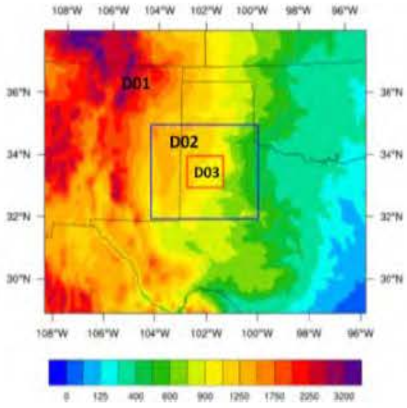
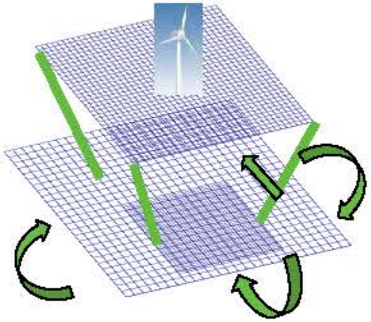
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY



Mesoscale to Microscale Coupling
Project ID #T5



Sue Ellen Haupt

National Center for Atmospheric Research
Subcontractor to Pacific Northwest
National Laboratory

FY17-FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

Technology Development

- Atmosphere to Electrons
- Offshore Wind
- Distributed Wind
- Testing Infrastructure
- Standards Support and International Engagement
- Advanced Components, Reliability, and Manufacturing

Market Acceleration & Deployment

- Stakeholder Engagement, Workforce Development, and Human Use Considerations
- Environmental Research
- Grid Integration
- Regulatory and Siting

Analysis and Modeling (cross-cutting)

Project Overview

T5: A2e Mesoscale to Microscale Coupling (MMC) Project

Project Summary

The team will build new high-performance-computing-based multiscale wind plant simulation tools coupling a broad range of scales. The scale interactions enable the optimization needed to ensure the efficient, reliable production and integration of future wind-generated electricity.

Project Objectives & Impact

- Establish a validation framework with well-defined performance metrics, and apply it to benchmark wind-plant simulation cases.
- Improve the current state-of-the-science of coupling mesoscale information into high-fidelity HPC-based wind-plant simulations to reduce error in predicting wind speed and turbulence characteristics.
- Disseminate methods with stakeholders.
- Verify and Validate results using formal and reproducible techniques.
- Quantify the uncertainty in the results.

Project Attributes

Project Principal Investigator(s)

Sue Ellen Haupt (NCAR)
Larry Berg (PNNL)
Jeffrey Mirocha (LLNL)
Matthew Churchfield (NREL)
Rao Kotamarthi (ANL)
Rodney Linn (LANL)
Brandon Ennis (SNL)

DOE Lead

Michael Derby

Project Partners/Subs

Pacific Northwest National Lab (PNNL), Lead Lab
Argonne National Lab (ANL)
Lawrence Livermore National Lab (LLNL)
Los Alamos National Lab (LANL)
National Center for Atmospheric Research (NCAR - sponsored by National Science Foundation)
National Renewable Energy Lab (NREL)
Sandia National Lab (SNL)

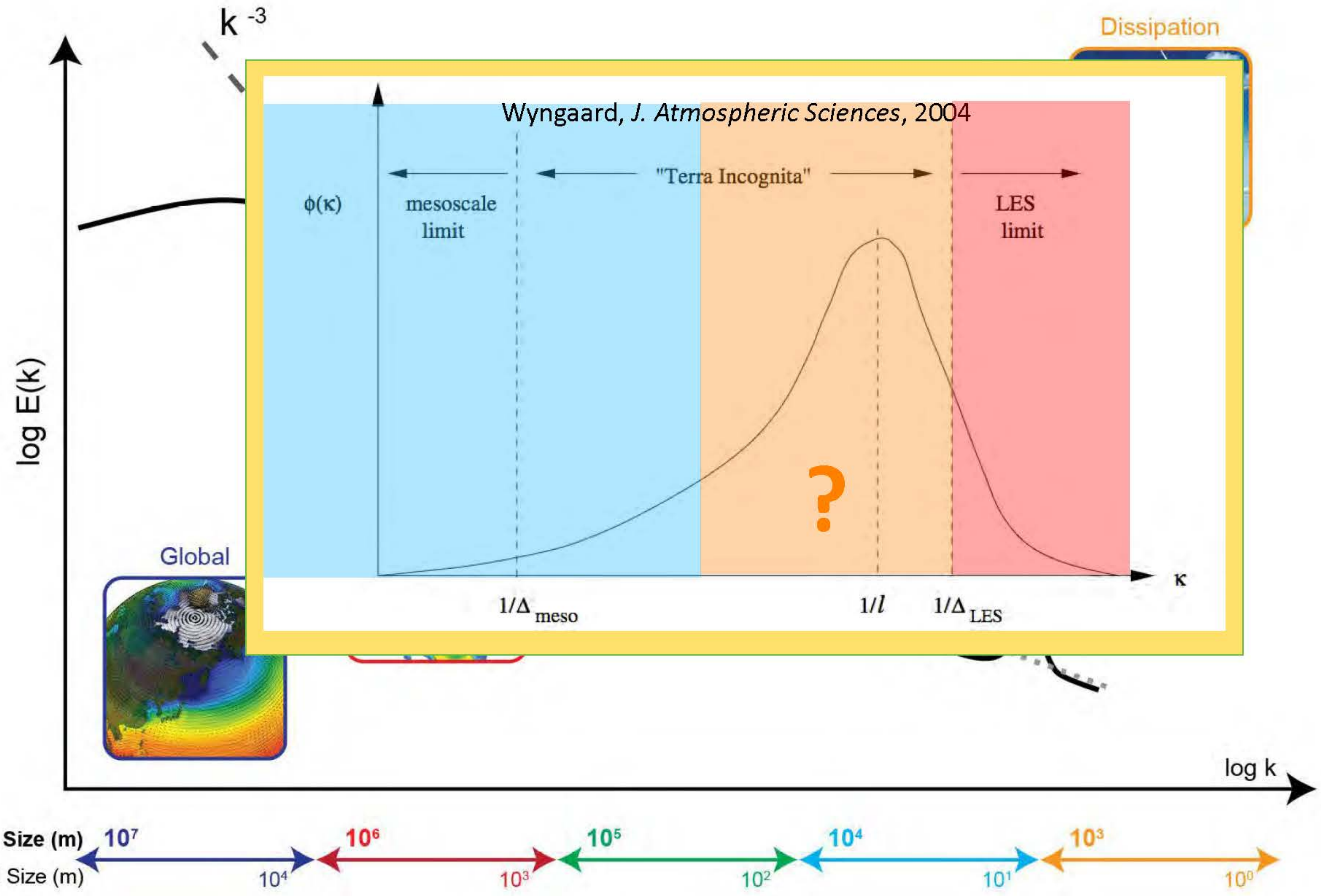
Project Duration

March 2015 – September 2019

Technical Merit and Relevance

- Successful models of wind plants require forcing from the larger-scale atmospheric flow to capture the full range of energy-containing flow, including nonstationary motions.
- Integrating the full range of scales allows optimization of wind plant siting, design and operation.
- The resulting tools will be applicable to diverse locations and operating conditions, as required to support wind energy integration at future high penetration levels.

