Application of the immersed boundary method to simulations of flow over steep, mountainous terrain

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Motivation

- Quantify impact of terrain-following coordinates in steep terrain
  - Immersed boundary method (IBM) implemented into WRF (Lundquist et al. 2010, 2012)
    - WRF: capable mesoscale and LES code; cannot handle complex terrain
    - IBM-WRF: *can* handle complex terrain at LES scales
  - Want to use IBM-WRF to nest from meso to microscale
    - Best practices unknown

MATERHORN Project

- Multi-university research initiative
  - PIs at Notre Dame, Naval Postgraduate School, UC Berkeley, University of Utah, University of Virginia
- Study of the predictability of meteorological events in complex terrain
  - Field site: Granite Mountain Atmospheric Testbed (GMAST), located at the US Army Dugway Proving Grounds, Utah
    - Dense existing instrumentation + IOPs
    - Large existing datasets

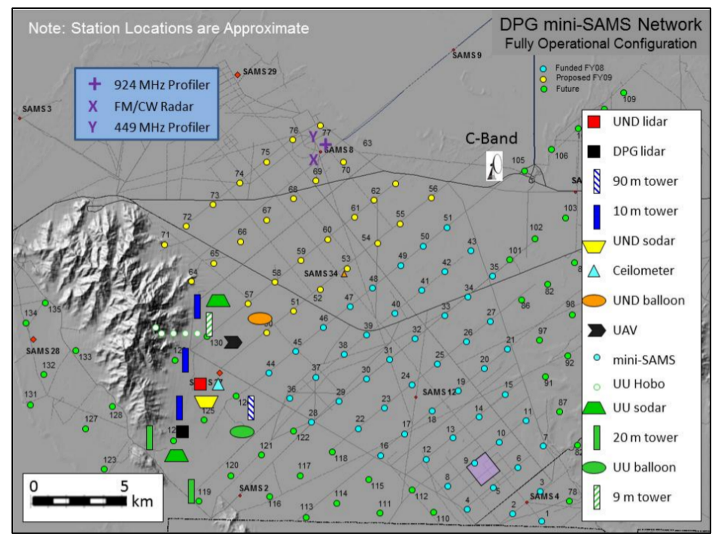

Figure 1: Locations of sensors at GMAST.

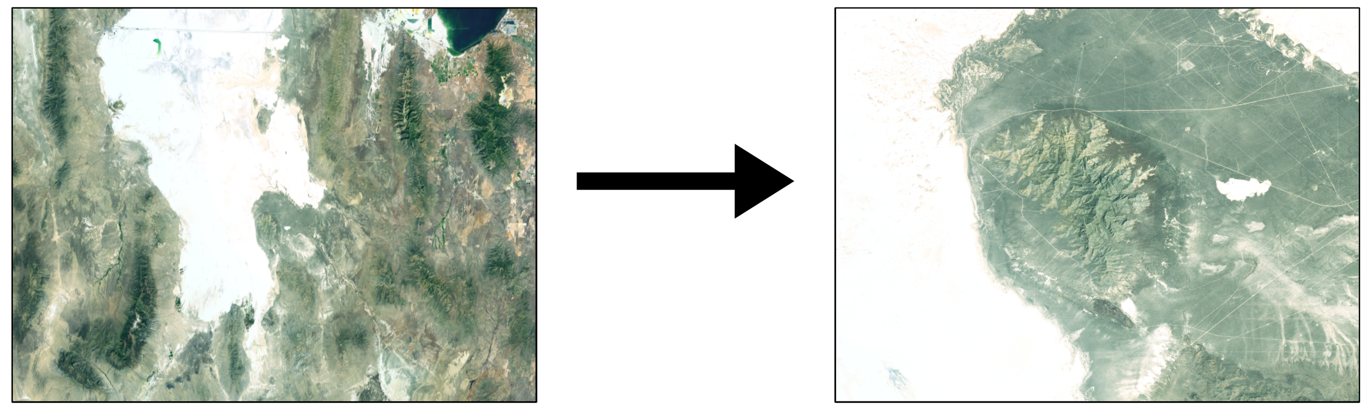

Figure 2: GMAST at scales appropriate for WRF (left) and IBM-WRF (right). We intend to nest between the two.

