13.1 IMPROVED SUBFILTER TURBULENCE MODELING FOR LARGE EDDY SIMULATION USING WRF

J. D. Mirocha*[1], F. K. Chow[2], J. K. Lundquist[1] and K. A. Lundquist[2]
[1]Lawrence Livermore National Laboratory
[2]University of California, Berkeley

1. INTRODUCTION

A new suite of models for representing subfilter-scale (SFS) turbulence stresses has been implemented into the Weather Research and Forecasting (WRF) model for improved large eddy simulation (LES) capability. Our dynamic reconstruction SFS stress model (DRM) is based upon reconstruction of the resolvable subfilter-scale (RSFS) stresses combined with separate subgrid-scale (SGS) eddy viscosity models. The DRM includes a module for reconstructing the RSFS stresses, a dynamic subgrid eddy viscosity (SGS) model and a near-wall stress model (following Chow et al, 2005).

The DRM SFS models are physically based, permit backscatter of energy, and do not assume a local balance between turbulence production and dissipation (as many SFS models do). As such, our models are well suited to simulating flow over complex terrain, including urban environments, where turbulence production and dissipation are frequently not in local balance. Further discussion of turbulence modeling requirements in urban flows is given in a companion paper (J. K. Lundquist et al. 2007).

Here we present a brief overview of the turbulence modeling approach as well as results from simulations in the WRF model for neutral boundary-layer flow over both flat terrain and an isolated two-dimensional hill.

2. BASIS OF THE DRM TURBULENCE MODEL

The large eddy simulation technique is based on application of a low-pass filter to the flow field equations. This filter separates the fields into a resolved component that is advanced using the filtered governing equations and a subfilter component that is parameterized in an SFS model.

The standard configuration of the WRF model contains no explicit low-pass filter, hence the grid implicitly provides the filtering that separates the fields into resolved and subgrid components. The effects of all unresolved motions on the resolved-scale fields are modeled as one piece using one of WRF's two SGS eddy-viscosity models.

Our DRM model is instead based on velocity partitioning, also known as explicit filtering with reconstruction (Gullbrand and Chow, 2003). We apply a smooth, explicit (tophat) filter with a width twice that of the grid spacing to the flow field variables to separate those into resolved and subfilter components and to help reduce errors arising from finite difference operators. The application of an explicit filter is separate from the discretization effects inherent in finite-difference schemes. The discretization can be interpreted as an implicit operator that separates the subfilter-scale portion of the velocity into two subregions, one containing motions that are smaller than the grid (subgrid scales) and another that exists between the grid and the filter (see Figure 1).

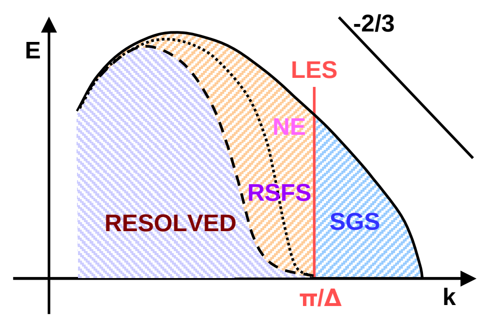


Figure 1: Idealized partitioning of spectral energy during LES. The solid line depicts the full energy spectrum for a turbulent flow. The explicit filter (dashed line) improves representation of the resolved component by damping numerical errors due to finite differencing. The velocities in the RSFS region can be reconstructed using inverse filtering, up to the limit of numerical errors arising from the discrete solver (NE, dotted line). The vertical line shows the grid cutoff, π/Δ. The effect of motions beyond the grid cutoff on the resolved scales is represented with an SGS model. (Figure adapted from Chow et al, 2005).

