An immersed boundary method in WRF for complex mountainous terrain

Tina Katopodes Chow\textsuperscript{1}, Jingyi Bao\textsuperscript{1}, Jason Simon\textsuperscript{1}, Katherine A. Lundquist\textsuperscript{2}

\textsuperscript{1}Civil and Environmental Engineering, University of California, Berkeley
\textsuperscript{2}Lawrence Livermore National Laboratory
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

Enforce conditions on the immersed boundary

Nearest neighbors

Immersed boundary

Ghost point
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

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

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

\[
\frac{\partial U}{\partial t} = - \frac{\partial \tau_{13}}{\partial z} \quad \ldots
\]

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

\[
\tau_{13}|_1 = \tau_{wall} = -u_*^2 = -C_D |U_1|U_1
\]
IBM – log law implementation

\[ u_{\text{surface}} = v_{\text{surface}} = w_{\text{surface}} = 0 \]

\[ \bar{U} \cdot \hat{n} = 0 \]

\[ \tau_w = -\mu \left( \frac{\kappa}{\ln \frac{z_i - h}{z_o}} \right)^2 |\bar{U}| u \]
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

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IBM-WRF
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
- Funding thanks to the ONR MURI MATERHORN project