Background

WRF
- Terrain-following coordinates
  - Accurate at coarse resolution
  - Inaccurate at high resolutions due to steep terrain slopes

IBM-WRF
- Immersed boundary method
  - Accurate at high resolution
  - Inaccurate at low resolution due to interpolation
    - At very low resolution, terrain becomes a flat plate; accurate

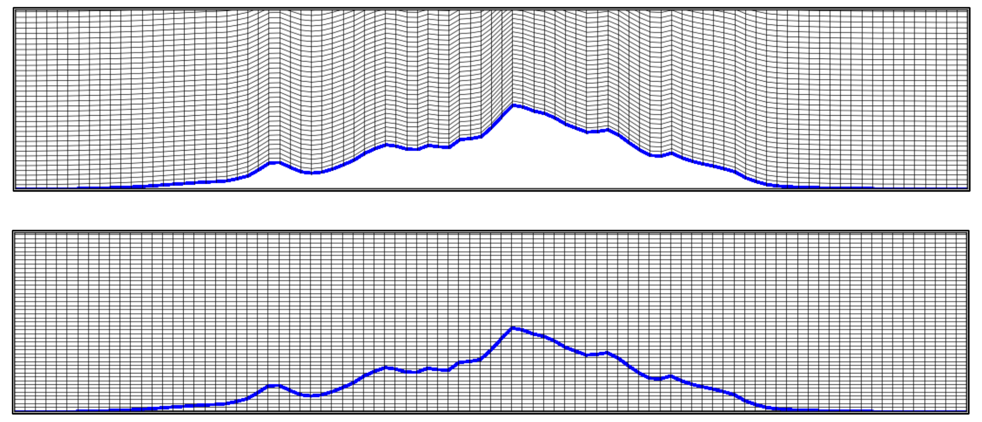

Figure 3: GMAST terrain (100m horizontal resolution) with terrain-following coordinates (top) and as an immersed boundary (bottom). Plots to scale.

Other Notes

- WRF blows up at fine resolution
  - Breaking point depends on a lot of factors
  - Want to evaluate impact of terrain alone
  - **Need to steepen terrain and keep WRF stable**
- Large eddy viscosity reduces terrain influence

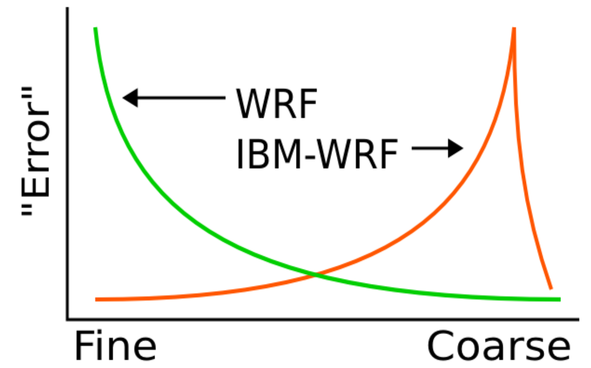

Figure 4: Hypothetical inaccuracies of WRF and IBM-WRF as a function of resolution, as outlined on the left.

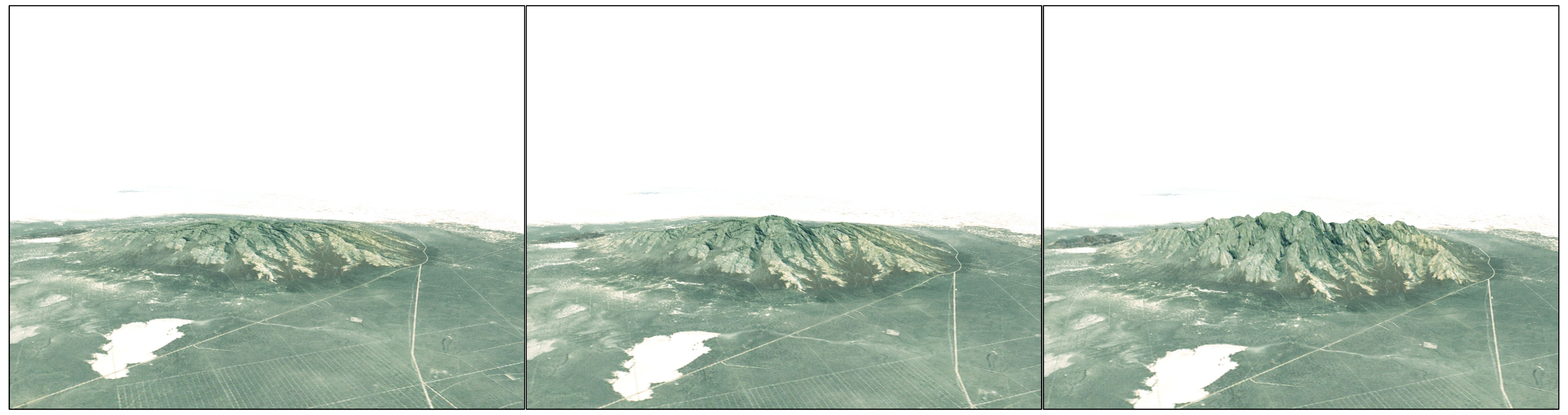

Figure6: Granite Mountain rendered in 3D at 1km (left), 500m (center) and 50m (right) horizontal grid resolution. The z axis is scaled by 2.

