Nesting large-eddy simulations within mesoscale simulations in WRF for wind energy applications

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Accurate meteorological forecasts can maximize power generated from the wind, a clean and renewable energy source

- **Turbine design** – what “inflow” characteristics affect large structures? (LES)
- **Wake Effects** – how does the atmosphere modify the wakes which cause “downwind” turbines to collect less energy than upwind turbines? (LES)
- **Turbine siting and resource assessment** in complex terrain – what locations are optimal for maximizing wind and minimizing turbulence? (LES-mesoscale)
- **Operational forecasting** – how can wind park owners and power grid operators anticipate wind energy to balance power supply and demand? (mesoscale with LES-based wind farm parameterizations)

Premature fatigue of a turbine’s main shaft bearing, courtesy S. Schreck, NREL
Large-eddy simulation can represent very local effects due to topography or stratification as experienced by individual eddies.

- Colors indicate temperature
- White barbs indicate wind speed and direction

Flow reverses direction twice above the surface in this valley!
Mesoscale numerical weather prediction models excel at predicting “weather”

- Mesoscale models capture the evolving pressure gradients over regions ~ 1000s of km
- Historically, mesoscale model evaluations and improvements have focused on surface temperature and precipitation improvements, not winds in the lowest 200m
- Mesoscale boundary-layer parameterizations have least predictive capability in stable conditions, complex terrain, or over complex and varied surfaces

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Nesting large-eddy simulations within mesoscale simulations utilizes the strengths of each

- Large-eddy simulation (LES) represents micro-meteorological turbulence more exactly by representing full spectrum of turbulence

- Although WRF 3.0.1 provides two subfilterscale turbulence models, several others have been developed and/or implemented at LLNL for use in WRF LES capability (see Kirkil et al. poster, P2B.2)

- A robust LES model can provide guidance to improving mesoscale parameterizations
But this nesting must be addressed with care

- **One-way** or two-way nesting?
- Is the representation of terrain appropriate (see K.A. Lundquist et al., Thursday @ 2:15, talk 6.4)?
- Which PBL scheme is more appropriate?
  - MYJ provides “TKE”, but that means different things to mesoscale and to LES
- Does the LES represent the turbulence spectrum appropriately? (See previous talk, Mirocha et al.)
- Is the subfilterscale model robust to atmospheric conditions (stable conditions)?
- Is the LES sufficiently spun up? Are artificial inertial oscillations present?
Our one-way nesting of LES simulations within mesoscale simulations is initialized with three mesoscale nests.

Domain 1:
- 600 km x 600 km
- 12 km horizontal resolution
- 1 km terrain & land cover
- NARR BC

Domain 2:
- 200 km x 200 km
- 4 km horizontal resolution
- 1 km terrain & land cover

Domain 3:
- 65 km x 65 km
- 1.33 km horizontal resolution
- 1 km terrain & land cover
Our one-way nesting of LES simulations within mesoscale simulations is initialized with three mesoscale nests.

These elevation contours and subsequent results are based on simulations for a location in the Eastern United States during fall: high pressure, no clouds, moderate winds.

With each progressively higher atmospheric resolution, higher resolution surface databases and different physics models may be used.
Results shown here are from a series of seven nested simulations with complex terrain in mesoscale, complex slopes in LES.

Domain 1: $\Delta x=12\text{km}$  
Domain 2: $\Delta x=4\text{km}$  
Domain 3: $\Delta x=1.33\text{km}$

mesoscale runs

Domain 4: $\Delta x=444\text{m}$  
D 5: $\Delta x=148\text{m}$  
D 6: $\Delta x=49\text{m}$  
D 7: $\Delta x=16.5\text{m}$

LES runs
Results shown here are from a series of seven nested simulations

- **Domain 1:** $\Delta x = 12\text{km}$
- **Domain 2:** $\Delta x = 4\text{km}$
- **Domain 3:** $\Delta x = 1.33\text{km}$
- **Domain 4:** $\Delta x = 444\text{m}$
- **Domain 5:** $\Delta x = 148\text{m}$
- **Domain 6:** $\Delta x = 49\text{m}$
- **Domain 7:** $\Delta x = 16.5\text{m}$

**LES runs**

**800m x 800 m**
Time-height cross sections from the center of each domain enable comparison of mesoscale and LES simulations.

