Development of a Multi-Scale Modeling Framework for Urban Simulations in the Weather Research and Forecasting Model

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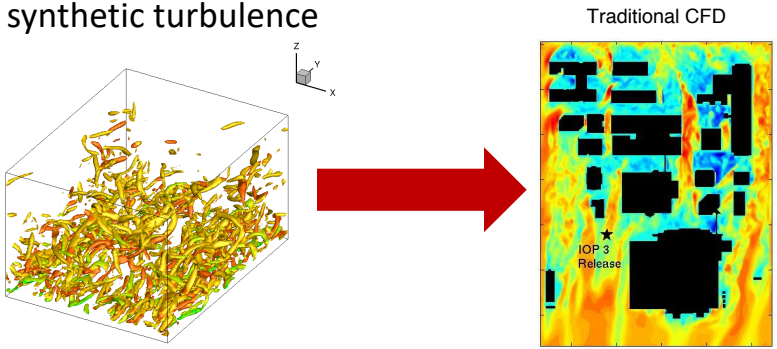
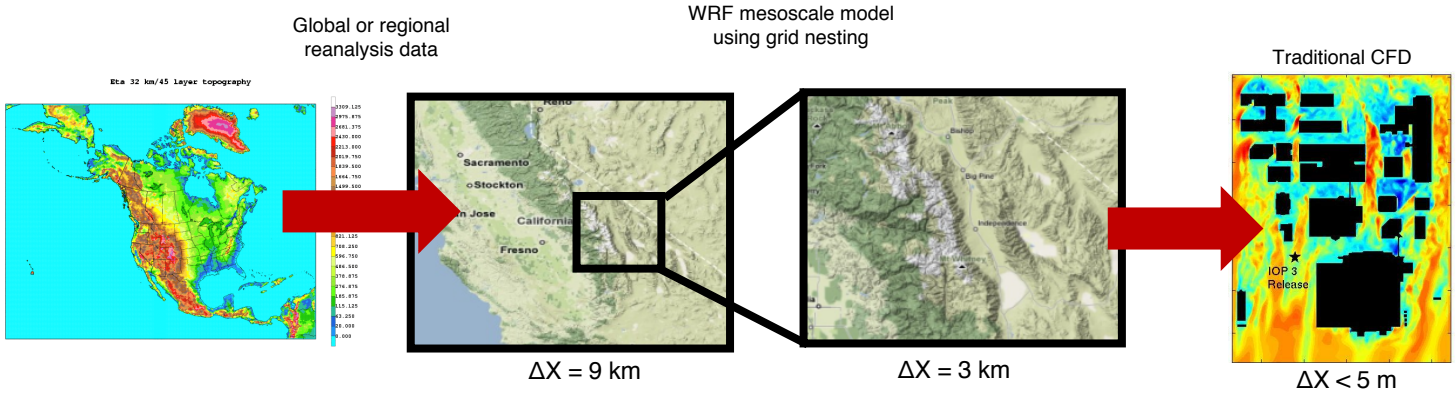
Current approach to urban simulations

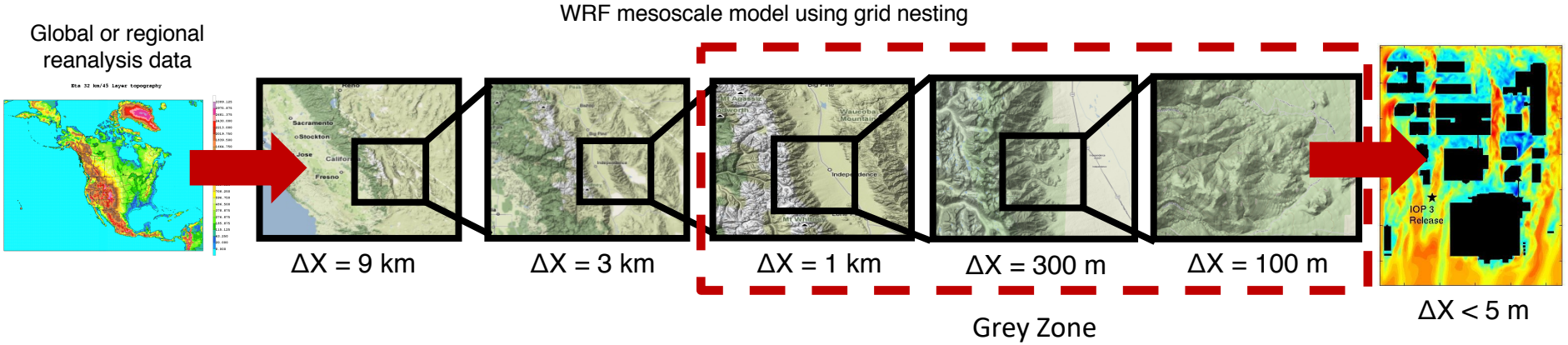
- Precursor simulations or synthetic turbulence



