed to the CFD model grid before use in the simulations.

The CFD-Urban model resolve building structures explicitly by considering different urban aerodynamic features, such as channeling, enhanced vertical mixing, downwash, and street-level flow. These microscale flow features can be aggregated and transferred back, through upscaling, to WRF to increase the accuracy of mesoscale forecasts for urban and downstream regions. The models can be coupled in real time; and data transfer is realized through the Model Coupling Environmental Library (MCEL).

As an example, Tewari et al. (2010) ran the WRF model at a sub-kilometer resolution (0.5 km), and its temporal and spatial meteorological fields were downscaled and used in the unsteady coupling mode to supply initial and time-varying boundary conditions to the CFD-Urban model developed by Coirier et al. (2005). Traditionally, most CFD models used for T&D studies are initialized with a single profile of atmospheric sounding data, which does not represent the variability of weather elements within urban areas. This often results in errors in predicting urban plumes. The CFD-Urban T&D predictions using the above two methods of initialization were evaluated against the URBAN 2000 field experiment data for Salt Lake City (Allwine et al., 2002). For concentrations of a passive tracer, the WRF-CFD-Urban downscaling better produced the observed high-concentration tracer in the northwestern part of the downtown area, largely due to the fact that the turning of lower boundary layer wind to NNW from N is well represented in WRF and the imposed WRF simulated pressure gradient is felt by the CFD-Urban calculations (Fig. 6). These improved steady-state flow fields result in significantly improved plume transport behavior and statistics.

The NCAR LES model EULAG has been coupled to WRF. EULAG is a multi-scale, multi-physics computational model for simulating urban canyon thermodynamic and transport fields across a wide range of scales and physical scenarios (see Prusa et al., 2008 for a review). Since turbulence in the mesoscale model (WRF in our case) is parameterized, there is no direct downscaling of the turbulent quantities (e.g., TKE) from WRF to the LES model. The LES model assumes the flow at the boundaries to be laminar (with small scale random noise added to the mean flow), and the transition zone is preserved between the model boundary and regions where the turbulence develops internally within the LES model domain. Contaminant transport in urban areas is simulated with a passive tracer in time-dependent adaptive mesh geometries (Wyszogrodzki and Smolarkiewicz, 2009). Building structures are explicitly resolved using the immersed boundary (IMB) approach, where fictitious body forces in the equations of motion represent internal boundaries, effectively imposing no-slip boundary conditions at building walls (Smolarkiewicz et al., 2007). The WRF/EULAG coupling with a downscaling data transfer capability was applied for the daytime Intensive Observation Period (IOP)-6 case during the Joint Urban Oklahoma City 2003 experiment (JU2003, Allwine et al., 2004). With five two-way nested domains, with grid spacing ranging from 0.5 to 40 km, the coupled model was integrated from 1200UTC 16 July 2003 (0700CDT) for a 12-h simulation. WRF was able to reproduce the observed horizontal wind and temperature fields near the surface and in the boundary layer reasonably well. The macroscopic features of EULAG-simulated flow compare well with measurements. Figure 7 shows EULAG-generated near-surface wind and dispersion of the passive scalar from the first release of IOP-6, starting at 0900 CDT.

3 Challenges in initializing the WRF/urban model system

Executing the coupled WRF/urban modeling system raises two challenges: 1) initialization of the detailed spatial distribution of UCM state variables, such as temperature profiles within wall, roofs, and roads and 2) specification of a potentially vast number of parameters related to building characteristics, thermal properties, emissivity, albedo, anthropogenic heating, etc. The former issue is discussed in this section and the latter in Section 4.

