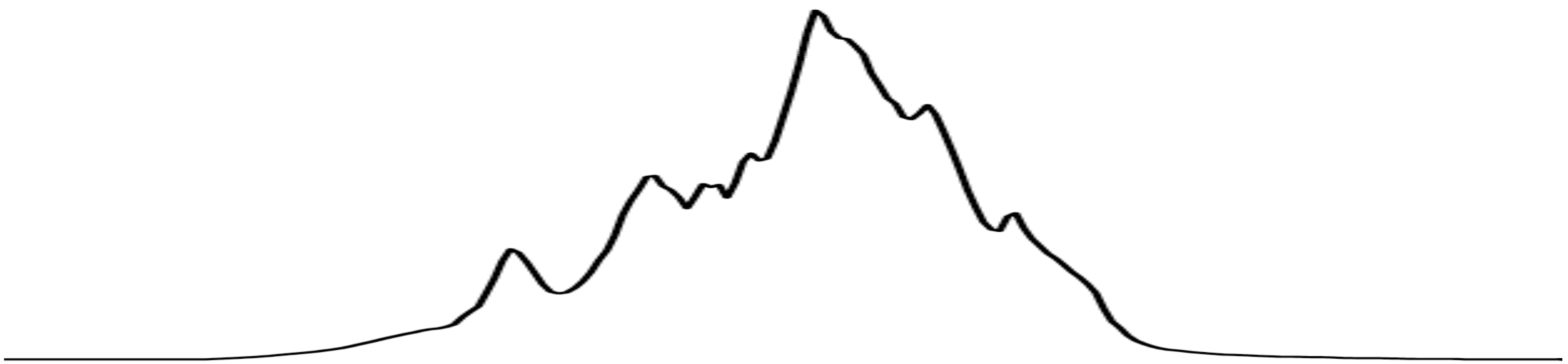
An immersed boundary method in WRF for complex mountainous terrain



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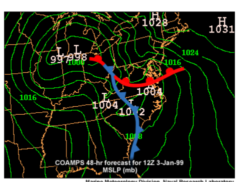
Overview

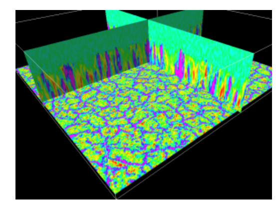
- WRF-IBM for mesoscale to microscale
  - Terra incognita
- Log law implementation
  - Method development and testing
- Application to Granite Mountain
  - Preliminary results

Terra incognita

- Flow features “partially” resolved

- Also -> terrain features “partially” resolved





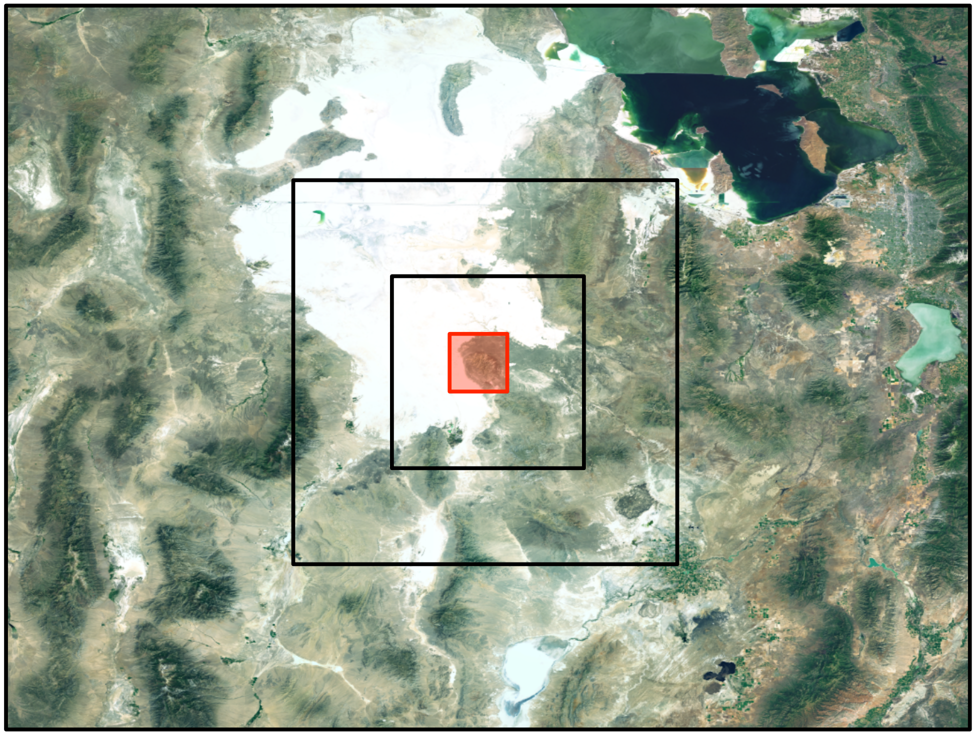
Meso-scale
L ~ 2-2000 km

“Terra incognita”
Wyngaard (JAS 2004)

LES
L < 2 km

What we are doing

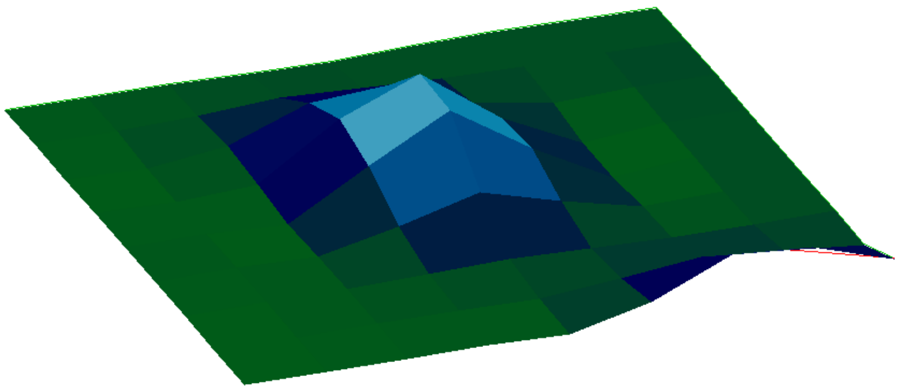
- Weather and Research Forecasting (WRF) model
  - Mesoscale to microscale
- One tool for all scales
  - Improved turbulence models for LES
  - Immersed boundary method (IBM) for steep terrain