- Boundary conditions from a numerical weather model



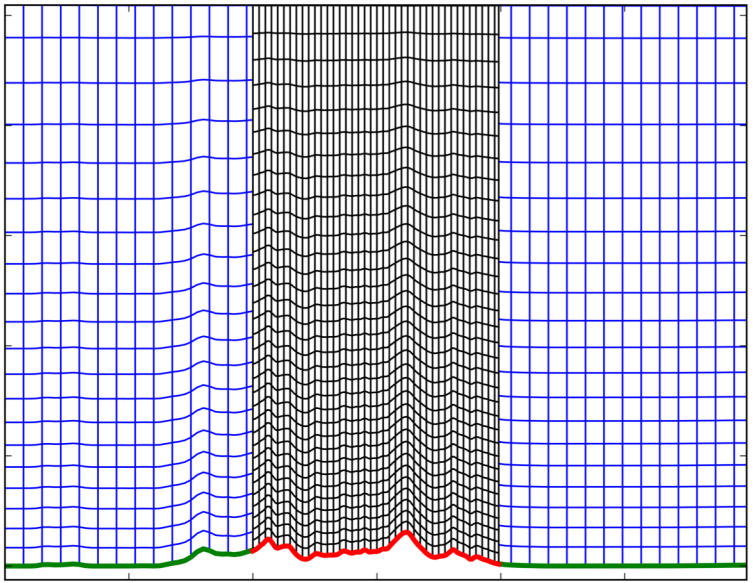
Can we just use more grid nesting?



Most models & parameterizations were not built with multi-scale in mind

- Difficulties downscaling information
  - Turbulence
  - Parameterizations of atmospheric physics
  - Subgrid-scale terrain
- Numerical errors arise from poor grid quality
- Computationally expensive
- Additional data requirements
  - High-resolution topography, land use, and land cover

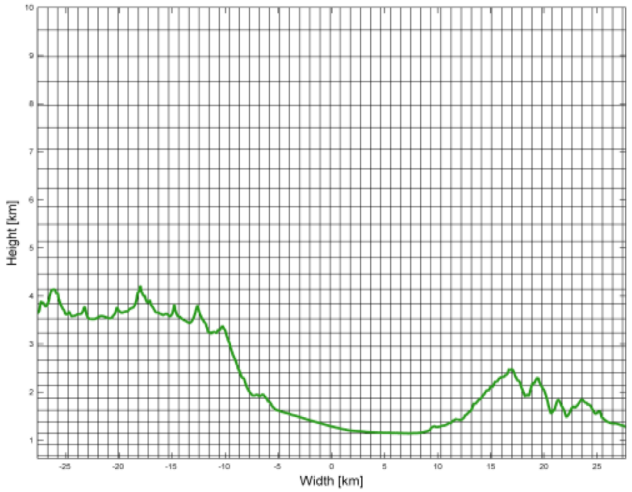
Features introduced to improve grid quality

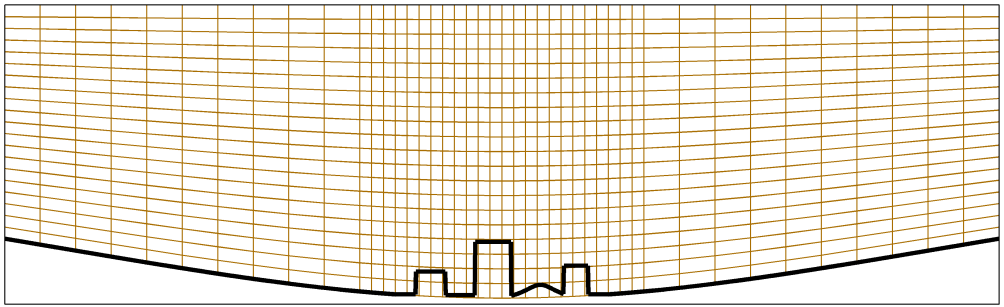


Vertical grid nesting

- Enables vertical grid refinement for nested domains
- Increases flexibly for modeling across scales in WRF through control of grid aspect ratio
  - Mesoscale: grid aspect ratio can affect model stability in complex terrain
  - Large-eddy simulation: Grid aspect ratio has been show to affect simulation results (Mirocha et al. 2010)
- Released in WRF v3.8.1 (Daniels et al. 2016)
- Limited to one-way nesting, RRTM

