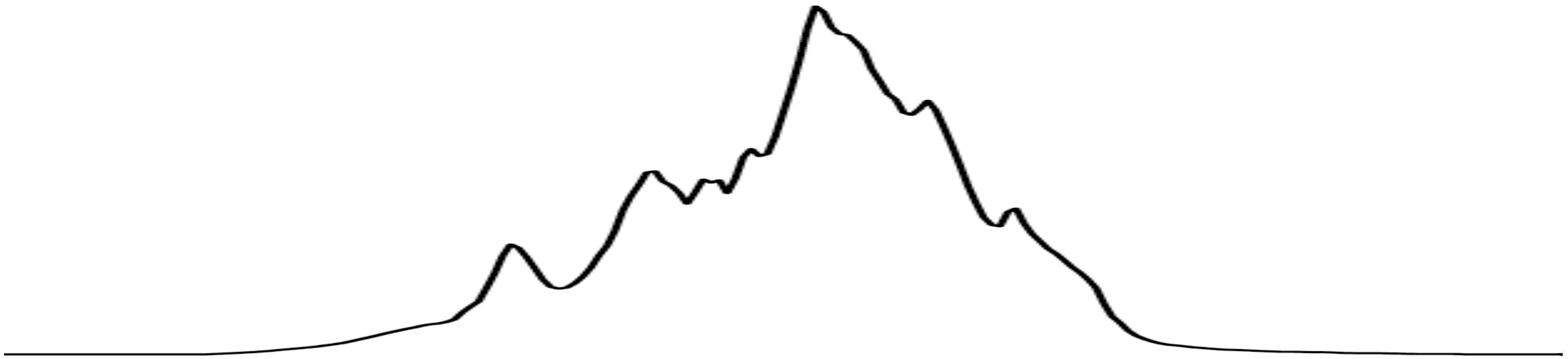
MATERHORN
The immersed boundary method for flow over complex terrain



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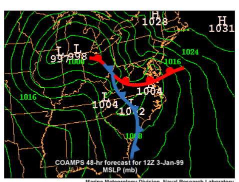
Overview

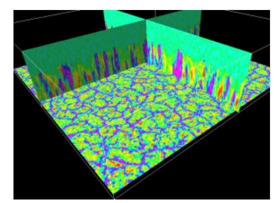
- Field work
- Owens Valley rotor simulations

- WRF-IBM for mesoscale to microscale
  - Terra incognita
- Log law implementation
  - Method development and testing
  - Comparisons with WRF
- Application to Granite Mountain
  - Preliminary results

Terra incognita

- Push mesoscale models to higher resolution?
- Or increase domain size for LES?
- Is there a conflict?





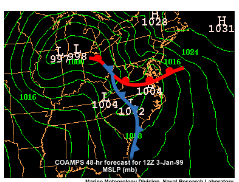
Meso-scale
L ~ 2-2000 km

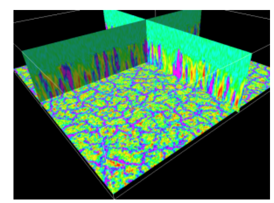
"Terra incognita"
Wyngaard (JAS 2004)

LES
L < 2 km

Challenges in the "Terra incognita"

- Steep topography
  - Terrain-following coordinate system
- Turbulence modeling
- Land-surface fluxes – similarity theory
- Lateral boundary forcing
- Other physics parameterizations





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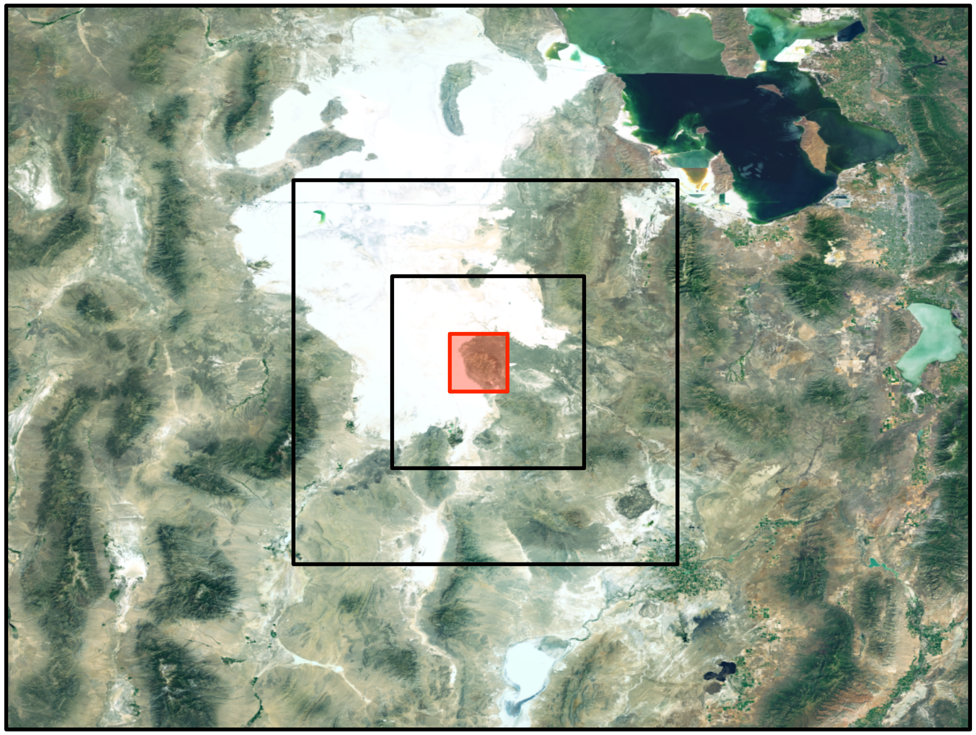
What we are doing

- Weather and Research Forecasting (WRF) model
  - Mesoscale to microscale
- One tool for all scales
  - Improved turbulence models for LES
  - Immersed boundary method (IBM) for steep terrain

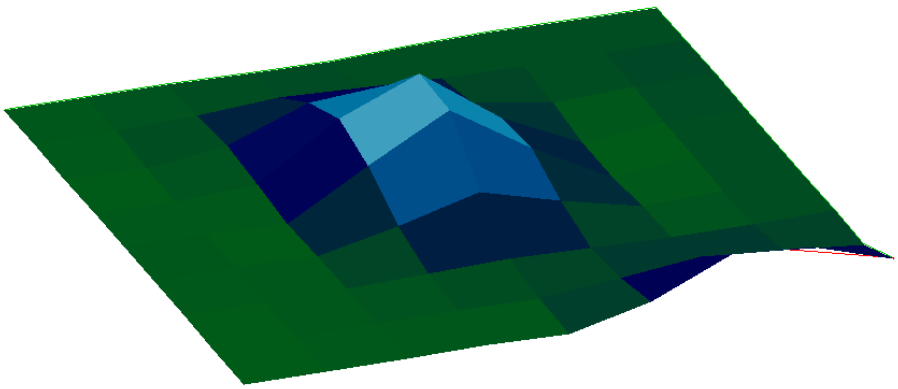


WRF-IBM Framework

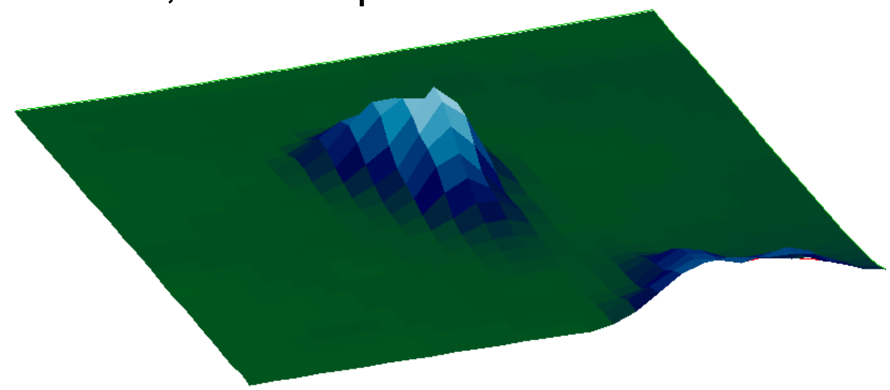
- Capable as mesoscale or LES code
- WRF fails with steep terrain slopes
- WRF-IBM (Lundquist et al. 2010, 2012)
  - WRF + immersed boundary method (IBM)
  - Same model; just a switch
  - Nesting possible

