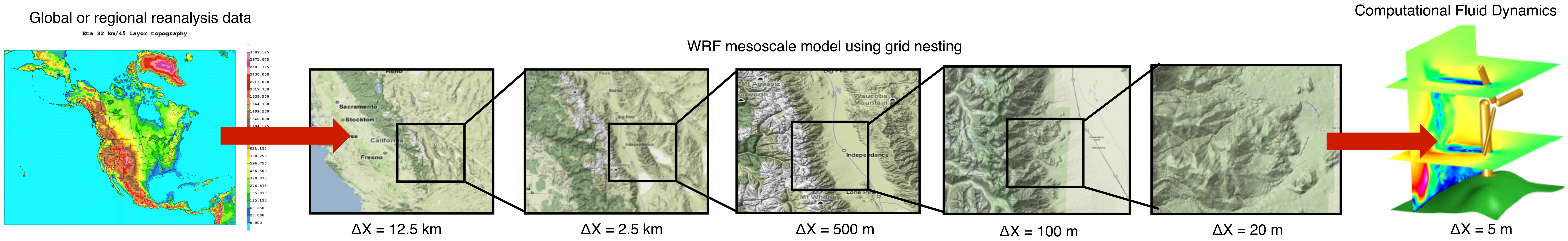
Enabling high-resolution simulations of atmospheric flow over complex terrain in the WRF model

K.A. Lundquist[1], J.D. Mirocha[1], J. Bao[2], D.J. Wiersema[2], and F.K. Chow[2]

[1]Lawrence Livermore National Laboratory, [2]University of California, Berkeley

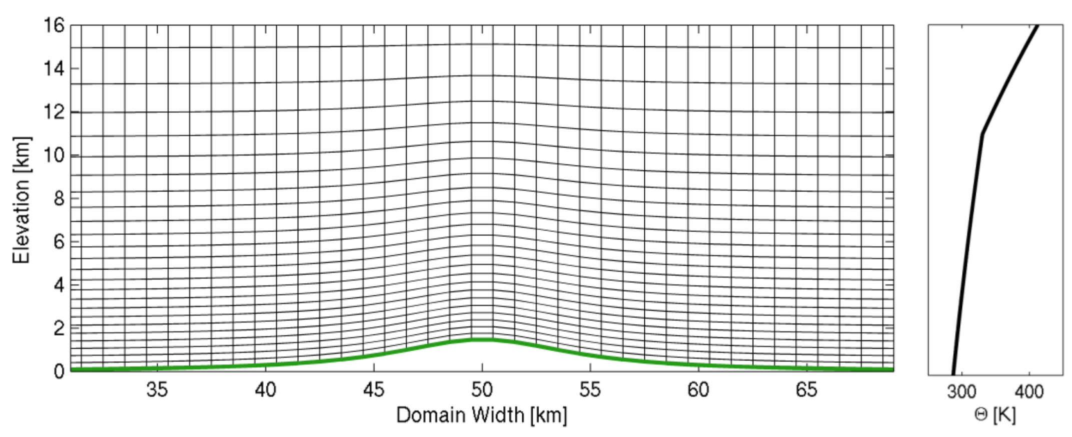
1. Motivation

The current approach to multi-scale atmospheric modeling is to use reanalysis data to provide boundary conditions to a mesoscale model, such as the Weeather Research and Forecasting (WRF) model. Grid nesting is used within the mesoscale model to provide higher-resolution simulations of a geographic region. The mesoscale model provides boundary conditions to a traditional computational fluid dynamics model, which provides high-resolution simulations.