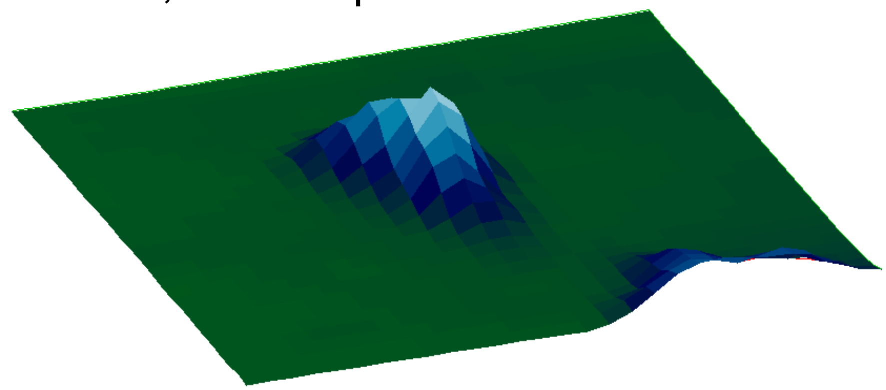
Granite Mountain, Utah

Increasing resolution ➡ steeper slopes

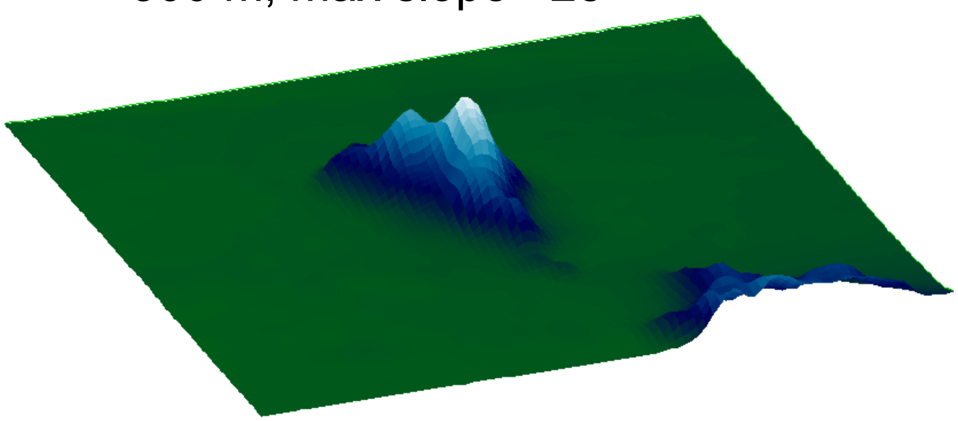
3 km, max slope ~4°



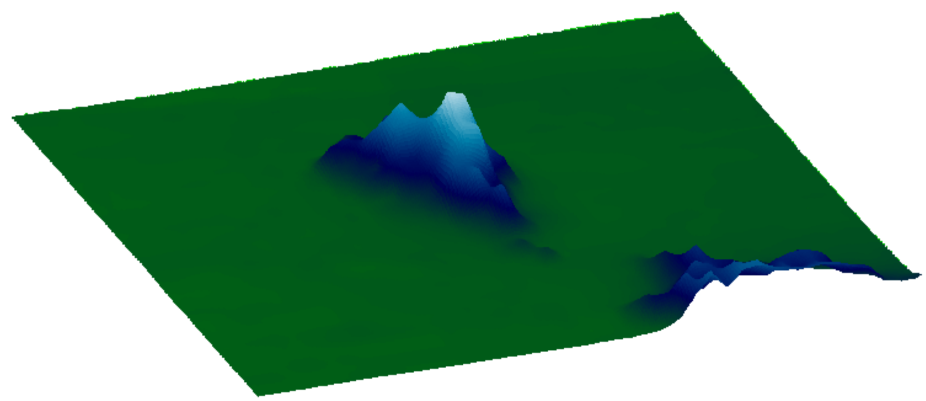
1 km, max slope ~14°



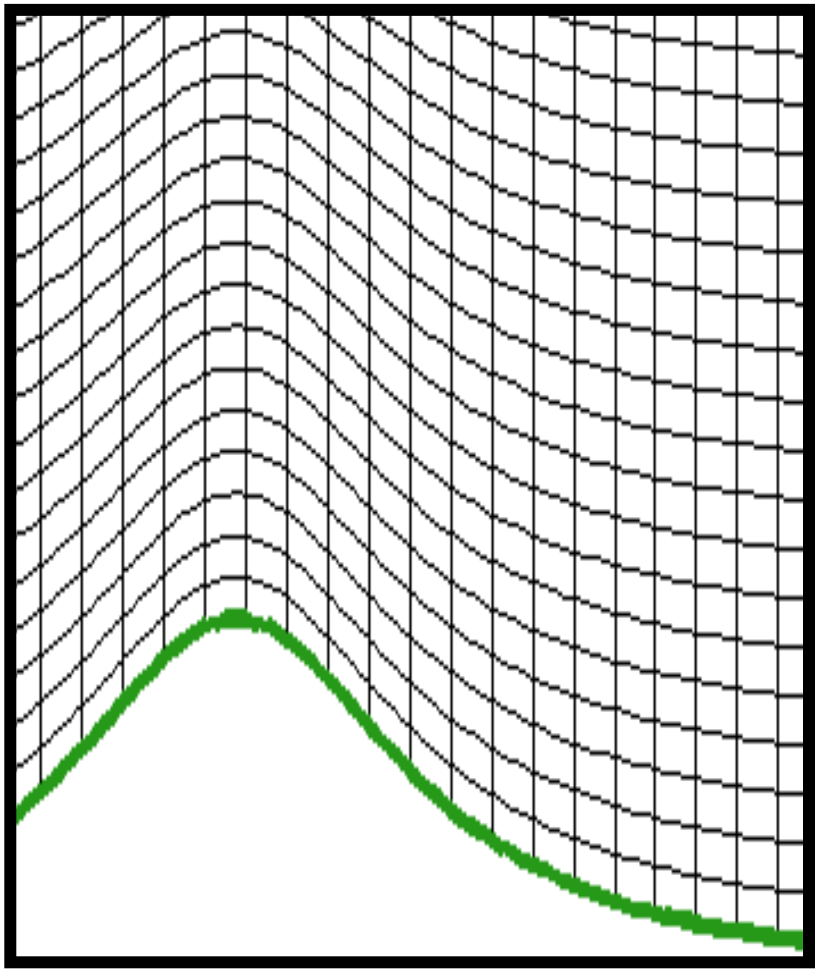
300 m, max slope ~28°