Increasing resolution ➡ steeper slopes

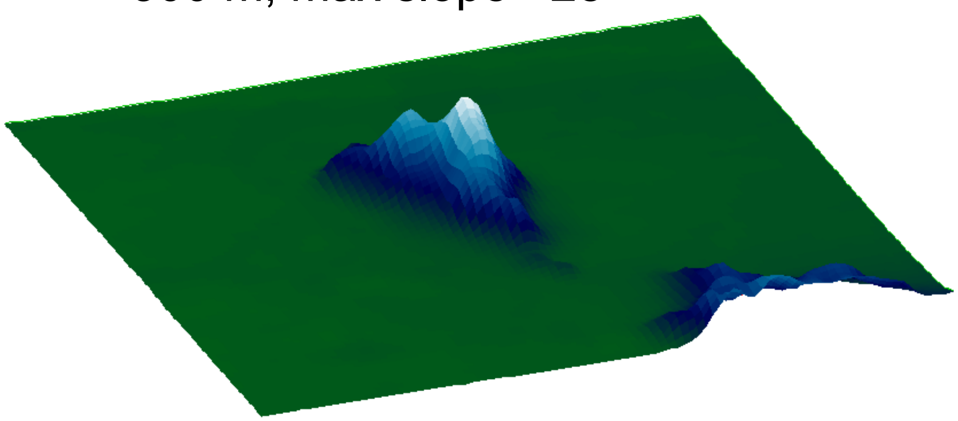
3 km, max slope ~4°



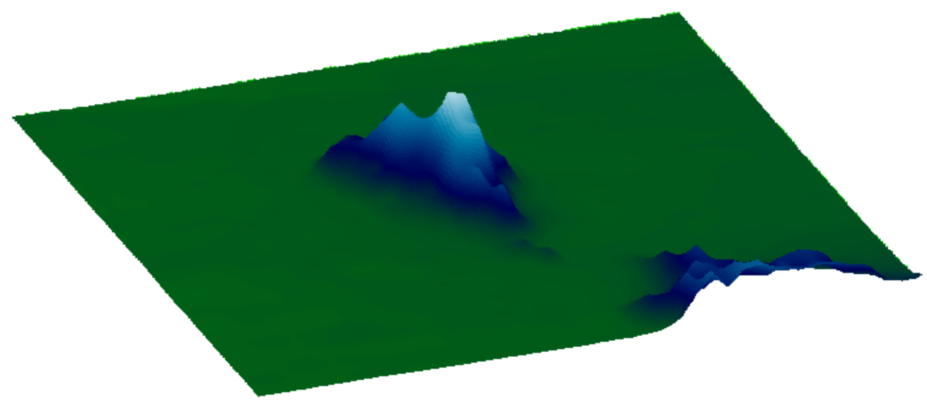
1 km, max slope ~14°



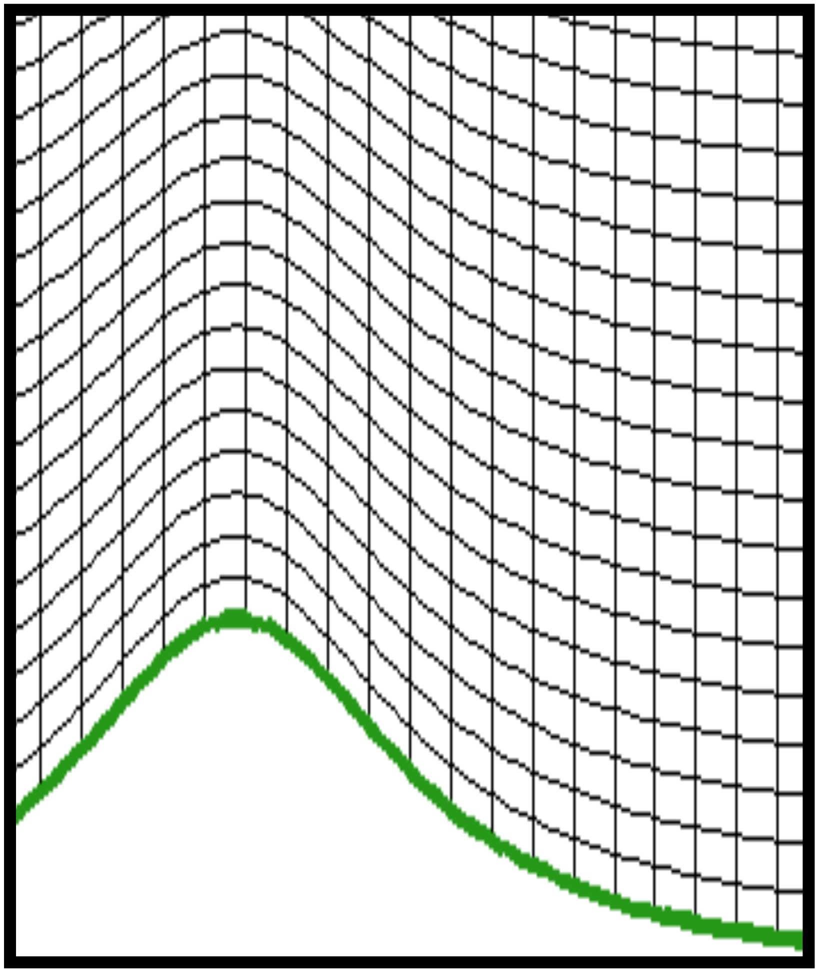
300 m, max slope ~28°



100 m, max slope ~32°



Terrain slope limit

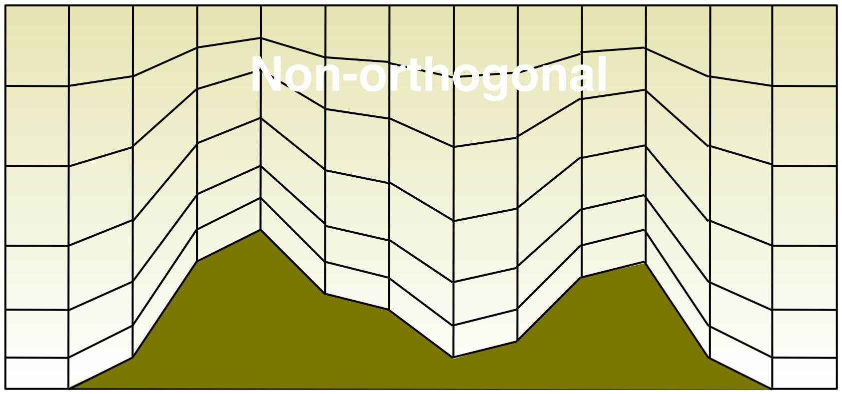


Terrain-following coordinates

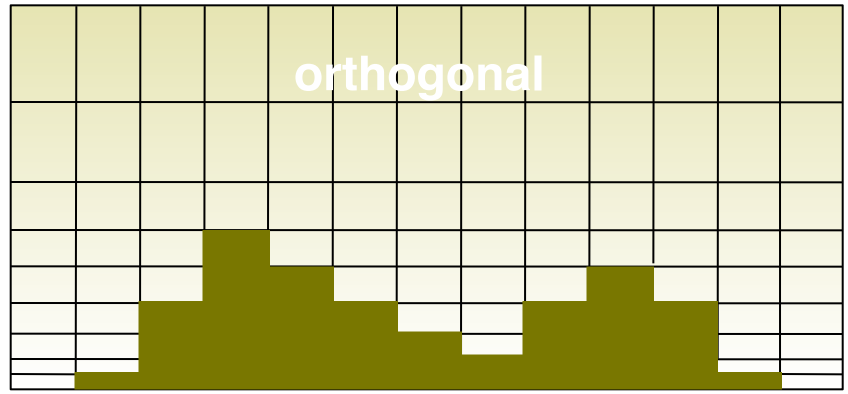
- Horizontal pressure gradient errors
  - 45° limit, usually ~30° starts causing problems (e.g. Mahrer 1984)
- Grid aspect ratio limitations
- Numerical stability

Vertical coordinate systems

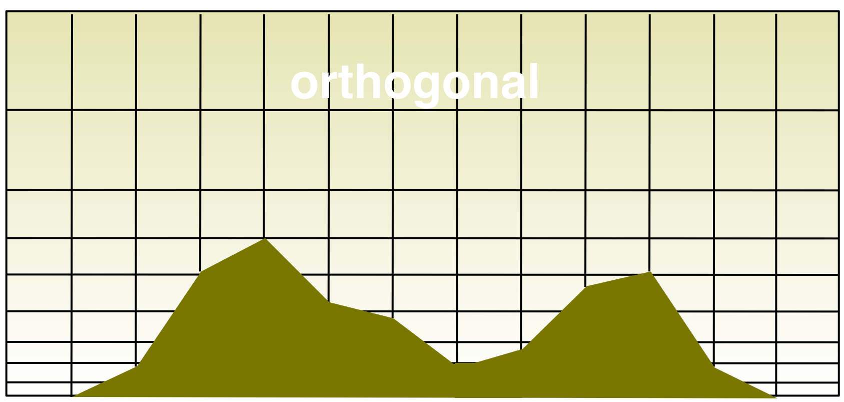
sigma, or terrain-following



eta, or "step mountain"

