4.4 AN IMPROVED WRF FOR URBAN-SCALE AND COMPLEX-TERRAIN APPLICATIONS

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1. INTRODUCTION

Simulations of atmospheric flow through urban areas must account for a wide range of physical phenomena including both mesoscale and urban processes. Numerical weather prediction models, such as the Weather and Research Forecasting model (WRF), excel at predicting synoptic and mesoscale phenomena. With grid spacings of less than 1 km (as is required for complex heterogeneous urban areas), however, the limits of WRF's terrain capabilities and subfilter scale (SFS) turbulence parameterizations are exposed. Observations of turbulence in urban areas frequently illustrate a local imbalance of turbulent kinetic energy (TKE), which cannot be captured by current turbulence models. Furthermore, WRF's terrain-following coordinate system is inappropriate for high-resolution simulations that include buildings.

To address these issues, we are implementing significant modifications to the ARW core of the Weather Research and Forecasting model. First, we are implementing an improved turbulence model, the Dynamic Reconstruction Model (DRM), following Chow et al. (2005). Second, we are modifying WRF's terrain-following coordinate system by implementing an immersed boundary method (IBM) approach to account for the effects of urban geometries and complex terrain. Companion papers detailing the improvements enabled by the DRM and the IBM approaches are also presented (by Mirocha et al., paper 13.1, and K.A. Lundquist et al., paper 11.1, respectively).

This overview of the LLNL-UC Berkeley collaboration presents the motivation for this work and some highlights of our progress to date. After implementing both DRM and an IBM for buildings in WRF, we will be able to seamlessly integrate mesoscale synoptic boundary conditions with building-scale urban simulations using grid nesting and lateral boundary forcing. This multi-scale integration will enable high-resolution simulations of flow and dispersion in complex geometries such as urban areas, as well as new simulation capabilities in regions of complex terrain.

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2. MOTIVATION

2.1 Dynamic Reconstruction of Subfilter-scale Turbulent Stresses

Recent advances in computational capabilities and resources have increased the horizontal resolution for many standard numerical weather prediction simulations. For example, as of September 2007, the US National Centers for Environmental Prediction provides regular forecasts for the continental United States with 12 km horizontal resolution from their North American Meso (NAM) model, and 4km or even ~ 1 km resolution simulations are often reported in the literature. At the UK Met Office, testing of the 4km version of the Unified Model was underway in December 2006 (Galvin, 2006). As models are run at higher resolution than perhaps originally envisioned when some model parameterizations were developed, some of the underlying physics represented in those parameterizations become inappropriate. This problem has been recognized notably for convection parameterization. In some cases, multi-scale convection was both parameterized and resolved explicitly, resulting in "double-counting" of the convection energetics among other problems (Gerard and Geleyn, 2005).

Similar difficulties arise in the regime of turbulence modeling as well. A scalar eddy-diffusivity model is usually assumed, which requires a balance of the production and dissipation of turbulence within a given grid cell, hence assuming horizontal advection is negligible. With increasing resolution, however, the length scale of the energetic eddies being simulated can approach the order of the grid scale of the model used for the simulations. Then, the assumption that the horizontal advection of turbulence is negligible compared to vertical motions becomes invalid. A tensor form, which allows for horizontal motions, rather than a scalar form for eddy diffusivity may be more appropriate (Wyngaard, 2005).

The importance of horizontal advection becomes apparent when considering flow through an urban environment. As the buildings in an urban area shed vortices and break large eddies up into smaller ones, TKE is produced. A significant portion of this TKE is often carried downwind to be dissipated away from the site of its production. Horizontal motions carry significant amounts of

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TKE, and dissipation of TKE can greatly exceed the local production of TKE.

Observations collected in an urban environment verify this hypothesis. During the Joint Urban 2003 (JU2003) field program, a profile of eight sonic anemometers was located about 500m downwind of the central business district (Allwine et al., 2004). In Lundquist and Chan (2007), turbulence kinetic energy budget profiles are calculated from data collected at this platform. For every time period investigated, the largest term of the TKE budget is the residual term, which includes the horizontal advection of TKE as well as any errors in the data processing. With scrupulous accounting for errors, the dissipation of TKE and the advection of TKE are found to be the dominant terms in the TKE budget (see Fig. 1), indicating that a form for eddy diffusivity that allows for significant horizontal transport is required when simulating the urban environment at resolutions on the order of 1 km or higher.