Relevance – Energy Transfer in the Atmosphere

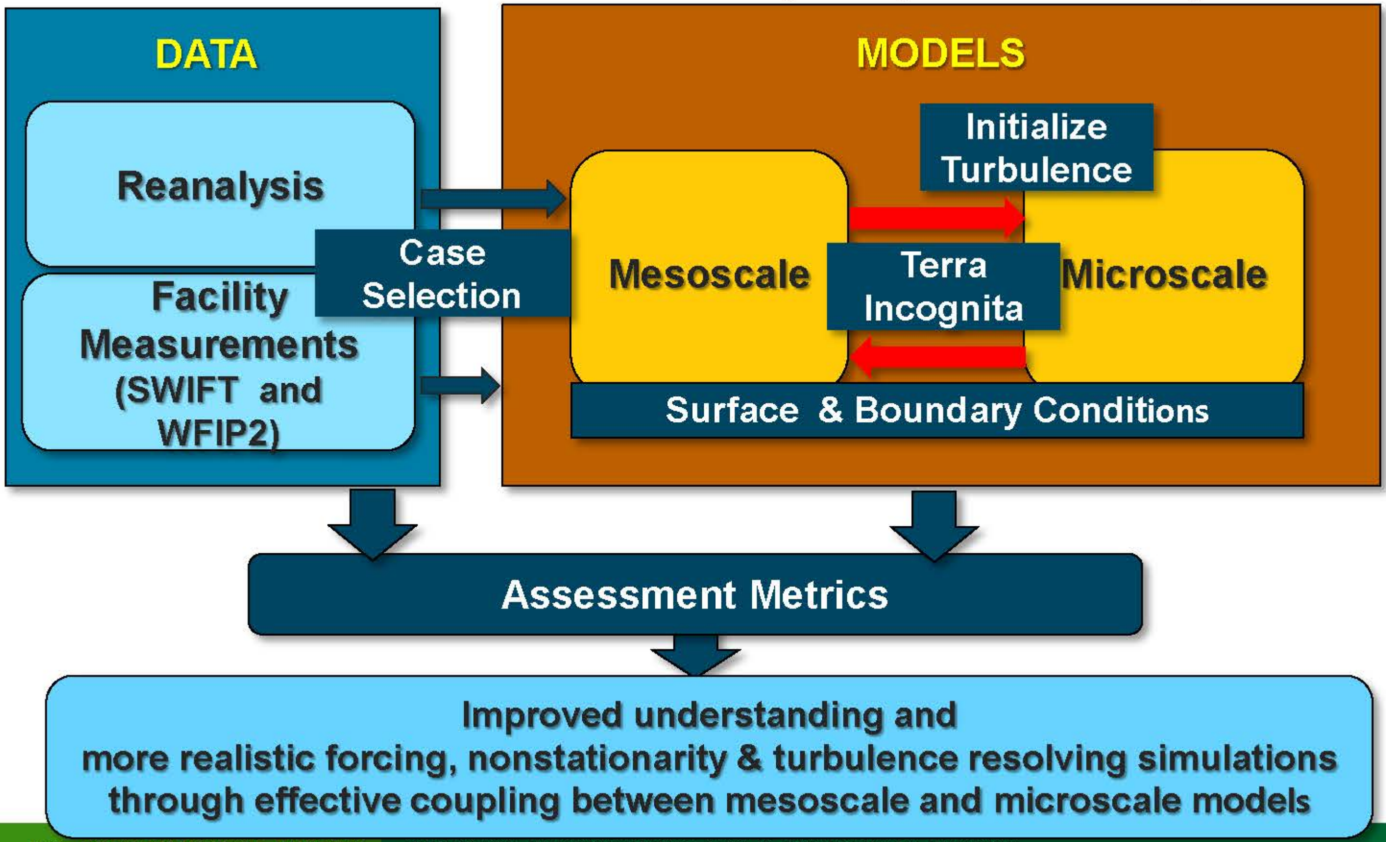


Wyngaard, *J. Atmospheric Sciences*, 2004

Approach and Methodology

Important Science Questions:

1. How do we best bridge the *terra incognita,* about 100 m to 1000 m?
2. What are the best coupling strategies?
3. How to initialize turbulence at the microscale?
4. What are appropriate boundary and initial conditions?
5. How do we validate the results and quantify the uncertainty?



DATA

Reanalysis

Facility Measurements (SWIFT and WFIP2)

Case Selection

MODELS

Mesoscale

Initialize Turbulence

Terra Incognita

Microscale

Surface & Boundary Conditions

Assessment Metrics

Improved understanding and
more realistic forcing, nonstationarity & turbulence resolving simulations
through effective coupling between mesoscale and microscale models

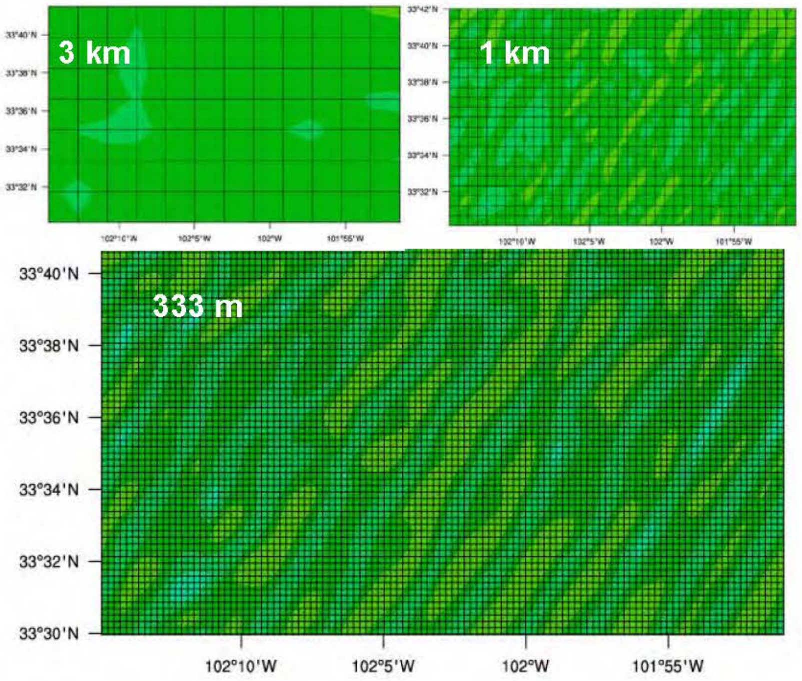
Approach:

- Microscale Large Eddy Simulations (LES)
- Project grounded in observations
  - ✓ Flat terrain at Scaled Wind Farm Technology (SWiFT) facility in Texas
  - ✓ Complex terrain from the Wind Forecasting Improvement Project 2 (WFIP2) in Pacific Northwest
- Systematic testing of multiple methodologies
- Rigorous validation
- Communicate with stakeholders
- Publish results in peer reviewed literature

Approach and Methodology

1. How to best bridge the *terra incognita*?

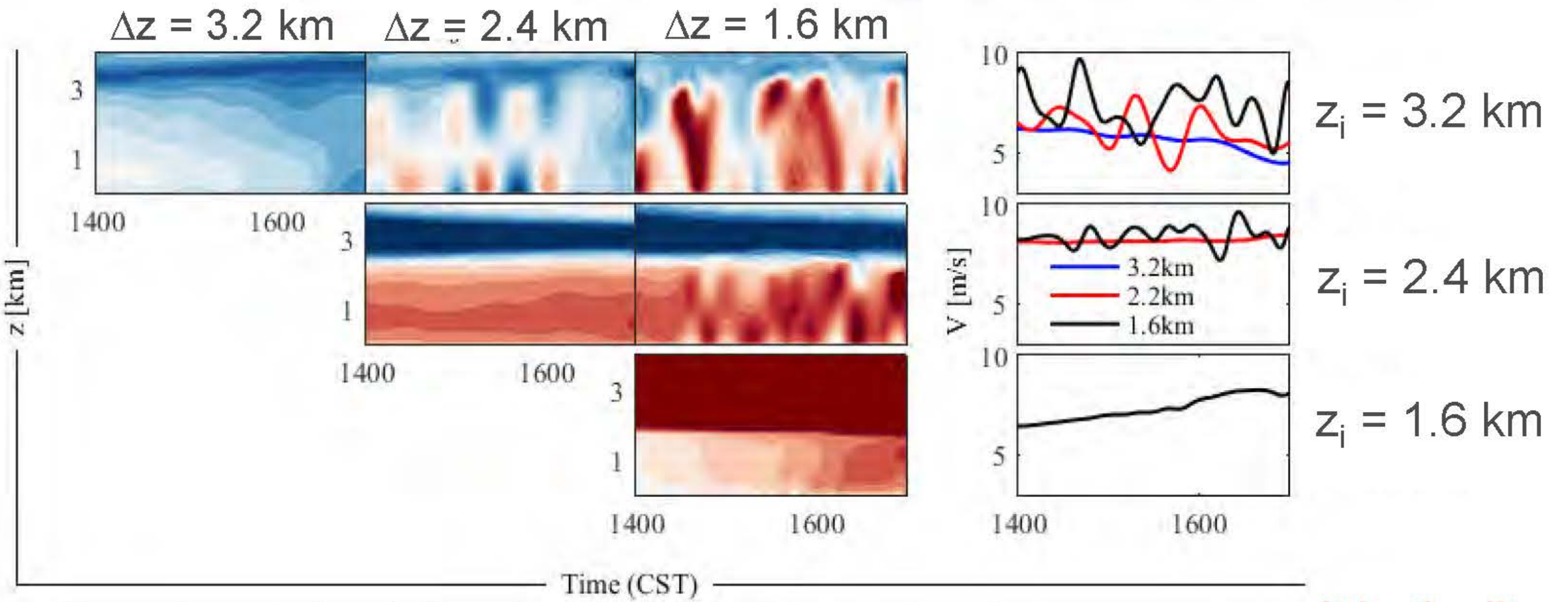
- Mesoscale models can display numerical artifacts (spurious rolls) when horizontal resolutions are in the so-called *terra incognita*.
- Terra incognita traditionally defined as range between 100 m and 1000 m where neither weather prediction Reynolds Average Navier-Stokes (RANS) nor Large Eddy Simulation (LES) models are appropriate.
- Wind plant modeling requires resolving this issue.



Contours of instantaneous horizontal velocity in a horizontal plane 117 m above the surface during the peak of convective activity in the SWiFT November 8 case study.

Accomplishments and Progress

1. How to best bridge the *terra incognita*?



Suite of WRF simulations designed to look at impact of grid spacing and refinement ratio for a site with simple terrain.

- *Terra incognita* defined as height of boundary layer – new result in the literature.
- More energy observed at microscale when coupled to mesoscale nest.
- Impact of *terra incognita* on mesoscale simulations is more important as grid spacing shrinks.
- Flow structures change with closure model used on finest resolution (mesoscale or LES).
- LES results are insensitive to mesoscale or terra incognita parent grid for certain conditions, but more research is needed to be definitive.

Rai et al. 2018

Accomplishments and Progress

2. What are the best coupling strategies?

- Mesoscale models capture the full variability and physics derived from the larger scale flow
    - Compressible
    - Non-hydrostatic
    - Forcings from radiation, surface, boundary layer processes, etc.
- Want microscale model to dynamically follow the changes forced at the mesoscale
- Approaches:
    - Nesting
    - Forcing

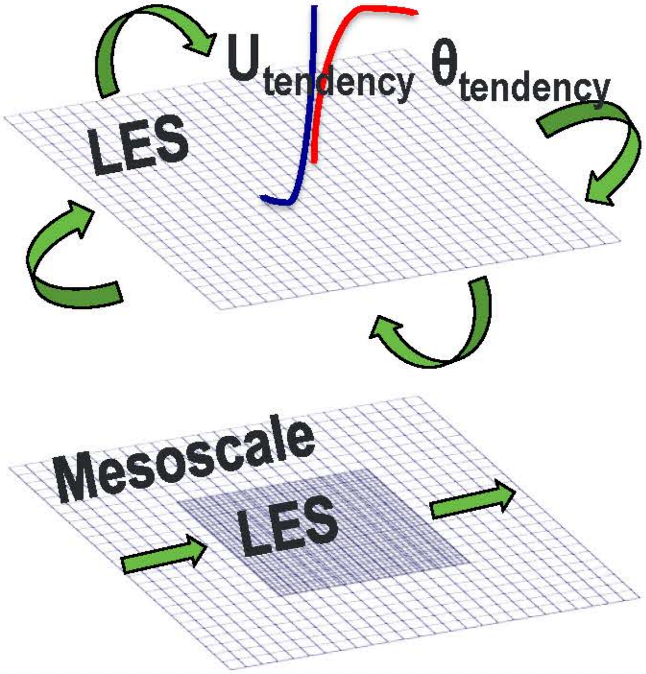
Black: Solved at microscale

Red: Mesoscale forcing

$$\frac{1}{f_c}\frac{\partial U}{\partial t} = U_{adv} + V - V_g - \frac{1}{f_c}\frac{\partial \overline{uw}}{\partial z}$$