Experiment

WRF to IBM-WRF: Where to switch?

- Choose optimal transition from WRF to IBM-WRF when nesting
- Accuracy a function of resolution, slope, aspect ratio, turbulence closure
- Focus on grid skewness (terrain slope)
  - Fixed resolution
    - Find a resolution WRF can handle
  - Constant eddy viscosity
    - Larger values -> less terrain influence
    - Five values used (20, 30, 40, 50 and 100 m^2/s)
  - Scale GMAST terrain (slope "knob")
    - WRF will run for all cases; resolution and aspect ratio stay constant

Setup

- 2D domain
- Simulated for 6 hours
- dx = 500m
- dt = 0.25s
- dz = 50m - 85m
- $u_g = u_0 = 5m/s$
- $K_h = K_v = 20 - 100m^2/s$
- neutral temperature profile
- physics off
- BCs
  - lateral: periodic
  - top: 2km Rayleigh layer
  - bottom: no-slip

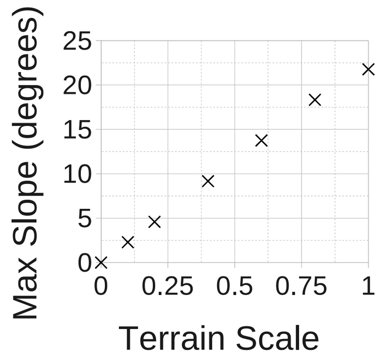

Figure 5: Maximum terrain slope as a function of scaling coefficient.

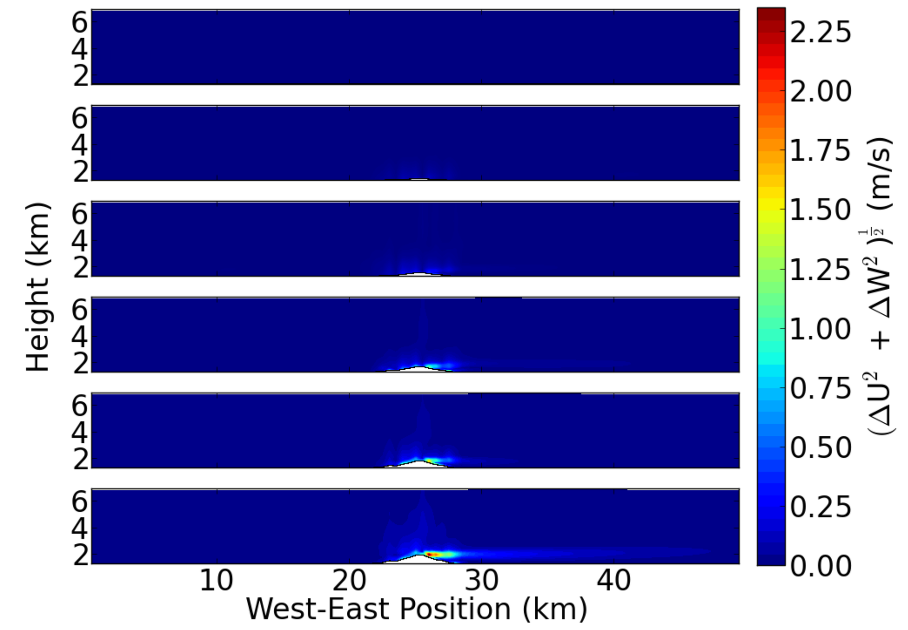

Figure 7: Differences in velocity magnitude between WRF and IBM-WRF when scaling terrain height by 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 (top to bottom). $K=20m^2/s$. Plots to scale.