2. Challenges with Grid Nesting

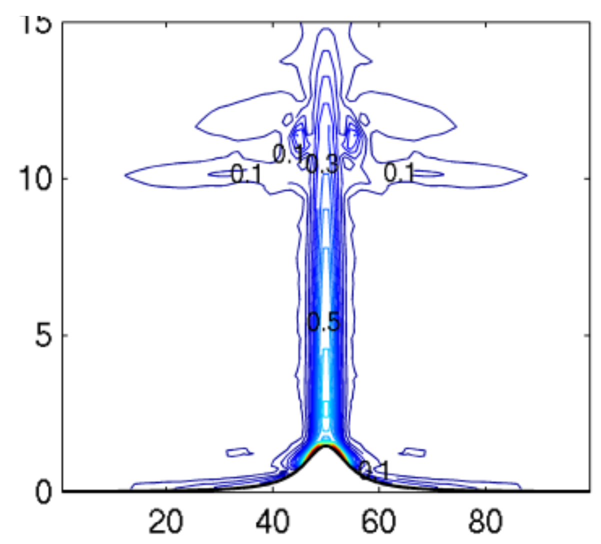
The current approach to multi-scale modeling is inadequate because the terrain-following coordinates used by mesoscale models introduce numerical errors when complex terrain is present.



Case study:
- Atmosphere at rest
- Stable temp. sounding
- 3D hill, no forcing
- 10 degree slope (not very steep)
- ΔX = 1 km (not very high resolution)
- Integrate for 24 hrs

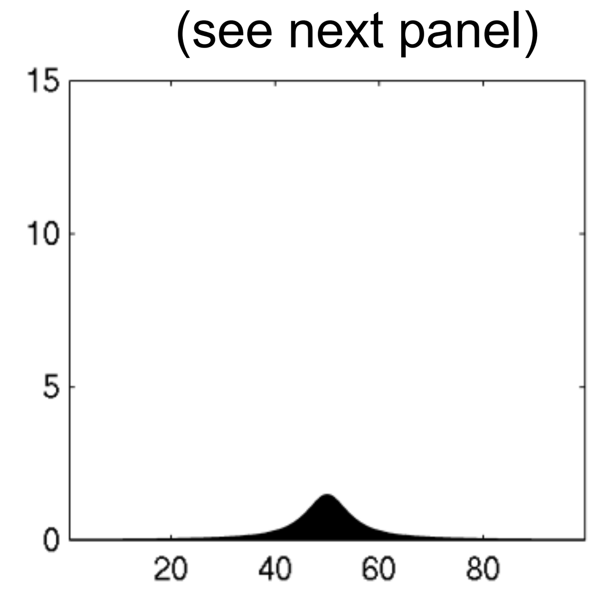
No Flow Should Develop!

WRF with terrain-following coordinates



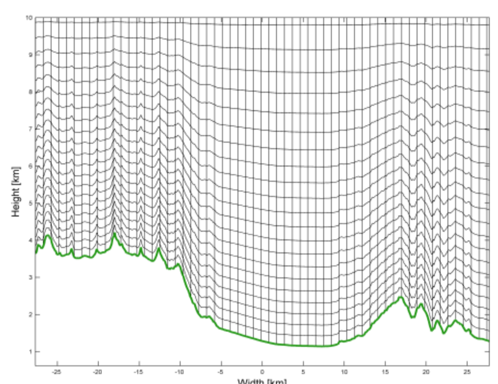
Max velocity 1.7 m/s

Immersed Boundary Method (see next panel)