The motions contained in the latter category are, in principle, resolvable on the grid, hence denoted as resolvable subfilter-scales (RSFS). The RSFS motions are modeled separately from the subgrid scales using a velocity reconstruction approach. This approach approximates the inverse of the explicit filter using a series expansion to reconstruct the unfiltered velocity from the resolved (filtered) velocities (Stoltz and Adams, 1999). These velocities are then used to compute the

*Corresponding author address: J. D. Mirocha, Lawrence Livermore National Laboratory, P.O. Box 808, L-103, Livermore, CA 94551, e-mail: **jmirocha@llnl.gov**.

RSFS portion of the total SFS stress. The RSFS stresses are then added to the SGS stresses that represent stresses beyond the resolution of the grid. The SGS stresses are modeled using an eddy-viscosity formulation.

While the RSFS component of the SFS stress can (and should) be included in any discrete SFS model, deficiencies in currently-used SGS models may limit the effectiveness of the combined SGS/RSFS approach. For example, static Smagorinsky and 1.5-order TKE eddy-viscosity closures tend to be overly dissipative. To avoid the limitations of these models we have implemented an improved SGS model, the dynamic model of Wong and Lilly (1994). This model (denoted DWL) determines the eddy viscosity as a function of time and space using stresses computed on both the original mesh and a test mesh of width 2Δ using the least squares approach of Lilly, 1992. The eddy diffusivity coefficients are smoothed using a filter and negative values are clipped at -1.5e-5. This stabilizes the model while still allowing for local backscatter of energy. An additional near-surface stress is added for $z < 4\Delta$ to augment the SGS stresses provided by the DWL, since the dynamic procedure is known to underestimate near-surface stresses. Further discussion of the DRM and its components can be found in Chow et al, 2005.

3. RESULTS

The DRM model is compared to results obtained from WRF's standard SGS models using idealized simulations of neutral flow over flat terrain and a two-dimensional hill. Each simulation was advanced using a constant, uniform geostrophic wind of 10 m/s in the x-direction and a surface stress given by the log law using a roughness of 0.1m. The simulations were conducted using a domain of 1312m in each horizontal direction and a height of 1500m with 42 gridpoints in each direction. The mesh spacing was 32m in each horizontal direction while the vertical grid was stretched from ~5m near the surface to ~50m at the domain top.

3.1 Neutral boundary-layer flow over flat terrain

Neutral flow over flat terrain allows comparison to a similarity solution which predicts a logarithmic vertical distribution of wind speed (the log law) in the near-surface layer. Figure 2 shows the vertical distribution of wind speed versus height using the Smagorinsky, TKE and DRM closures compared to and the log law. The profiles were averaged at 20-minute intervals for 24 hours after 24 hours of spinup to achieve statistical equilibrium. Figure 2 clearly demonstrates superior agreement of the DRM with the log law.

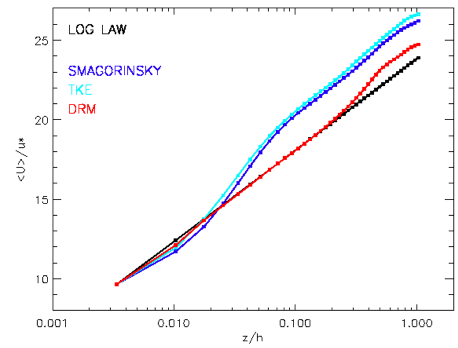
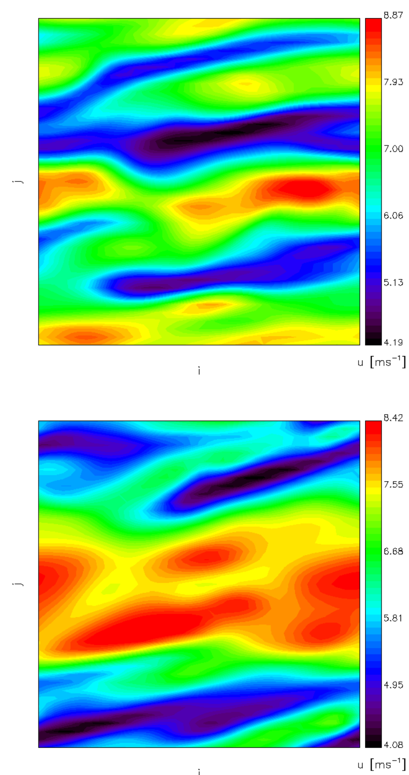


Figure 2: Dimensionless wind speed versus normalized height for simulations of neutral boundary-layer flow over flat-terrain.