$$\frac{1}{f_c}\frac{\partial V}{\partial t} = V_{adv} - U + U_g - \frac{1}{f_c}\frac{\partial \overline{vw}}{\partial z}$$

$$\frac{\partial \Theta}{\partial t} = \Theta_{adv} - \frac{\partial \overline{w\theta}}{\partial z}$$



Accomplishments: Coupling Nonstationary Cases via Momentum Budget

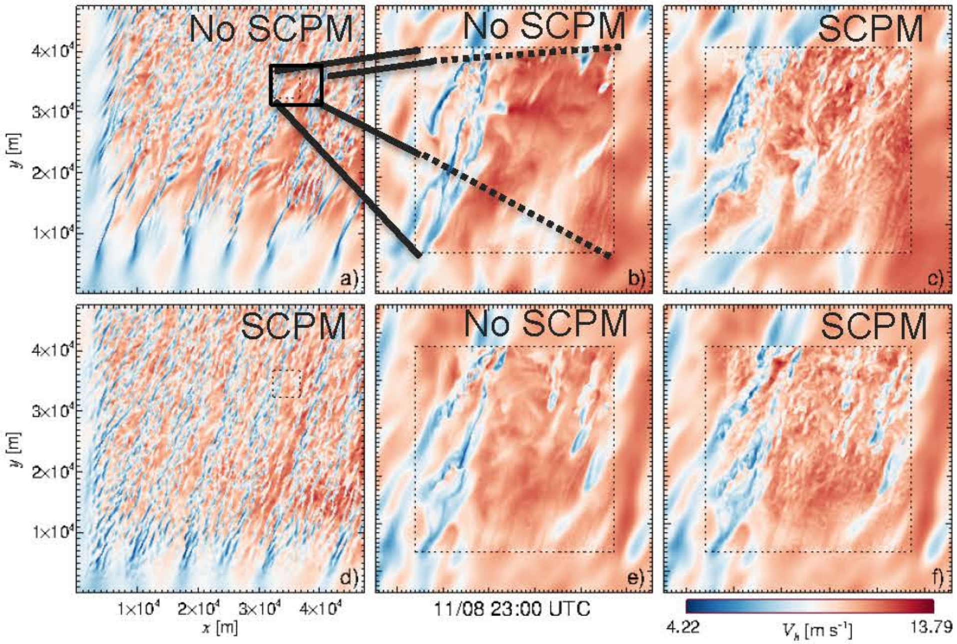
- Mesoscale WRF captures dynamic forcing

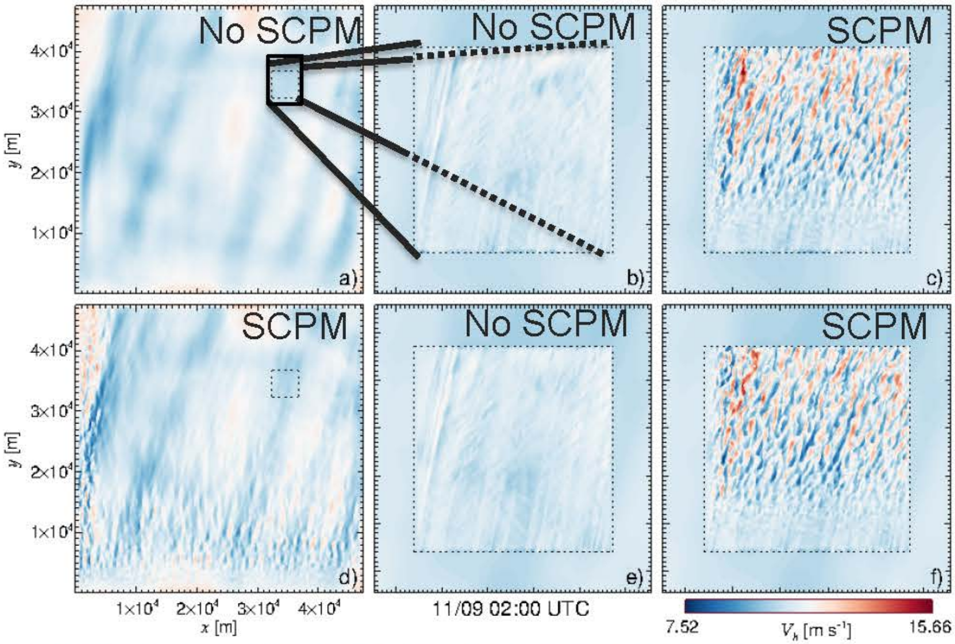
$$U_{tend} \approx U_{adv} + U_{cor} + U_{pgf} + U_{pbl}$$

U U_{tend} U_{pg} $[ms^{-1}]$

Accomplishments and Progress: Stochastic Cell Perturbation Method (SCPM)

3. How to initialize turbulence at the microscale?


Convective


Stable

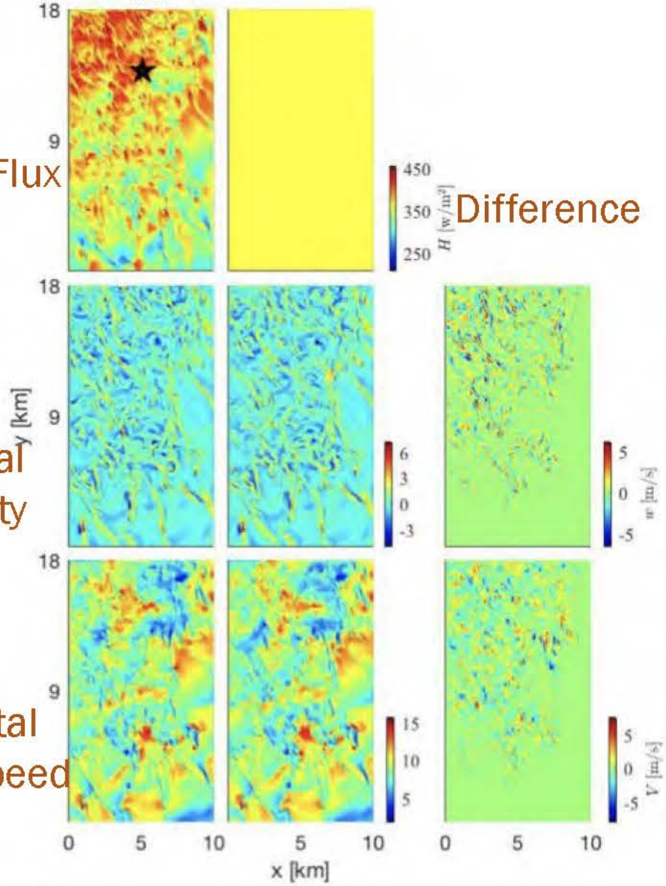
LES of a diurnal cycle, from late morning through the evening transition and into the nocturnal period, observed on November 08-09 2013 at the SWiFT site.

