Development of the WRF-IBM model for flow over complex terrain

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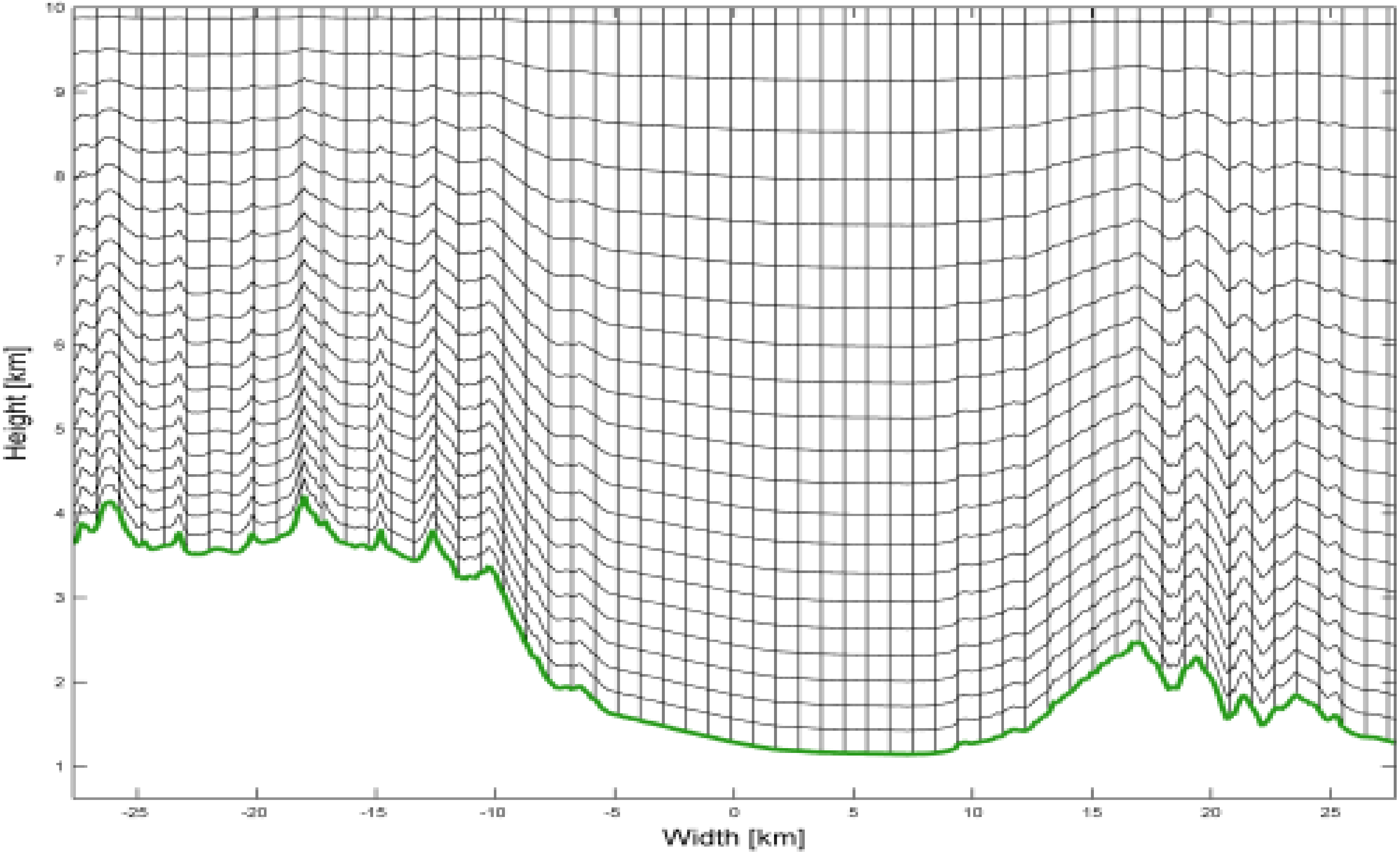
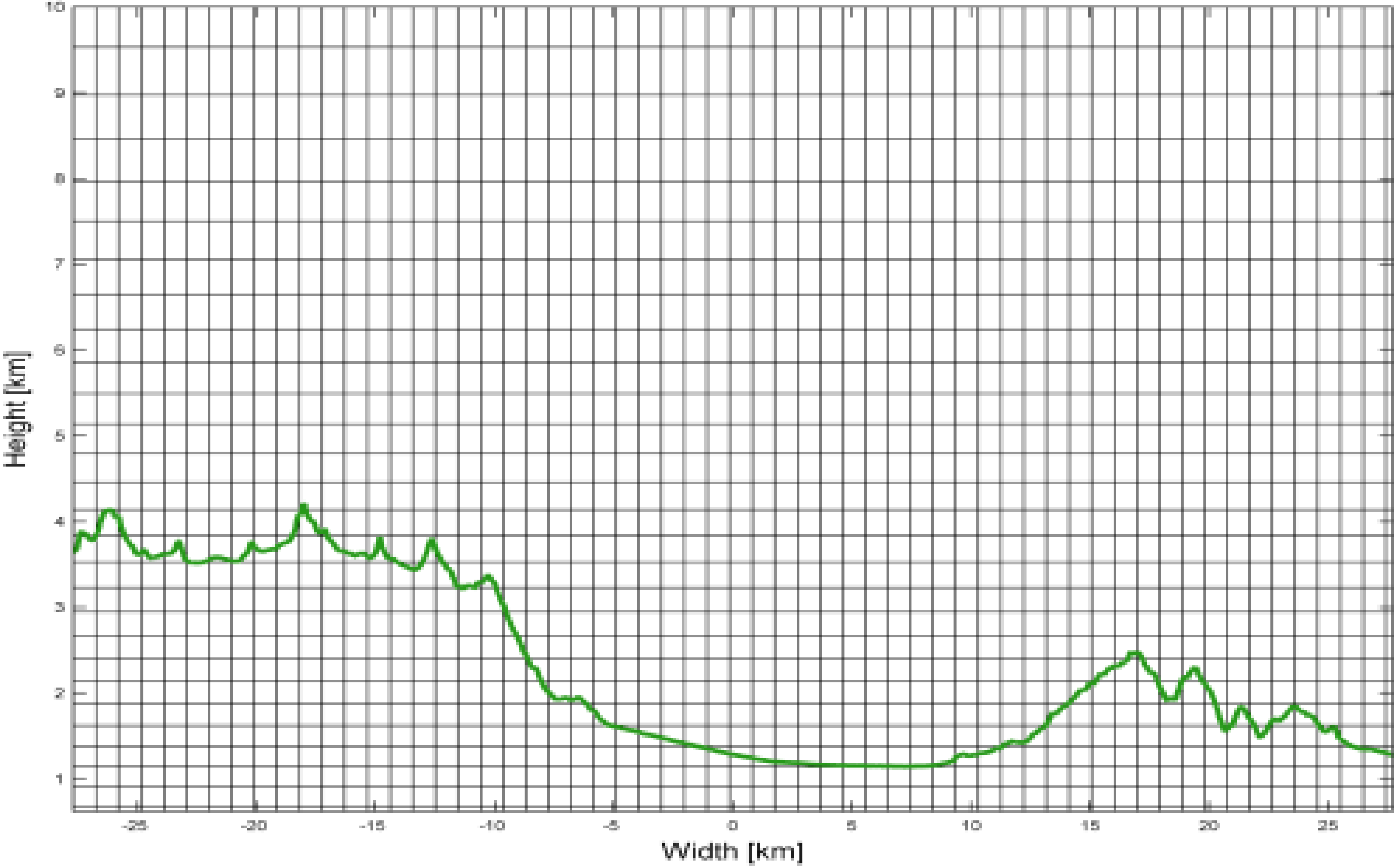
Terrain-following coordinates