Shown in Figure 3 are horizontal cross-sections of zonal velocity at ~50m using the TKE (top) and Smagorinsky (middle) SGS and the DRM (bottom) closures. Noteworthy are the reductions in streakiness in the streamwise direction as well as increased small-scale variability afforded by the DRM model. The DRM allows backscatter of energy from small to large scales and thus does not form the large coherent structures observed with the standard eddy-viscosity closures. The improvements in prediction of neutral boundary layer flow indicate the potential of the DRM to enhance WRF's applicability to LES of urban flows. Backscatter of energy is particularly important under stably-stratified conditions and for flow over complex terrain.



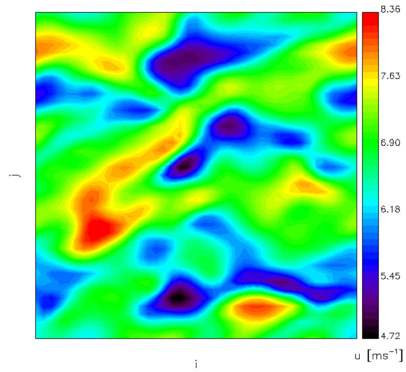


Figure 3: Horizontal cross sections of u velocity at ~50m for simulations of neutral boundary-layer flow over flat terrain using TKE (top), Smagorinsky (middle) and DRM (bottom) turbulence closures.

3.2 Flow over a 2-D hill

The implementation of the DRM over idealized terrain was validated using simulations of flow over a symmetric 2-D hill. The 2-D hill simulations used the same parameters as the simulations conducted over flat terrain except for the introduction of a Gaussian hill which is defined by sloping terrain in the x-direction and constant height (maximum 100m) in the y-direction. These simulations were run for three hours for demonstration purposes, hence the flow had not yet reached a statistically steady state. However several significant differences between the DRM and the Smagorinsky and TKE SGS models are already clearly identifiable.

Figure 4 shows the geometry of the surface terrain (note the compressed vertical axis which makes the hill appear taller and steeper than it is) as well as the existence of well-defined eddy structures in the lee of the hill. These and similar features indicating the existence of recirculation vortices, are observed regularly throughout the latter two hours of the