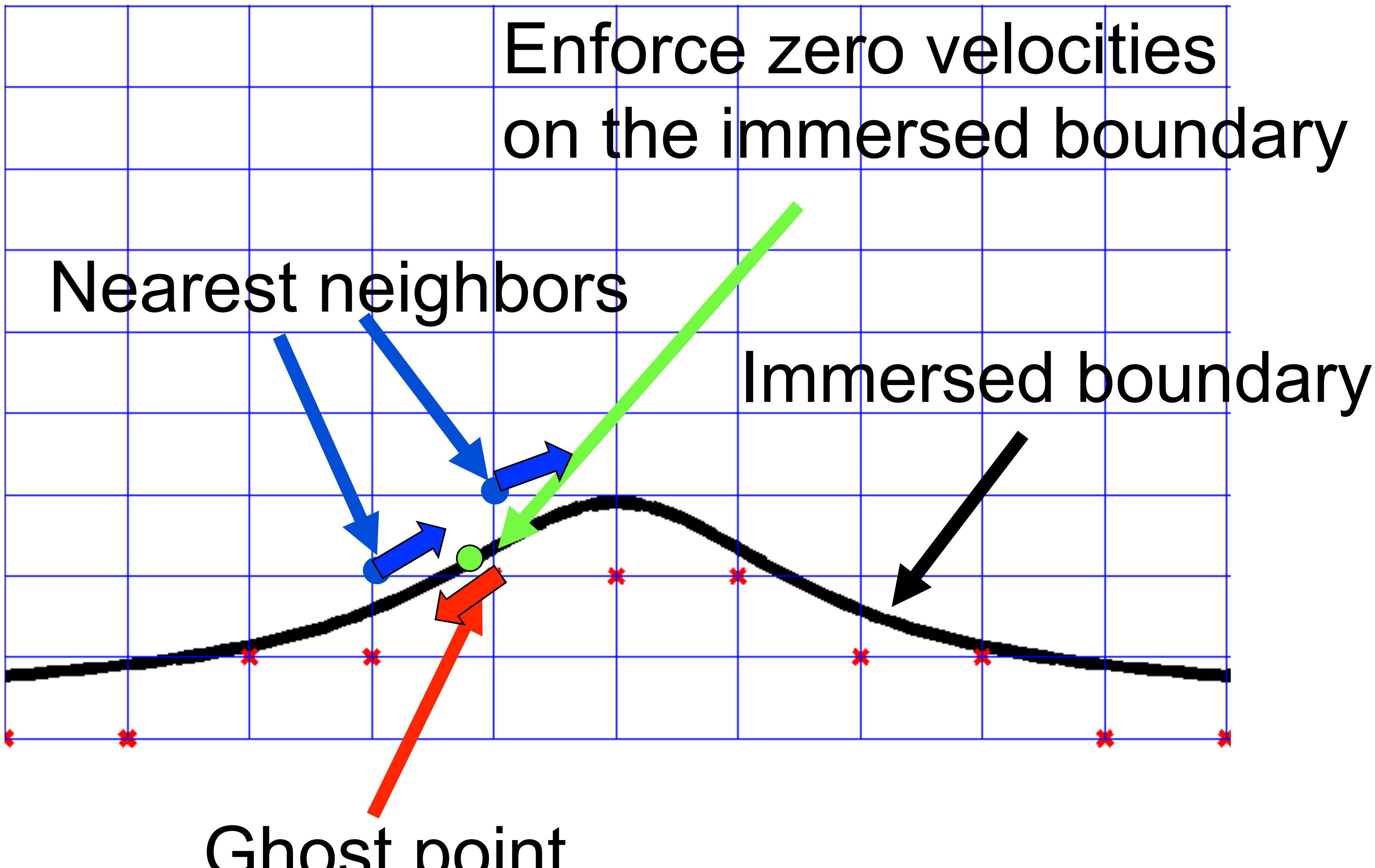


immersed boundary



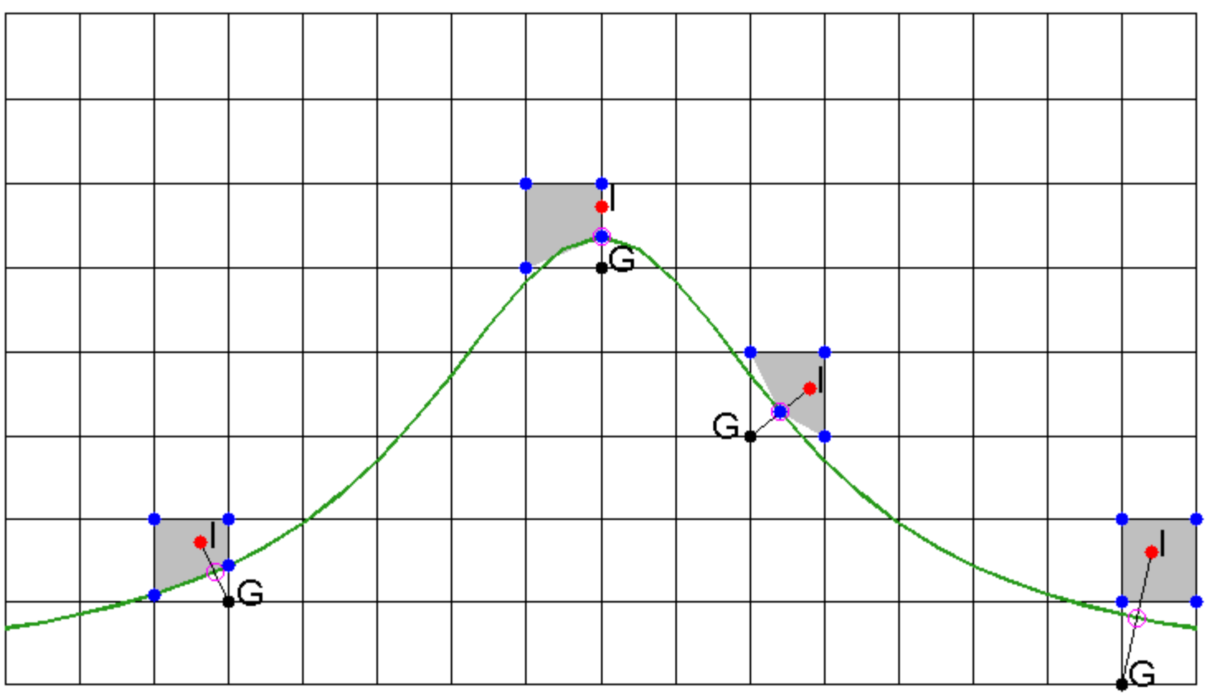
others include sigma-pressure, isentropic, and hybrids

Ghost-cell immersed boundary method



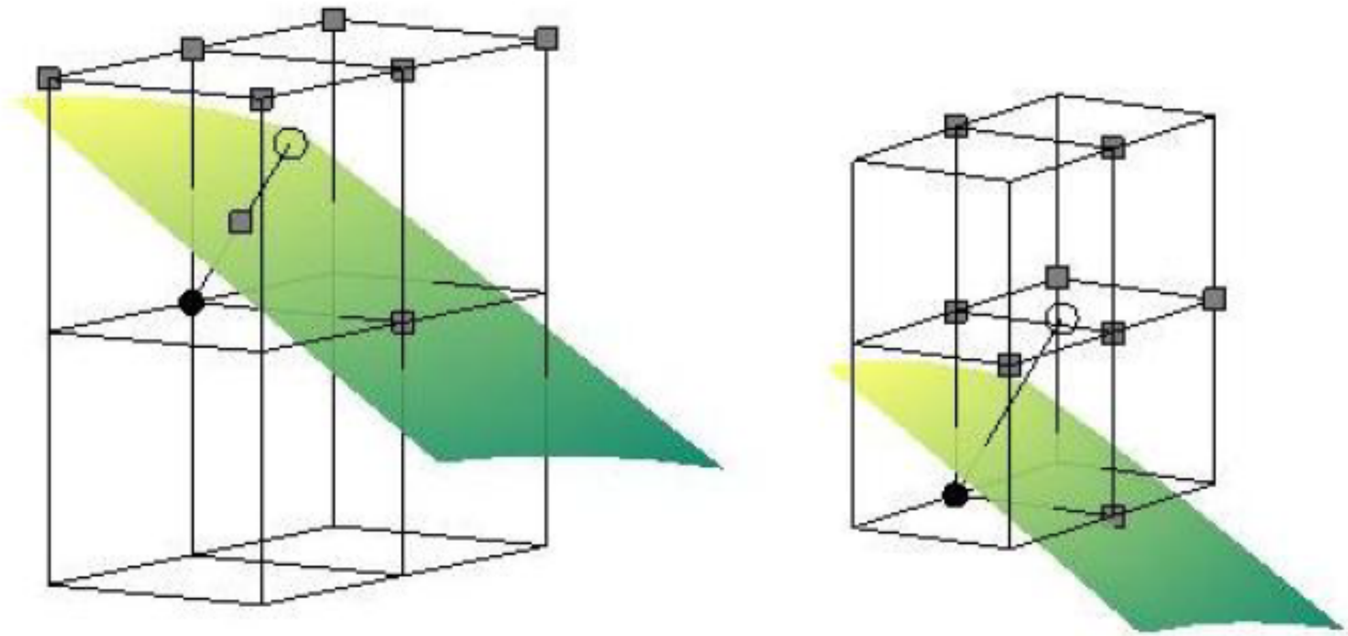
IBM - Boundary reconstruction

- IBM implemented in WRF
- 2 different interpolation algorithms
- Handles highly complex topography