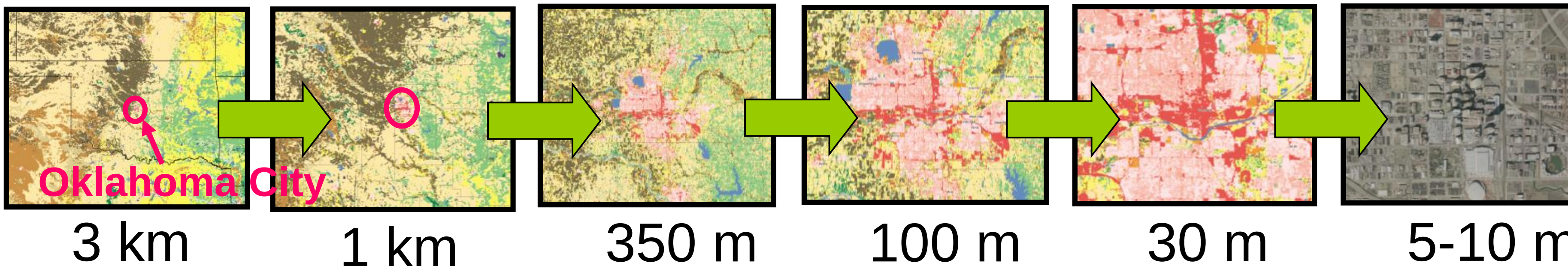
Immersed boundary method



Road map

- WRF-IBM for complex terrain
- Surface fluxes - scalars and momentum
- Nesting interface within WRF
- Initialization with real meteorological data

WRF to WRF-IBM – seamless grid nesting



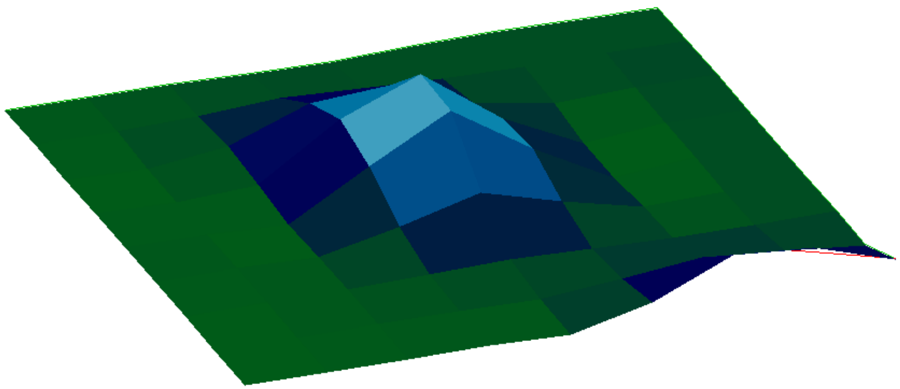
WRF -> WRF-IBM

transition

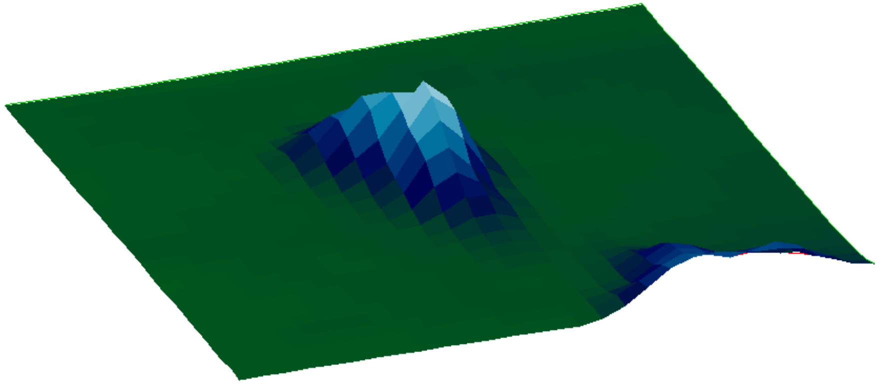
- Weather and Research Forecasting (WRF) model
  - Mesoscale to microscale
- One tool for all scales
  - Improved turbulence models for LES
  - Immersed boundary method (IBM) for steep terrain