100 m, max slope ~32°



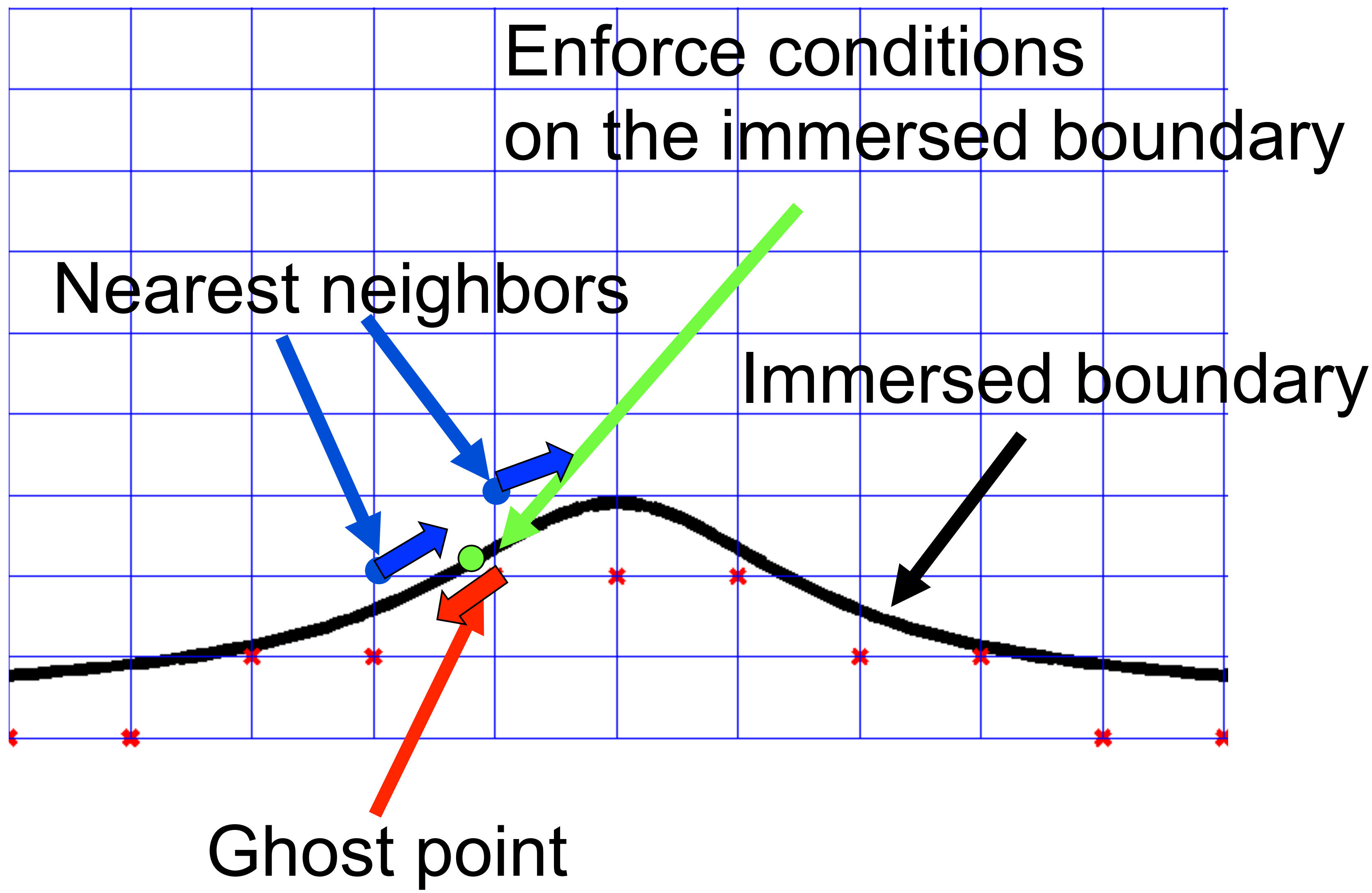
Terrain slope limit



Terrain-following coordinates

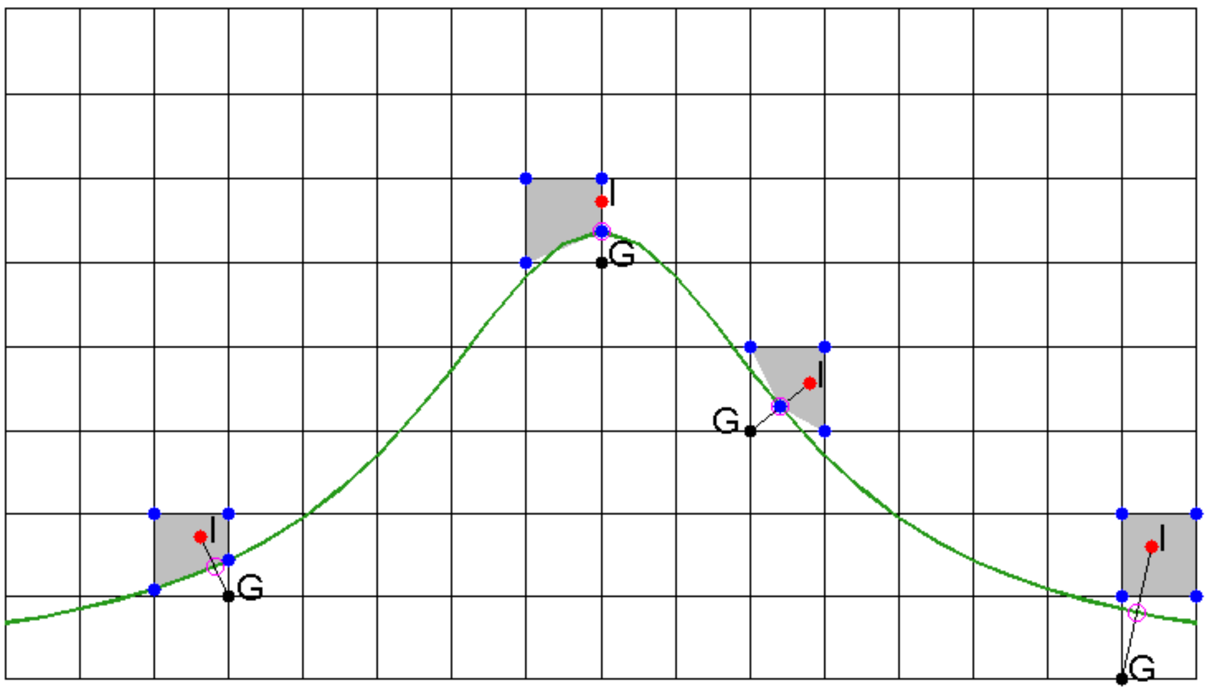
- Horizontal pressure gradient errors
  - 45° limit, usually ~30° starts causing problems (e.g. Mahrer 1984)
- Grid aspect ratio limitations
- Numerical stability