Lundquist et al. MWR 2010

Inverse distance weighting



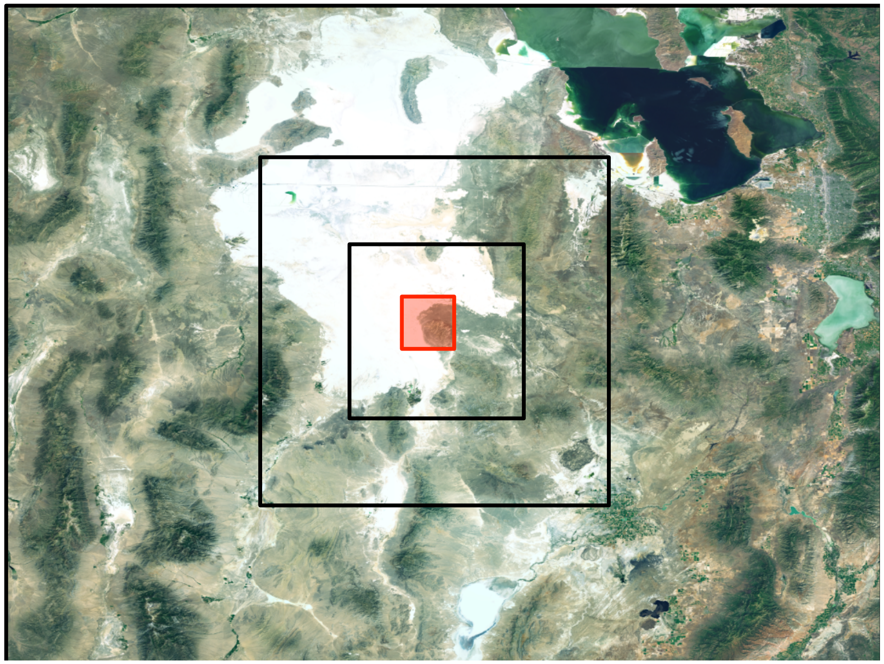
(a) Dirichlet (b) Neumann

For complex urban geometries

Lundquist et al. 2010, 2012

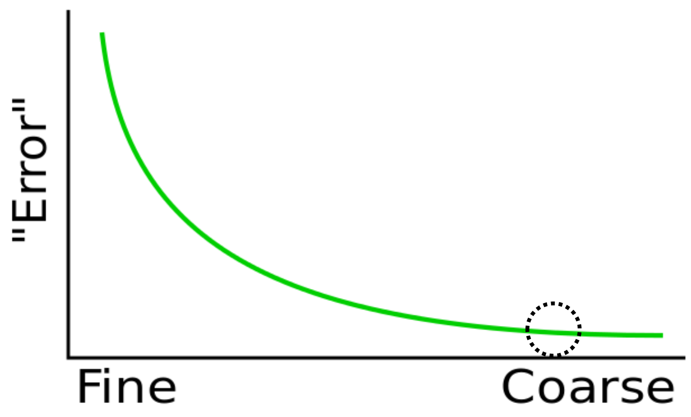
Seamless grid nesting

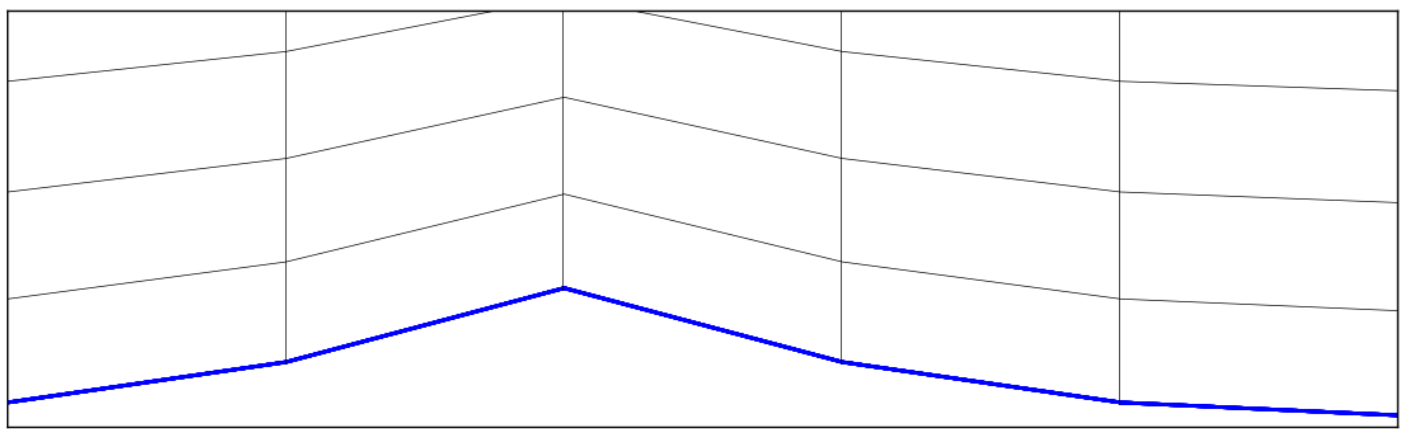
- Mesosacle to microscale
- Must switch from WRF to IBM-WRF
- When to switch?
    - Resolution, steepness, aspect ratio, turbulence closure



WRF Alone

- Coarse resolution
  - smooth terrain
  - low error
- Fine resolution
  - steep terrain
  - high error





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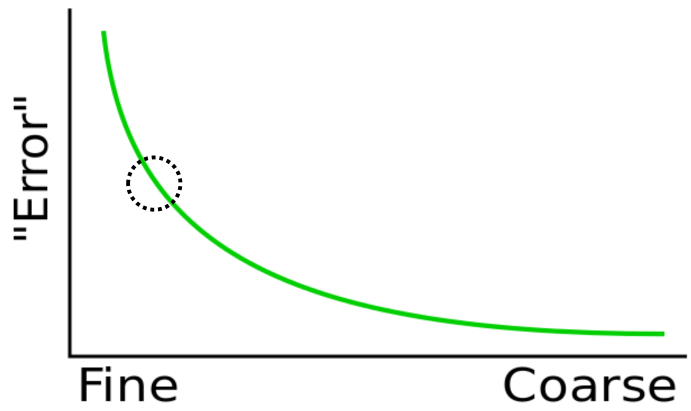
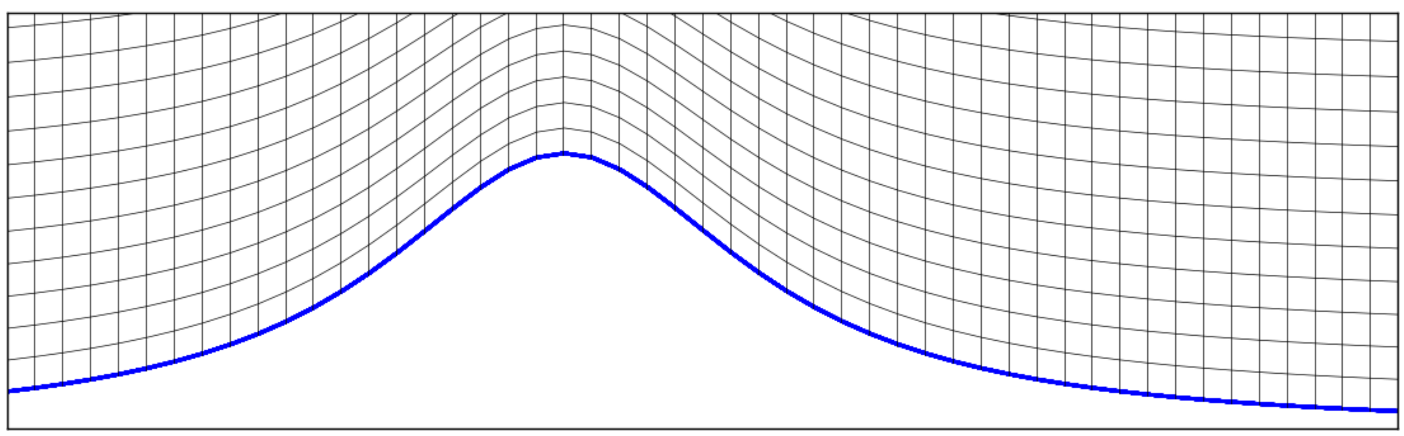
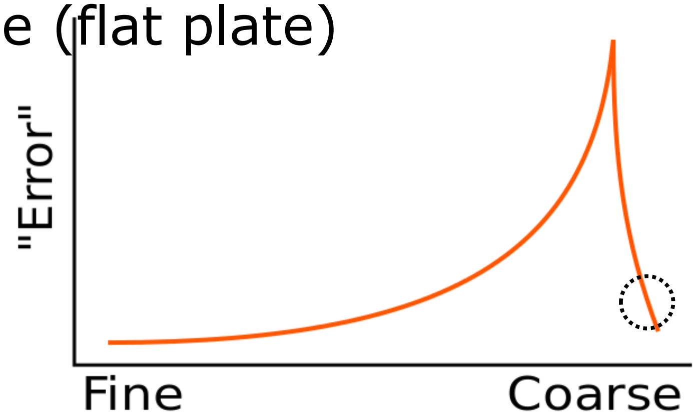
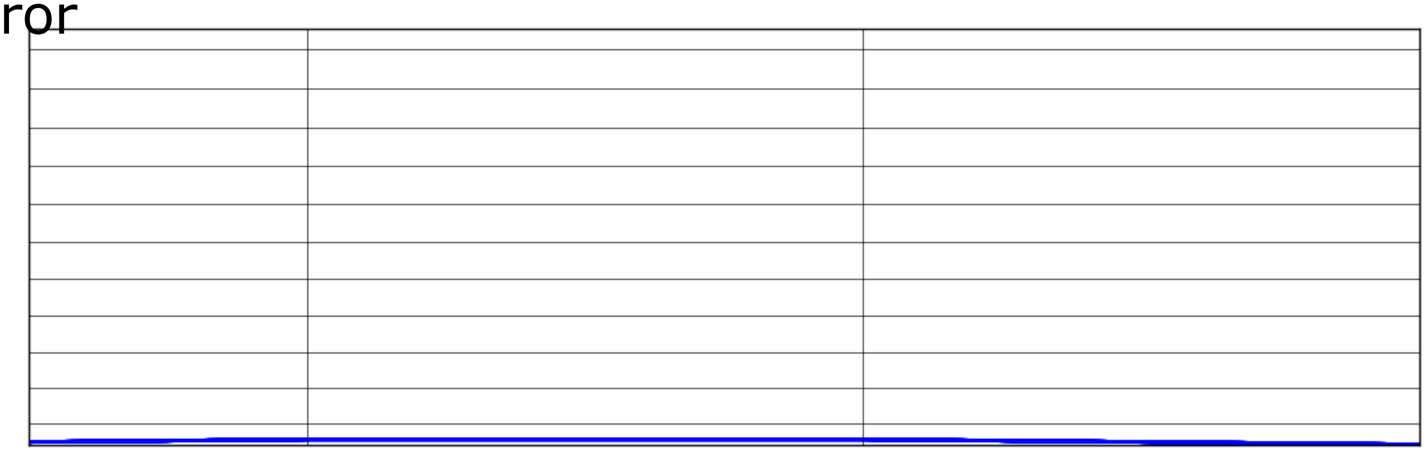