- SCPM neither improved nor degraded the simulations during the late morning to mid-afternoon hours, due to turbulence generated by buoyancy.
- SCPM considerably improved the representation of turbulence during the neutral and stable conditions later in the afternoon and overnight.

Accomplishments and Progress

4. What are appropriate boundary and initial conditions?

- WRF-LES includes land surface model, Nalu does not.
- Thus, Nalu cannot estimate time-varying fluxes consistent with flow.
- Can the WRF output provide time-varying, but spatially homogeneous fluxes that are consistent? Will it impact turbulence?
- Found that differences in turbulence statistics are quite small: thus it is a promising method.



Spatially Varying Fluxes

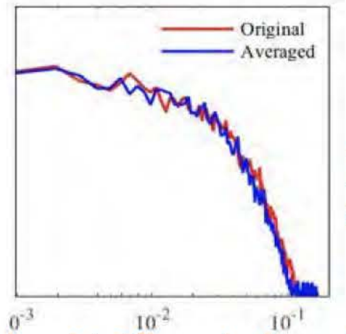
Homogeneous Surface Fluxes

Difference

Heat Flux

Vertical Velocity

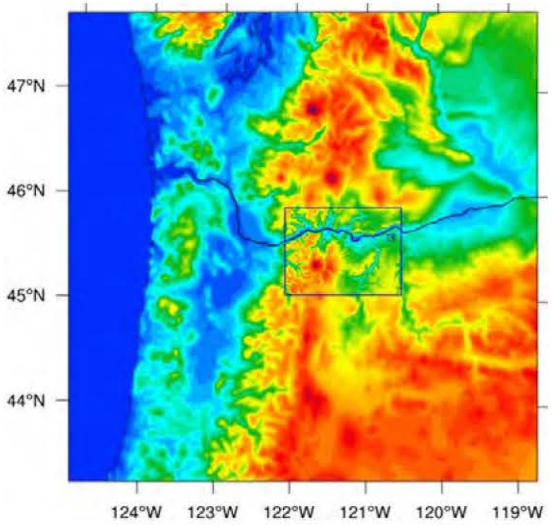
Horizontal Wind Speed

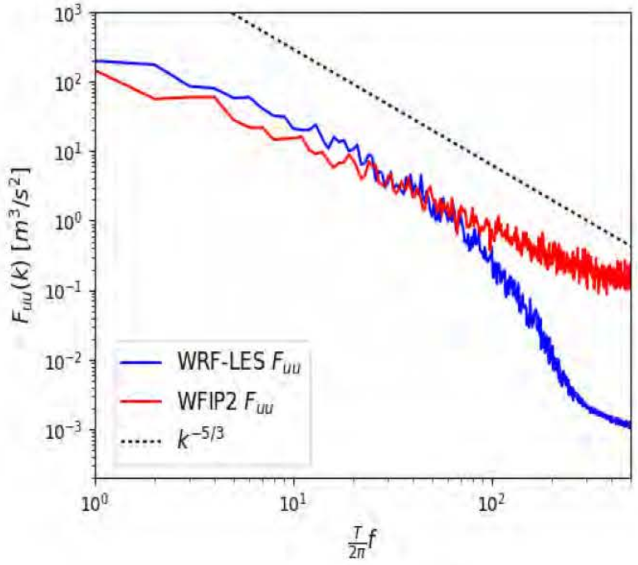


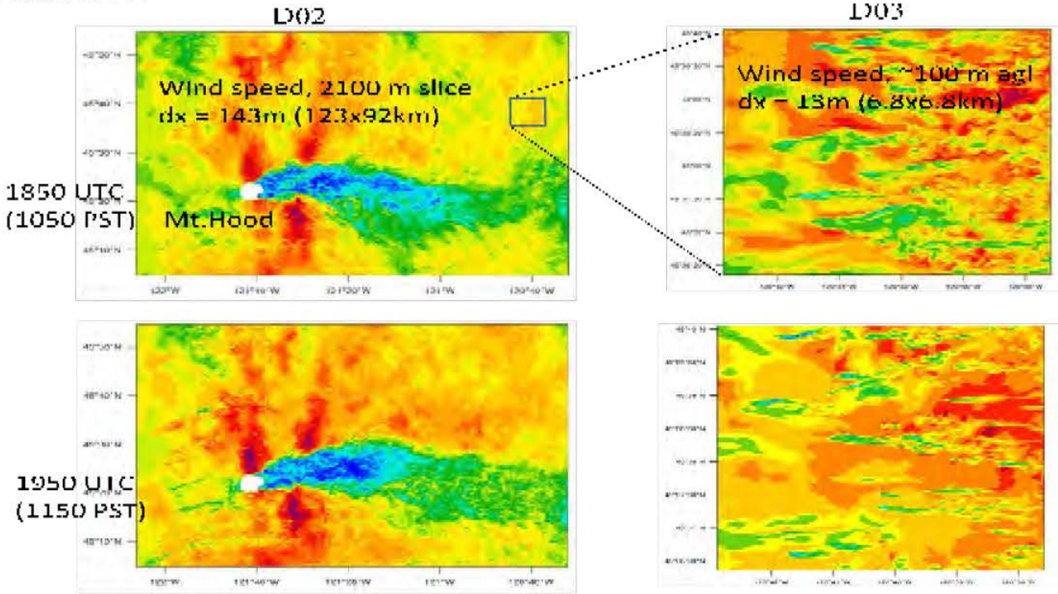
No significant change in turbulence spectra

Nested MMC Over Complex Terrain

- November 21, 2016 case selected for assessment of mesoscale to microscale coupling in complex terrain.
- During the night between November 20 and 21 the measured wind speed at the Physics Site was relatively low, 4 – 5 m s^{-1}, after 19 UTC (11 AM local time) the wind speed increased to 10 m s^{-1}.
- Coupled simulations capture waves, topographic turbulence, and meandering behavior.





