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

- Oklahoma City
- 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 → WRF-IBM transition
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

-enforce conditions on the immersed boundary

-nearest neighbors

-ghost point

-immersed boundary
Complex terrain applications

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

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

\[
\tau_{\text{wall}} = -u_*^2 = -C_D |U_1| U_1
\]
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 $\tau_{13}$
WRF implementation of log law

\[
\frac{\partial U}{\partial t} = \frac{\partial}{\partial z} = \frac{13|_2}{z}\text{ wall} 
\]

\[13|_2 = v_T \frac{\partial U}{\partial z} = v_T \frac{U_2}{z} \frac{U_1}{U_1}\]

\[\text{wall} = u_*^2 = C_d |U_1| U_1\]
WRF-IBM implementation of log law

\[ \frac{\partial U}{\partial z} = \frac{U_I}{z} = \frac{U_g}{v_t} \]

\[ U_g = U_I + \frac{wall}{v_t} z \]

\[ u_*^2 = C_d |U_I| |U_I| \]
Neutral boundary layer

Grid Setup

WRF-IBM log law - testing
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 $dz$

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
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