IBM-WRF Alone

- Very coarse resolution
  - grid-scale > mountain-scale (flat plate)
  - low error
- Coarse resolution
  - large spacing
  - high error (interpolation)
- Fine resolution
  - small spacing
  - low error





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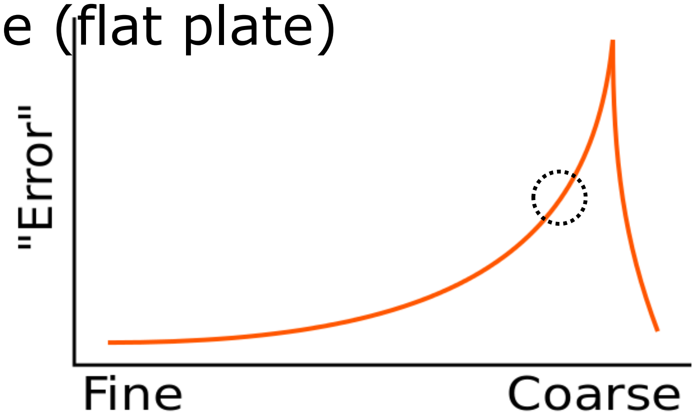

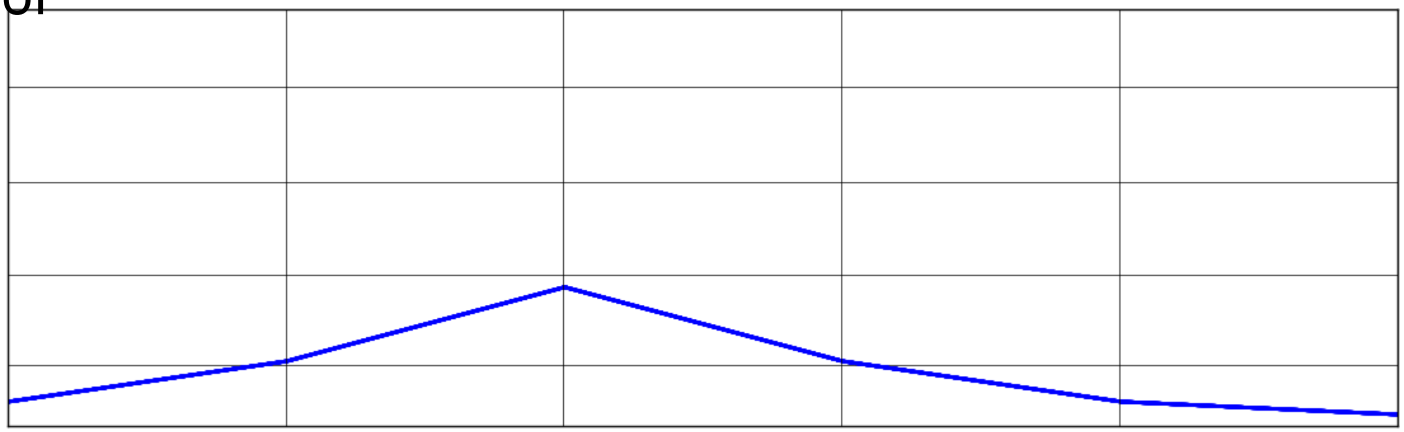

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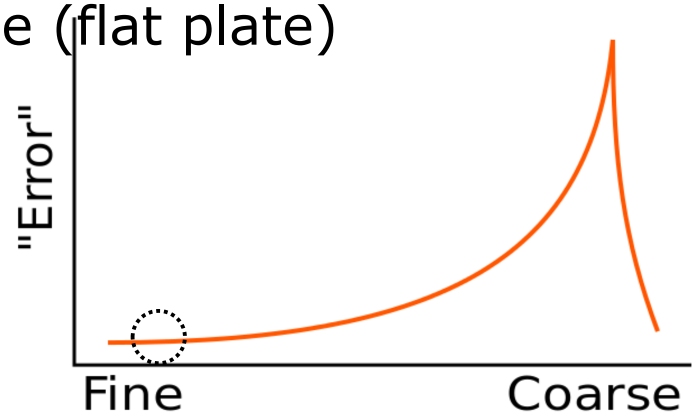
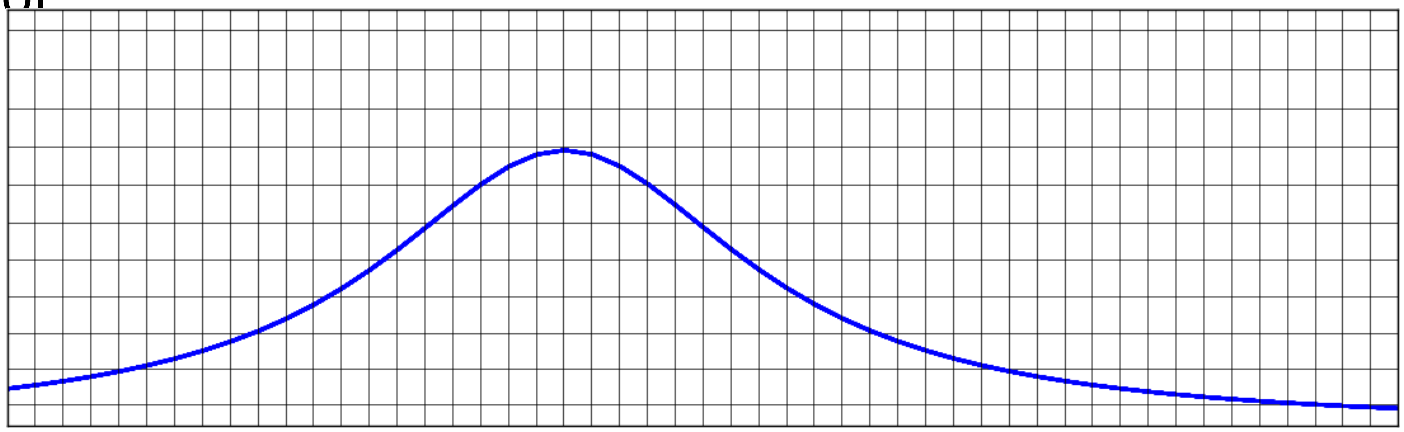
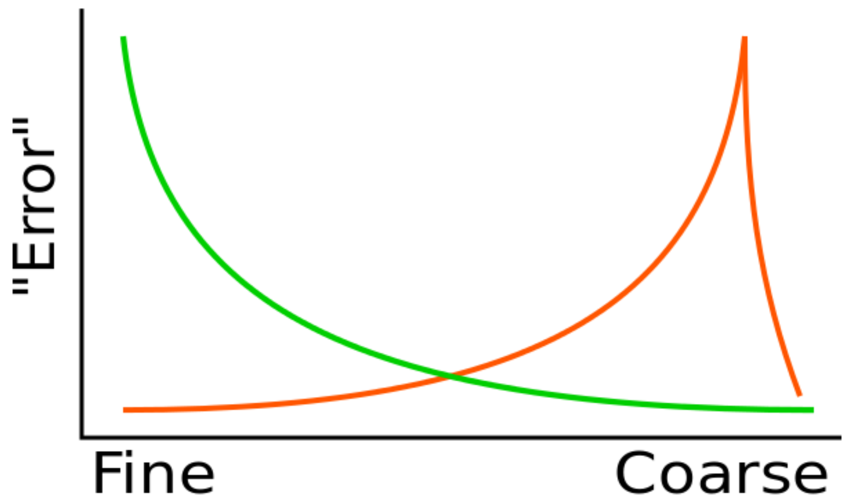




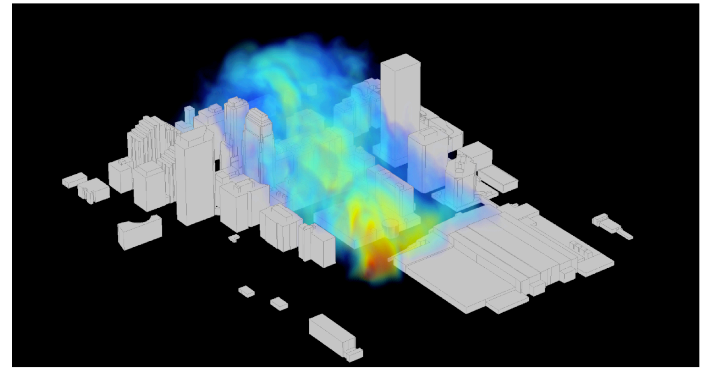
WRF to IBM-WRF

- Switch at intersection for best results
- Want to develop general guidelines for this curve
  - WRF starts blowing up near 300m resolution on 2D GMAST



Complex terrain applications

- Current implementation for no-slip
  - Good for urban environments at ~1 m resolution
- Need log law wall stress for complex terrain