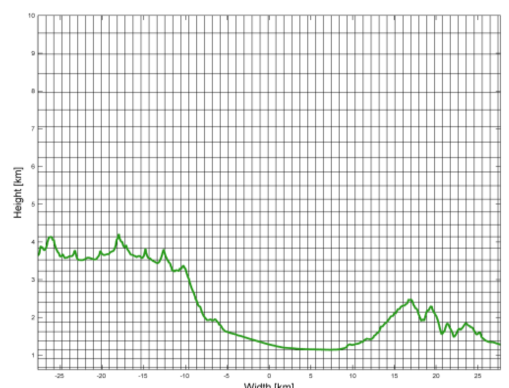


Max velocity 3.8 e-5 m/s

3. Alternative Grid for Complex Terrain



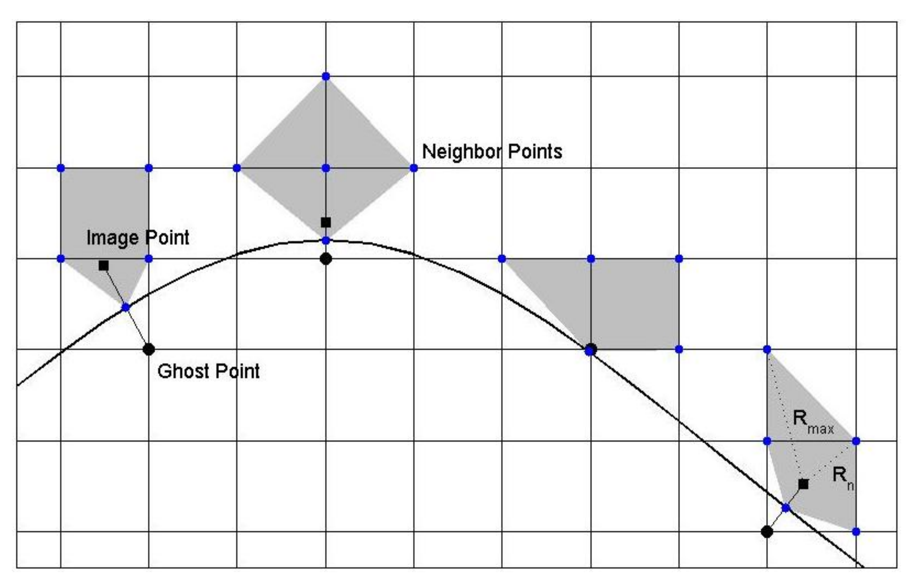
Terrain-Following Grid



Immersed Boundary Method Grid

The immersed boundary method is a non-conforming gridding technique that can be used to eliminate errors arising from skewed grids, as demonstrated in the case study in panel 2.

IBM adds a forcing term to the Navier-Stokes equations to account for the presence of terrain.



Conservation equations for mass, momentum, and scalars

$$\partial_t \rho + \nabla\cdot(\rho \mathbf{V}) = 0$$

$$\partial_t \mathbf{V} + \mathbf{V}\cdot\nabla\mathbf{V} = -\alpha\nabla p + \nu_t \nabla^2 \mathbf{V} + \mathbf{F}_B + \mathbf{F}_{IBM}$$

$$\partial_t \varphi + \mathbf{V}\cdot\nabla\varphi = \nu_t \nabla^2 \varphi + F_\varphi + F_{IBM}$$

Interpolant for the IBM

$$\varphi_{image} = \frac{\sum_n c_n \varphi_n}{\sum_n c_n} \qquad c_n = \left(\frac{R_{\max} - R_n}{R_{\max} R_n}\right)^p$$