High-resolution routine observations of wall/roof/road temperature are rarely available to initialize the WRF/urban model, which usually covers a large domain (e.g., ~10^6 km^2) and may include urban areas with a typical size of ~ 10^2 km^2. Nevertheless, to a large extent, this initialization problem is analogous to that of initializing soil moisture and temperature in a coupled atmospheric-land surface model. One approach is to use observed rainfall, satellite-derived surface solar insolation, and meteorological analyses to drive an uncoupled (off-line) integration of an LSM, so that the evolution of the modeled soil state can be constrained by observed forcing conditions. The North-American Land Data Assimilation System (NLDAS, Mitchell et al., 2004) and the NCAR High-Resolution Land Data Assimilation System (HRLDAS, Chen et al., 2007) are two examples that employ this method. In particular, HRLDAS was designed to provide consistent land-surface input fields for WRF nested domains and is flexible enough to use a wide variety of satellite, radar, model, and in-situ data to develop an equilibrium soil state. The soil state spin-up may take up to several years and thus cannot be reasonably handled within the computationally-expensive WRF framework (Chen et al., 2007).

Therefore, the approach adopted is to urbanize HRLDAS (u-HRLDAS) by running the coupled Noah/urban model in an offline mode to provide initial soil moisture, soil temperature, snow, vegetation, and wall/road/roof temperature profiles. As an example, a set of experiments with the u-HRLDAS using Noah/SLUCM was performed for the Houston region. Similar to Chen et al. (2007), an 18-month u-HRLDAS simulation was considered long enough for the modeling system to reach an equilibrium state, and the temperature difference ΔT between this 18-month simulation and other simulations with shorter simulation period (e.g., 6 months, 2 months, etc.) is used to investigate the spin-up of SLUCM. The time required for SLUCM state variables to reach a quasi-equilibrium state (ΔT<1 K) is short (less than a week) for roof and wall temperature (Fig. 8), but longer (approximately two months) for road temperature, due to the larger thickness and thermal capacity of roads. However, this spin-up is considerably shorter than that for natural surfaces (up to several years, Chen et al., 2007). Results also show that the spun-up temperatures of roofs, walls, and roads are different (by ~ 1-2 K) and exhibit strong horizontal heterogeneity in different urban land-use and buildings. Using a uniform temperature to initialize WRF/urban will not capture such urban variability.

4 Challenges in specifying parameters for urban models

4.1 Land-use based approach, gridded data set, and NUDAPT

Using UCMs in WRF requires users to specify at least 20 urban canopy parameters (UCPs) (Table 1). A combination of remote-sensing and in-situ data can be used for this purpose thanks to recent progress in developing UCP data sets (Burian et al., 2004, Feddema et al., 2006, Taha, 2008b, Ching et al., 2009). While the availability of these data is growing, data sets are currently limited to a few geographical locations. High-resolution data sets on global bases comprising the full suite of UCPs simply do not exist. In anticipation of increased database coverage, we employ three methods to specify UCPs in WRF/urban: 1) urban land-use maps and urban-parameter tables, 2) gridded high-resolution UCP data sets, and 3) a mixture of the above.

For many urban regions, high-resolution urban land-use maps, derived from in-situ surveying (e.g., urban planning data) and remote-sensing data (e.g., Landsat 30-m images) are readily available. We currently use the USGS National Land Cover Data (NLCD) classification with three urban land-use categories: 1) low-intensity residential, with a mixture of constructed materials and vegetation (30-80 % covered with constructed materials), 2) high-intensity residential, with highly-developed areas such as apartment complexes and row houses (usually with 80-100 % covered with constructed materials), and 3) commercial/industrial/ transportation including infrastructure (e.g., roads, railroads, etc.). An example of the spatial distribution of urban land-use for Houston is given in Fig. 9. Once the type of urban land-use is defined for each WRF model grid, urban morphological and thermal parameters can be assigned using the urban-parameters in Table 1. Although this approach may not provide the most accurate UCP values, it captures some degree of their spatial heterogeneity, given the limited input land-use-type data.