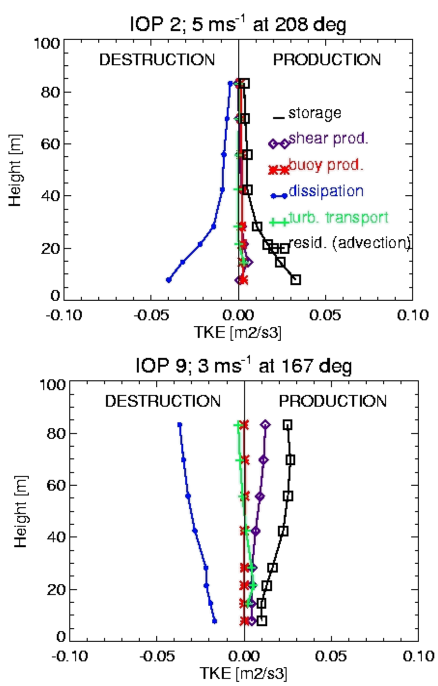

Figure 1: Profiles of the turbulence kinetic energy budget as measured at the JU2003 crane pseudo-tower for a daytime (IOP2, top) and a nighttime (IOP9, bottom) case. The mean wind speed and wind direction during the first continuous release of each IOP is noted in the title of each figure. For all IOPs, the dissipation rate is very large. The residual term, also large for all IOPs, consists of advected turbulence, the pressure transport of turbulence, and accumulated errors from the estimation of the other terms. (Following Lundquist and Chan, 2007, *Journal of Applied Meteorology and Climatology.*)

The Dynamic Reconstruction Model of Chow et al. (2005) offers possibilities for restoring local imbalances. Explicit filtering and reconstruction are used to improve the representation of the resolvable subfilter-scale (RSFS) stresses, and a dynamic eddy-viscosity model is used for the subgrid-scale (SGS) stresses. A companion paper (Mirocha et al., paper 13.1) discusses the DRM implementation in WRF in greater detail. The dynamic eddy-viscosity model of Wong and Lilly (1994) is used for the SGS component in the combined DRM closure, but can also be used as a stand-alone eddy-viscosity model. Additionally, we are implementing the nonlinear backscatter model of Kosović (1997) to improve representation of SGS motions under stably-stratified conditions.

The DRM implementation should be compared with existing capabilities in WRF. In WRF version 2.2, released December 2006, four subgridscale turbulence options are available, though only two of these options are considered useful in large-eddy simulation mode. A constant eddy coefficient option (km_opt=1), a 1.5-order TKE closure option (km_opt =2), and a Smagorinsky first order closure (km_opt=3) are available. Finally, use of a horizontal Smagorinsky closure (recommended for real-data case to complement the vertical diffusion calculated by WRF's PBL scheme) is available (km_opt = 4). The Smagorinsky first order closure and the 1.5 order TKE closures are considered here in comparison to DRM-WRF.

2.2 Immersed Boundary Method

WRF solves the equations of motion and executes its physics parameterizations on a structured grid with terrain-following coordinates. In regions of especially complex terrain, like the Cascade Mountain Range of the Pacific Northwest, it has been suggested that ~1 km grid spacing is required for resolution of mountain waves over narrow ridges in complex terrain (Garvert et al. 2005). With increasing terrain steepness, computational cells become distorted, making simulations of steep mountainous terrain difficult. For resolution of vertical walls on buildings, terrain-following coordinates are simply not possible.

The typical approach to resolve the effects of buildings on atmospheric flow utilizes building-resolving computational fluid dynamics (CFD) models, such as LLNL's FEM3MP (Gresho and Chan 1998, Calhoun et al. 2005) or CFD-Urban (Coirier et al. 2005; Coirier and Kim 2006a,b). These CFD codes solve the incompressible Navier-Stokes equations and allow limited options for representing atmospheric processes such as differential surface heating, atmospheric stability, or moisture-driven processes. Furthermore, CFD models are typically forced with simplified boundary conditions that fail to include important regional-scale phenomena that can strongly influence the flow within and downwind of the urban complex.