Imposing immersed boundary conditions

Dirichlet

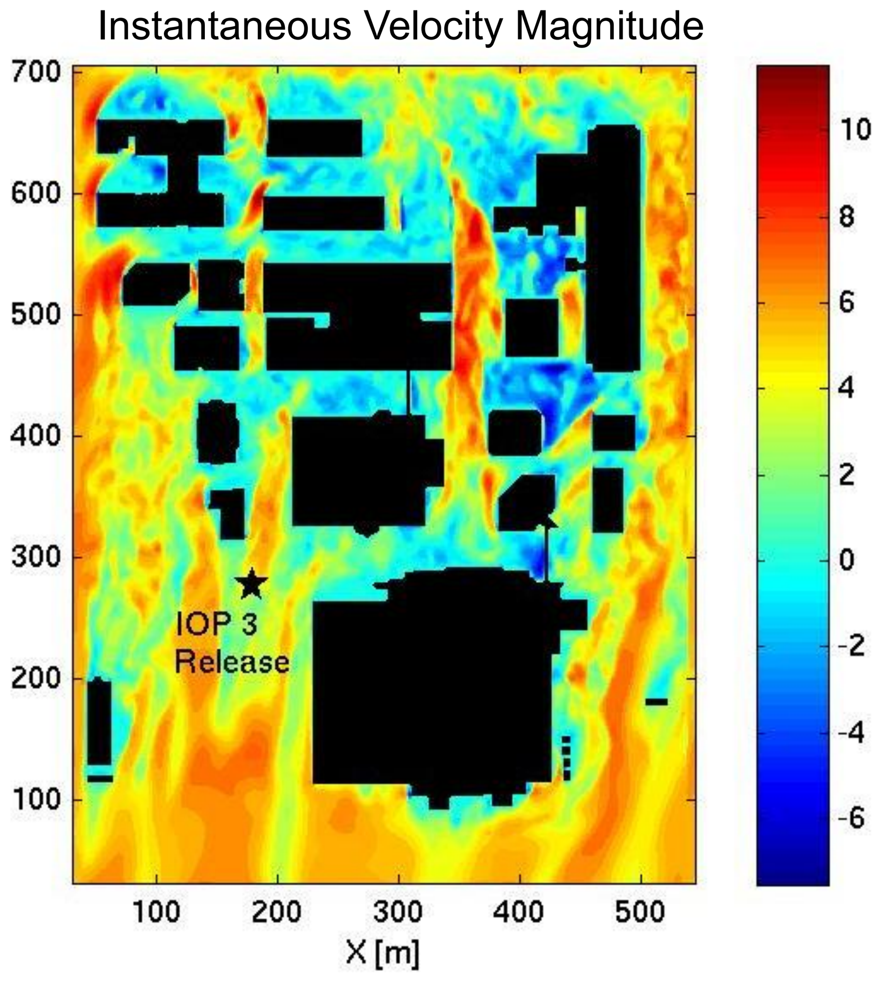
$$\varphi_{ghost} = 2\varphi_\Omega - \varphi_{image}$$

Neumann

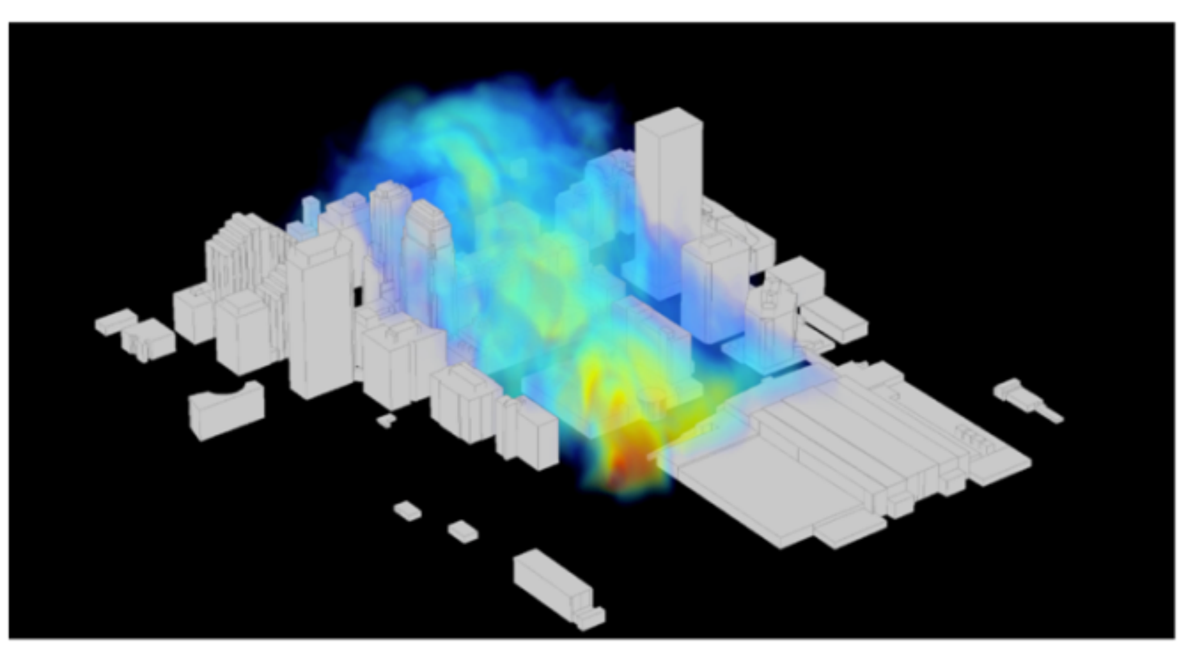
$$\varphi_{ghost} = \varphi_{image} - \overline{GI}\left.\frac{\partial \varphi}{\partial \mathbf{n}}\right|_\Omega$$