Increasing resolution ➡ steeper slopes

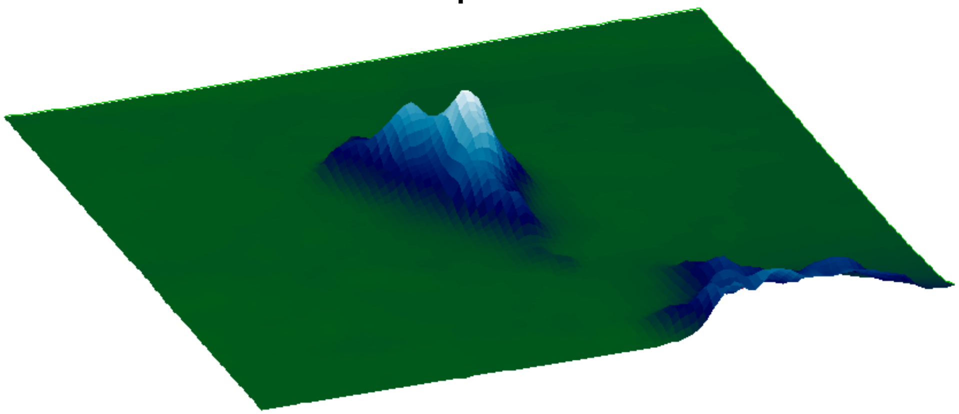
3 km, max slope ~4°



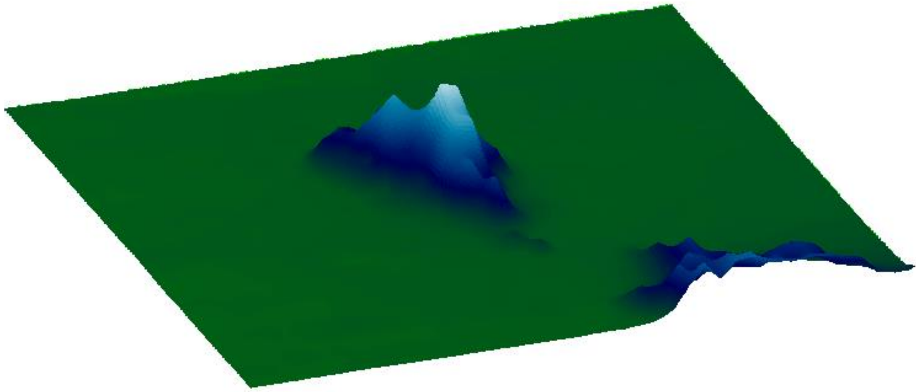
1 km, max slope ~14°



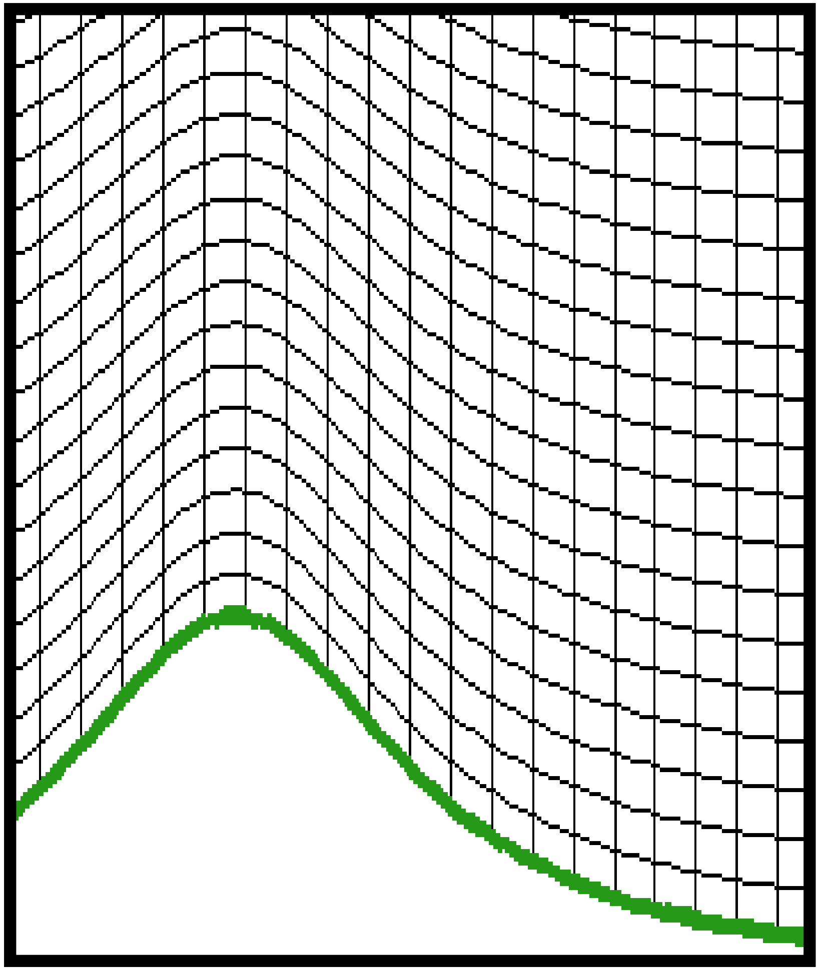
300 m, max slope ~28°



100 m, max slope ~32°



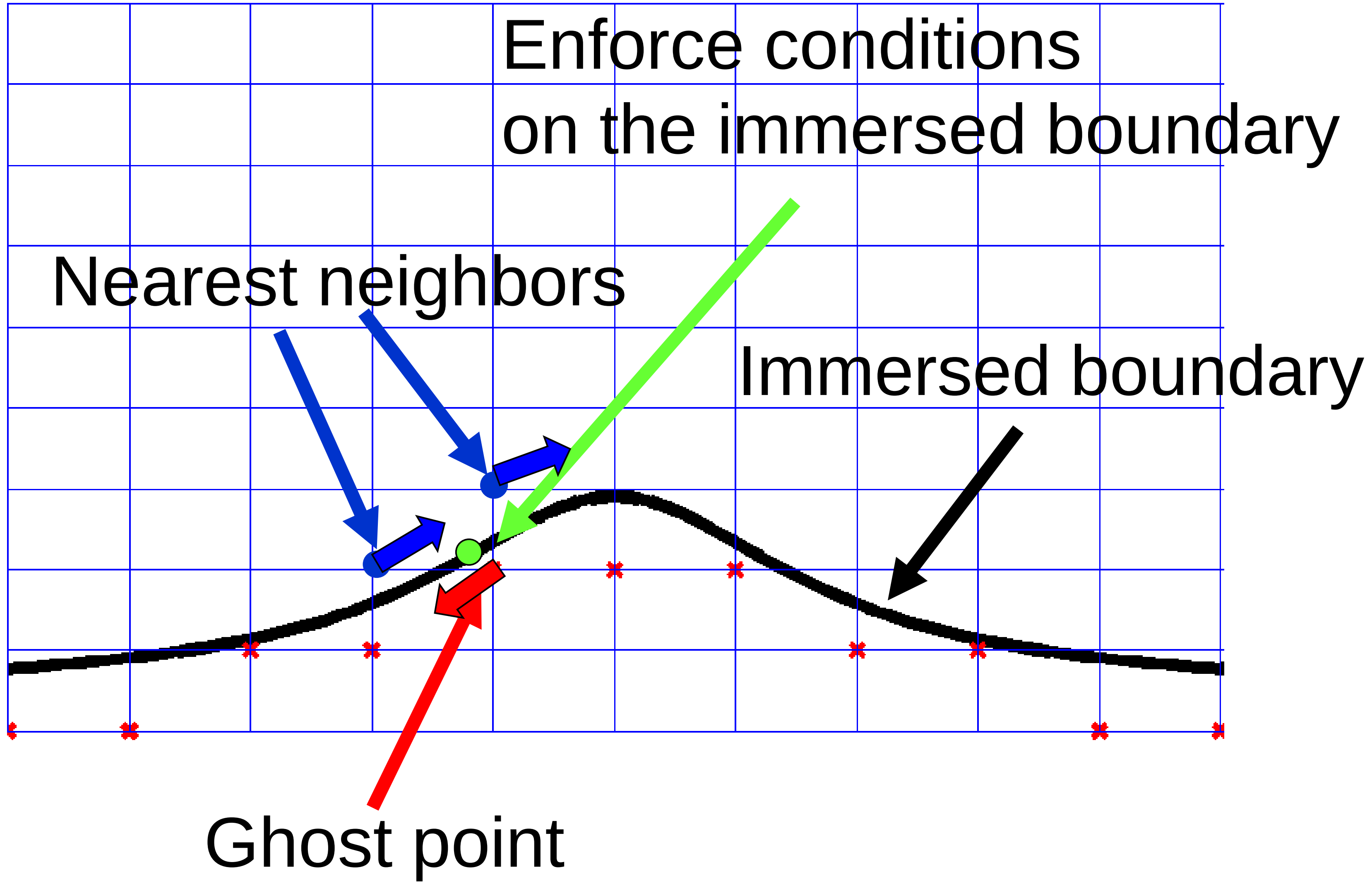
Terrain slope limit



Terrain-following coordinates

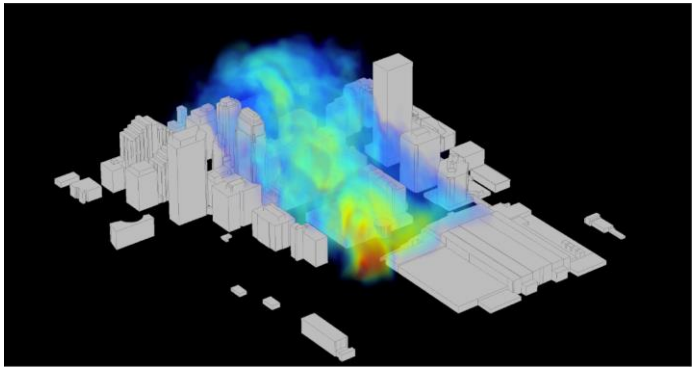
- Horizontal pressure gradient errors
  - 45° limit, usually ~30° starts causing problems (e.g. Mahrer 1984)
- Grid aspect ratio limitations
- Numerical stability