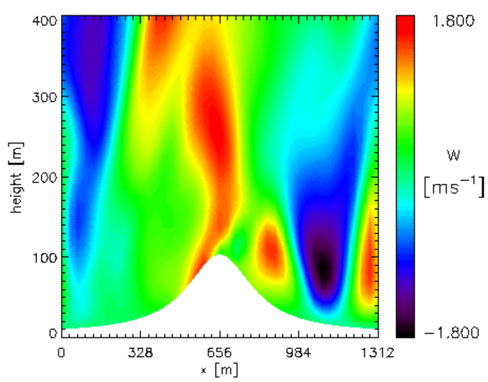


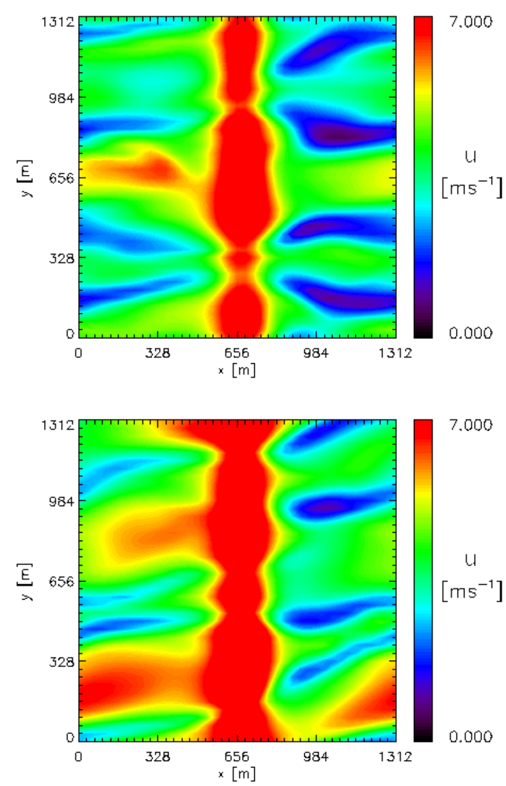
Figure 4: Contours of w-velocity in the x-z plane showing both the terrain geometry as well as the well-defined vortices in the lee of the hill produced by the DRM.

simulations using the DRM. Each of the standard WRF SGS models, in contrast, produce comparatively much weaker, shallower and more intermittent recirculation patterns (not shown).

Figure 5 shows cross-sections of the u-velocity in the horizontal plane using the TKE (top), Smagorinsky (middle) and DRM (bottom) closures at ~25m above the ground surface. As with the flat terrain simulations, each of the standard WRF SGS models again results in the prediction of elongated streaks in the streamwise direction that are not replicated by the DRM. In addition, while the standard WRF schemes produce minimal negative velocities indicative of recirculation in the lee of the hill, the DRM produces several regions of strong reverse flow (note the different contour levels).

4. CONCLUSIONS

The simulations described herein demonstrate the implementation of an improved SFS model for use in large eddy simulations with WRF. While these simulations are idealized, they provide a framework for careful validation of the implementation as well as a straightforward basis for the interpretation of the resulting simulation differences in the absence of complicating factors. The improvements obtained from the DRM in these idealized settings justify confidence that similar improvements will emerge from future validation experiments using more complicated real-world atmospheric forcing and surface terrain.



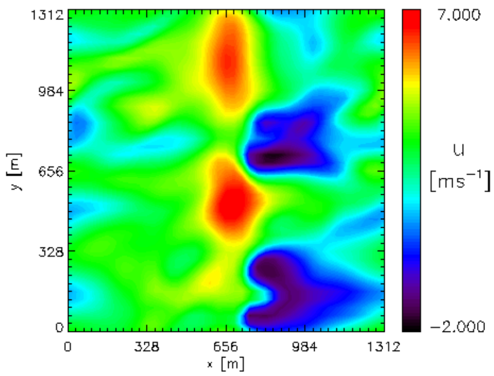


Figure 5: Contours of u-velocity at ~25m using the TKE (top), Smagorinsky (middle) and DRM (bottom) closures during simulations of flow over a 2-D hill.

7. REFERENCES

Chow, F.K., R. L. Street, M. Xue and J. H. Ferziger, 2005: Explicit Filtering and Reconstruction Turbulence Modeling for Large-Eddy Simulation of Neutral Boundary Layer Flow, *J. Atmos. Sci.*, 62, 2058-2077.

Lilly, D. K., 1992: A proposed modification of the Germano subgrid-scale closure method, *Phys.-Fluids*, 4, 633-635.

Lundquist, J. K., F. K. Chow, J. D. Mirocha and K. A. Lundquist, 2007: An Improved WRF for Urban-Scale and Complex terrain Applications. American Meteorological Society's 7th Symposium on the Urban Environment, San Diego, CA, Amer. Meteor. Soc., 4.4.

Stolz, S and N. A. Adams, 1999: An approximate deconvolution procedure for large-eddy simulation, *Phys.-Fluids*, 11, 1699-1701.

Wong, V. C., and D. K. Lilly, 1994: A comparison of two dynamic subgrid closure methods for turbulent thermal-convection, *Phys.-Fluids*, 6, 1016-1023.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. UCRL-CONF-234278.