Implementation of a log-law immersed boundary method for flow over steep terrain

Jingyi Bao[1], Katherine A. Lundquist[2], Fotini K. Chow[1]
[1]University of California, Berkeley, CA, USA, jingyib@berkeley.edu, tinakc@berkeley.edu
[2]Lawrence Livermore National Laboratory, Livermore, CA, USA, lundquist3@llnl.gov

Abstract
In this work, a new log law boundary condition for the immersed boundary method (IBM) is implemented and tested in WRF-IBM. Validation is carried out by direct comparison of WRF-IBM and standard WRF for neutral atmospheric boundary layer flow over flat terrain, and for the Askervein and Bolund field experiments.
Keywords: *WRF, Multi-scale simulation, Immersed boundary method*

Introduction

Mesoscale models, such as the Weather Research and Forecasting (WRF) model, are increasingly being used at higher resolutions. A grid nesting framework, which uses multiple telescoping grids of increasing resolution, provides the ability to pass information across scales, which is important for wind energy prediction. As the grid resolution increases, so does the resolved terrain slope, posing a challenge to the terrain-following coordinates used by WRF and other mesoscale models. An immersed boundary method (IBM) was previously implemented into WRF (1,2). The IBM uses non-conforming coordinates with the terrain boundary "immersed" in the grid. Boundary conditions are set for grid cells intersected by the immersed surface. In this work, we extend WRF-IBM to include a boundary condition which parameterizes surface stresses in the unresolved surface layer using Monin-Obukhov (M-O) similarity theory. We initially consider only neutral stability, in which case M-O theory simplifies to the commonly known "log law".

Method

The surface treatment used in this work is known as direct forcing. With this method, the velocity or the shear stress value is modified at the points near the boundary to enforce the correct boundary condition. The velocity is reconstructed at the first fluid node outside of the immersed surface, as represented by the open circle in Figure 1. Fadlun (3) used linear interpolation between a point in the fluid and a no-slip boundary condition at the surface to reconstruct the velocity at a layer of fluid points outside of the immersed surface. Choi (4) suggested a similar method where the log law is used to reconstruct the velocity at the first fluid node. Assuming that multiple nodes reside within the logarithmic layer, and that u_* is constant within this region, Equation 1 can be used to calculate the velocity at the first fluid node based on the velocity at the second fluid node above the surface.

$$U_1 = U_2 \frac{ln\frac{z_1}{z_0}}{ln\frac{z_2}{z_0}} \qquad [1]$$

Figure 1 illustrates the method as implemented in WRF-IBM. Here, velocity is reconstructed at the first fluid node U_1 above the immersed boundary for each cut cell. An interpolation point U_i is found based on projecting the surface normal vector outward until it intersects a cell containing only fluid nodes, so that U_1 and U_i are normal to the immersed boundary. This scheme then uses the equation above to calculate the value of U_1 at each cut cell, where U_2 and z_2 take values from the interpolated point.

Validation and Results

Test cases include neutral atmospheric boundary layer flow over flat terrain and simulations of the Askervein and Bolund field experiments, to evaluate the performance of the log-law surface treatments in WRF-IBM over complex terrain. Direct comparisons between standard WRF and WRF-IBM with the log-law boundary condition are made for the flat terrain and Askervein cases, where the slopes are shallow enough for WRF with its standard terrain following coordinates. Figure 2 shows the averaged velocity profile over Askervein hill. WRF-and WRF-IBM agree well. For the Bolund experiment, the slopes are too steep for standard WRF, so the WRF-IBM results are compared to field data and other previous simulations only.

Conclusions

The results indicate that the velocity reconstruction method, newly implemented into WRF-IBM is able to reproduce the results of WRF using terrain-following coordinates for both flat terrain and mildly complex terrain (including good comparison to field data from the Askervein experiment). For steep terrain (Bolund experiment), which is too steep for standard WRF, the velocity reconstruction method is able to generate good results compared to observations. [This work is part of WFIP 2 (Wind Forecasting Improvement Project 2) funded by the DOE EERE Wind Energy Technologies Office.]

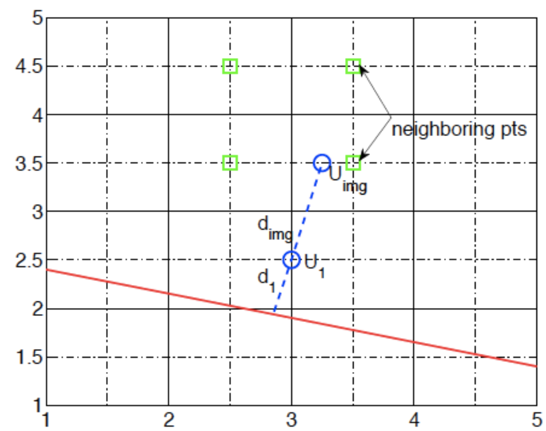

Figure 1. Schematic of velocity reconstruction log-law immersed boundary method.

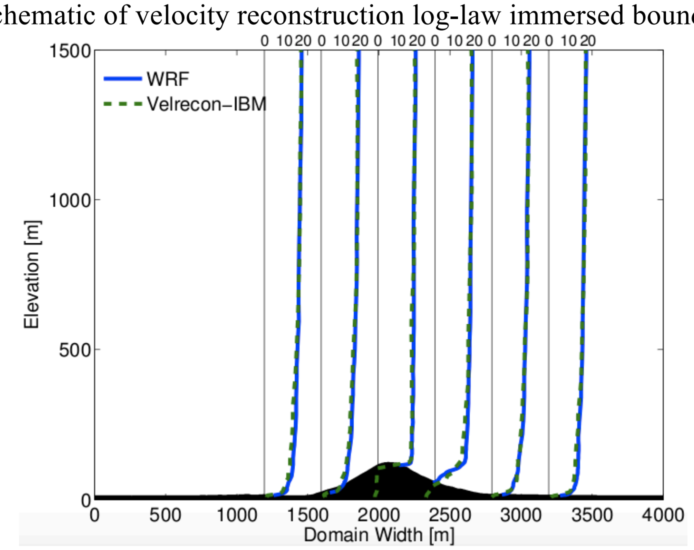

Figure 2. Wind profiles over Askervein Hill for WRF and WRF-IBM with velocity reconstruction.

References

1. Lundquist, K. A., Chow, F. K., and Lundquist, J. K. (2010). An Immersed Boundary Method for the Weather Research and Forecasting Model. Monthly Weather Review, 138(3):796–817.
2. Lundquist, K. A., Chow, F. K., and Lundquist, J. K. (2012). An Immersed Boundary Method Enabling Large-Eddy Simulations of Flow over Complex Terrain in the WRF Model. Monthly Weather Review, 140(12):3936–3955.
3. Fadlun, E. A., Verzicco, R., Orlandi, P., and Mohd-Yusof, J. (2000). Combined Immersed-Boundary-Finite-Difference Methods for Three-Dimensional Complex Flow Simulations. Journal of Computational Physics, 161:35–60.
4. Choi, J.-I., Oberoi, R. C., Edwards, J. R., and Rosati, J. A. (2007). An Immersed Boundary Method for Complex Incompressible Flows. J. Comput. Phys., 224(2):757–784.