Ghost-cell immersed boundary method



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

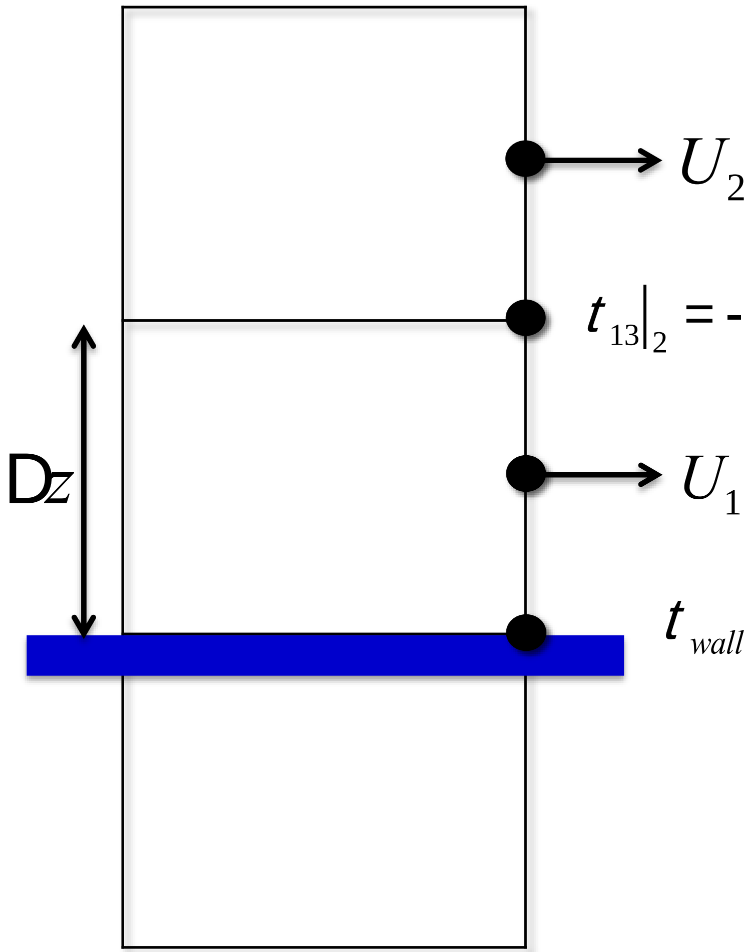
- Momentum equation in U direction

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

- Requires gradient in τ_{13}

WRF implementation of log law

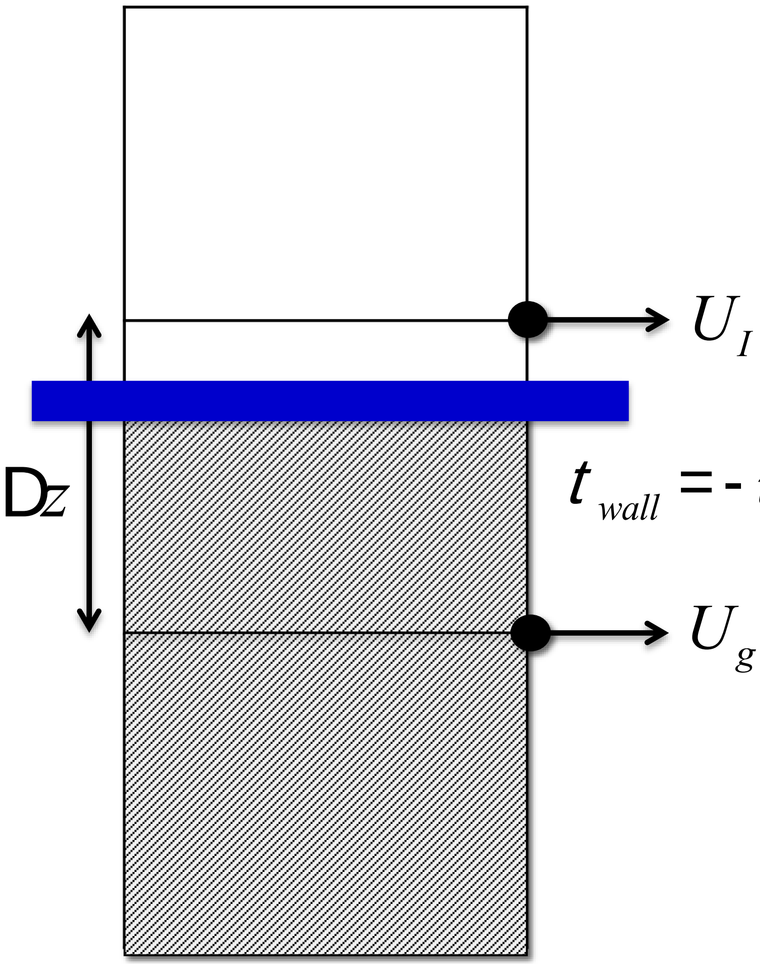
$$\frac{\partial U}{\partial t} = -\frac{\partial \tau_{13}}{\partial z} = -\frac{\tau_{13}\big|_2 - \tau_{wall}}{\Delta z} \ldots$$



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

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

WRF-IBM implementation of log law



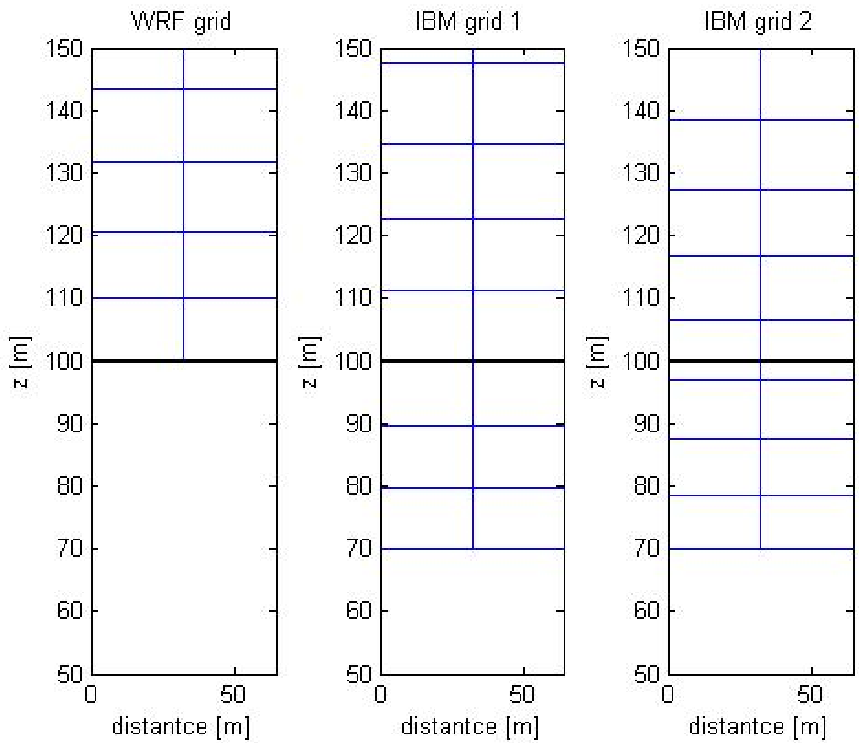
$$\tau_{wall} = -u_*^2 = C_d |U_I| U_I$$

$$\frac{\partial U}{\partial z} = \frac{U_I - U_g}{\Delta z} = -\frac{\tau_{wall}}{\nu_t}$$

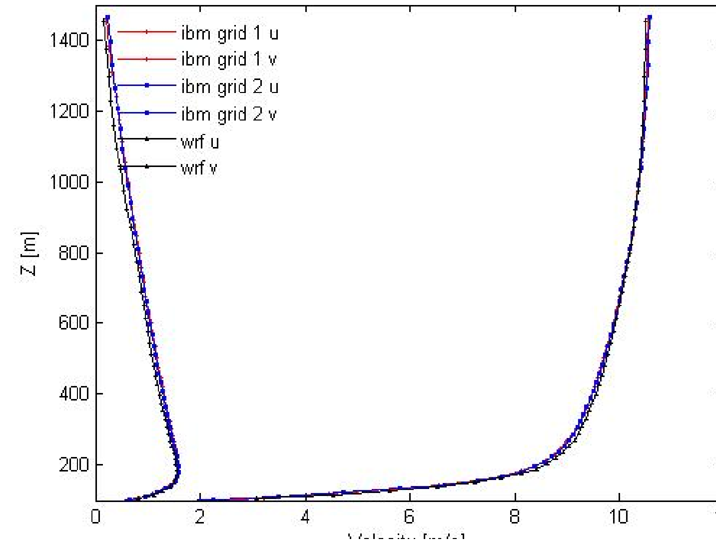
$$U_g = U_I + \frac{\tau_{wall}}{\nu_t} \Delta z$$