Ghost-cell immersed boundary method



IBM - Boundary reconstruction

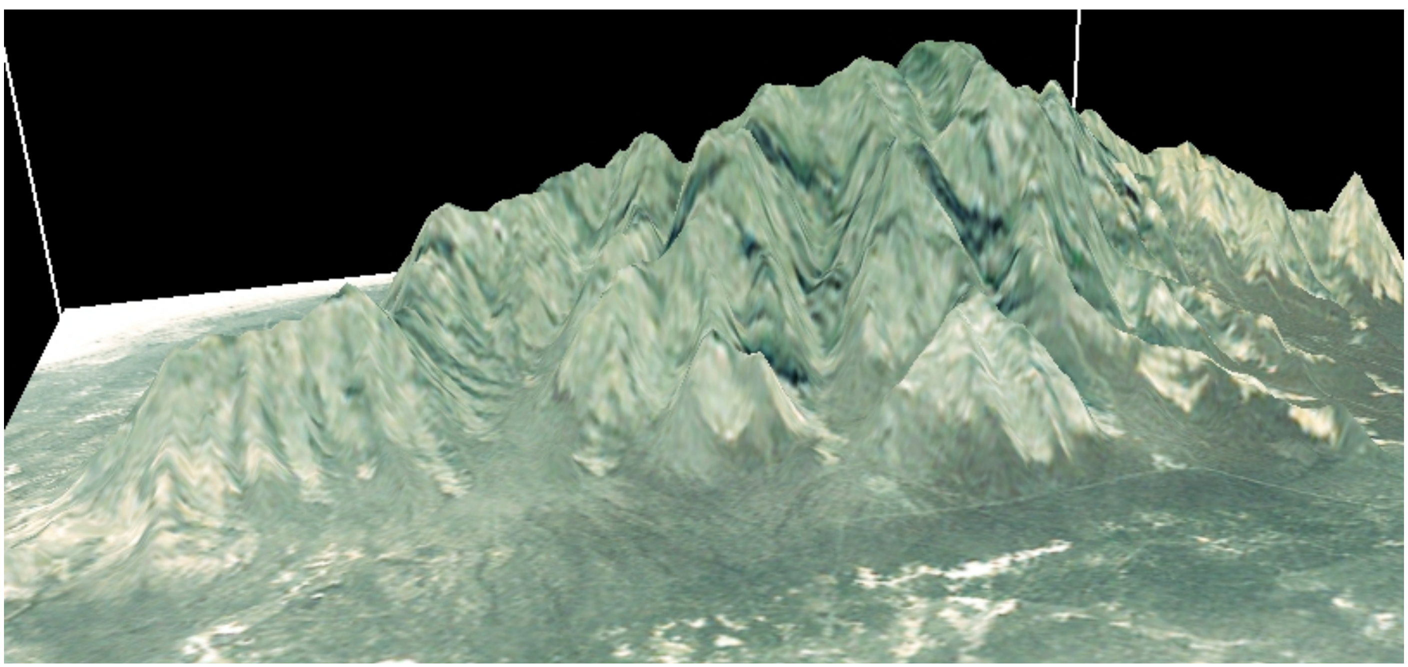
- IBM implemented in WRF
- 2 different interpolation algorithms
- Handles highly complex topography