The second approach, to directly incorporate gridded UCPs into WRF, was tested in the context of the National Urban Database and Access Portal Tool (NUDAPT) project (Ching et al., 2009). NUDAPT was developed to provide the requisite gridded sets of UCPs for urbanized WRF and other advanced urban meteorological, air quality, and climate modeling systems. These UCPs account for the aggregated effect of sub-grid building and vegetation morphology on grid-scale properties of the thermodynamics and flow fields in the layer between the surface and the top of the urban canopy. High definition (1 to 5 m) three-dimensional data sets of individual buildings, conglomerates of buildings, and vegetation in urban areas are now available, based on airborne lidar systems or photogrammetric techniques, to provide the basis for these UCPs (Burian et al., 2004, 2006, 2007). Each cell can have a unique combination of UCPs. Currently, NUDAPT hosts datasets (originally acquired by the National Geospatial Agency, NGA) for more than 40 cities in the United States, with different degrees of coverage and completeness for each city. In the future, it is anticipated that high-resolution building data will become available for other cities. With this important core-design feature, and by using web portal technology, NUDAPT can serve as the database infrastructure for the modeling community to facilitate customizing of data handling and retrievals (http://www.nudapt.org) for such future datasets and applications in WRF and other models.

4.2 Incorporating anthropogenic heat sources

The scope of NUDAPT is to provide ancillary information, including gridded albedo, vegetation coverage, population data, and anthropogenic heating (AH) for various urban applications ranging from climate to human exposure modeling studies. Taha (1999), Taha and Ching (2007), and Miao et al. (2009a) demonstrated that the intensity of the UHI is greatly influenced by the introduction of AH, probably the most difficult data to obtain. If AH is not treated as a dynamic variable (section 2.4), then it is better to treat it as a parameter rather than to ignore it.

Anthropogenic emissions of sensible heat arise from buildings, industry/manufacturing, and vehicles, and can be estimated either through inventory approaches or through direct modeling. In the former approach (e.g., Sailor and Lu, 2004), aggregated consumption data are typically gathered for an entire city or utility service territory, often at monthly or annual resolution, and then must be mapped onto suitable spatial and temporal profiles. Waste heat emissions from industrial sectors can be obtained at the state or regional level (from sources such as the Federal Energy Regulatory Commission, FERC 2006), but it is difficult to assess the characteristics of these facilities that would enable estimation of diurnal (sensible and latent) anthropogenic flux emission profiles.

Regarding the transportation sector, the combustion of gasoline and diesel fuel produces sensible waste heat and water vapor. Since the network of roadways is well established, the transportation sector lends itself to geospatial modeling that can estimate diurnal profiles of sensible and latent heating from vehicles, as illustrated by Sailor and Lu (2004). A more sophisticated method incorporating mobile source emissions modeling techniques is from the air quality research community.

Existing whole-building-energy models can estimate both the magnitude and timing of energy consumption (Section 2.4). The physical characteristics of buildings, with details of the mechanical equipment and building internal loads (lighting, plug loads, and occupancy), can be used to estimate hourly energy usage, and hence to produce estimates of sensible and latent heat emissions from the building envelope and from the mechanical heating, cooling, and ventilation equipment. Correctly estimating AH relies on building size and type data spatially explicit for a city. Such geospatial data are commonly available for most large cities and can readily be combined with output from simulations of representative prototypical buildings (Heiple and Sailor, 2008). Recently the US Department of Energy and the National Renewable Energy Research Laboratory created a database of prototypical commercial buildings representing the entire building stock across the US (Torcellini et al., 2008). This database provides a unique opportunity to combine detailed building energy simulation with

Geographical Information System (GIS) data to create a US-wide resource to estimate anthropogenic heat emissions from the building sector at high spatial and temporal resolutions.

Gridded fields of AH from NUDAPT (Ching et al. 2009), based on methodologies described in Sailor and Lu (2004) and Sailor and Hart (2006), provide a good example of a single product, combining waste heat from all sectors, that can be ingested into WRF/urban. Inclusion of hourly gridded values of AH, along with the BEM indoor-outdoor model in WRF/urban, should provide an improved base to conduct UHI mitigation studies and simulations for urban planning.