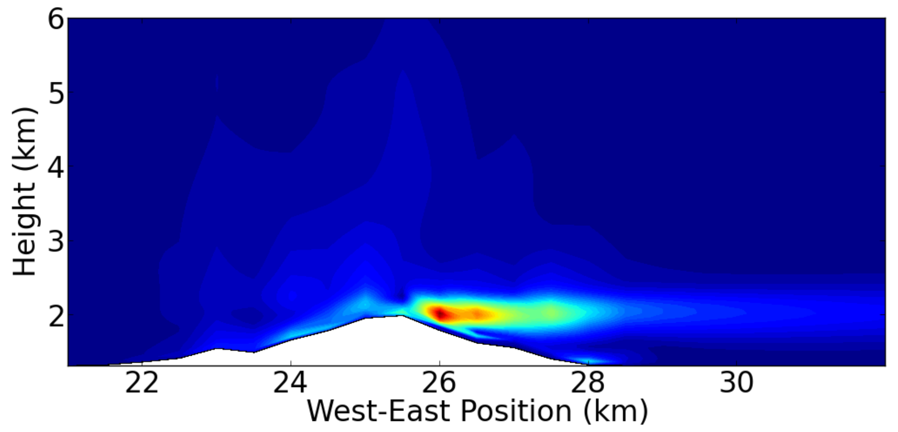

Figure 8: Zoomed view of the difference in velocity magnitude between WRF and IBM-WRF after six hours. See Figure 7 for colorbar. $K=20m^2/s$. GMAST at full scale. Plot to scale.

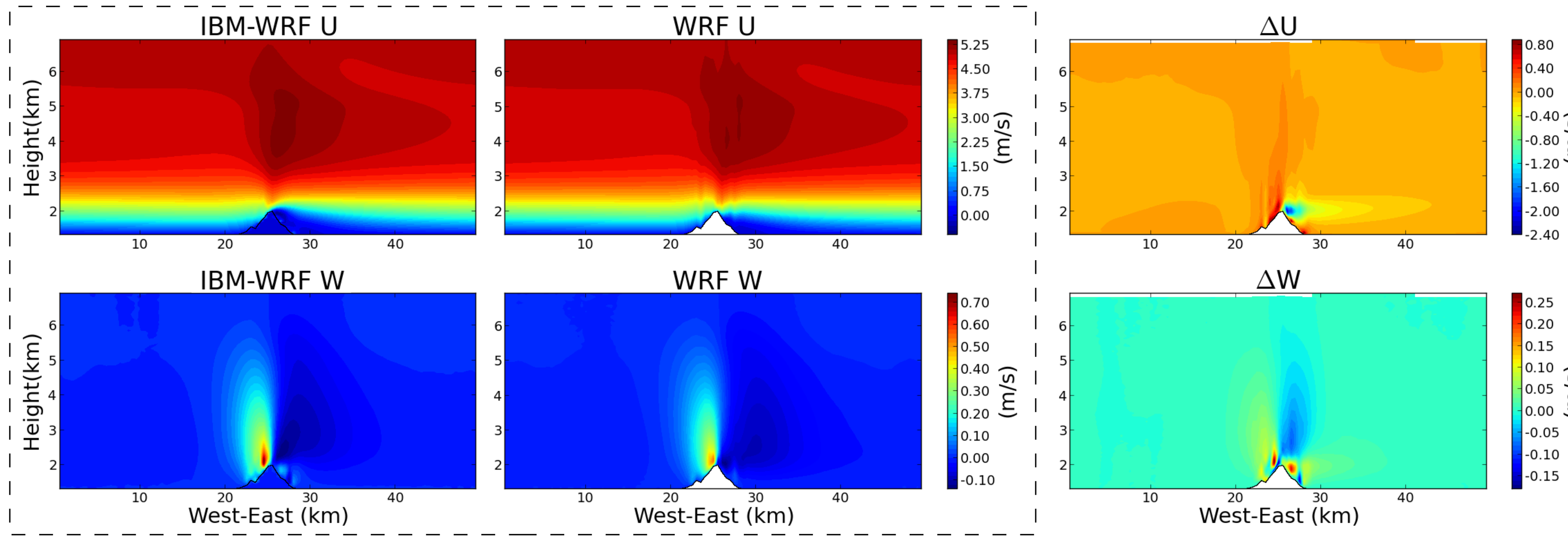

Figure 9: 2D velocity components for IBM-WRF and WRF after six hours of simulation. GMAST at full scale. Difference in velocity magnitude shown in Figures 6 (bottom) and 7.