IBM-WRF for Oklahoma City

$$U = \frac{u_*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \qquad C_D = \left[\frac{1}{\kappa} \ln\left(\frac{z_1 + z_0}{z_0}\right)\right]^{-2}$$

$$\tau_{wall} = -u_*^2 = -C_D \left|U_1\right| U_1$$

WRF implementation of log law

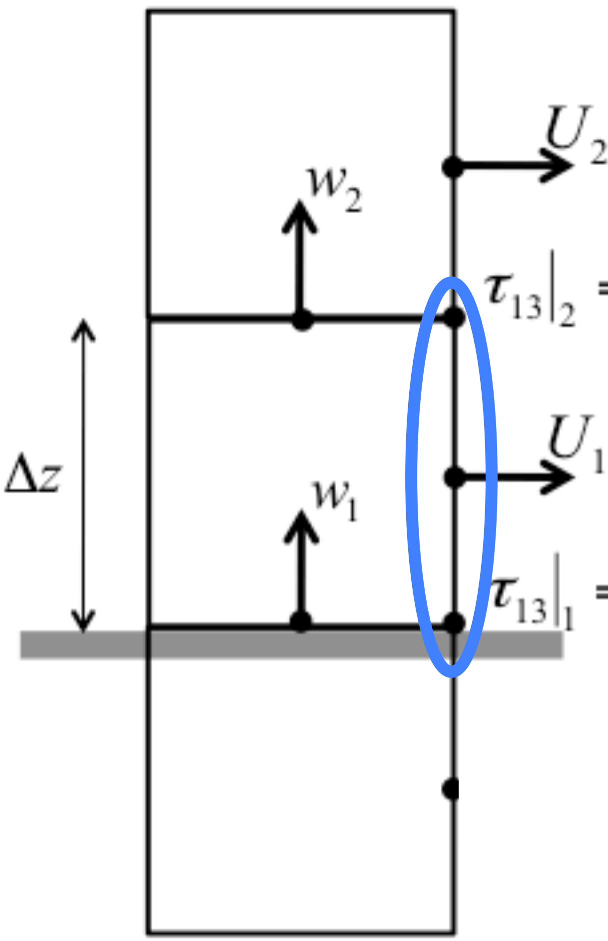
- Momentum equation in U direction

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - \left(\frac{\partial \tau_{11}}{\partial x} + \frac{\partial \tau_{12}}{\partial y} + \frac{\partial \tau_{13}}{\partial z}\right)$$

- Requires gradient in τ_{13}

WRF implementation of log law

$$\frac{\partial U}{\partial t} = -\frac{\partial \tau_{13}}{\partial z} \quad \cdots$$

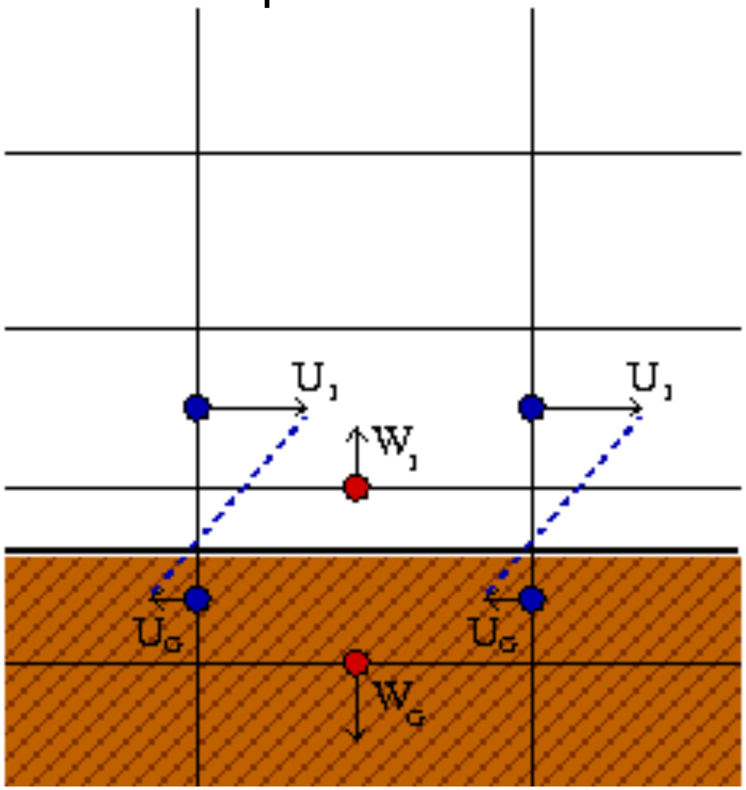


$$\tau_{13}\big|_2 = -\nu_T \frac{\partial U}{\partial z} \approx -\nu_T \frac{U_2 - U_1}{\Delta z}$$

