Using Mesoscale Weather Model Output as Boundary Conditions for Atmospheric Large-Eddy Simulations and Wind-Plant Aerodynamics Simulations

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Subject and Motivation

• *The Subject*: Mesoscale-microscale one-way coupled simulation of atmospheric flow with focus on turbulence evolution

• *The Motivation*: Real wind plants are subject to microscale weather that is driven by mesoscale weather. Canonical microscale simulations do not capture:
  - Frontal passages
  - Large-scale mean wind direction/speed changes
  - Significant wind direction/speed variation across the plant
Simulation Tools

• **Mesoscale – WRF**
  - Nested Weather Research and Forecasting (WRF) model
  - Compressible, structured, higher-order finite-difference spatial scheme

• **Intermediary – WRF-LES**
  - Large-eddy simulation (LES) mode WRF (WRF-LES)
  - 1.5 equation turbulent-kinetic-energy (TKE) subgrid-scale (SGS) model

• **Microscale – OpenFOAM**
  - Created from Open-source Field Operations and Manipulations (OpenFOAM) computational fluid dynamics toolbox
  - Incompressible atmospheric LES solver with buoyancy forcing and shear stress lower boundaries
  - Unstructured, second-order finite-volume solver
  - Standard Smagorinsky model, $C_s=0.135$ (dynamic models available)

• **Turbine Model – FAST**
  - NREL’s Fatigue, Aerodynamics, Structures, and Turbulence (FAST) tool
  - Blade element actuator line rotor with turbine system dynamics and control response model
Simulation Tools

NREL’s Multiscale Coupling Effort:

The Simulator for On/Offshore Wind Farm Applications (SOWFA)

- Mesoscale weather modeling (WRF)
- Microscale/wind-plant-scale large-eddy simulation (LES) (OpenFOAM)
- Turbine system/structural dynamics (FAST)

Available at http://wind.nrel.gov/designcodes/simulators/sowfa/
1. Run WRF and WRF-LES
2. Interpolate time history to OpenFOAM boundary locations and initial field to OpenFOAM interior
3. Run OpenFOAM using WRF-LES initialization and boundary conditions

Neumann: U, T, p
Dirichlet: U, T from WRF
Neumann: p
Dirichlet: surface T flux from WRF
Neumann: p
Surface stress model
Case Simulated

- Crop and Wind Energy eXperiment (CWEX)
- Wind plant in Iowa over relatively flat farm land
- Summer, daytime case – moderately convective
- 1 hr of coupled simulation
Results: Coupling with No Turbines

Instantaneous velocity at 85 m above surface
Results: Coupling with No Turbines

WRF-LES initialized flow field

Finer-scale flow features begin to develop

Region in which finer scales visually appear fully developed

Black crosses denote actual turbine locations (turbines not included in this simulation)

Horizontal velocity time history at 80 m above surface from OpenFOAM microscale calculation
Results: Coupling with No Turbine

Spectra evolution in time

Spectrum of different segments of time history averaged over y constant line

Higher frequency energy substantially builds, then slightly decreases
Results: Coupling with No Turbines

Spectra evolution in space

Spectrum of segments of time history averaged over time and y-constant lines

Higher frequency energy substantially builds, then slightly decreases
Results: Coupling with No Turbines

Spectra evolution in space

Time-averaged integral of high wavenumber part of spectrum at every location

- Roughly 1.5 km required for high wave number energy to "fill in"
- High wave number content "overshoots" then decays
Results: Coupling with No Turbines

- Near the surface, the horizontal velocity predicted in OpenFOAM domain rapidly decreases with distance from the inflow boundaries.
- Unclear why this mismatch between WRF-LES and OpenFOAM LES occurs.
Coupling with Turbines

- Eight 1.5-MW turbines modeled using rotating actuator lines
- Turbine model includes control so rotor speed reacts to flow
- Multi-resolution unstructured mesh
  - 10 m background
  - 1.25 m around turbine and in wake

Horizontal slice through microscale mesh with region of refinement around turbines and wakes.
Results: Coupling with Turbines

Blade out-of-plane bending load

Time = 601.00s
Conclusions

• **One-way mesoscale-microscale coupling allows for non-canonical conditions**
  o Extreme events
  o Nonhomogeneous flow across farm
  o Ramp events

• **Extension to two-way coupling will facilitate wind plant parameterization for mesoscale models**
  o Plant-to-plant interaction
  o Environmental effects

• **Significant distance necessary for microscale high wavenumber content to develop** (1.5 km in this case)

• **Some time also required for high wavenumber development**

• **Following the flow direction or progressing in time, an overshoot in high wavenumber energy is observed, followed by decay**
Future Work

• Examine effect of mesoscale inner nest resolution
  o Does coarser resolution require more distance in microscale domain for high wave number turbulence development?

• Examine effect of atmospheric stability
  o Do neutral conditions require more distance in microscale domain for high wave number turbulence development?

• Examine inflow perturbation methods
  o i.e., Muñoz-Esparza and Kosović

• Would a dynamic SGS model avoid overshoot of high wavenumber energy content?
Questions

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