Lundquist et al. MWR 2010, 2012

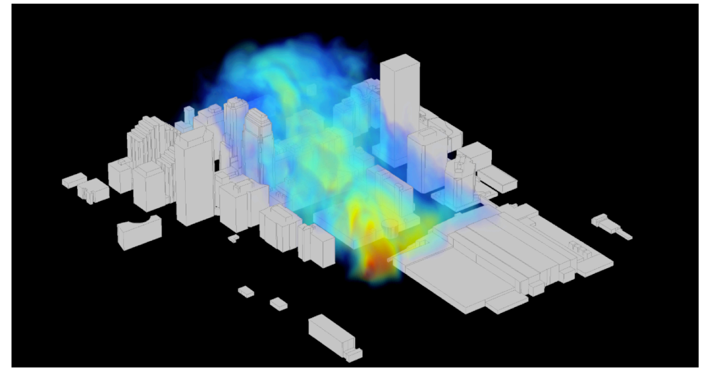
Seamless grid nesting

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



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

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

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

WRF implementation of log law

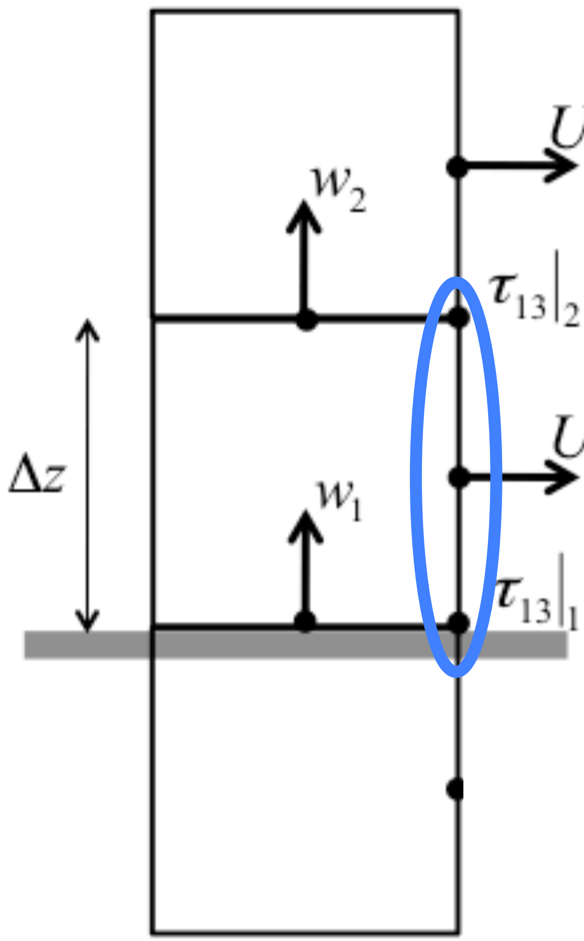
- Momentum equation in U direction

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

- Requires gradient in τ_{13}

WRF implementation of log law

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

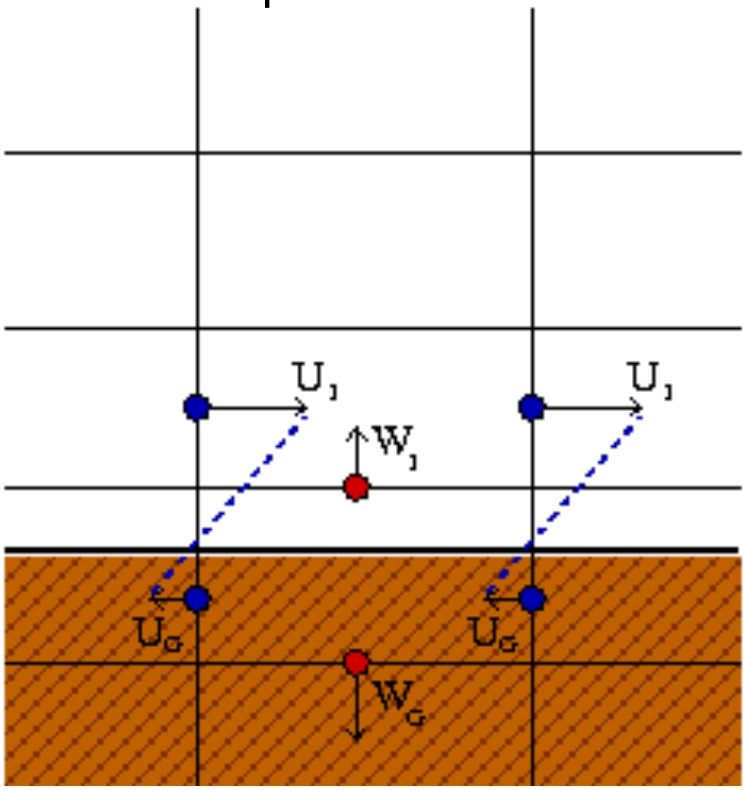


$$\tau_{13}\big|_2 = -\nu_T \frac{\partial U}{\partial z} \approx -\nu_T \frac{U_2 - U_1}{\Delta z}$$

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

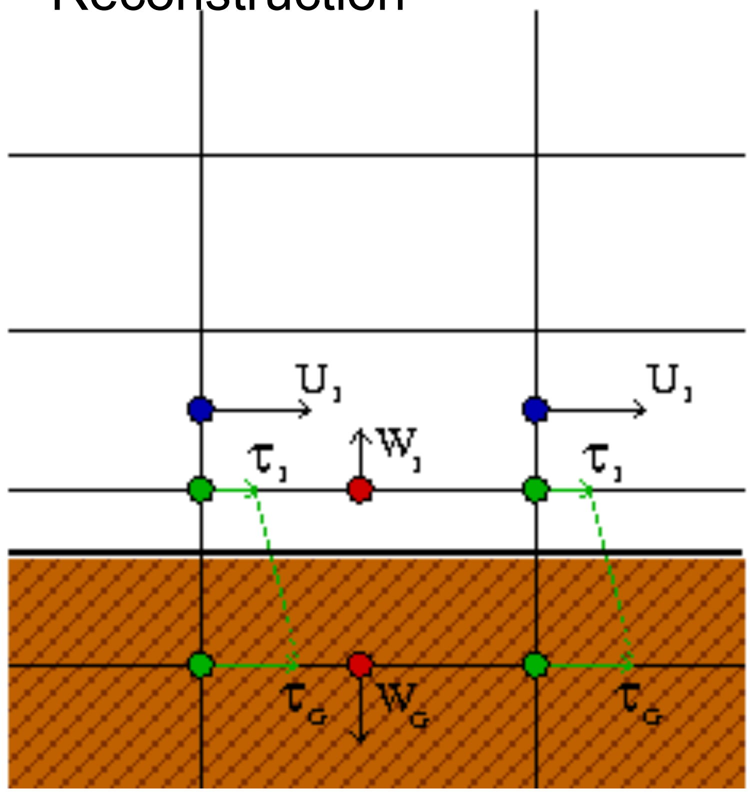
IBM – log law implementation

No-Slip



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

Shear Stress Reconstruction



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

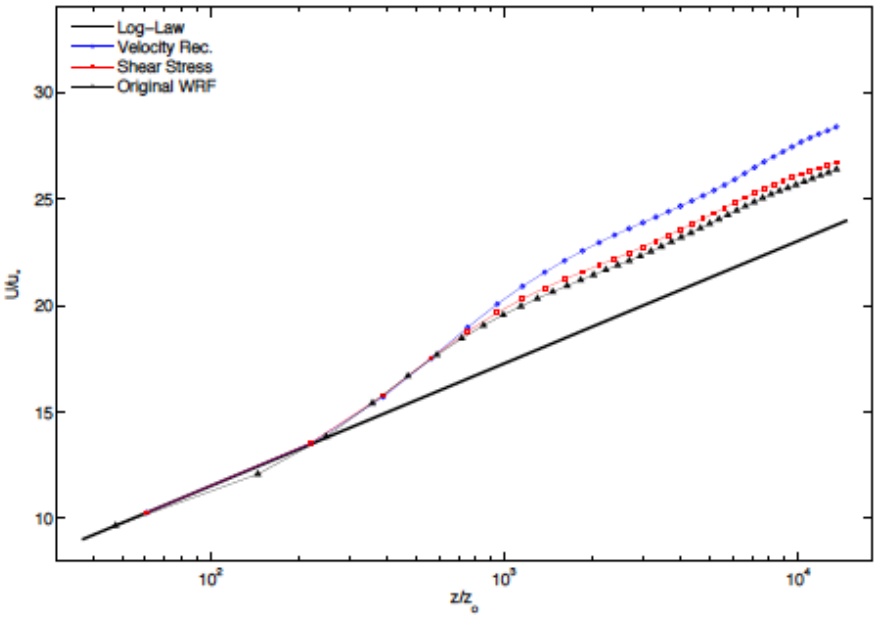
$$\tau_w = -\mu \left(\frac{\kappa}{\ln \frac{z_1 - h}{z_o}} \right)^2 \left| \vec{U} \right| u$$