Features introduced to improve grid quality

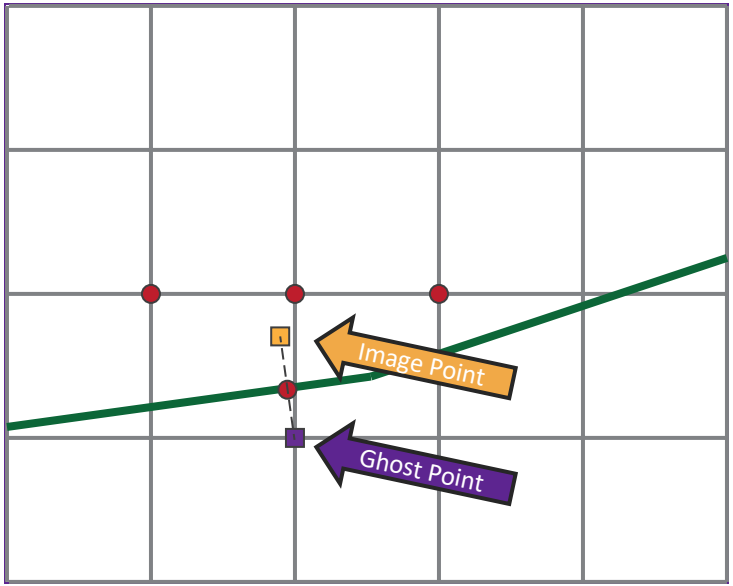




Immersed Boundary Method (IBM)

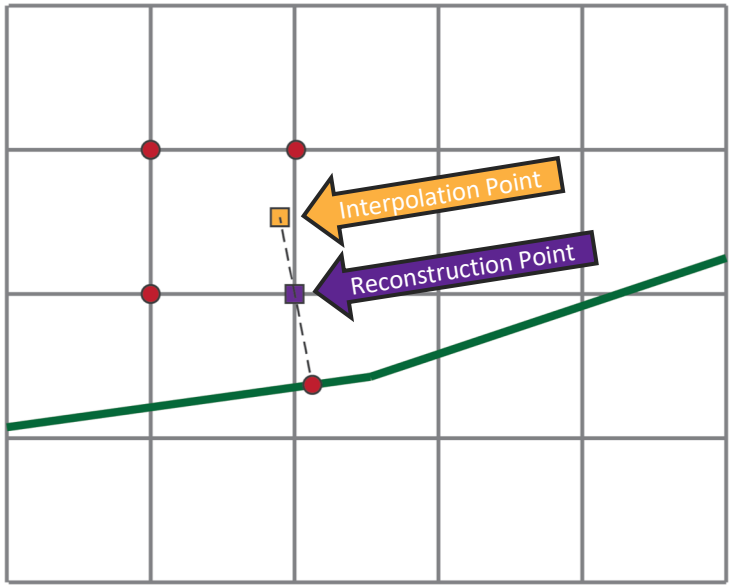
- Non-conforming grid technique
- Reduces/eliminates numerical errors from skewed grids over complex terrain
- New improvements include:
  - Framework for nesting domains using IBM within domains using terrain-following coordinates
  - Implemented multiple stress parameterizations at the terrain surface based on the “log law”
  - Coupled to topographic shading routines

Modifications to IBM for nesting framework



The Ghost Point Method

- Modifies values directly below the immersed boundary (Lundquist et al. 2010, 2012)