4.3 Model sensitivity to uncertainty in UCPs

A high level of uncertainty in the specification of UCP values is inherent to the methodology of aggregating fine-scale heterogeneous UCPs to the WRF modeling grid, particularly to the table-based approach. It is critical to understand impacts from such uncertainty on model behavior. Loridan *et al*. (2010) developed a systematic and objective model response analysis procedure by coupling the offline version of SLUCM with the Multi-objective Shuffled Complex Evolution Metropolis (MOSCEM) optimization algorithm of Vrugt *et al.* (2003). This enables direct assessment of how a change in a parameter value impacts the modeling of the surface energy balance (SEB).

For each UCPs in Table 1, upper and lower limits are specified. MOSCEM is set to randomly sample the entire parameter space, iteratively run SLUCM, and identify values that minimize the Root Mean Square Error (RMSE) of SEB fluxes relative to observations. The algorithm stops when it identifies parameter values leading to an optimum compromise in the performance of modeled fluxes. As an example, Fig. 10 presents the optimum values selected by MOSCEM for roof albedo (α_r) when using forcing and evaluation data from a measurement campaign in Marseille (Grimmond *et al.*, 2004; Lemonsu *et al.*, 2004). The algorithm is set to minimize the RMSE for net all-wave radiation (Q^*) and turbulent sensible heat flux (Q_H) (two objectives) using 100 samples. The optimum state identified represents a clear trade-off between the two fluxes, as decreasing the value of α_r improves modeled Q^* (lower RMSE) but downgrades modeled Q_H (higher RMSE). Identification of all parameters leading to such trade-offs is of primary importance to understand how the model simulates the SEB, and consequently how default table parameter values should be set.

This model-response-analysis procedure also provides a powerful tool to identify the most influential UCPs, i.e., by linking the best possible improvement in RMSE for each flux to corresponding parameter value changes, all inputs can be ranked in terms of their impact on the modeled SEB. A complete analysis of the model response for the site of Marseille is presented in Loridan *et al.* (2009). Results show that for a dense European city like Marseille, the correct estimation of roof-related parameters is of critical importance, with albedo and conductivity values as particularly influential. On the other hand, the impact of road characteristics appears to be limited, suggesting that a higher degree of uncertainty in their estimation would not significantly degrade the modeling of the SEB. This procedure, repeated for a variety of sites with distinct urban characteristics (i.e., with contrasting levels of urbanization, urban morphology, and climatic conditions) can provide useful guidelines for prioritizing efforts to obtain urban land use characteristics for WRF.

5 Evaluation of the WRF/Urban model and its recent applications

The coupled WRF/Urban model has been applied to major metropolitan regions (e.g., Beijing, Guangzhou/Hong Kong, Houston, New York City, Salt Lake City, Taipei, and Tokyo), and its performance was evaluated against surface observations, atmospheric soundings, wind profiler data, and precipitation data (Chen et al., 2004, Holt and Pullen, 2007, Miao and Chen, 2008, Lin et al., 2008, Jiang et al., 2008, Miao et al., 2009a, Miao et al., 2009b, Wang et al., 2009, Kusaka et al., 2009; Tewari et al., 2010).

For instance, Fig. 11 shows a comparison of observed and WRF/SLUCM simulated diurnal variation of 2-m temperature, surface temperatures, 10-m wind speed, and 2-m specific humidity averaged over high-density urban stations in Beijing. Among the urban surface temperatures, urban ground surface temperature has the largest diurnal amplitude, while wall surface temperature has the smallest diurnal range, reflecting the differences in their thermal conductivities and heat capacities. Results show the coupled WRF/Noah/SLUCM modeling system able to reproduce the following observed features reasonably well (Miao and Chen, 2008, Miao et al., 2009a): 1) diurnal variation of UHI intensity; 2) spatial distribution of the UHI in Beijing; 3) diurnal variation of wind speed and direction, and interactions between mountain-valley circulations and the UHI; 4) small-scale boundary layer horizontal convective rolls and cells; and 5) nocturnal boundary layer low-level jet.