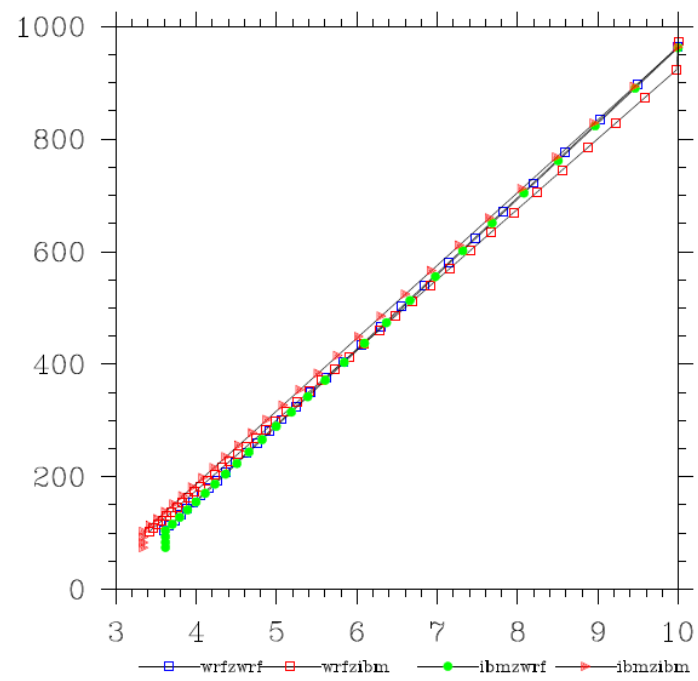
Test cases

- Flat terrain
- Idealized hill
- Granite Mountain

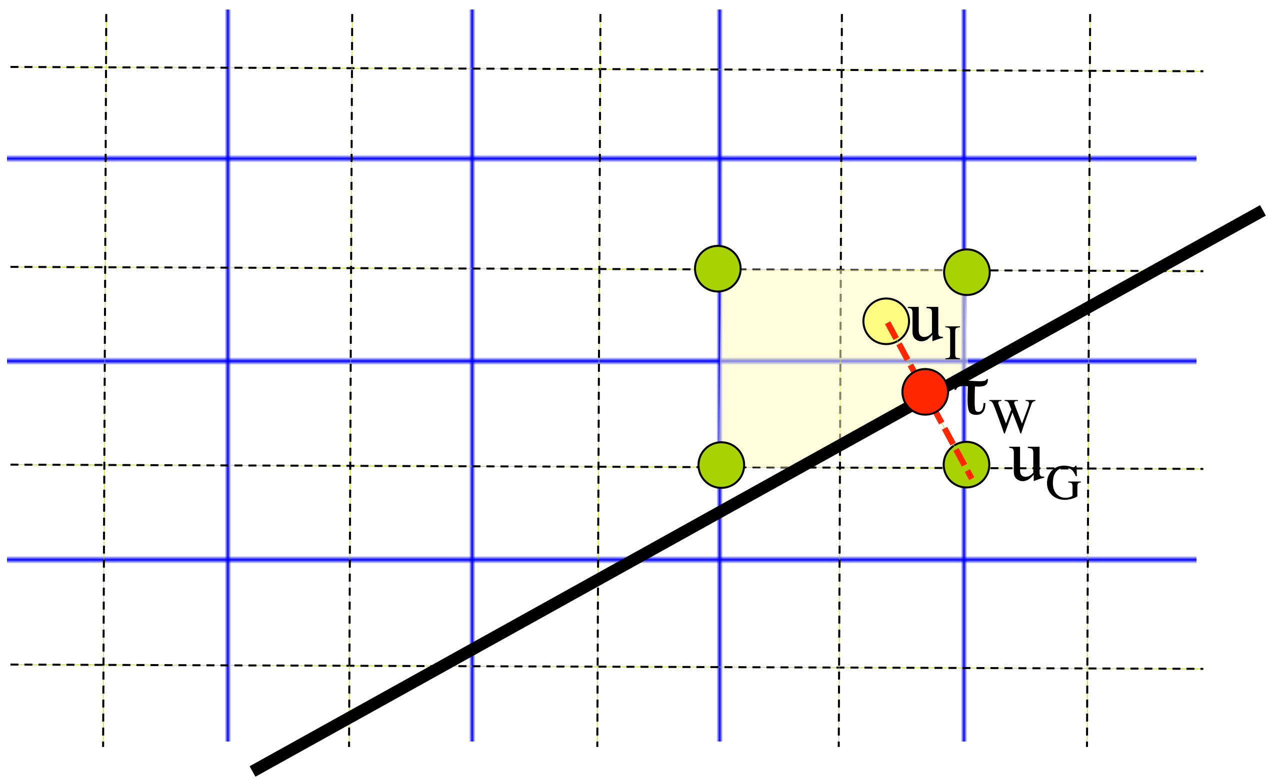
Validate with simple setup

- Small grid changes can make big difference
- Height of first grid cell above wall determines slope