$$\tau_{13}\big|_1 = \tau_{wall} = -u_*^2 = -C_D |U_1| U_1$$

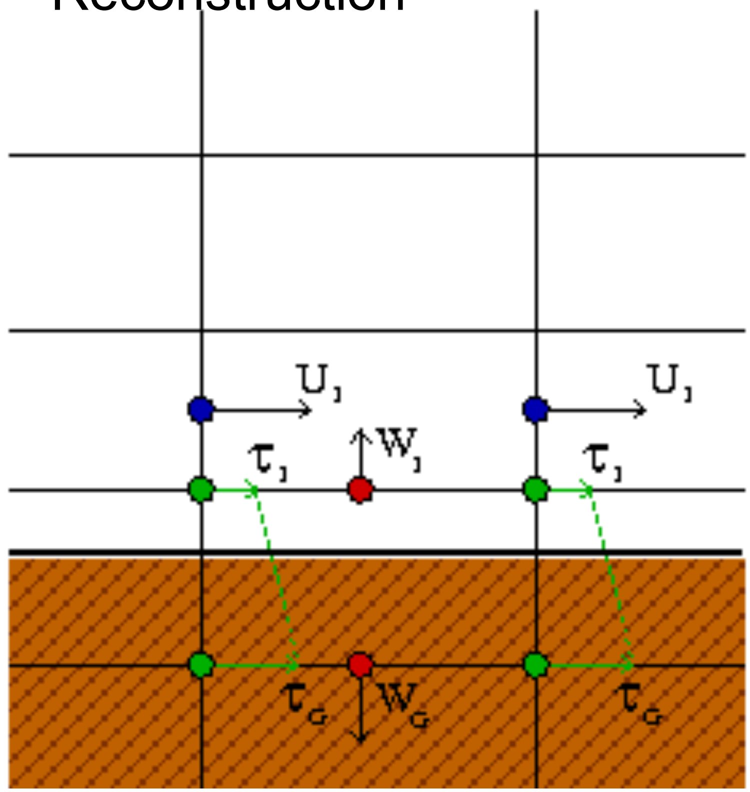
IBM – log law implementation

No-Slip



$$u_{surface} = v_{surface} = w_{surface} = 0$$

Shear Stress Reconstruction

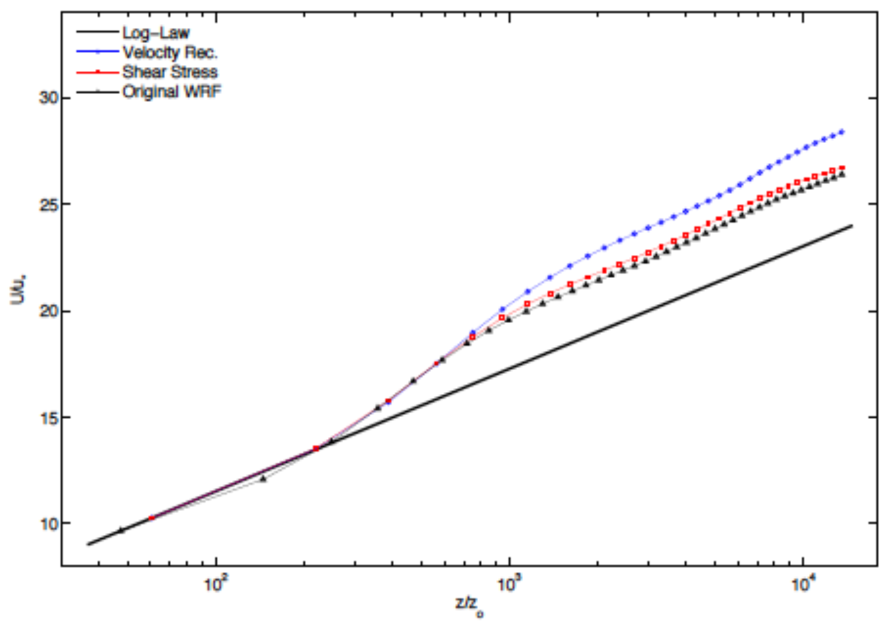


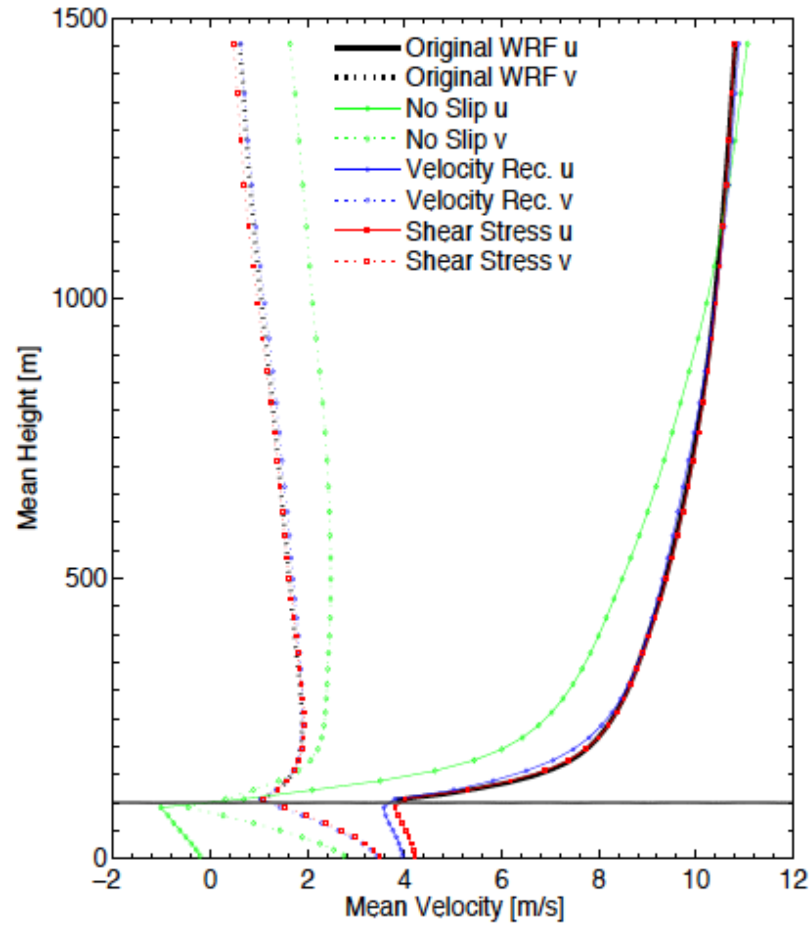
$$\vec{U} \cdot \hat{n} = 0$$

$$\tau_w = -\mu \left(\frac{\kappa}{\ln \frac{z_1 - h}{z_o}} \right)^2 \left| \vec{U} \right| u$$

How to validate?

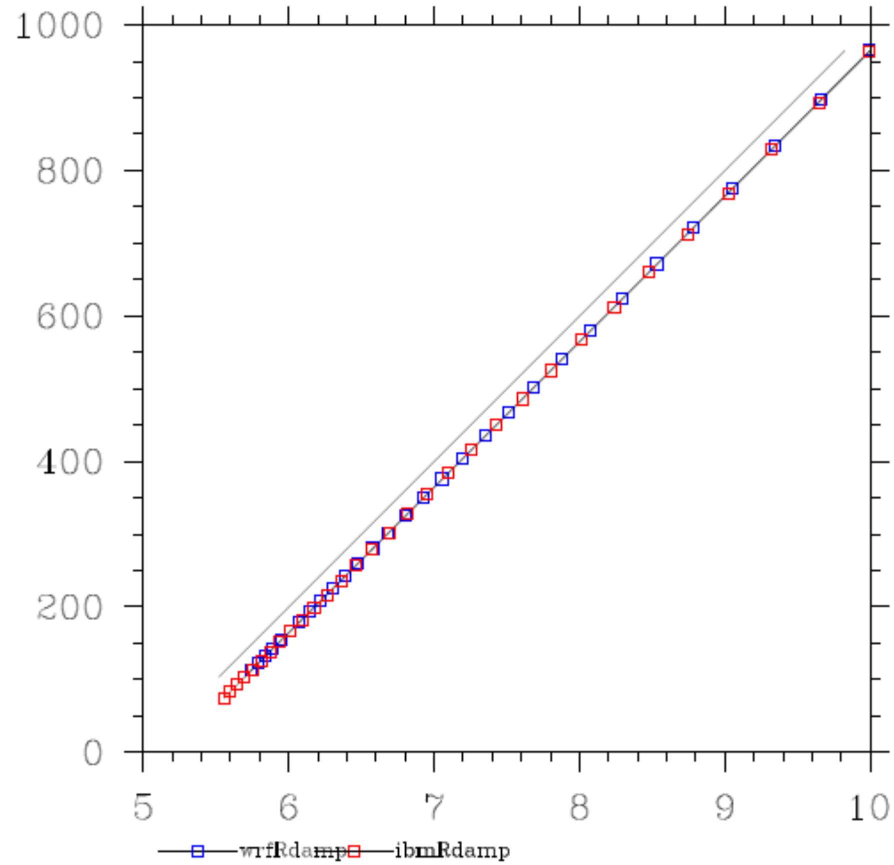
- Small changes can make big difference





Test Case 1

- Flat plate
- Constant eddy viscosity
- Top Rayleigh damping layer
- Constant shear stress at wall
- Analytical solution

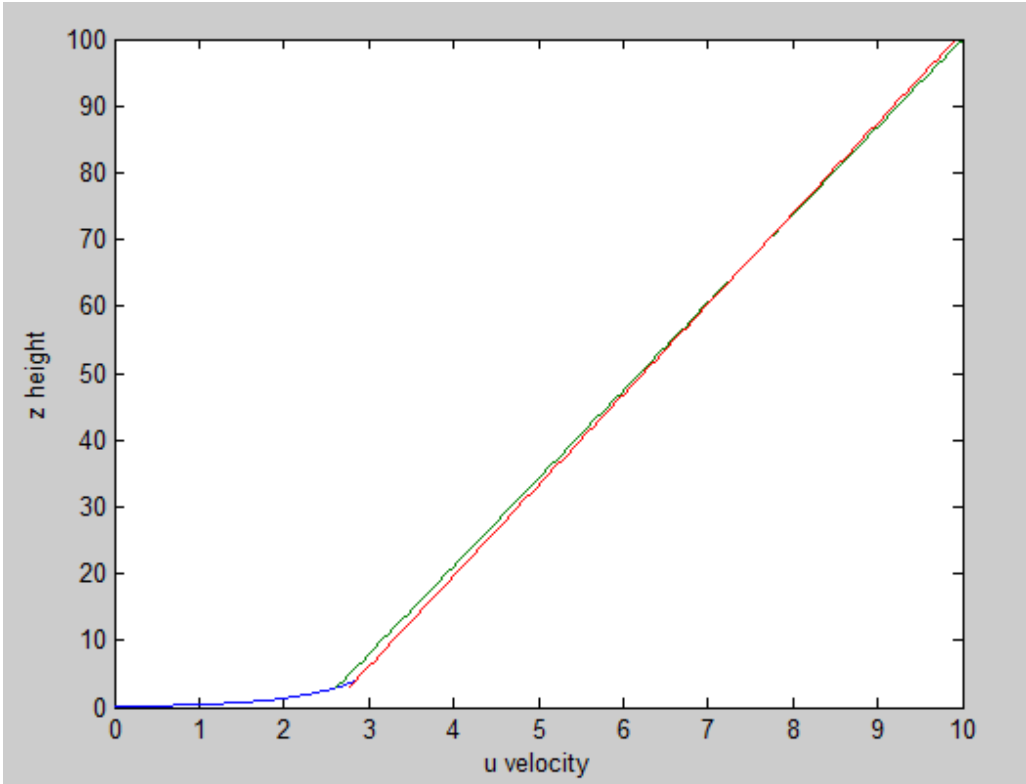


$$u = \frac{\tau_w}{\upsilon_t} z + 5.25$$

$\tau_w = 0.1 \quad \upsilon_t = 20$

Test Case 2

- Flat plate
- Constant eddy viscosity
- Top Rayleigh damping layer
- Log law at wall
- Analytical solution
  - Below z1, velocity assumed logarithmic, above linear
  - Location of z1 determines slope



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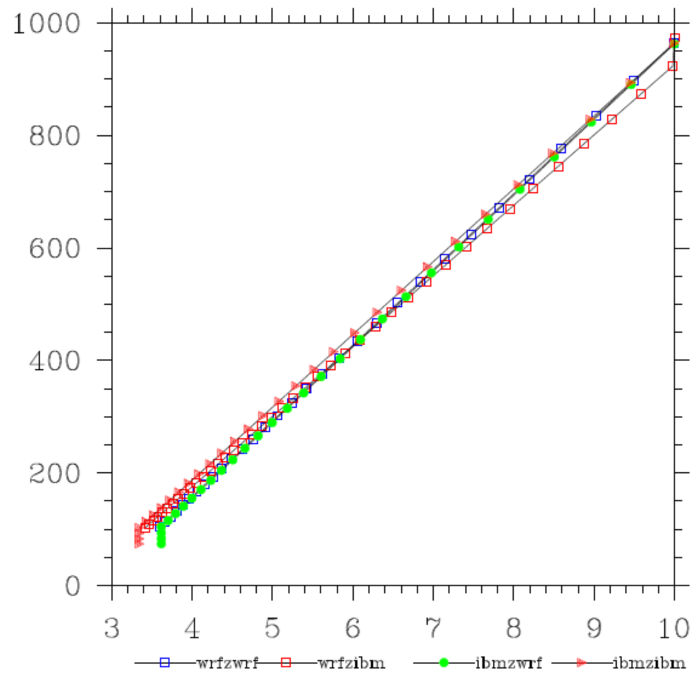
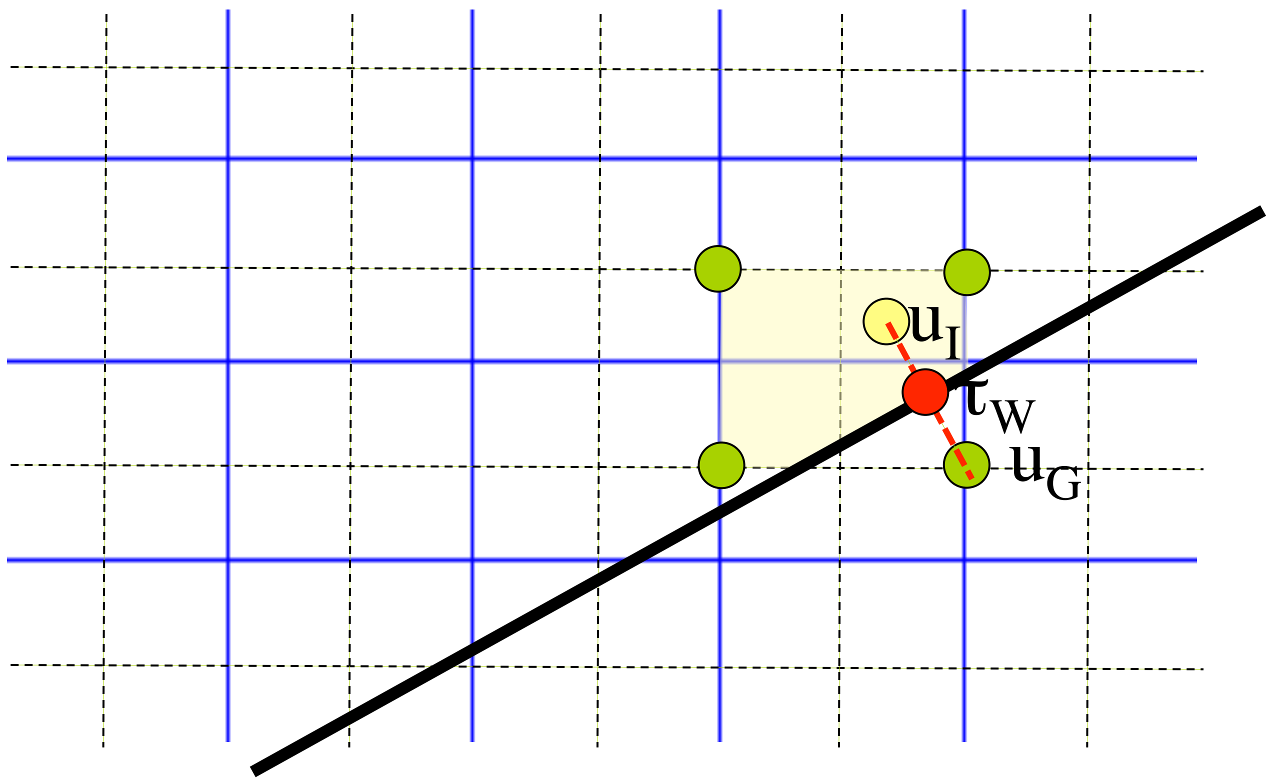