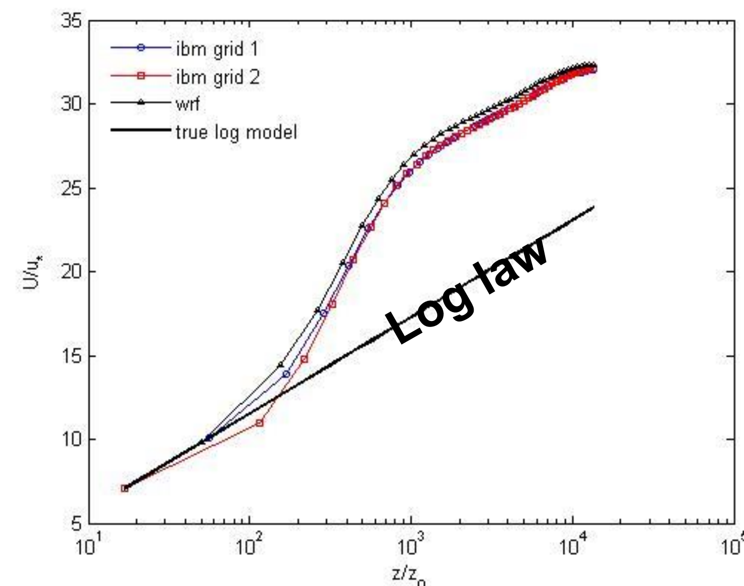
WRF-IBM log law - testing

Neutral boundary layer

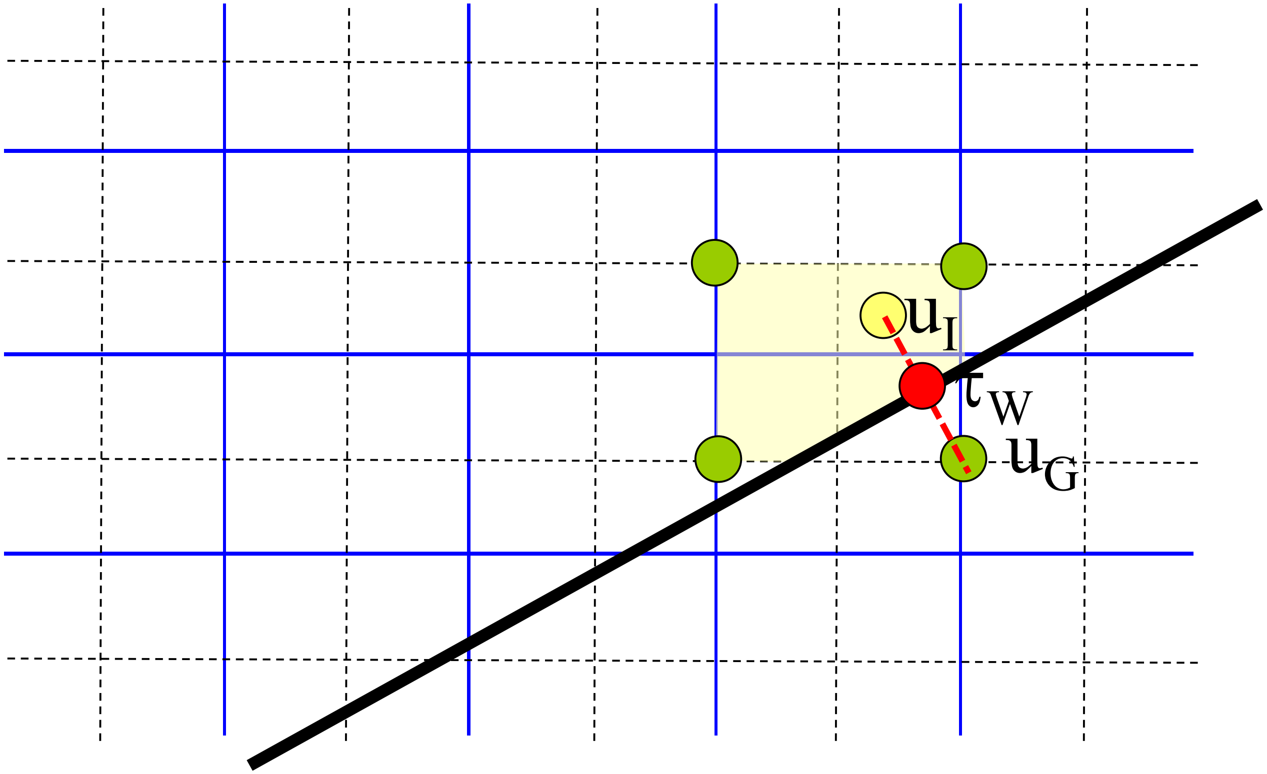


Grid Setup





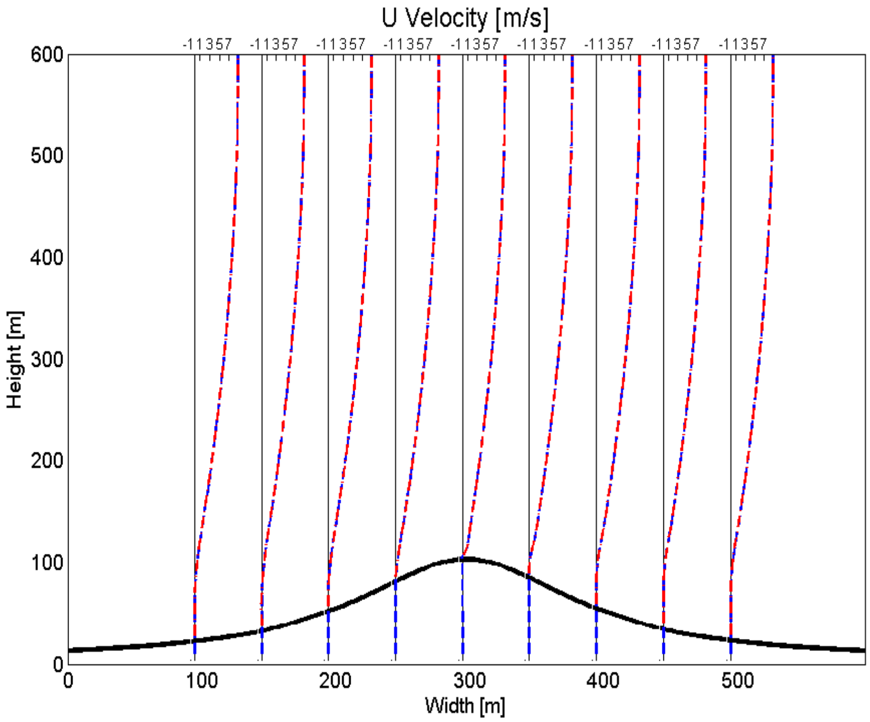
3D log law implementation



Idealized hill

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

No slip conditions



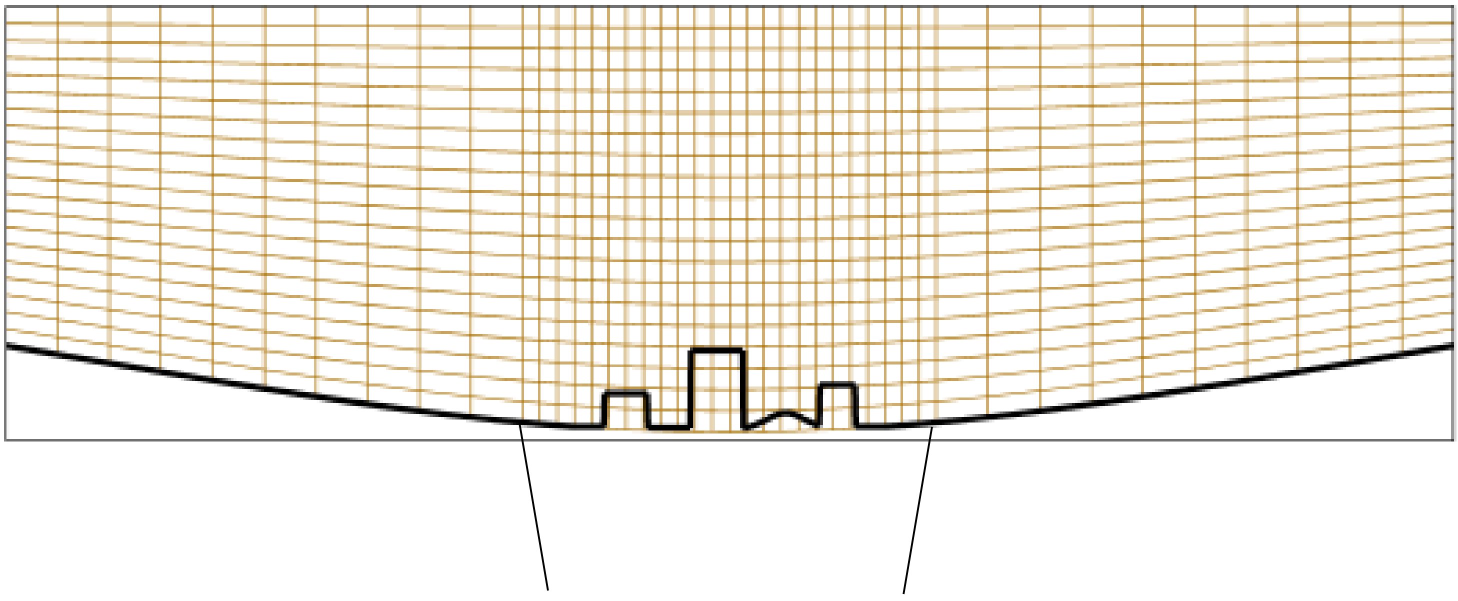
Red – terrain following coordinates (WRF)

Blue – Immersed Boundary Method (IBM-WRF)