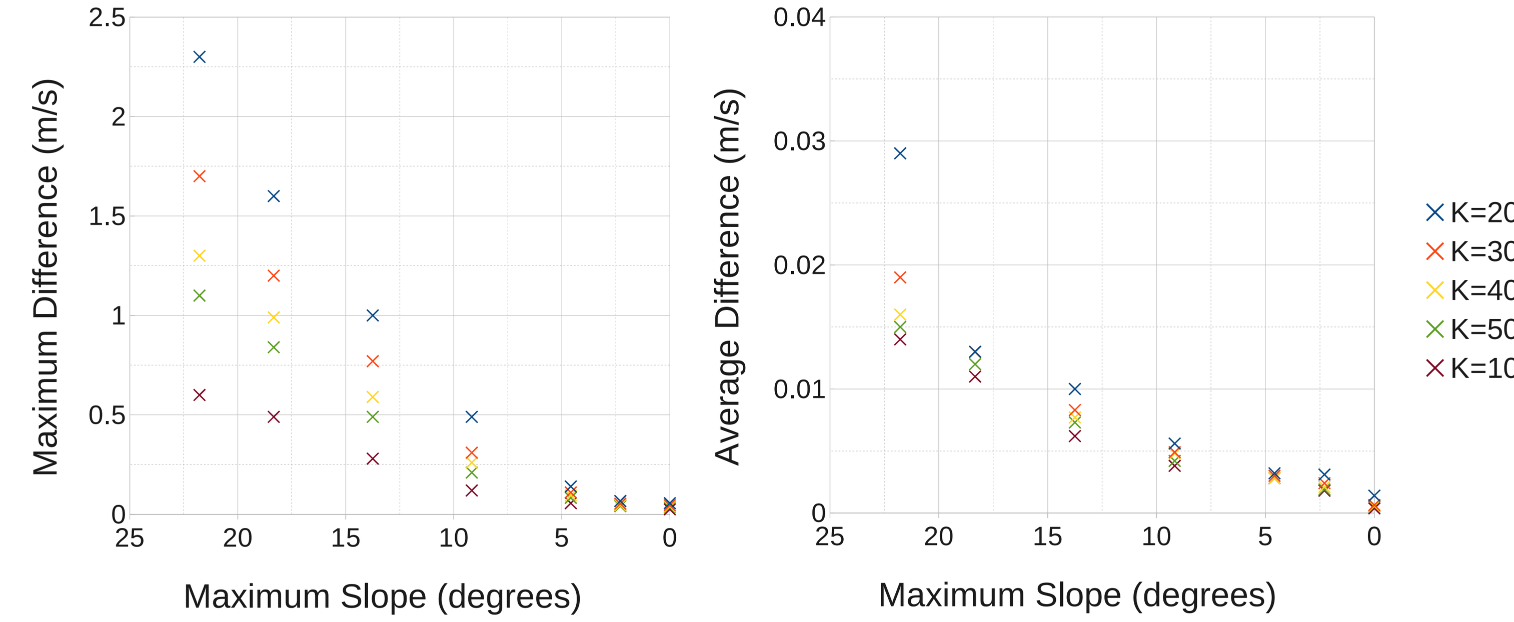

Figure 10: Maximum difference (left) and average difference (right) in velocity magnitude between WRF and IBM-WRF as a function of slope for different eddy viscosities. The x-axis is reversed so that slope may be considered analogous to grid spacing.

IBM Background

- Immersed boundary method
- Places terrain on Cartesian-like grid
- Nodes just below terrain surface are ghost nodes
- Ghost nodes are reflected across boundary (image point)
- Image point value found
  - Interpolated from nearest fluid nodes
  - Two interpolation options
    - Bi/trilinear, inverse distance weighted
- Ghost node value found
  - Linear interpolation between image, boundary and ghost nodes

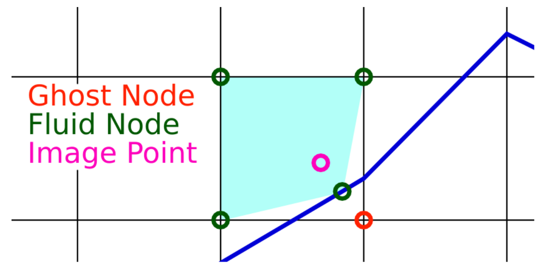

Figure 11: 2D representation of interpolation scheme used in IBM-WRF for Dirichlet conditions.

Summary

- IBM-WRF excellent candidate for meso-to-micro framework
  - Many questions still outstanding
- WRF and IBM-WRF agree well for small slopes
- Strong correlation between slope and disagreement
  - **GMAST steep enough to warrant IBM-WRF**

Future Work

- Nesting from WRF to IBM-WRF
- Log-law bottom condition
- IBM-WRF performance optimization

References

- Lundquist, K.A., Chow, F.K., and J.K. Lundquist. 2010: An immersed boundary method for the Weather Research and Forecasting model. *Monthly Weather Review* **138 (3)**, 796-817.
- Lundquist, K.A., Chow, F.K., and J.K. Lundquist. 2012: An immersed boundary method enabling large-eddy simulations of complex terrain in the WRF model. *Monthly Weather Review*, in press.

Acknowledgements

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