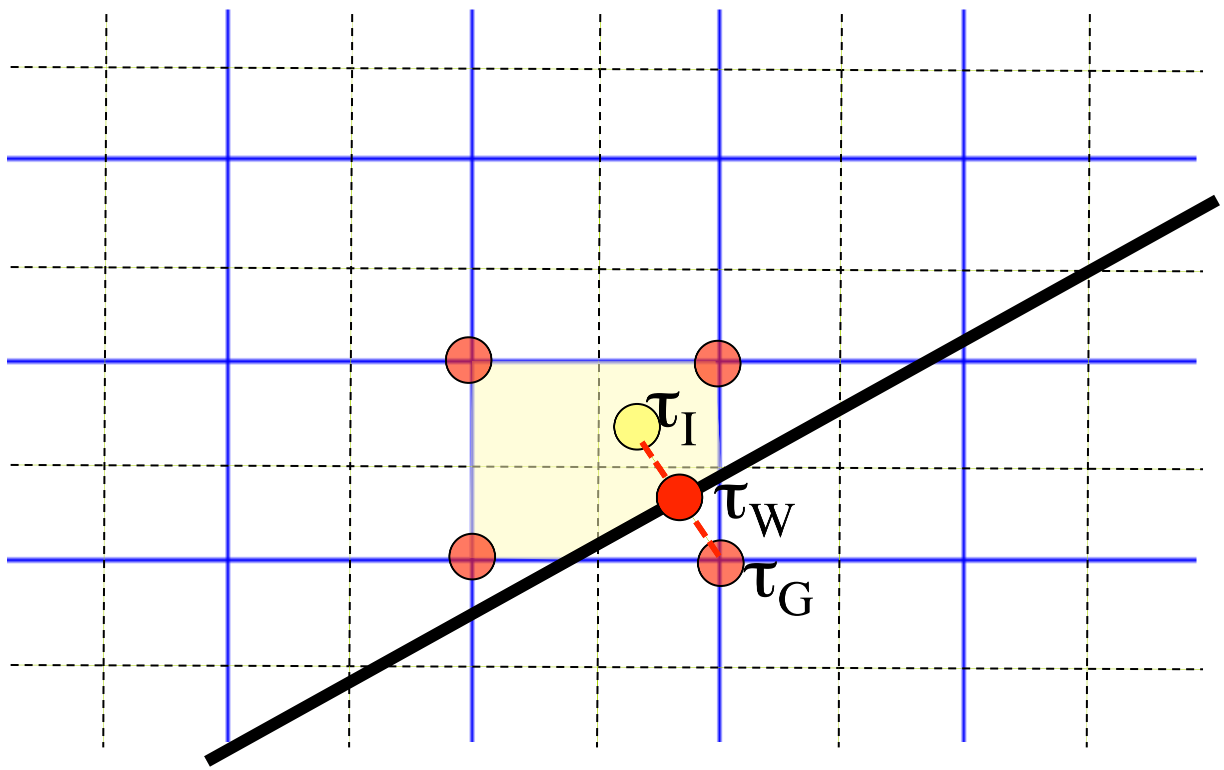
Test Case 3

- Flat plate
- Constant eddy viscosity
- Top Rayleigh damping layer
- Log law at wall
- Pressure gradient forcing

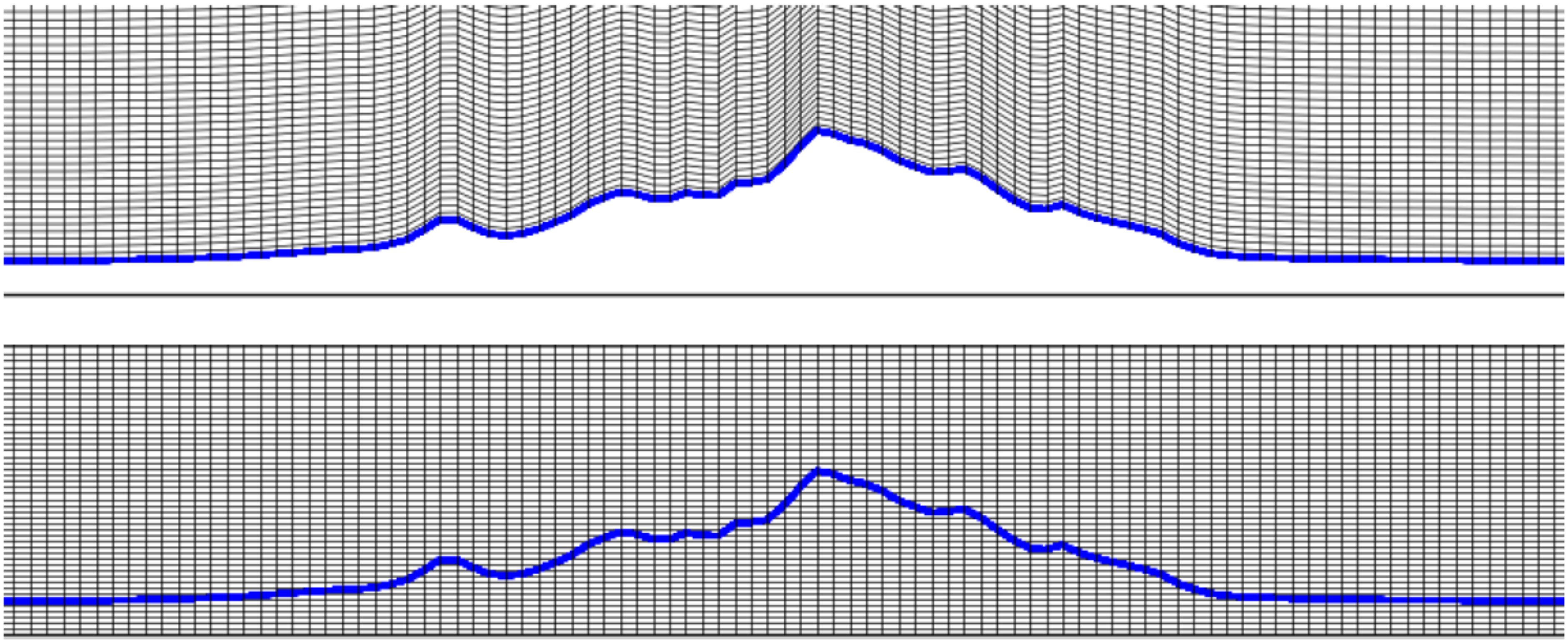
3D log law implementation



3D log law implementation



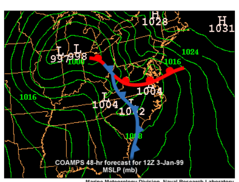
Granite Mountain – IBM test case



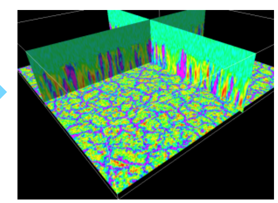
Granite Mountain, Utah

MATERHORN: addressing challenges in the "Terra incognita"

- Steep topography
- Turbulence modeling
- Land-surface fluxes – similarity theory



DRM and IBM-WRF



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LES
L < 2 km

Ongoing work

- IBM log law
  - 3D implementation
  - Validation
- Granite Mountain
  - Semi-idealized
  - Real case
- Turbulence closure
- Owens Valley