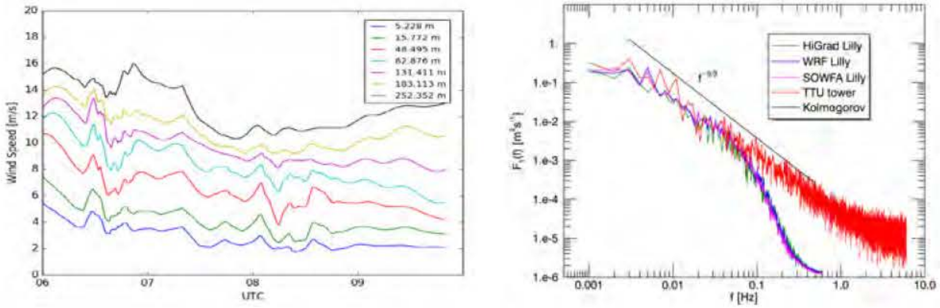


Accomplishments and Progress

5. How to validate the results and quantify the uncertainty?

Assessment

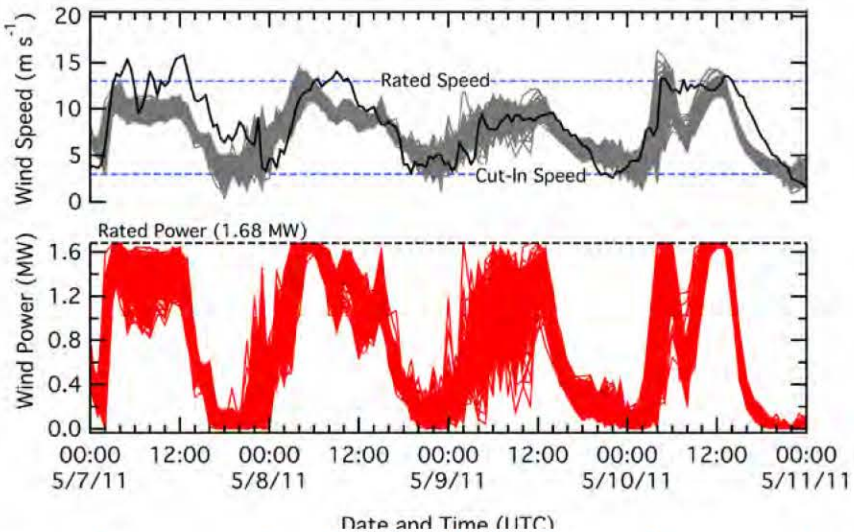
- Select case studies from observational campaigns
- Select metrics relevant to wind energy, such as
  - ✓ Velocity profiles (speed and direction)
  - ✓ Shear across rotor disk
  - ✓ Velocity spectra a various heights
  - ✓ Profiles of turbulent kinetic energy
- **Next: Turbines as a Metric**



Velocity profiles (left) and spectra (right) are helpful for assessing differences between differing approaches.

Uncertainty Quantification

- Structural uncertainty
- Parametric uncertainty
- Boundary condition uncertainty



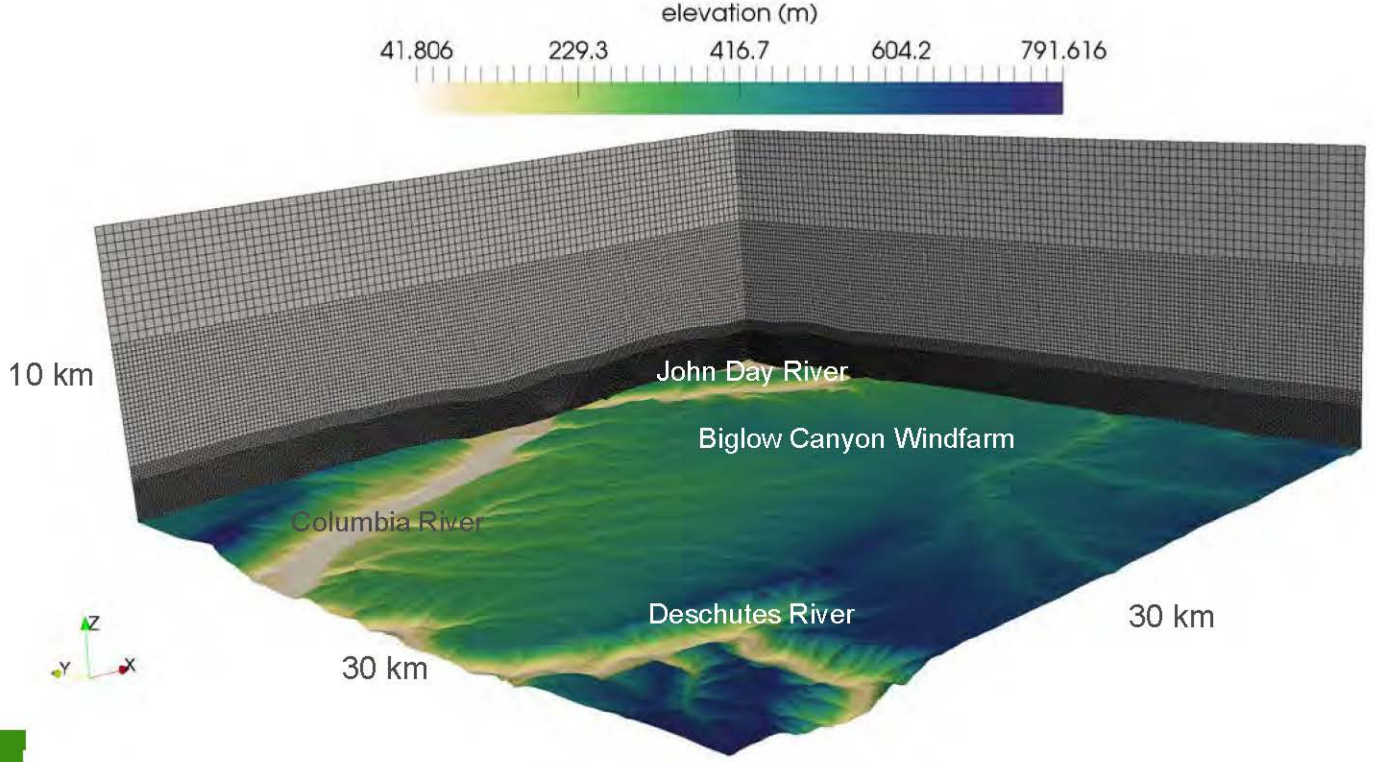
Uncertainty ranges in simulated wind speed (gray, top), observed wind speed (black, top) and generated wind power (bottom) for ensemble with perturbed parameter values. Small variations in parameter values can have dramatic impact on predictions of power generation.