The incorporation of time-evolving boundary conditions into a CFD model is typically difficult (Chan, 2004; Chan and Leach, 2004).

These constraints can undermine the utility of CFD simulations, particularly in complex mesoscale conditions. For example, the Joint URBAN 2003 dataset yields two very different cases of mesoscale phenomena nocturnal low-level jets (LLJs) interacting with the Oklahoma City urban geometry. (These cases are discussed in more detail in Lundquist and Mirocha, 2007). Although the WRF model captures the wind speed profile of both LLJs as observed by a boundary-layer wind profiler (see Figure 2), a CFD model is unable to capture the complex turbulence profile observed with sonic anemometers downwind of the central business district in the case of IOP8.

Turbulence observations (see Lundquist and Mirocha (2007)) support the hypothesis that the failure of the CFD model in the JU2003 IOP 8 case is due to complex interactions between the turbulence propagating down from the nocturnal LLJ and the mechanically-generated turbulence induced by urban geometry. For this case, accurate simulation of flow in the urban area would also require simulation of the time evolution of the LLJ. Of course, not all cases demand representation of such a broad spectrum of physical processes. As also seen in Figure 2, the IOP 9 case is well-simulated by both the WRF model and the CFD model, due to limited vertical propagation of turbulent mixing from the LLJ.

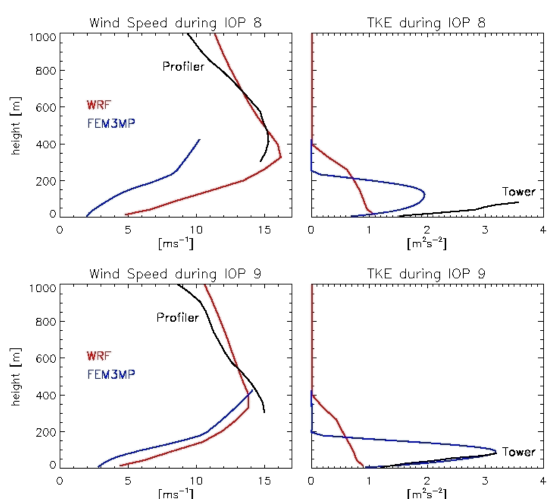

Figure 2: Simulations and observations of wind speed (left, from a 915 MHz boundary-layer wind profiler) and turbulence kinetic energy (right, from the LLNL pseudo-crane profile of 8 sonic anemometers) for the Joint URBAN 2003 IOPs 8 (top) and 9 (bottom). Simulations and observations are those discussed in Lundquist and Mirocha (2007).

Accounting for the complex and rapidly evolving mesoscale behavior as well as the dynamics induced by the urban geometries can be accomplished with our new developments in WRF. Our approach is to explicitly resolve urban terrain in the innermost nest of a nested mesoscale model via an immersed boundary method (IBM). This method uses a non-conforming structured grid, and allows solid boundaries to pass through the computational cells. As the terrain passes through the mesh in an arbitrary manner, the main goal of the IBM is to apply the boundary condition on the interior of the domain as accurately as possible. The outer nests provide evolving mesoscale information, via boundary conditions, to the innermost IBM nest. A companion paper (K.A. Lundquist et al., paper 11.1) discusses the IBM implementation in WRF in greater detail.

3. RESULTS

3.1 Dynamic Reconstruction of Subfilter-scale Stresses: neutral flow over flat, rough terrain

The DRM model has been compared to WRF's native SGS models using idealized simulations of neutral flow over both flat terrain and a two-dimensional hill. Only results from the former case are presented herein; the companion paper (P13.1) of Mirocha et al. (2007) includes discussion of flow over a two-dimensional hill. The simulations (42^3 gridpoints) encompass a domain of approximately 1300 m (x) by 1300 m (y) by 1500 m (z), with a horizontal grid spacing of 32 km. The vertical grid is stretched from approximately 5m near the surface to approximately 50m at the top of the domain. The dynamic Wong-Lilly subgrid model is used in these DRM simulations (Wong and Lilly 1994).

