Analyzing and Improving Turbulence Characterization in a Multiscale Atmospheric Model of Transport and Dispersion Through an Urban Area

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Meteorology and Climate – Modeling for Air Quality Conference
September 12, 2019
Multiscale Modeling Over Complex Terrain

Goal: dynamically downscale from the mesoscale (Δ=10’s of km) to the microscale (Δ=10’s of m) within a single numerical weather prediction (NWP) model.

Microscale-only approach:
- Periodic boundary conditions
- Initialized from a static vertical profile

animation credit: Jeff Mirocha
Multiscale Modeling Over Complex Terrain


Flexible grid configurations enabling mesoscale and microscale domains in the same simulation

downscale turbulence and transition from mesoscale to LES

resolve flow over complex terrain
Multiscale Modeling Over Complex Terrain

• Vertical grid nesting

• Immersed Boundary Method (IBM)

• Cell Perturbation Method (CPM)
The Immersed Boundary Method

For more information, see Robert Arthur’s poster “Ongoing improvements to surface-layer turbulence modeling in the Weather Research and Forecasting model”

- Grids become skewed in regions of steep terrain, leading to errors and model failure.

- Reduces grid-related errors; boundary conditions are applied by interpolation to the “immersed boundary.”
The Cell Perturbation Method

- Development continues through DOE’s Mesoscale-Microscale Coupling project (Jeff Mirocha’s presentation from yesterday)
- Adds temperature perturbations along inflow boundaries
- Speeds the development of turbulence after grid refinement
- Especially useful between a mesoscale parent → LES nest

Small amplitude (≅1K) perturbations applied to $\theta$ at inflow boundaries
Joint Urban 2003 Field Campaign, Oklahoma City

- Intensive Observational Period 3
- July 7th 2003, 16:00 – 16:30 UTC
- Continuous release of SF$_6$ at 5 g s$^{-1}$

- 1 SODAR
  - Argonne National Laboratory
- 11 propeller/vane anemometers
  - Dugway Proving Ground (DPG) portable weather information display systems (PWIDS)
- 16 sonic anemometers
  - 15 DPG super PWIDS
  - 1 NOAA Air Resources Laboratory Field Research Division (ARL FRD)
- 44 integrated gas samplers
  - 19 LLNL “bluebox” samplers
  - 25 NOAA ARL FRD programmable integrating gas samplers (PIGS)
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Multiscale simulation (above)
- 5-domain nested configuration
- Forced using NARR (no tuning)
- WRF-IBM ($\Delta = 10$ m & 2 m)

Microscale-only simulations (right)
- 2-domain nested configuration
- Periodic lateral boundary conditions ($\Delta = 10$ m)
- Forced by the addition of a pressure gradient
  - Tuned to match observations
- Immersed boundary method (WRF-IBM)
Model Skill Compared to Observations

FAC\(x\) = fraction satisfying ...
\[
\frac{1}{x} \leq \frac{X_p}{X_o} \leq x
\]

FB = \(2 \frac{(X_o - X_p)}{(X_o + X_p)}\)

MG = \(\exp\left(\ln(X_o) - \ln(X_p)\right)\)

VG = \(\exp\left(\left(\ln(X_o) - \ln(X_p)\right)^2\right)\)

NMSE = \(\frac{(X_o - X_p)^2}{X_o X_p}\)

SAA = \(\sum |U_i||\phi_i| / N|\bar{U}_i|\)
Model Skill Compared to Observations

FAC\(x\) = fraction satisfying...
\[ \frac{1}{x} \leq \frac{x_p}{x_o} \leq x \]

\[ FB = 2 \left( \frac{X_o - X_p}{X_o + X_p} \right) \]

\[ MG = \exp \left( \ln(X_o) - \ln(X_p) \right) \]

\[ NMSE = \frac{(X_o - X_p)^2}{X_o X_p} \]
Time-Averaged SF$_6$ Plumes

the multiscale simulation produces a wider plume than the microscale-only simulation

significantly more transport “upwind” in the multiscale simulation
Wind Speed / Direction Timeseries

multiscale results show stronger gusts

multiscale recreates periods of low wind speed

multiscale displays more meandering

Legend:
- green: microscale-only
- purple: multiscale
- orange: multiscale CPM
- red: P11
- blue: SP17 (10s rolling avg)
Energy Spectra at SF$_6$ Release Location

The multiscale simulations (purple and orange) resolve more of the inertial subrange than the microscale-only simulation (green).

Using CPM yields a slightly more resolved inertial subrange.
Vertical grid nesting
Immersed Boundary Method
Cell Perturbation Method

Intelligent downscaling & multiscale modeling
Improved predictions for transport & dispersion

- Katherine A. Lundquist
- Jeffrey D. Mirocha
- Robert Arthur
- Tina Katopodes Chow
- Lawrence Graduate Scholars Program