Mesoscale to Microscale Coupling for Complex Terrain

Team continues to develop 3D-boundary layer scheme for heterogeneous flow

Simulating the Biglow Canyon Region with WRF+SOWFA

- Challenges
  1. Microscale domain boundaries that include both inflow and outflow
  2. Spurious gravity waves at mesoscale-microscale interface
  3. Mismatch in terrain resolution between meso and micro
     - Mesoscale: 750 m
     - Microscale: 10-40 m
  4. Need to rapidly generate realistic turbulence within microscale domain given unresolved mesoscale boundary layer turbulence



Successively refined mesh with hexahedral elements (half resolution mesh shown)

Target resolution:
- 10 m in wind plant
- 1-2 m in wakes
- 20-40 m away from wind plant
- > 40 m above boundary layer

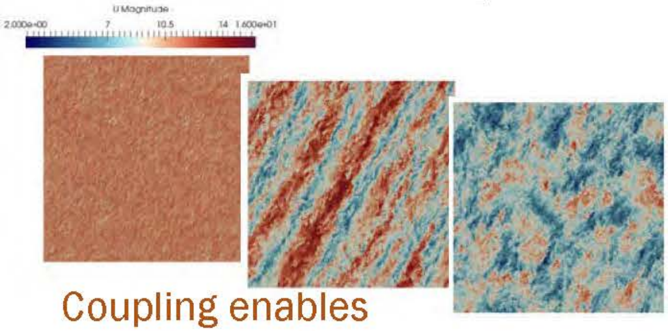
Project Accomplishments and Progress

Fiscal Year	FY15		FY16				FY17				FY18				FY 19
Milestone	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Modeling Case Setup															
Select Cases	⬛		⬛				⬛				⬛				
Select Metrics	⬛		⬛				⬛				⬛				
Characterize SWiFT Site	🟩	🟩	🟩				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Downselect Models															
Model Sensitivity Studies	🟩	🟩	🟩	🟩	🟩	🟩									
Mesoscale Model Selection						⬛									
Model Selection/ WRF-LES & NALU						⬛									
Test Model Forcing and Boundary Strategies															
Analyze Forcing for WRF-LES		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
SOWFA forcing					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Analyze Terra Incognita															
Test Terra Incognita – flat terrain			🟩	🟩	🟩	🟩	🟩	🟩							
Test Terra Incognita – complex terrain									🟩	🟩	🟩	🟩	🟩	🟩	🟩
Test 3D PBL Scheme for complex terrain													🟩	🟩	🟩
Evaluate Methods to Initialize Turbulence															
Turbulence initialization in WRF-LES		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Turbulence initialization in NALU / SOWFA								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Formal assessment of methods													🟩	🟩	🟩
Test Coupling Strategies															
WRF-LES/WRF Online and Offline		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
WRF-LES/ Asynchronous									🟩	🟩	🟩	🟩	🟩	🟩	🟩
NALU/ WRF offline coupling/forcing strategy					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Reporting															
Annual Report Completed			⬛				⬛				⬛				⬛

Project Accomplishments and Progress

During the first phase of the MMC project, team made a number of significant accomplishments:

- Downselected the mesoscale model to be the Weather Research and Forecasting (WRF) model.
- Downselected microscale model to Nalu, which is adopting the wind plant modeling capabilities of SOWFA [in collaboration with the A2e High Fidelity Modeling (HFM) project].
- Established metrics for verification and validation of these models relevant for wind plants and the coupling mechanism, including evaluating turbulence and power generation.
- Developed, tested, and evaluated various methods to couple mesoscale to microscale simulations, determining that on-line coupling is needed within WRF into the LES scales and that applying tendency mesoscale forcing in SOWFA , allowing it to follow the non-stationary behavior of WRF for diurnal cycle cases.
- Developed, tested, and evaluated various methods of initializing turbulence in the microscale models that is subgrid to the mesoscale models.
- Developed, tested, and evaluated methods to deal with spurious rolls resulting from models with grid spacing in the *terra incognita*. Showed that the upper end of the *terra incognita i*s roughly equal to the boundary-layer depth. Found that in most cases it is possible to configure WRF to skip grid spacings in the *terra incognita*.
- Demonstrated and evaluated coupled simulations for complex terrain associated with WFIP2.
- Explored methods to better represent the surface layer in both mesoscale and microscale simulations.
- Communicated with industry representatives regularly.