Similarly, Lin et al. (2008) showed that using the WRF/Noah/SLUCM model significantly improved the simulation of the UHI, boundary-layer development, and land-sea breeze in northern Taiwan, when compared to observations obtained from weather stations and lidar. Their sensitivity tests indicate that anthropogenic heat (AH) plays an important role in boundary layer development and UHI intensity in the Taipei area, especially during nighttime and early morning. For example, when AH was increased by 100 Wm^{-2}, the average surface temperature increased nearly 0.3-1 ºC in Taipei. Moreover, the intensification of the UHI associated with recent urban expansion enhances the daytime sea breeze and weakens the nighttime land breeze, substantially modifying the air pollution transport in northern Taiwan.

The WRF/urban model was used as a high-resolution regional climate model to assess the uncertainty in the simulated summer UHI of Tokyo for four consecutive years (Fig. 12). When the simple slab model is used in WRF, the heat island of Tokyo and of the urban area in the inland northwestern part of the plain is not reproduced at all. When the WRF/Noah/SLUCM is used, however, a strong nocturnal UHI is seen and warm areas are well reproduced.

One important goal for developing the integrated WRF/urban modeling system is to apply it to understand the effects of urban expansion, so we can use such knowledge to predict and assess impacts of urbanization and future climate change on our living environments and risks. For instance, the Pearl River Delta (PRD) and Yangtze River Delta (YRD) regions, China, have experienced a rapid, if not the most rapid in the world, economic development and urbanization in the past two decades. These city clusters, centered around mega cities such as Hong Kong, Guangzhou, and Shanghai (Fig. 13), have resulted in a deterioration of air quality for these regions (e.g., Wang et al., 2007).

In a recent study by Wang et al. (2009), the online WRF Chemistry (WRF-Chem) model, coupled with Noah/SLUCM and biogenic-emission models, was used to explore the influence of such urban expansion. Month-long (March 2001) simulations using two land-use scenarios (pre-urbanization and current) indicate that urbanization: 1) increases daily mean 2-m air temperature by about 1 ^{0}C, 2) decreases 10-m wind speeds for both daytime (by 3.0 m s^{-1}) and nighttime (by 0.5 to 2 m s^{-1}), and 3) increases boundary-layer depths for daytime (more than 200 m) and nighttime (50-100 m) periods. Changes in meteorological conditions result in an increase of surface ozone concentrations by about 4.7-8.5% for nighttime and about 2.9-4.2% for daytime (Fig. 14). Furthermore, despite the fact that both the PRD and the YRD have similar degrees of urbanization in the last decade, and that both are located in coastal zones, urbanization has different effects on the surface ozone for the PRD and the YRD, presumably due to their differences in urbanization characteristics, topography, and emission source strength and distribution.

The WRF-Chem model coupled with UCMs is equally useful to project, for instance, air quality change in cities under future climate change scenarios. For example, the impact of future urbanization on surface ozone in Houston under the future IPCC A1B scenario for 2051–2053 (Jiang et al. 2008) shows generally a 2^0C increase in surface air temperature due to the combined change in climate and urbanization. In this example, the projected 62% increase of urban areas exerted more influence than attributable to climate change alone. The combined effect of the two factors on O_3 concentrations can be up to 6.2 ppbv. The Jang et al. (2008) sensitivity experiments revealed that future change in anthropogenic emissions produces the same order of O_3 change as those induced by climate and urbanization.