Lundquist et al. 2010, 2012

WRF to WRF-IBM interface

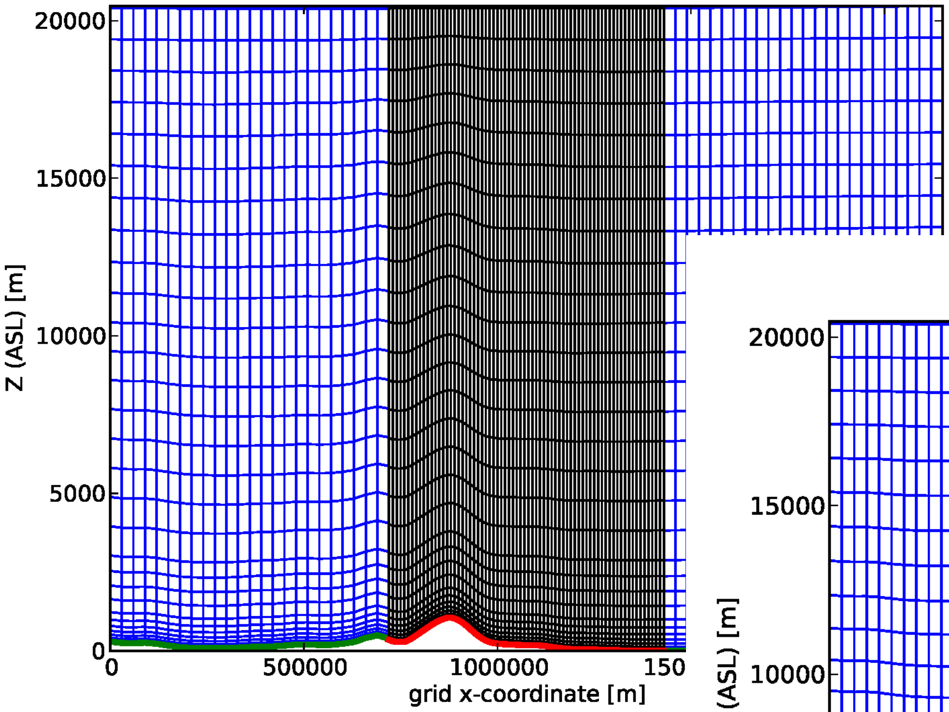
- Develop interpolation framework
- Grid nesting from WRF to IBM grids
  - And from IBM to IBM grids