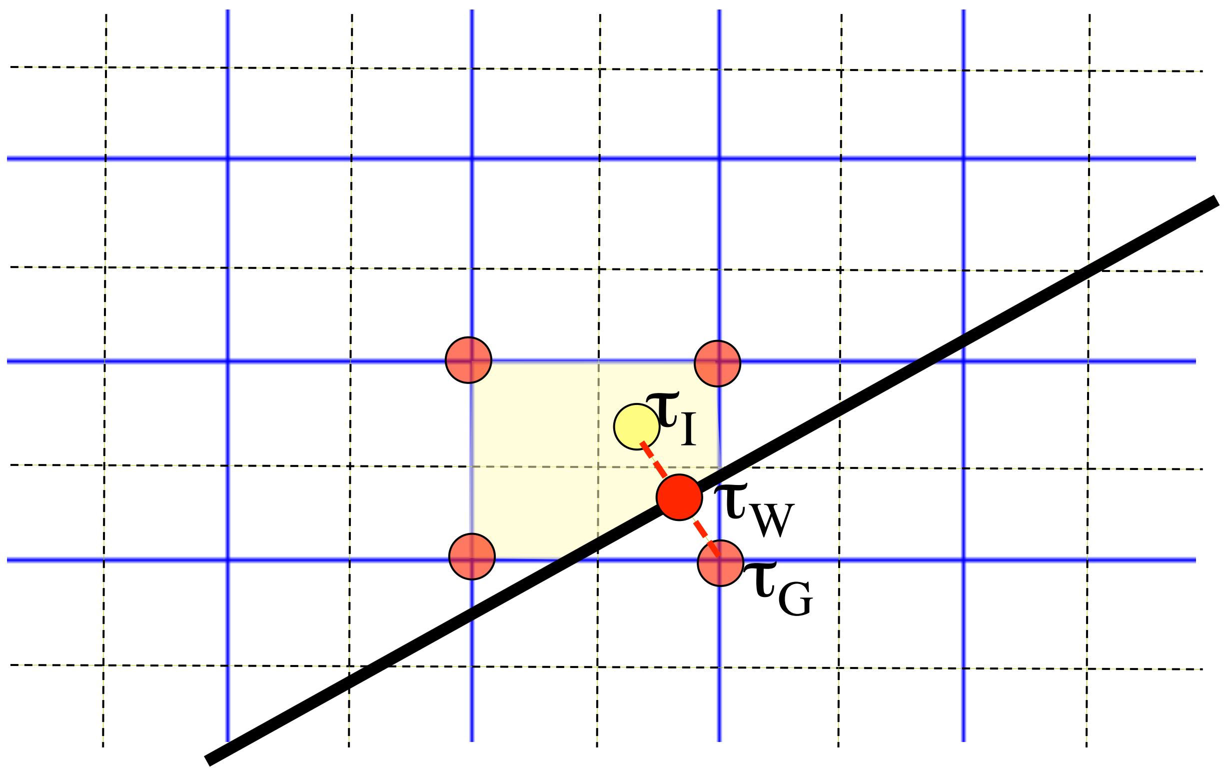




3D log law implementation



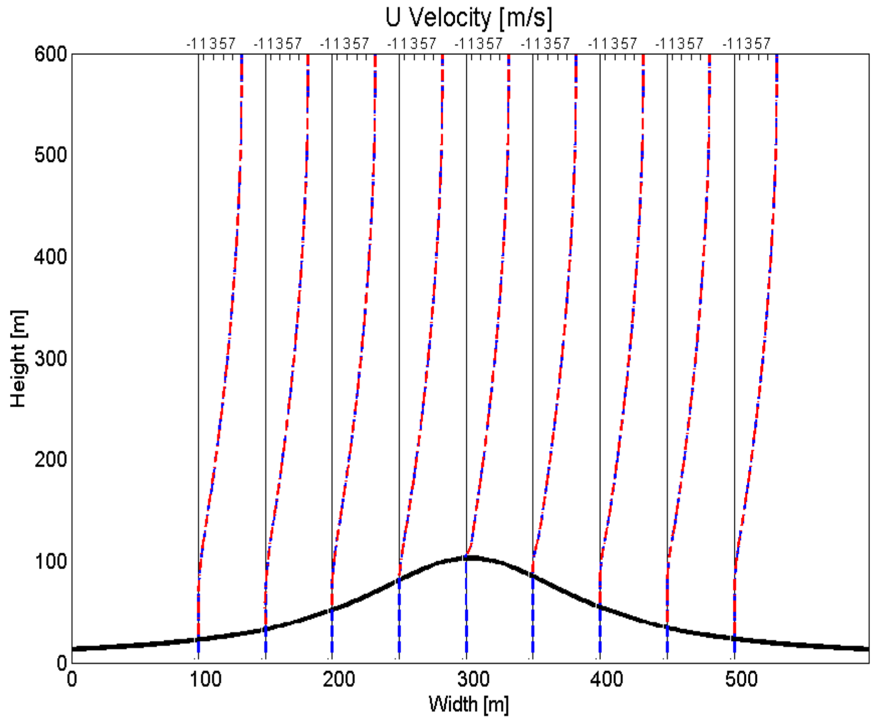
3D log law implementation



Idealized hill

- Goal: match WRF and WRF-IBM results
- Notes about log law:
  - WRF implements d/dz instead of d/dn
  - WRF results depend strongly on choice of dz

No slip conditions

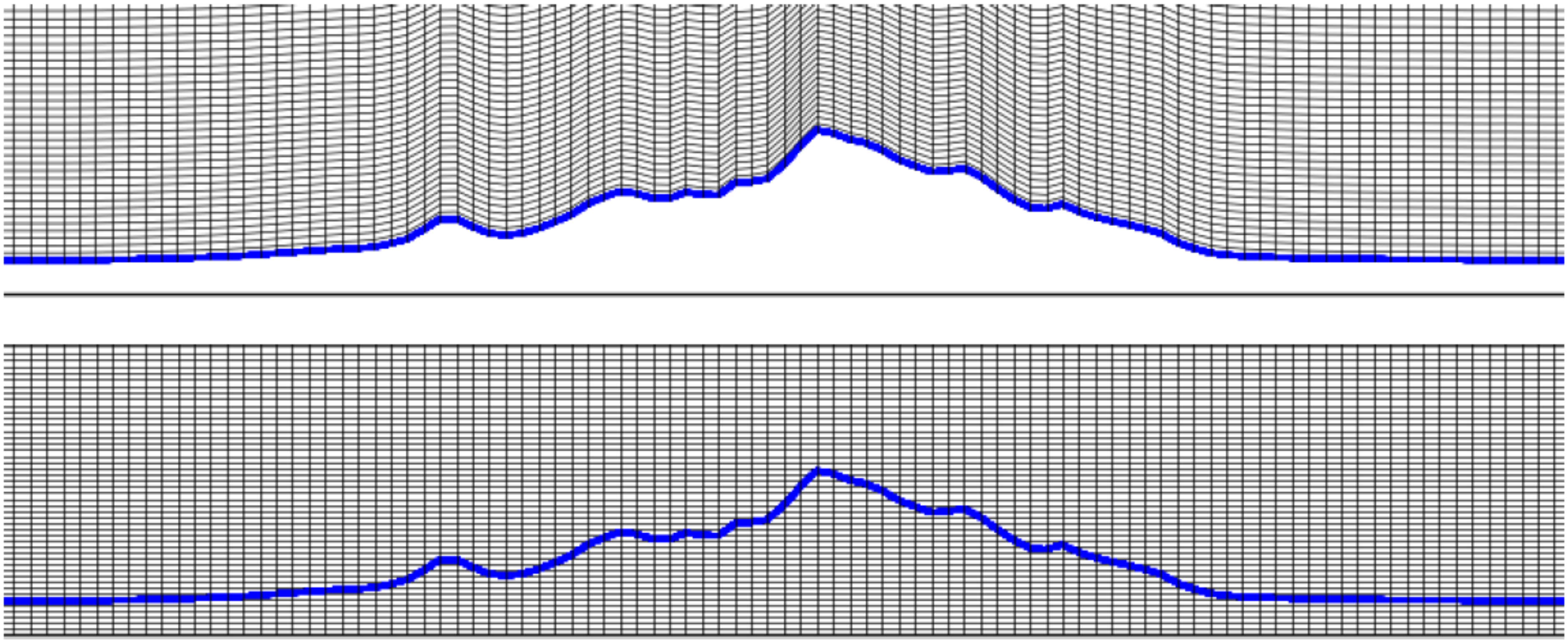


Red – terrain following coordinates (WRF)