6 Summary and conclusions

An international collaborative effort has been underway since 2003 to develop an integrated, cross-scale urban modeling capability for the community WRF model. The goal is not only to improve WRF weather forecasts for cities, and thereby to improve air quality prediction, but also to establish a modeling tool for assessing the impacts of urbanization on environmental problems by providing accurate meteorological information for planning mitigation and adaptation strategies in a changing climate. The central distinction between our efforts and other atmosphere-urban coupling work is the availability of multiple choices of models to represent the effects of urban environments on local and regional weather and the cross-scale modeling ability (ranging from continental, to city, and to building scales) in the WRF/urban model. These currently include: 1) a suite of urban parameterization schemes with varying degrees of complexities, 2) a capability of incorporating in-situ and remote-sensing data of urban land use, building characteristics, and anthropogenic heat and moisture sources, 3) companion fine-scale atmospheric and urbanized land data assimilation systems, and 4) ability to couple WRF/urban to fine-scale urban T&D models and with chemistry models.

Inclusion of three urban parameterization schemes (i.e., bulk parameterization, SLUCM, and BEP) provides users with options for treating urban surface processes. Parallel to an international effort to evaluate 30 urban models, executed in offline 1-D mode, against site observations (Grimmond et al., 2010), work is underway within our group to evaluate three WRF urban models in coupled mode against surface and boundary layer observations from the Texas Air Quality Study 2000 (TexAQS2000) field program in the greater Houston area, Central California Ozone Study (CCOS2000), and Southern California Ozone Study (SCOS1997). Choice of specific applications will dictate careful selection of different sets of science options and available databases. For instance, the bulk parameterization and SLUCM may be more suitable for real-time weather and air quality forecasts than the resource-demanding BEP. On the other hand, studying, for instance, the impact of air conditioning on the atmosphere and in developing an adaptation strategy for planning the use of air conditioning in less-developed countries in the context of intensified heat waves projected by IPCC, will need to invoke the more sophisticated BEP coupled with the BEM indoor-outdoor exchange model.

Initializing UCM state variables is a difficult problem, which has not yet received much attention in the urban modeling community. Although in its early stage of development (largely due to lack of appropriate data for its evaluation), u-HRLDAS may provide better initial conditions for the state variables required by UCMs than the current solution that assigns a uniform temperature profile for model grid points cross a city. Similarly, specification of twenty-some UCPs will remain a challenge, due to the large disparity in data availability and methodology for mapping fine-scale, highly variable data for the WRF modeling grid. Currently the WRF pre-processor (WPS) is able to ingest: 1) high-resolution urban land-use maps and to then assign UCPs based on a parameter table and 2) gridded UCPs, such as those from NUDAPT (Ching et al., 2009). It would be useful to blend these two methods whenever gridded UCPs are available. Bringing optimization algorithms together with UCMs and observations, as recently demonstrated by Loridan *et al*. (2010), is a useful methodology to identify a set of UCPs to which the performance of the UCM is most sensitive, and to eventually define optimized values for those UCPs for a specific city.

Among these UCPs, anthropogenic heating (AH) has emerged as the most difficult parameter to obtain. Methods to estimate AH from buildings, industry/manufacturing, and transportation sectors have been developed (e.g., Sailor and Lu, 2004, Sailor and Hart, 2006, Torcellini et al., 2008). Although data regarding the temporal and spatial distribution of waste heat emissions from industry, buildings, and vehicle combustion do exist for most cities, obtaining and processing these data are far from automated tasks. Nevertheless, the data currently available for major US cities in NUDAPT provide examples of combining all AH sources to create a single, hourly input for the WRF/urban model.

Evaluations and applications of this newly developed WRF/urban modeling system have demonstrated its utility in studying air quality and regional climate. Preliminary results that verify the performance of WRF/UCM for several major cities are encouraging (e.g., Chen et al., 2004, Holt and Pullen, 2007, Miao and Chen, 2008, Lin et al., 2008, Miao et al., 2009a, Miao et al., 2009b, Wang et al., 2009, Tewari et al., 2010, Kusaka et al., 2009). They show that the model is generally able to capture influences of urban processes on near-surface meteorological conditions and on the evolution of atmospheric boundary-layer structures in cities. More importantly, recent studies (Jiang et al., 2008, Wang et al., 2009, Tewari et al., 2010) have demonstrated the promising value of employing this model to investigate urban and street-level plume T&D and air quality, and to predict impacts of urbanization on our living environments and for risks in the context of global climate change.