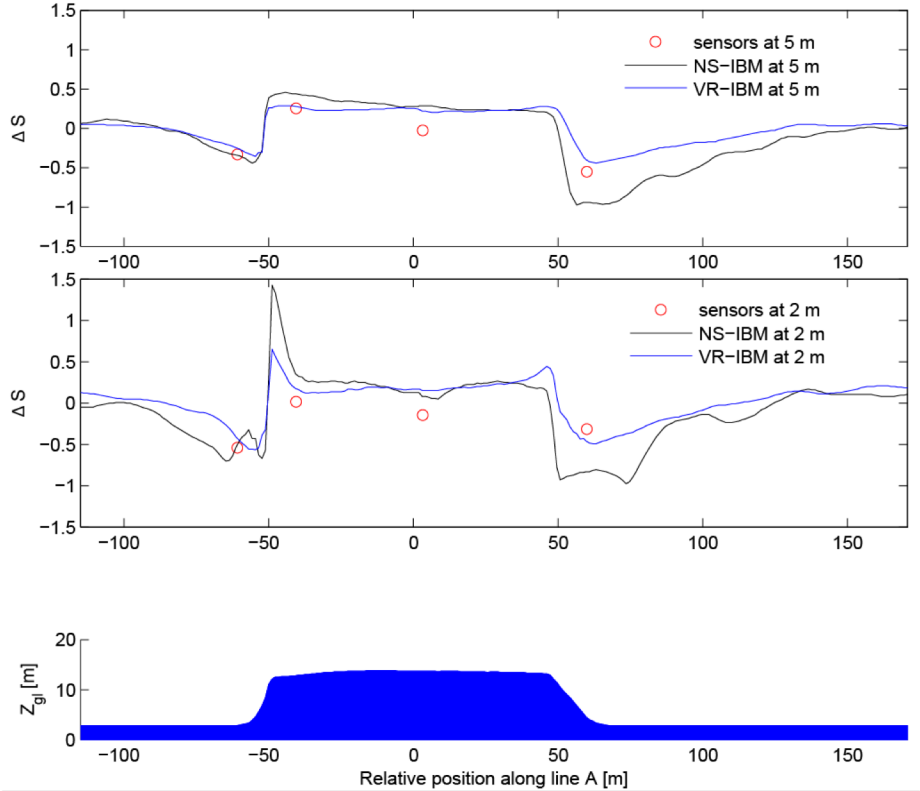


The Velocity Reconstruction Method

- Modifies values directly above the immersed boundary (Bao et al. *in review*)

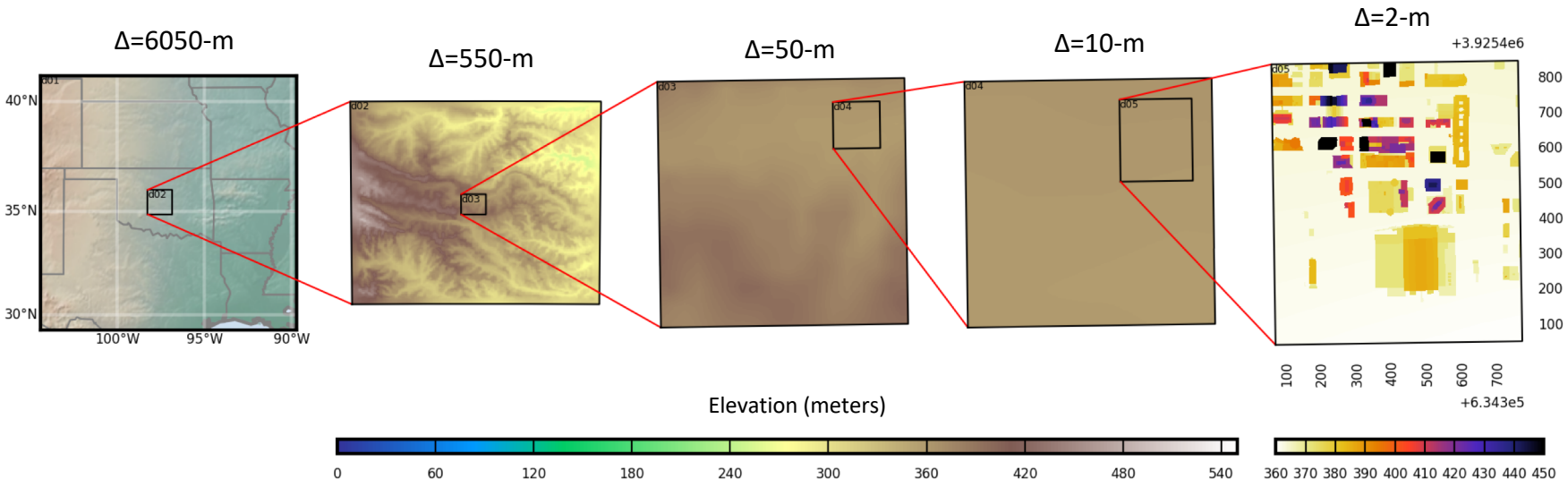
Improvements to the IBM

Validation of “log-law” surface stress parameterization for the Bolund Hill Experiment