4. Validation and Current Work

Instantaneous Velocity Magnitude



IOP 3 from the Joint Urban 2003 field campaign is simulated, and results are compared with observations. A domain with Oklahoma City terrain is nested within a parent domain with flat terrain. Horizontal grid spacing is 2 m with 259x340x170 points on the urban domain. The 3D Smagorinsky turbulence closure is used.



Scalar Concentration

Common performance metrics used to assess model skill indicate that IBM-WRF performs equal to or better than commonly used CFD models.

	FAC2 or FAC5	FB	MG	NMSE	SAA
Perfect Model	1	0	1	0	0
IBM-WRF (Velocity Magnitude)	1.0 (FAC2)	-0.24	0.82	0.18	26.2
IBM-WRF (Scalar Concentration)	0.53 (FAC5)	-1.54	0.32	28.70	

FACx = Predictions within a factor of X
FB = Fractional bias
MG = Geometric mean bias
NMSE = Normalized mean square error
SAA = Scaled average angle

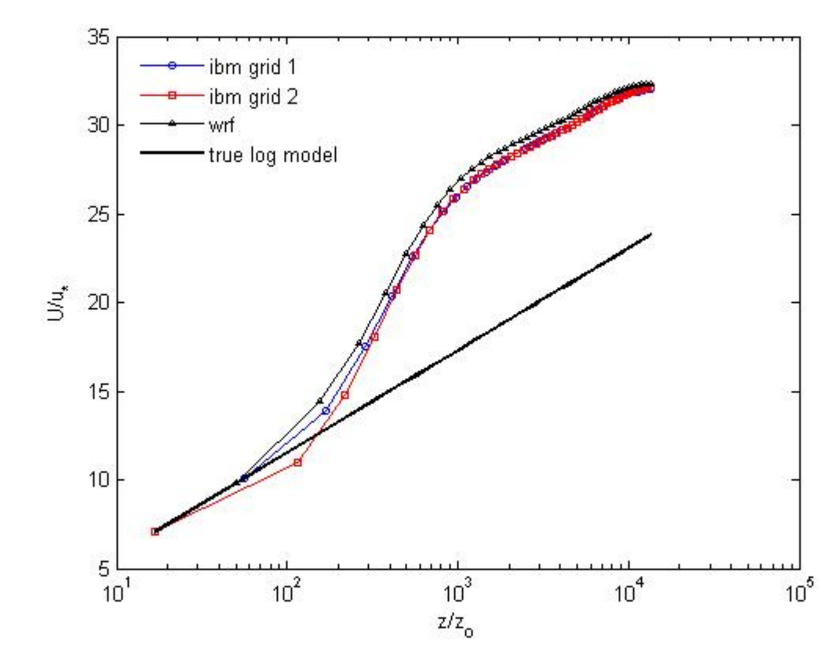
IBM-WRF is currently being extended to function seamlessly within the WRF framework. Current developments include:

- Development of a new boundary condition at the immersed terrain surface based on Monin-Obukhov similarity theory
- Development of an interface to nest IBM-WRF grids within native terrain-following WRF grids
- Initialization and forcing of IBM domains using standard meteorological and land-surface data

Surface fluxes of momentum are parameterized using Monin-Obukhov similarity theory. A Neumann boundary condition is set for velocity using:

$$\frac{\partial U}{\partial \eta} = \frac{u_*}{\kappa z}$$

$$U = \frac{u_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right)$$



The test case of a neutral atmospheric boundary layer shows excellent agreement between IBM and WRF using similarity theory at the surface. The 3D Smagorinsky turbulence closure is used here.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.