While this WRF/urban model has been released (WRF V3.1, April 2009), except for the BEM model that is in the final stages of testing, much work still remains to be done. We continue to: further improve the UCMs, explore new methods of blending various data sources to enhance the specification UCPs, increase the coverage of high resolution data sets, particularly enhancing anthropogenic heating and moisture inputs, and link this physical modeling system with, for instance, human-response models and decision support systems.

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Table 1. Urban canopy parameters currently in WRF for three urban land-use categories: low-intensity residential, high-intensity residential, and industrial and commercial. The last two columns indicate if a specific parameter is used in SLUCM and BEP, and the last three parameters are exclusively used in BEP.

Parameter	Unit	Specific Values for			SLUCM	BEP
		Low intensity residential	**High intensity residential**	**Industrial, commercial**		
h (Building Height)	m	5	7.5	10	Yes	No
l_{roof} (Roof Width)	m	8.3	9.4	10	Yes	No
l_{road} (Road Width)	m	8.3	9.4	10	Yes	No
AH (Anthropogenic Heat)	$W\ m^{-2}$	20	50	90	Yes	No
F_{urb} (Urban fraction)	Fraction	0.5	0.9	0.95	Yes	Yes
C_R (Heat capacity of roof)	$J\ m^{-3}\ K^{-1}$	1.0E6	1.0E6	1.0E6	Yes	Yes
C_W (Heat capacity of building wall)	$J\ m^{-3}\ K^{-1}$	1.0E6	1.0E6	1.0E6	Yes	Yes
C_G (Heat capacity of road)	$J\ m^{-3}\ K^{-1}$	1.4E6	1.4E6	1.4E6	Yes	Yes
λ_R (Thermal Conductivity of roof)	$J\ m^{-1} s^{-1} K^{-1}$	0.67	0.67	0.67	Yes	Yes
λ_W (Thermal Conductivity of building wall)	$J\ m^{-1} s^{-1} K^{-1}$	0.67	0.67	0.67	Yes	Yes
λ_G (Thermal Conductivity of road)	$J\ m^{-1} s^{-1} K^{-1}$	0.4004	0.4004	0.4004	Yes	Yes
α_R (Surface Albedo of roof)	Fraction	0.20	0.20	0.20	Yes	Yes
α_W (Surface Albedo of building wall)	Fraction	0.20	0.20	0.20	Yes	Yes
α_G (Surface Albedo of road)	Fraction	0.20	0.20	0.20	Yes	Yes
ε_R (Surface emissivity of roof)	-	0.90	0.90	0.90	Yes	Yes

ε_W (Surface emissivity of building wall)	-	0.90		0.90		0.90		Yes	Yes
ε_G (Surface emissivity of road)	-	0.95		0.95		0.95		Yes	Yes
Z_{0R} (Roughness length for momentum over roof)	m	0.01		0.01		0.01		Yes*	Yes
Z_{0W} (Roughness length for momentum over building wall)	m	0.0001		0.0001		0.0001		No*	No
Z_{0G} (Roughness length for momentum over road)	m	0.01		0.01		0.01		No*	Yes
b) Parameters used only in BEP									
Street Parameters		Directions from North (degrees)		Directions from North (degrees)		Directions from north (degrees)		No	Yes
		0	90	0	90	0	90		
W (Street Width)	m	15	15	15	15	15	15		
B (Building Width)	m	15	15	15	15	15	15		
h (Building Heights)	m	Height	%	Height	%	Height	%		
		5	50	10	3	5	30		
		10	50	15	7	10	40		
				20	12	15	50		
				25	18				
				30	20				
				35	18				
				40	12				
				45	7				
				50	3				

*Note: For SLUCM, if the Jurges' formulation is selected instead of Monin-Obukhov formulation (a default option in WRF V3.1), Z_{0W} and Z_{0G} are not used.