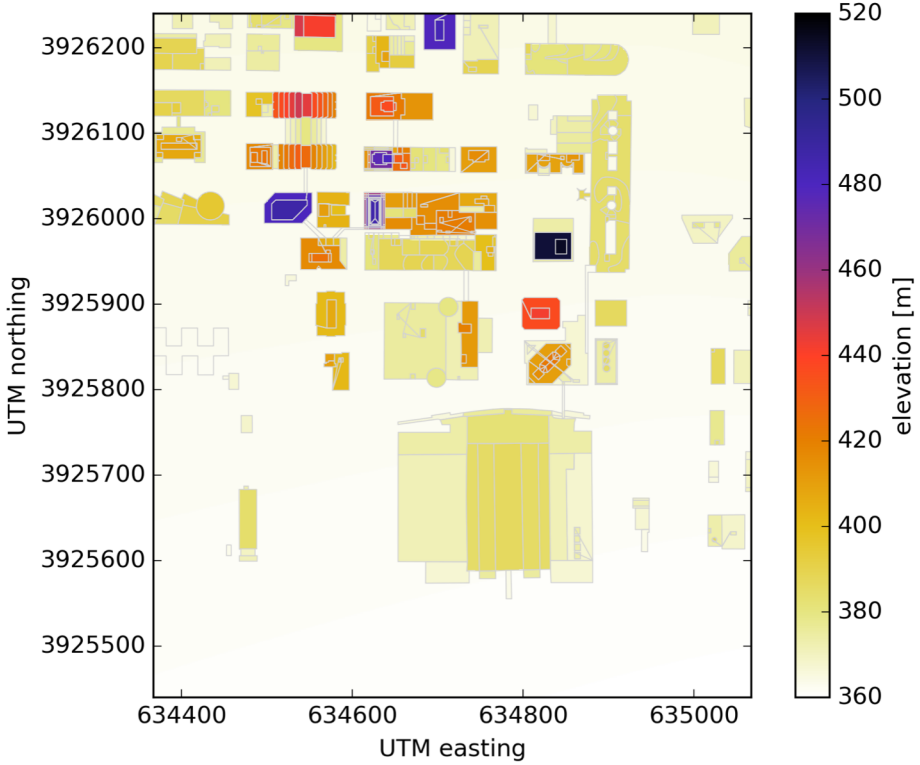


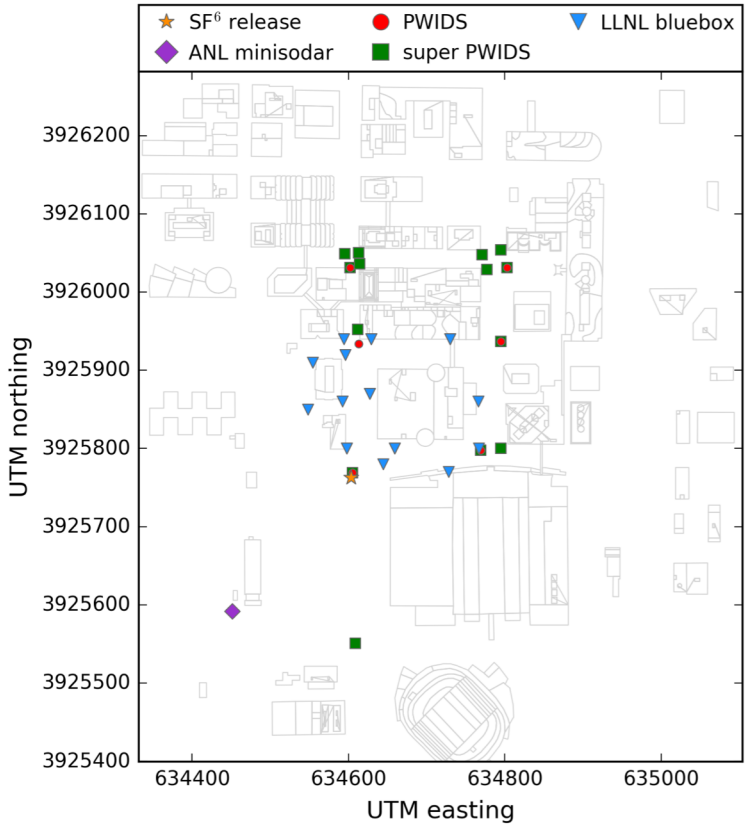
Bao, J., F. K. Chow, and K. Lundquist,
2018. *Large-eddy simulation over complex terrain using an immersed boundary method in the Weather Research and Forecasting model*. Monthly Weather Review (in review).