Neutrally-stable flow over a flat, rough surface allows comparison to a theoretical solution, the logarithmic wind speed profile (the so-called "log-law") as well as comparison to WRF's native subgrid models. Figure 3 shows the vertical profile of wind speed versus height for the Smagorinsky subgrid model, the 1.5-order TKE closure, and the DRM model compared with the expected log law. The DRM simulations agree most closely with the log-law in the surface layer.

DRM-WRF simulations also show significant qualitative differences from the Smagorinsky and TKE subgrid model results. Figure 4 depicts horizontal cross-sections of zonal velocity at ~20m elevation using the 1.5-order TKE, Smagorinsky, and the DRM closures. Note the reduction of unphysical elongated streaks in the streamwise direction by the DRM model, due to the backscatter of energy allowed from small to large scale (through the velocity reconstruction and dynamic SGS model components). The Smagorinsky and 1.5-order TKE closures are known to be overly dissipative in the near-wall region. DRM-WRF is thus likely more appropriate for scenarios where backscatter of energy is important, such as in urban or complex terrain and in cases of stable stratification.

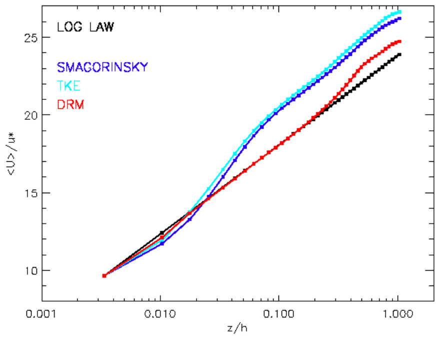

Figure 3: Dimensionless wind speed versus normalized height for neutral boundary layer flow simulations. Note that the log-law is considered valid in the surface layer, the lowest 10-15 points in this simulation.

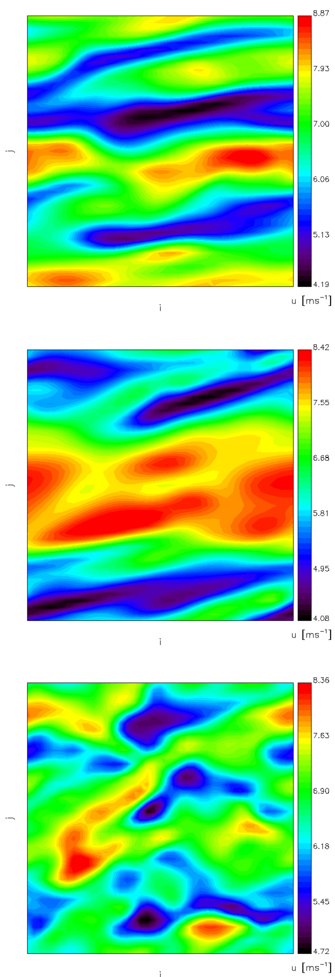

Figure 4: Horizontal cross sections of the u velocity component at ~20m for flat plate simulations using TKE (top), Smagorinsky (center), and DRM with Dynamic Wong-Lilly (bottom) turbulence closures

The results of this idealized test case verify the DRM-WRF approach. Other tests explore the performance of DRM-WRF in more complex scenarios, such as the flow over a 2-dimensional hill case discussed in Mirocha et al., 2007.

3.2 Immersed Boundary Method: neutral flow over flat terrain and 2-dimensional complex terrain

When accommodating urban terrain with IBM, grid points are not required to align with terrain or building boundaries. Rather, an interpolation method is used to determine the forcing at computational nodes. This procedure is often called boundary reconstruction. Within the framework of the IBM, several approaches to reconstructing velocities in the vicinity of terrain are possible. To represent stress at a rough boundary, the velocity reconstruction method of Senocak et al. (2004) was tested along with a new model that reconstructs shear stress (K. A. Lundquist, 2006). Both of these models represent rough surfaces by employing wall models based on the log-law. With the exception of these two models, all IBM models to date enforce a no-slip boundary condition for viscous flows that is inappropriate for the tough bottom boundary in atmospheric boundary layer flows.