Figure Captions

Figure 1. Overview of the integrated WRF/urban modeling system, which includes urban-modeling data-ingestion enhancements in the WRF Preprocessor System (WPS), a suite of urban modeling tools in the core physics of WRF V 3.1, and its potential applications.

Figure 2. A schematic of the single-layer UCM (SLUCM, on the left-hand side) and the multi-layer BEP models (on the right-hand side).

Figure 3. Simulated vertical profiles of nighttime temperature above a city and a rural site upwind of the city. Results obtained with WRF/BEP for a 2-D simulation (from Martilli and Schmitz, 2007).

Figure 4. Kinematic sensible heat fluxes: measured (solid line); computed offline with BEP+BEM and air conditioning working 24-h a day (ucp-bemac); with BEP+BEM and air conditioning working only from 0800 to 2000 LST (ucp-bemac*); with BEP+BEM, but without air conditioning (ucp-bem); and with the old version BEP. Results are at 18 m for a three-day period during the BUBBLE campaign (from Salamanca and Martilli, 2009).

Figure 5. Schematic representation of the coupling between the mesoscale WRF and the fine-scale urban T&D EULAG model.

Figure 6: Contours are the density of SF_6 tracer gas (in parts per thousand) 60 minutes after the third release, simulated by CFD-urban using: a) single sounding observed at the Raging Waters site and (b) WRF 12-h forecast. Dots represent observed density (in same scale as in scale bar) at sites throughout the downtown area of Salt Lake City (from Tewari et al. 2010).

Figure 7. Dispersion footprint for IOP6 0900 CDT release from source located at Botanical Gardens (near Sheridan & Robinson avenues, Oklahoma City, Oklahoma) calculated with WRF/EULAG.

Figure 8. Noah/SLUCM simulated differences in 4th-layer road temperature (K), valid at 1200 UTC 23 August 2006 for Houston, Texas, between the control simulation with 20-month spin-up time and a sensitivity simulation with: a) six-month, b) two-month, c) one-month, and d) 14-day spin-up times.

Figure 9. Land use and land cover in the Greater Houston area, Texas, based on 30-m Landsat from the NLCD 1992 data.

Figure 10: Optimum roof albedo values (α_r) identified by MOSCEM, when considering the RMSE (W m^{-2}) for Q^* and Q_H with forcing and evaluation data from Marseille.

Figure 11. The diurnal variation of: (a) temperature (°C), as observed (obs), modeled 2-m air temperature (t2) and within the canyon (T2C), modeled aggregated land surface (TSK), and facet temperatures for roof (TR), wall (TB) and ground (TG); (b) observed (obs) and modeled 10-m wind speed (wsp) and simulated wind-speed within the urban canyon in m s^{-1}; and (c) observed (obs) and modeled (q2) 2-m specific humidity (g kg^{-1}). Variables were averaged over high-density urban area stations for Beijing (from Miao et al., 2009a).

Figure 12. Monthly mean surface air temperature at 2 m in Tokyo area at 0500 JST in August averaged for 2004-2007: (a) AMeDAS observations, (b) from WRF/Slab model, and (c) from WRF/SLUCM (from Kusaka et al., 2009).

Figure 13. Urban land-use change in the PRD and YRD regions, China, marked in red from pre-urbanization (1992-93) and current (2004): a) WRF-Chem domain with 12-km grid spacing; b) 1992-1993 USGS data for PRD, c) 2004 MODIS data for YRD, d) 1992-1993 USGS data for PRD, and e) 2004 MODIS data for YRD (from Wang et al., 2009).

Figure 14. Difference of surface ozone (in ppbv) and relative 10-m wind vectors: (a) daytime, (b) nighttime (from Wang et al., 2009).