Mesoscale to Urban Scale Simulation Set-up



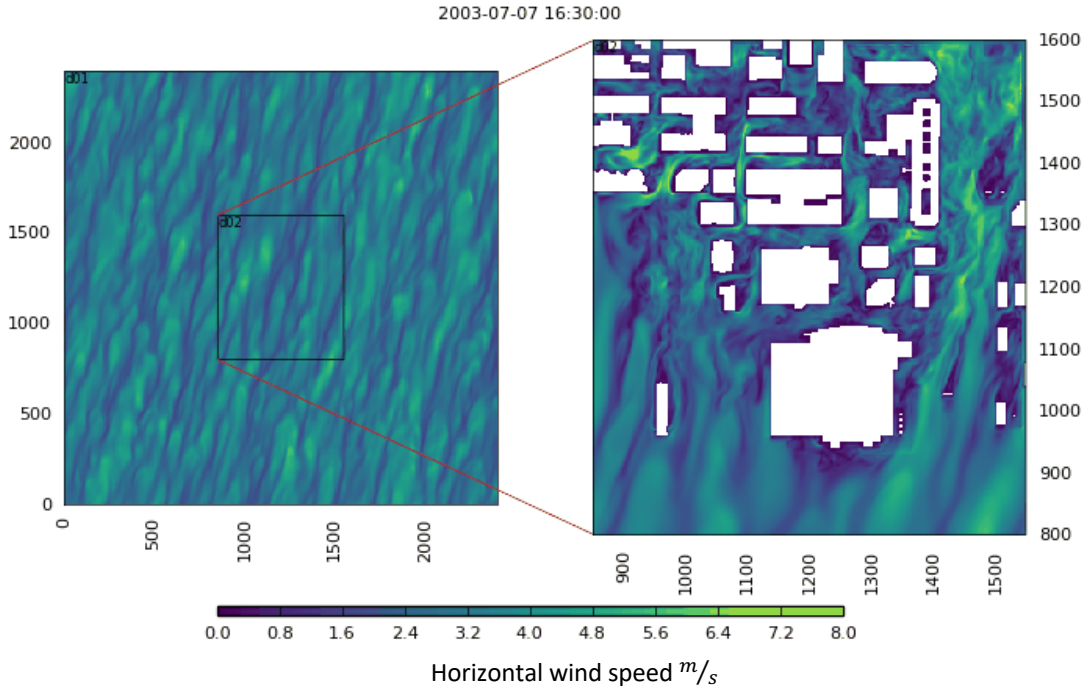
Joint Urban 2003 (IOP-3)