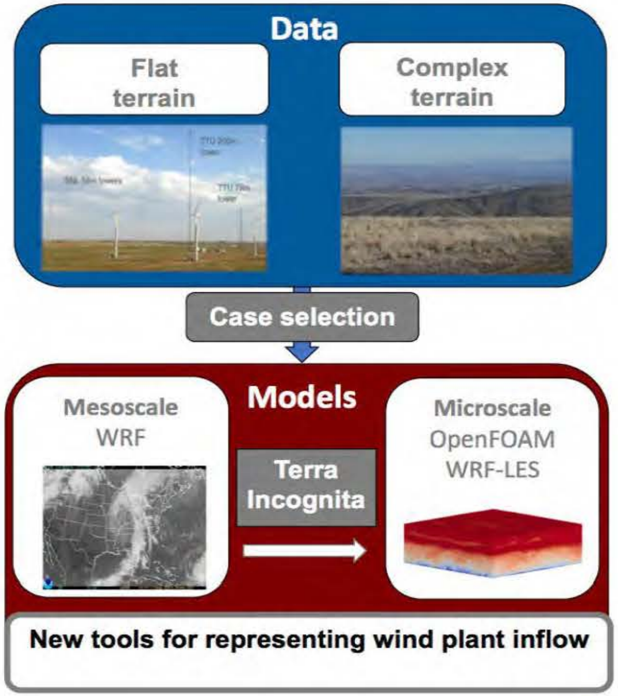
Coupling enables stability transitions

Communication, Coordination, and Commercialization

- **Workshops with Industry:**
  - September 2015
  - April 17-18, 2019
- **Quarterly Webinars**
- **Annual Reports – PNNL Reports**
- **Journal Publications:**
  1. Arthur, R. S., Mirocha, J. D., and Lundquist, K. A., 2018: Using a canopy model framework to improve large-eddy simulations of the atmospheric boundary layer in the Weather Research and Forecasting model, Accepted, *Mon.-Wea. Rev.*
  2. Haupt, S.E., B. Kosovic, W. Shaw, L. Berg, M. Churchfield, J. Cline, C. Draxl, B. Ennis, E. Koo, R. Kotamarthi, L. Mazzaro, J. Mirocha, P. Moriarty, D. Munoz-Esparza, E. Quon, R.K. Rai, M. Robinson, G. Sever, 2018: On Bridging a Modeling Scale Gap: Mesoscale to Microscale Coupling for Wind Energy, submitted to *Bulletin of the American Meteorological Society*.
  3. Mazzaro, L. J.; Koo, E.; Muñoz-Esparza, D.; Lundquist, J. K.; Linn, R. R. ,2019: Random force perturbations: a new extension of the cell perturbation method for turbulence generation in multi-scale atmospheric boundary layer simulations. *Submitted to the Journal for Advances in Modeling Earth Systems.*
  4. Mirocha, J. D., Churchfield, M. J., Muñoz-Esparza, D., Rai, R., Feng, Y., Kosović, B., Haupt, S. E., Brown, B., Ennis, B. L., Draxl, C., Rodrigo, J. S., Shaw, W. J., Berg, L. K., Moriarty, P., Linn, R., Kotamarthi, R. V., Balakrishnan, R., Cline, J., Robinson, M., and Ananthan, S., 2017: Large-eddy simulation sensitivities to variations of configuration and forcing parameters in canonical boundary layer flows for wind energy applications, submitted to *Wind Energy Science.*
  5. Muñoz-Esparza, D., J. K. Lundquist, J. A. Sauer, B. Kosovic´, and R. R. Linn, 2017: Coupled mesoscale-LES modeling of a diurnal cycle during the CWEX-13 field campaign: From weather to boundary-layer eddies, J. Adv. Model. Earth Syst., 9, 1572–1594, doi:10.1002/2017MS000960.
  6. Quon, E. W., Ghate, A. S., and Lele, S. K., 2018: Enrichment methods for inflow turbulence generation in the atmospheric boundary layer. J. Phys.: Conf. Ser., 1037, 072054, doi:10.1088/1742-6596/1037/7/072054.Quon, E. W., Ghate, A. S., and Lele, S. K., 2018: Enrichment methods for inflow turbulence generation in the atmospheric boundary layer. *J. Phys.: Conf. Ser.*, **1037**, 072054, doi. :10.1088/1742-6596/1037/7/072054
  7. Rai, R. K., Berg, L. K., Kosović, B., Mirocha, J. D., Pekour, M. S., and Shaw, W. J., 2016: Comparison of measured and numerically simulated turbulence statistics in a convective boundary layer over complex terrain. *Bound.-Layer Meteor.*, **163**, 69-98.
  8. Rai, R. K., Berg, L. K., Pekour, M., Shaw, W. J., Kosović, B., Mirocha, J. D., and Ennis, B. L., 2017: Spatiotemporal variability of turbulent kinetic energy budgets in the convective boundary layer over both simple and complex terrain. *J. Appl. Meteor. and Climatol.*, 56, 3285-3302. doi: 10.1175/JAMC-D-17-0124.1
  9. Rai, R. K., L. K. Berg, B. Kosovic, S. E. Haupt, J. D. Mirocha, B. L Ennis, and C. Draxl, 2018: Evaluation of the impact of horizontal grid spacing in Terra incognita on coupled mesoscale-microscale simulations using the WRF framework. Mon. Wea. Rev. https://journals.ametsoc.org/doi/abs/10.1175/MWR-D-18-0282.1
- **Many Conference Presentations in FY17 and FY18, including:**
  - 3 presentations at American Meteorological Society (AMS) Conference on Boundary Layers and Turbulence, 2018.
  - 5 presentations at AMS Annual Meeting, Conference on Weather, Climate , and the New Energy Economy, 2017 and 2018.
  - 2 Presentations at International Conference on Energy and Meteorology, 2017 (Bari, Italy) and 2018 (Shanghai, China).
  - 5 presentations at WindTech, 2017.
  - Also: North American Wind Energy Symposium, 2017. Torque, 2018. European Geophysical Union, 2018.

Upcoming Project Activities

- Take on the challenge of coupling for the offshore environment, including air/sea interface issues, air/sea coupling influences, and modeling the marine boundary layer.
- Apply rigorous verification and validation (V&V) techniques to the new modeling tools to ensure the accuracy of codes and results and develop estimates of the relative uncertainty,
- Improve computational performance of the coupled MMC models through developing methods to reduce turbulence spin-up time and hence the size of computational domains,
- Improve representation of the surface layer in microscale models to enhance simulations of hub-height wind speed,
- Develop guidance for the community describing the best ways to couple mesoscale and microscale models.
- Prepare guidance and a suite of software tools that can be used across the community.



Data

Flat terrain

Complex terrain

Case selection

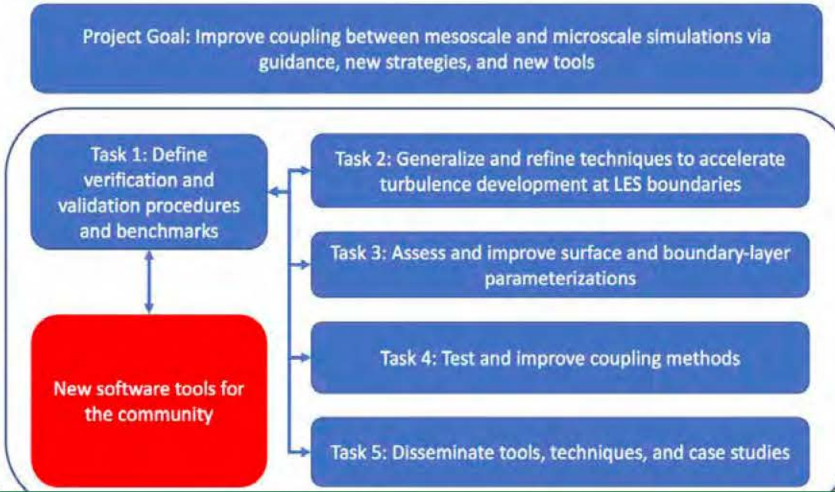
Models

Mesoscale
WRF

Terra Incognita

Microscale
OpenFOAM
WRF-LES

New tools for representing wind plant inflow



Project Goal: Improve coupling between mesoscale and microscale simulations via guidance, new strategies, and new tools

Task 1: Define verification and validation procedures and benchmarks

New software tools for the community

Task 2: Generalize and refine techniques to accelerate turbulence development at LES boundaries

Task 3: Assess and improve surface and boundary-layer parameterizations

Task 4: Test and improve coupling methods

Task 5: Disseminate tools, techniques, and case studies