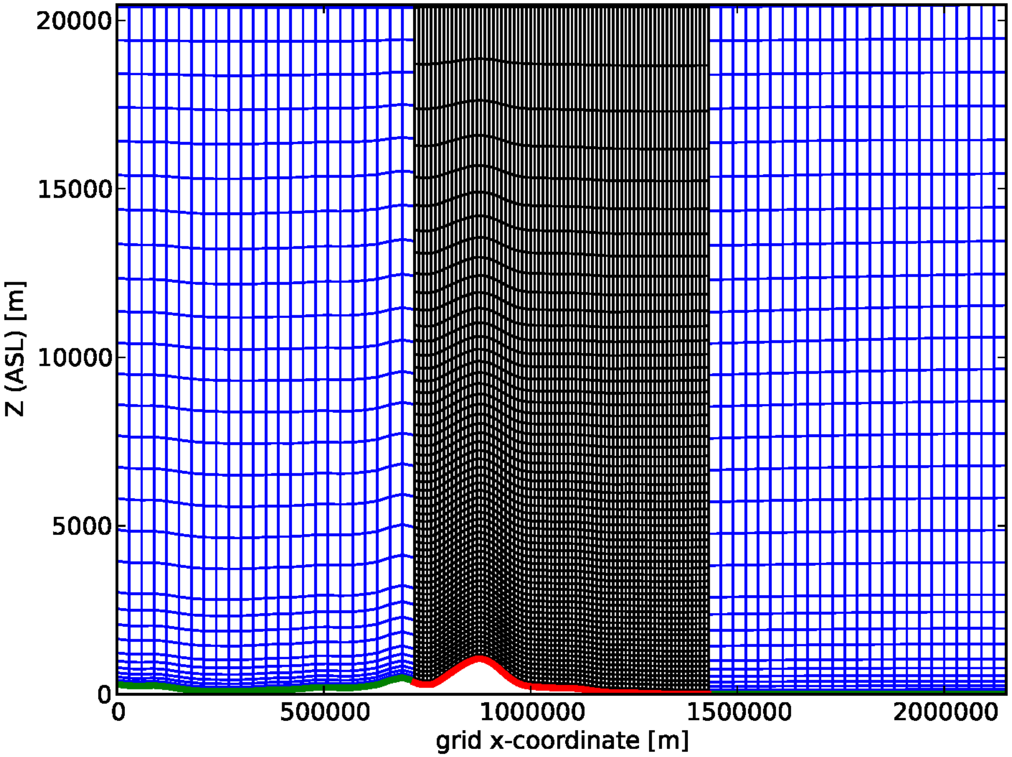
Nested IBM grid

WRF to WRF-IBM nesting

- WRF: same vertical levels
- IBM: interpolation needed
- Vertical nesting

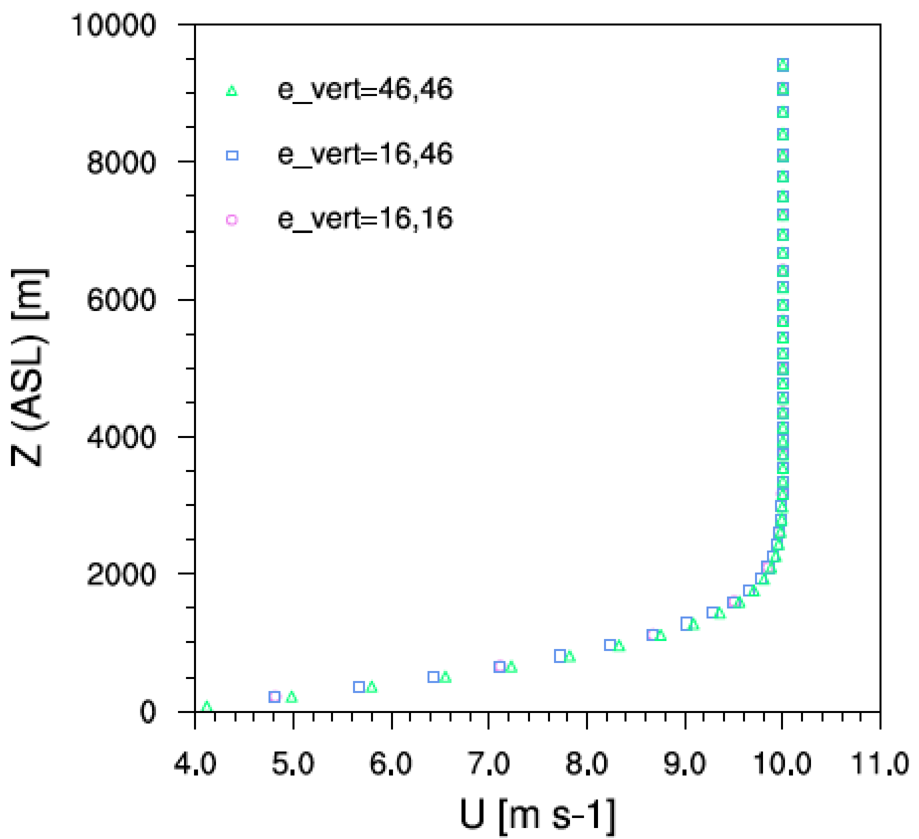


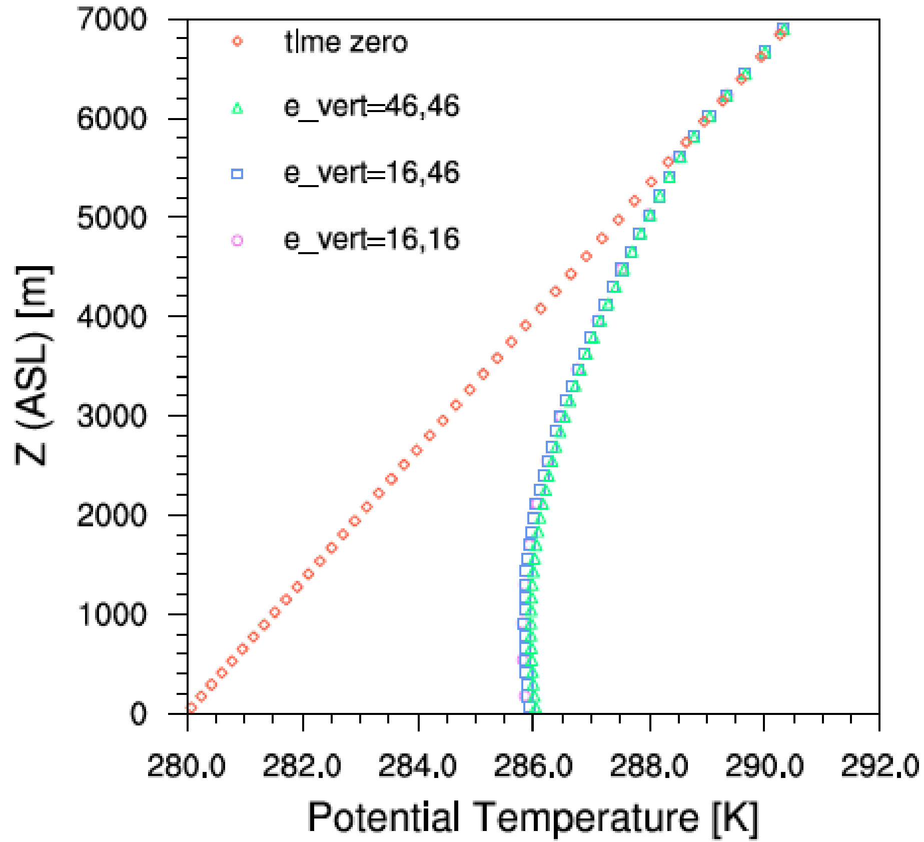
Nested grid



Vertical nesting in WRF

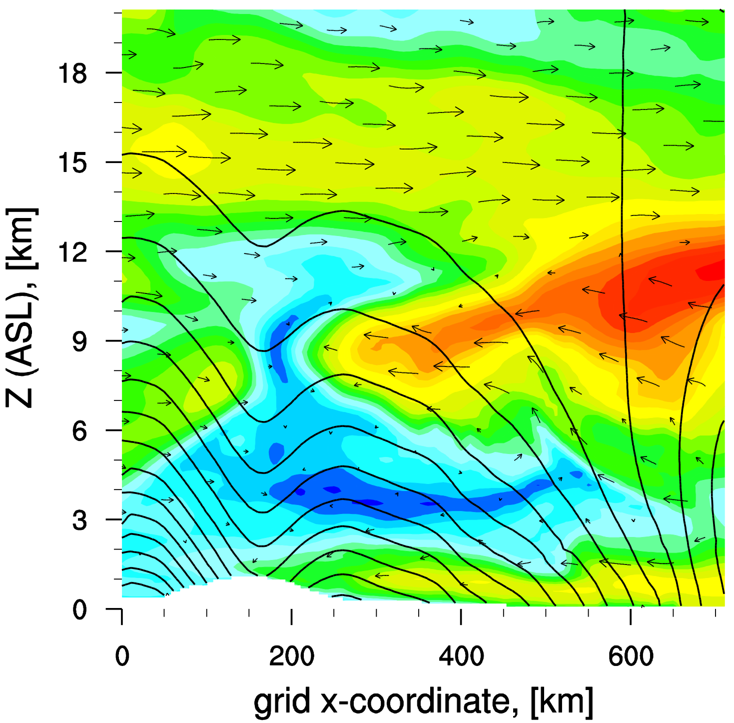
Idealized tests – flow over flat plate, heated flat plate