As a first test case, multiple implementations of IBM were compared to native terrain-following WRF for three-dimensional neutral boundary layer flow similar to that described in section 3.1. The flow is driven by a geostrophic wind of 10 ms^{-1}. The surface roughness is 0.1m. The vertical grid is stretched from approximately 5m near the surface to approximately 50m at the top of the domain. The setup is similar to that of Andren et al. (1994). Figure 5 shows that the new shear-stress reconstruction IBM more closely agrees with native WRF simulations than does the velocity reconstruction IBM. Recall that, here, the goal is to match native WRF, not the log-law as with the DRM-WRF example above. The subgrid turbulence model controls how close a simulation can approximate the log-law. WRF's Smagorinsky closure, which does not match the expected log-law profile, is used for all simulations here.)

The "terrain" introduced by the flat plate can be represented appropriately with IBM-WRF with no deviation from what would be simulated with native WRF. The small differences seen in Fig. 5 are due to the different grid stretching in the IBM and non-IBM cases resulting from the different representations of the terrain.

A more challenging test case for our IBM implementation is that of flow over a 2-dimensional square ridge, shown in Figure 6. Periodic boundary conditions with steady pressure gradient forcing are used. Because native WRF cannot represent vertical terrain surfaces with terrain-following coordinates, comparison to native WRF is not possible. Realistic effects, such as a lee vortex, appear in this simulation. Although streamlines within the topography are shown here to illustrate the IBM implementation, flow within the solid domain would normally be ignored.

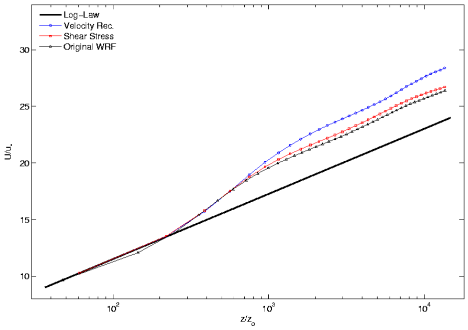

Figure 5: Non-dimensional mean velocity for neutral flow over flat terrain on a semi-log plot for IBM with velocity reconstruction, IBM with shear stress reconstruction, and original terrain-following WRF.

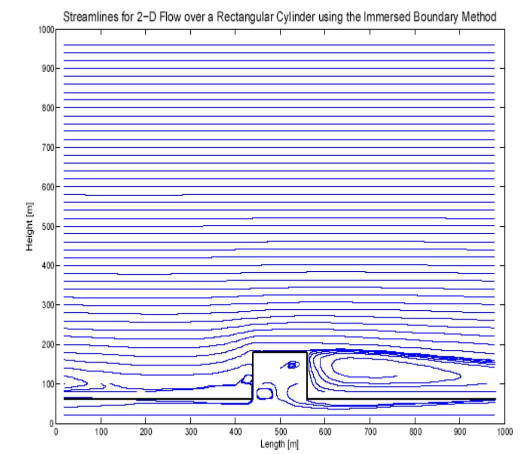

Figure 6: Streamlines from two-dimensional IBM-WRF for flow over a 2-d square ridge in a neutral atmosphere with periodic boundary conditions forced by a constant pressure gradient.

4. SUMMARY AND NEXT STEPS

Analysis of urban observations has demonstrated a need for both improved turbulence modeling and improved gridding capabilities for high-resolution simulations in the urban environment. Our team is expanding the capabilities of the community-supported Weather Research and Forecasting model for urban and complex-terrain applications. We anticipate applications including transport and dispersion in urban environments as well as high-resolution forecasting in regions of complex terrain.

Our DRM-WRF modifications have been tested on both simple cases (as presented herein) and on cases involving terrain (as presented in companion paper 13.1). Subsequent testing will include verification of the kinetic energy spectra, following Skamarock (2004) and verification against observations from the JU2003 field experiment and other observational datasets including a range of stability conditions and complexity of surfaces. We expect the most significant improvements to be in cases of stable atmospheric conditions or moderately complex terrain. DRM-WRF is intended for public release.

IBM-WRF, currently distinct from DRM-WRF, has been tested in 3d over flat terrain, and in 2d over complex terrain, including a square ridge and real building data (see companion paper 11.1). IBM-WRF will be extended to three dimensions over complex terrain before being merged with DRM-WRF. Future IBM tests will involve both meteorology and tracer release data from the JU2003 dataset.

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