Blue – Immersed Boundary Method (IBM-WRF)

Lundquist et al. 2010, 2012

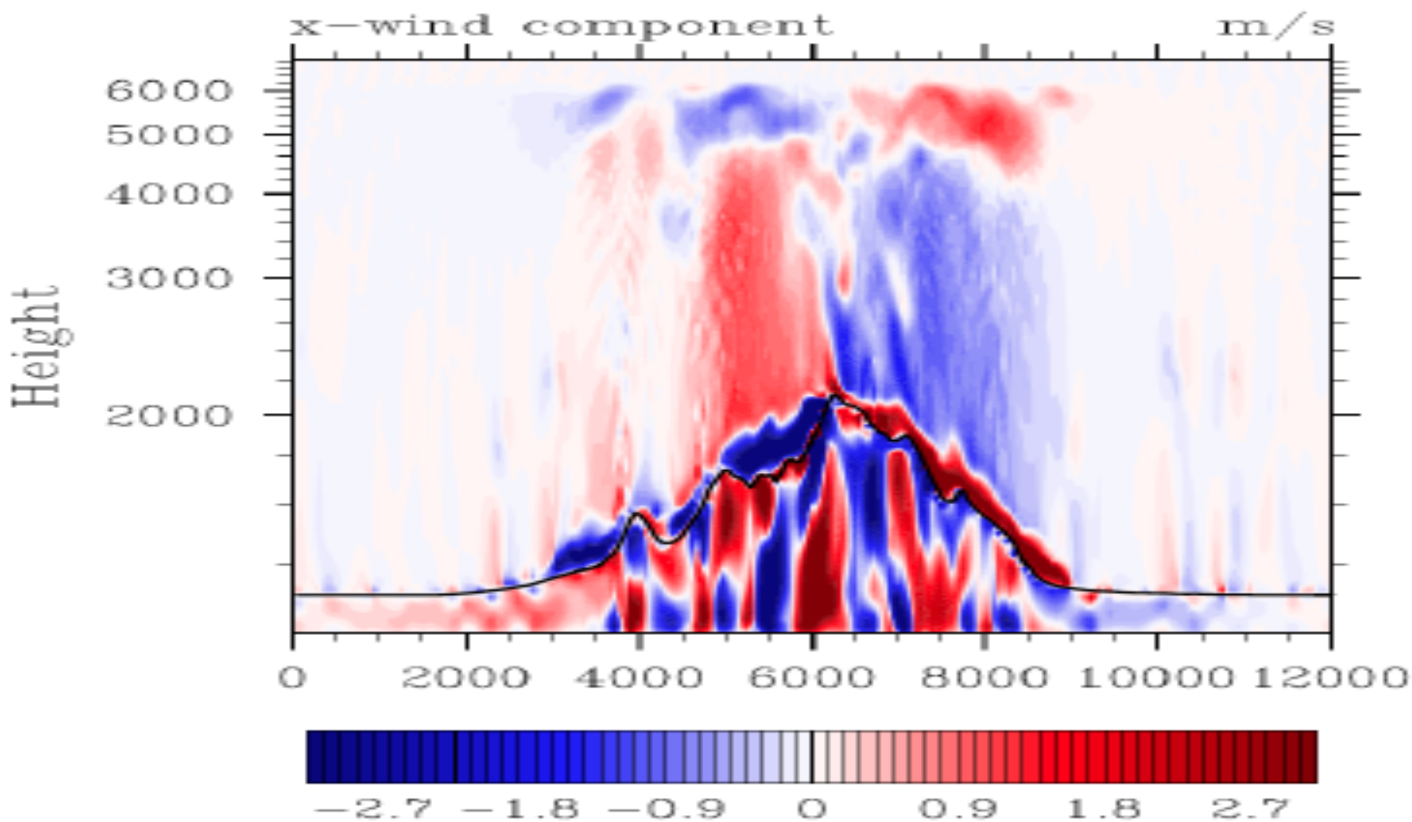
Granite Mountain – IBM test case



Granite Mountain, Utah

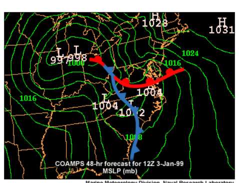
Preliminary simulations

- IBM-WRF can run at least 60m resolution
  - Standard WRF blows up at ~300m resolution for 3D Granite Mountain

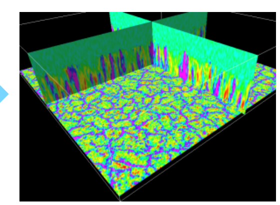


MATERHORN: addressing challenges in the "Terra incognita"

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



IBM-WRF



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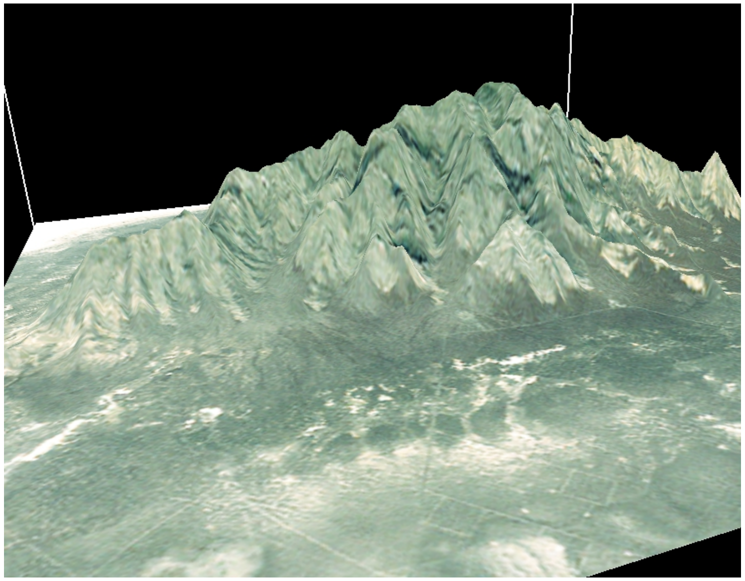
Take home messages

- There exists a “Terra incognita” for terrain
- Log law implementation very sensitive to resolution near the ground
- Ongoing work: stable boundary layer flows over Granite Mountain



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