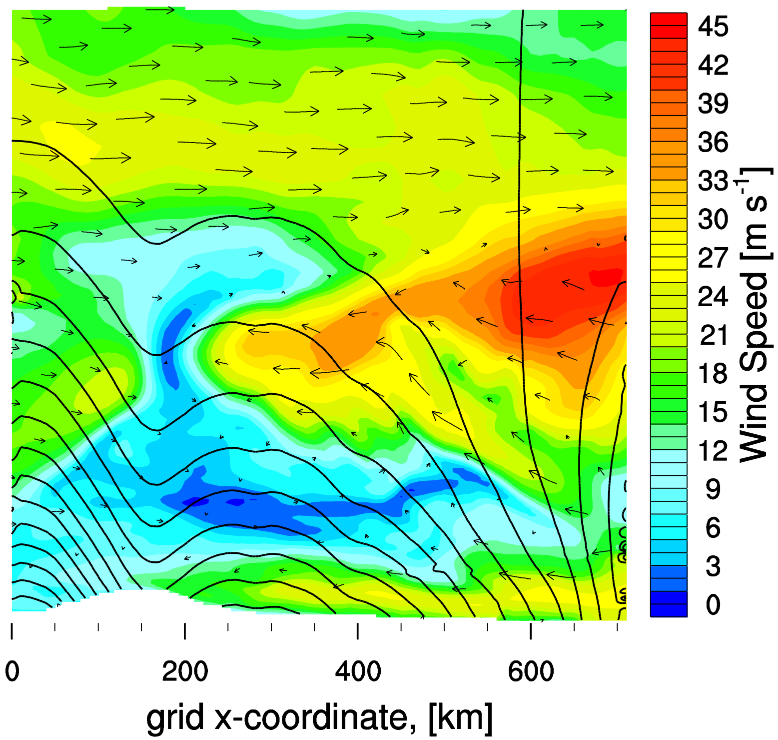


Vertical nesting in WRF

Real test cases – Jan 2000 snowstorm



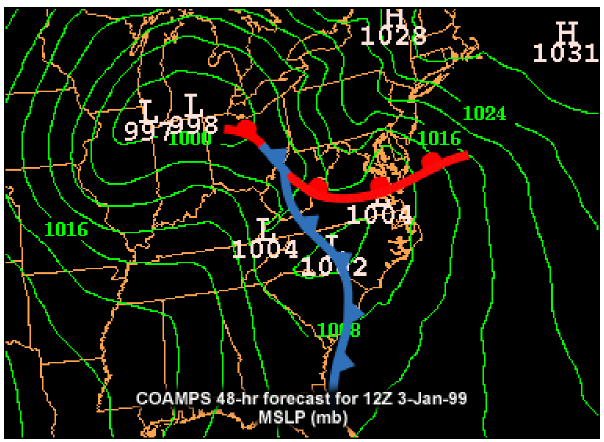
Same vertical levels, 30:30



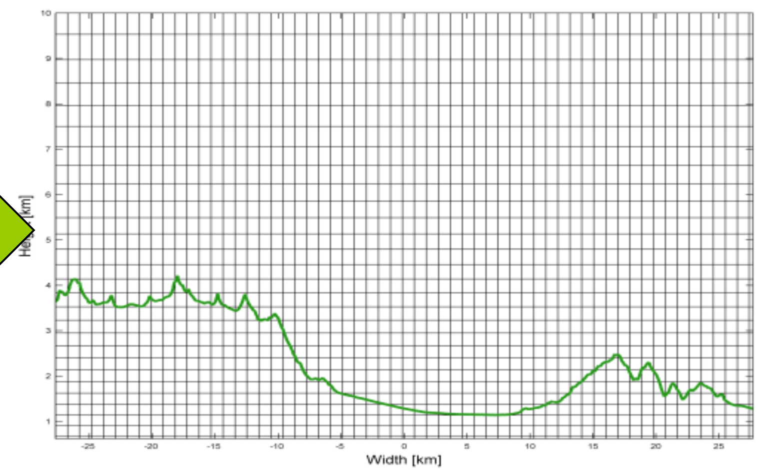
With vertical nesting, 30:60

Initialization with meteorological data

- Run WRF-IBM with direct forcing from met. data



Marine Meteorology Division, Naval Research Laboratory

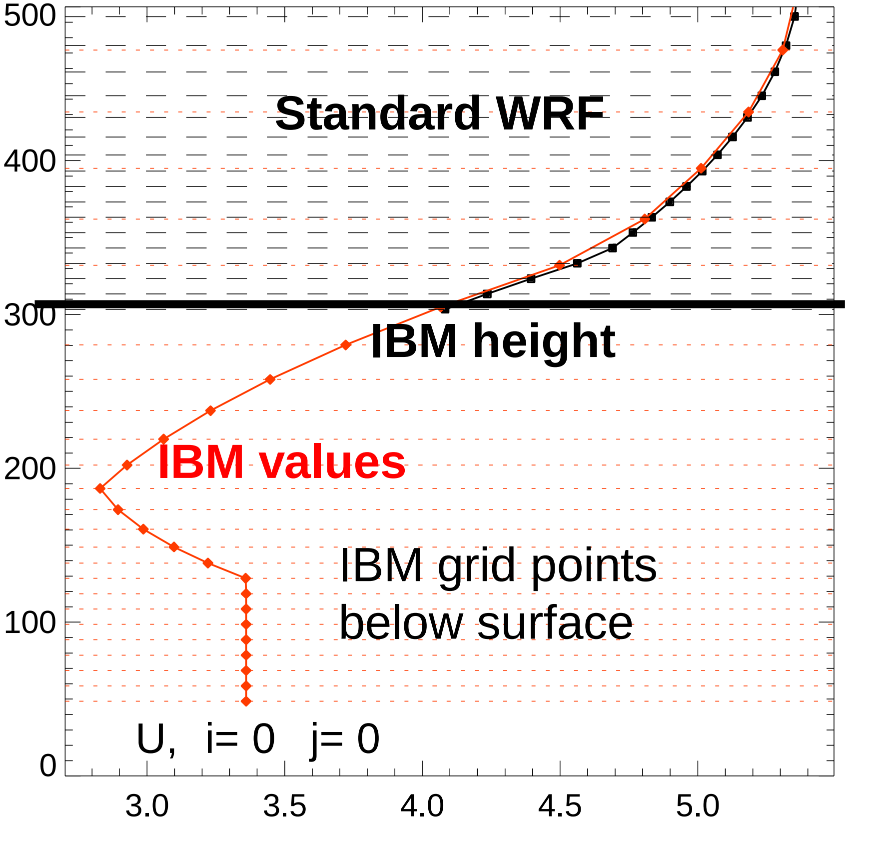


NAM

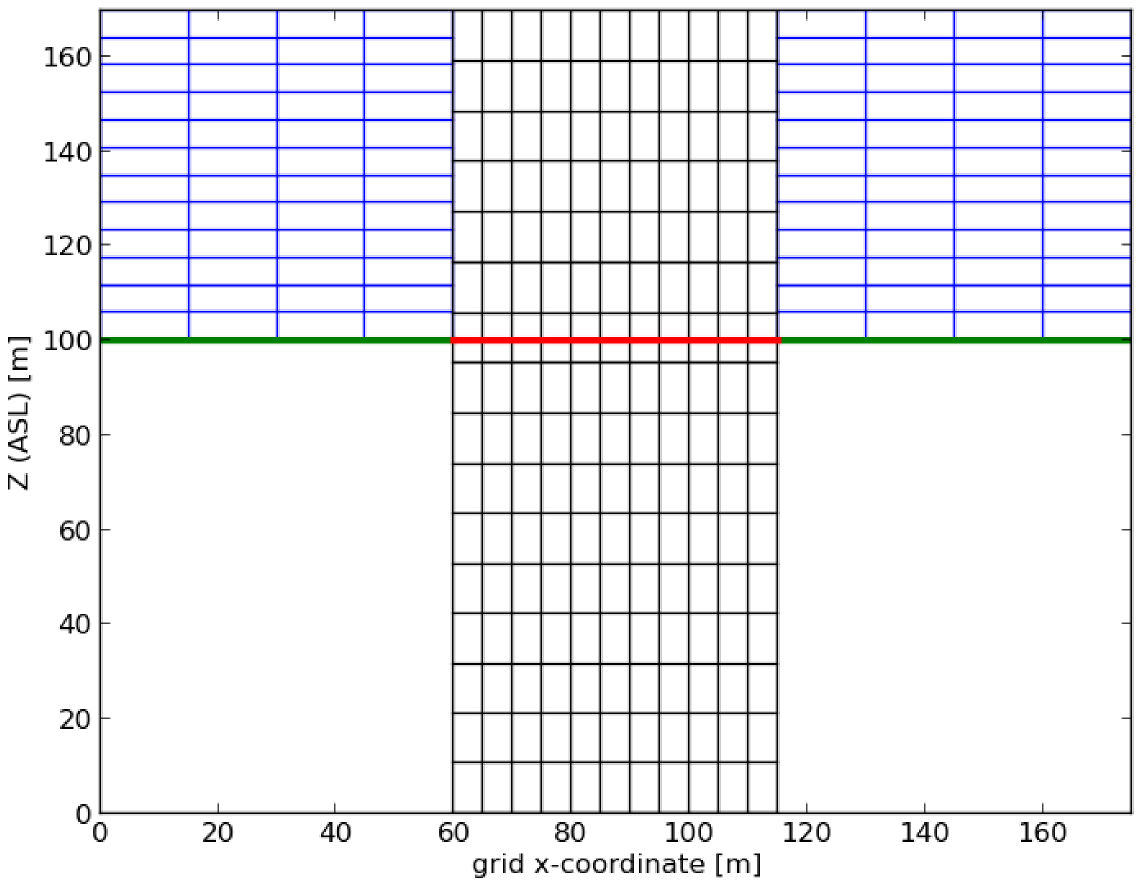
WRF-IBM

Initialization with meteorological data

- IBM domain extends below the lowest terrain height
- Interpolate met. data onto IBM grid for initialization and boundary forcing

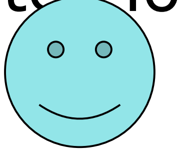


Nesting WRF to WRF-IBM



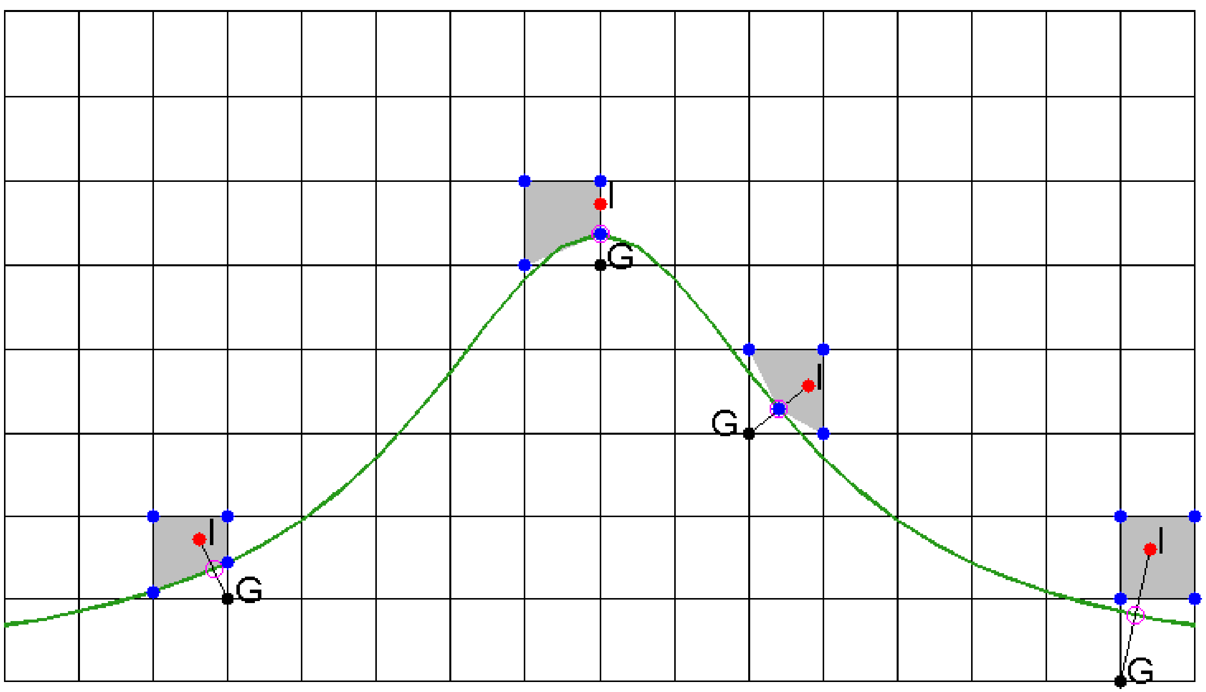
Road map – next steps

- WRF-IBM for complex terrain
  - In progress!
- Then we can simulate Granite Mountain!



IBM - Boundary reconstruction

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



Lundquist et al. MWR 2010, 2012