Interesting LLJ development the second evening -- with shear-induced mixing?

D03, mesoscale, $\Delta x = 1.33\text{km}$
36 hrs
MYJ
LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics.

Mesoscale shows winds aloft increasing through the morning, while LES shows a decrease aloft.
LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics.

LES shows increased variability in early LLJ development with quiescent period early and delayed onset of stronger winds.
LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics.

**D03, mesoscale,**
\[\Delta x = 1.33\text{km}\]
MYJ
36 hrs

**D06, LES,**
\[\Delta x = 49\text{m}\]
TKE SFS closure
36 hrs

LES suggests LLJ does not propagate below 200m through most of the night, in contradiction to mesoscale prediction.
Comparison of two LES domains indicates different representations of surface-based mixing – finer resolution shows more persistent mixing (for MYJ).
YSU results are strikingly consistent across range of scales – surface-based nocturnal mixing looks almost the same!

D06, LES,
Δx = 49m
TKE SFS closure
36 hrs

D07, LES,
Δx = 16.5m
TKE SFS closure
36 hrs
Nesting LES within mesoscale simulations can yield a powerful and accurate forecasting tool to enhance power collection from the wind

- Nesting enables consideration of both weather and boundary-layer phenomenon, including topographic effects ~ 10s of meters (although we have smoothed terrain for this example)
- One-way nesting is our preferred approach – two-way nesting seemed to induce nonsensical CFL violations in outer grids
- Caution must be taken:
  - Some PBL schemes provide TKE to inner LES nests, but this could be problematic: YSU results are more scale-independent, probably not because of real variability but because all TKE is LES TKE, not also mesoscale TKE
  - Also be aware of: spurious numerical inertial oscillations (not the real ones), aspect ratio, resolution of entire turbulent spectrum,
- Both models (PBL and SFS) should be capable of handling complex terrain, stable conditions, etc. (see 6.4 and P2B.2)

**Observations *from the site of interest* are vital for validation**
Questions?

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What observations are required for validation of these simulations?

- Simplest: wind profiles upwind of the wind farm
  - Tradeoff between spatial and temporal resolution
  - Ideal observations would ~10m vertical resolution between the surface and 200m at time intervals ~ 1 minute
- Temperature & pressure profiles in the lowest 200m enable characterization of atmospheric stability
- Turbulence measurements (in situ and/or remote sensing) help diagnose if models are correct for the right reason
But limitations of each approach must be addressed with care

- **Mesoscale model:**
  - Are you providing appropriate “weather”, including PBL dynamics, to the LES?
  - “TKE” means different things to mesoscale and to LES

- **Large-eddy simulations**
  - Does the LES appropriately use the pressure gradients provided by the mesoscale model?
  - Does the LES appropriately use the TKE at the boundary provided by the mesoscale model?
  - How does an LES “spin up” its TKE from the mesoscale TKE?
    - Inertial oscillations
  - Are you using appropriate resolution and aspect ratio?
    - Check turbulence spectra
YSU -> TKE Wind Speed
Classical stable boundary layer development is apparent in simulation results.

Contours of wind speed (left) and turbulent kinetic energy (right) for hours 12-36 of the previously-shown simulation: NARR forcing, nesting 12km → 4km → 1.33km resolution.
Use discretion and validation in choosing mesoscale boundary-layer turbulence parameterization – we see large differences on low-level shear.

Contours of wind speed for hours 12-36 from same model (WRF), same forcing (NARR), Same resolution (12km → 4km → 1.33km), but with different boundary-layer parameterizations (MYJ vs YSU).
LES results exhibit different jet behavior – next steps include validation

Contours of wind speed for hours 12-36 of the previouslyshown simulation: NARR forcing, nesting 12km → 4km → 1.33km → 150m resolution. LES results (right) are from a one-way nest, using the TKE subgridscale model at hourly output.