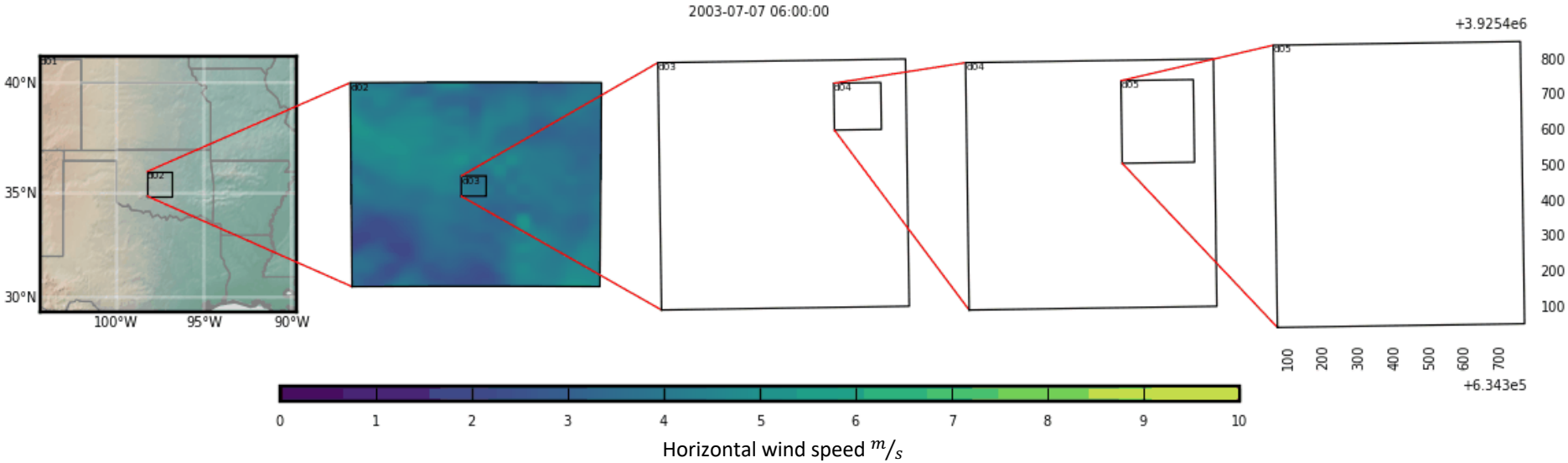
Idealized Simulations

- Parent
  - Δx=Δy=10-m
  - Δz=5-m (first 21 levels)
  - Periodic lateral BCs
  - LES (Smagorinsky)
- Nest
  - Δx=Δy=2-m
  - Δz=1-m (first 26 levels)
  - LES (Smagorinsky)

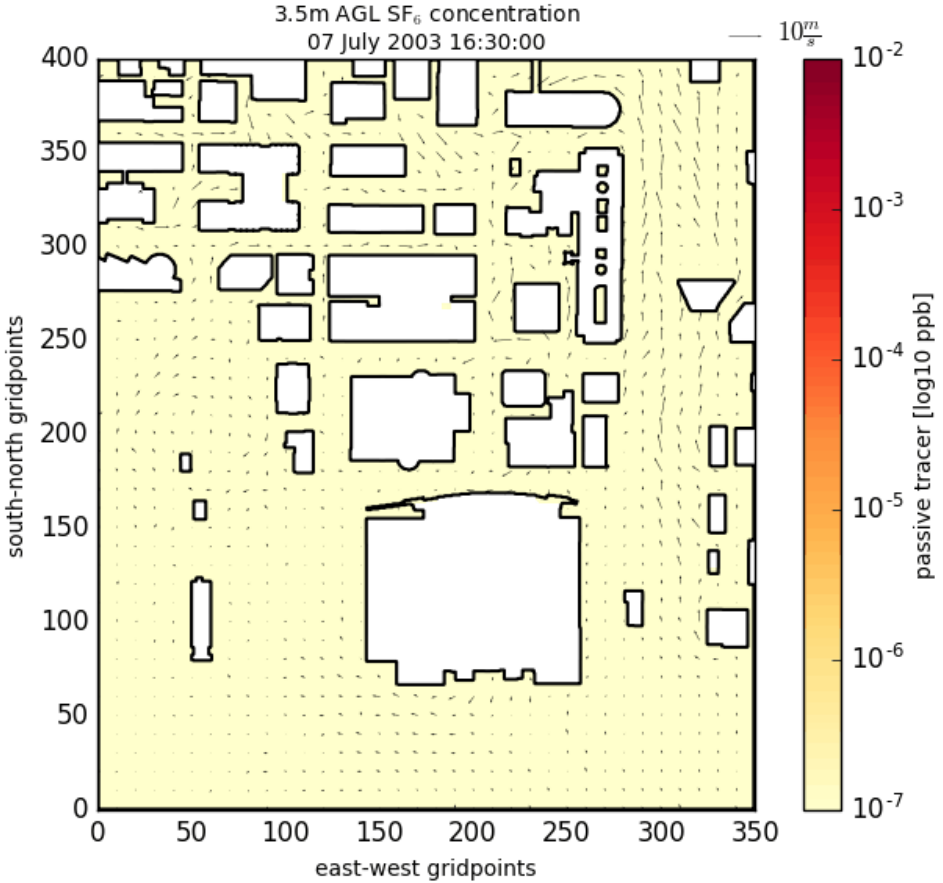


Multi-scale Simulations

	d01	d02	d03	d04	d05
start time	03:00	06:00	12:00	16:00	16:25
Δx & Δy	6050	550	50	10	2
Δz (near surface)			25	5	1
nz	51	51	96	146	243
coordinate	TF	TF	TF	IBM	IBM
turbulence	MYJ	MYJ	LES	LES	LES



Simulation of SF6 Release (IOP3)



Model Skill Tests

magnitude

- FACx

FACx = fraction of data that satisfy $^{1}/_{x} \leq {}^{X_p}/_{X_o} \leq x$

- Fractional Bias

$$FB = 2\left(\overline{X_o} - \overline{X_p}\right)/\left(\overline{X_o} + \overline{X_p}\right)$$

spread

- Geometric Mean

$$MG = \exp\left(\overline{ln(X_o)} - \overline{ln(X_p)}\right)$$

- Normalized Mean Squared Error

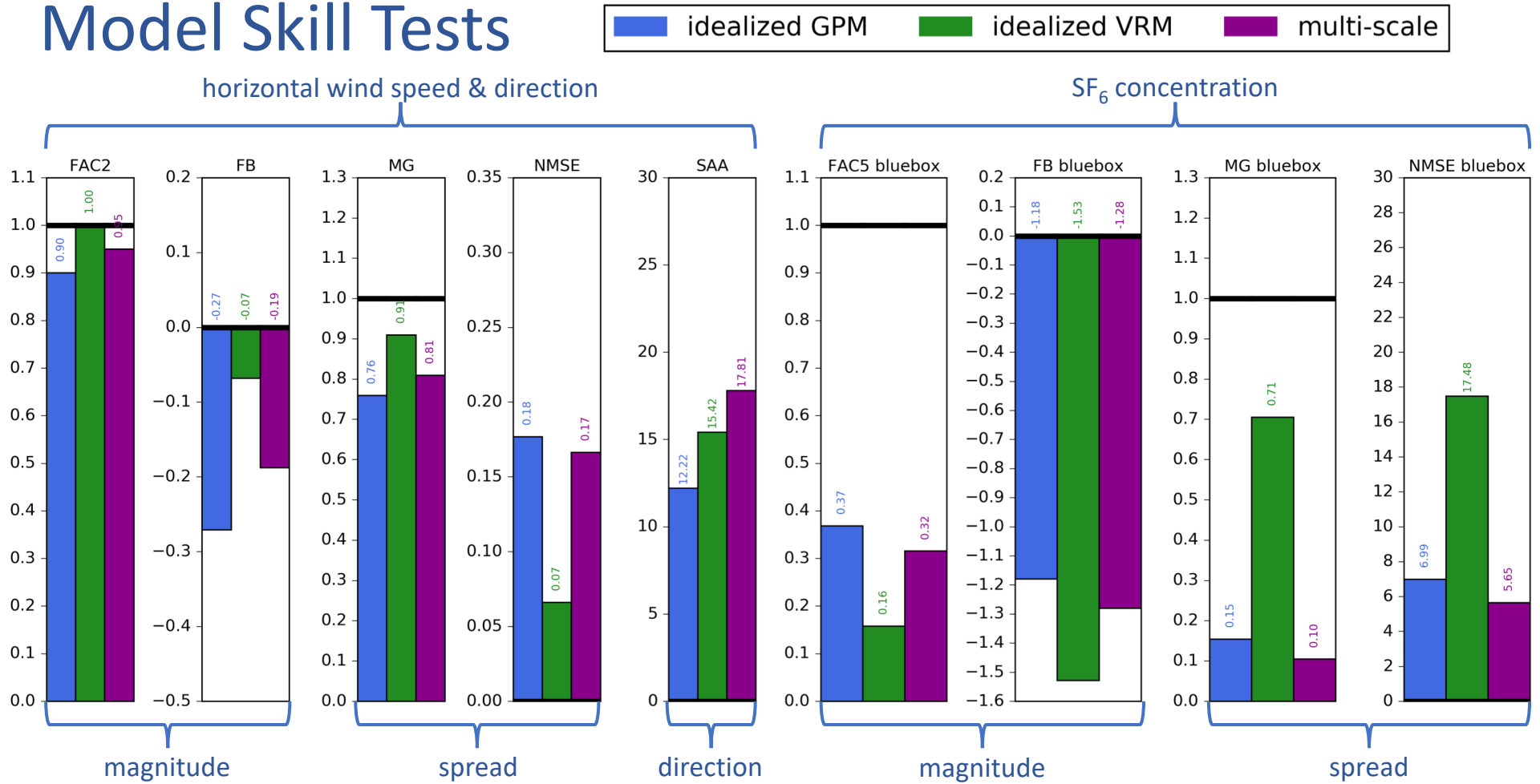
$$NMSE = \overline{\left(X_o - X_p\right)^2}/\left(\overline{X_o}\,\overline{X_p}\right)$$

wind direction

- Scaled Average Angle

$$SAA = \sum\left(|U_i||\phi_i|\right)/\left(N|U_i|\right)$$

Model Skill Tests



Next Steps in Development