Mesoscale to Microscale Coupling for Wind Energy Applications: Addressing the Challenges

S E Haupt[1] **,L Berg**[2] **, M Churchfield**[3] **, B Kosović**[1] **, J Mirocha**[4] **, and W Shaw**[2]

[1] National Center for Atmospheric Research, Boulder, CO, USA

[2] Pacific Northwest National Laboratory, Richman, WA, USA

[3] National Renewable Energy Laboratory, Golden, CO, USA

[4] Lawrence Livermore National Laboratory, Livermore, CA, USA

haupt@ucar.edu

Abstract. The purpose of the US DOE's Mesoscale to Microscale Coupling (MMC) Project is to develop, verify, and validate physical models and modeling techniques that bridge the most important atmospheric scales that determine wind plant performance and reliability. The project seeks to create a new predictive numerical simulation capability that represents a range of dynamic atmospheric flow conditions impacting wind plant performance.

1. Introduction

Coupling mesoscale (grid spacing on the order of kilometers) and microscale (grid spacing on the order of meters to tens of meters) models is an important step forward for the wind power industry. Appropriate techniques and tools are needed to better understand the turbulent wind flow into and within the wind plant, which impacts energy transfer between scales, and ultimately, the amount of energy available to harvest. The mesoscale models include the physical parameterizations to model the outer flow phenomena by including radiative transfer, surface layer models, land use models, physics parameterization, boundary layer parameterizations, and more. The microscale models seldom have those parameterizations, but often include the ability to grid around objects, allowing modelling of terrain details and flow around turbine blades. The ability to couple these scales is particularly important for non-stationary meteorological conditions (such as frontal passages, thunderstorm outflows, baroclinic systems, and low-level jets) or when considering changes of atmospheric stability associated with the diurnal cycle. Improved estimates of the driving flow are needed to optimize wind plant and turbine siting, design and operation.

Atmospheric flow drives the structures in wind plants, thus forming the atmospheric energetics that we seek to harvest from the wind. Resolving this mesoscale weather phenomenology thus directly impacts wind plant performance. This complex problem requires coupling those mesoscale phenomena to the flow in the wind plant itself. Modeling these phenomena requires the combined expertise of atmospheric physicists, numerical simulation experts, computational fluid dynamicists, and wind plant subject matter experts to formulate the tools needed to optimize turbine and plant design. Resolving the critical flow structures impacting performance and codifying these effects into design and performance prediction tools is the goal of the Mesoscale to Microscale Coupling (MMC) program. Hence several national laboratories have combined critical resources to resolve this difficult challenge as part of the U.S. Department of Energy's Atmosphere to electrons (A2e) program.

The MMC project addresses the significant technology barrier associated with the application of coupled modeling systems. At present, existing systems are complicated to evaluate and use and the primary goal of this project is to help break down that barrier by providing guidance related to best practices, revised software tools, and evaluation data sets that can be used by the community. The technology maturation plan is simple and straightforward, and consists of documentation and tools described below that can be distributed to the community.
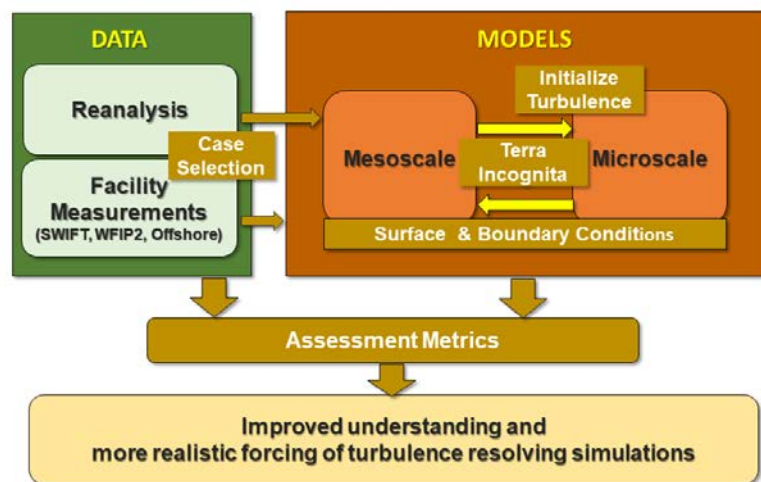
The project-specific objectives include:

- Apply rigorous verification and validation (V&V) techniques to the new modeling tools that are developed as part of the project to ensure the accuracy of our codes and results and develop estimates of the relative uncertainty,
- Improve computational performance of the coupled MMC models through the development of methods that can be used 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, including specific spatial scales at which the handoff to the microscale model should occur,
- Prepare guidance and a suite of software tools that can be used across the community.

Realizing these objectives will enable simulation of the full suite of mesoscale and microscale flow characteristics affecting turbine and wind-plant uncertainties and performance, thereby allowing for substantive improvements in wind-plant design, operation, and performance projections. Figure 1 diagrams the MMC approach to the project, taking into account the objectives described above.

The team's efforts have focused on some significant challenges that include 1) providing appropriate and consistent boundary and initial conditions; 2) bridging the so-called *terra incognita* [1], that range of spatial scales between about 100 m and the depth of the boundary layer that is problematic for boundary-layer parameterizations applied in mesoscale models [2]; 3) initializing turbulence at the correct scales in the microscale models; 4) testing appropriate coupling methodologies; and 5) quantifying the uncertainty of the methods. These challenges relate

Figure 1. Diagram of Project Approach of using case studies to address the challenges of mesoscale to microscale wind plant simulation challenges.

to well-known difficulties in capturing atmospheric phenomena correctly in mesoscale models and in using those runs to force microscale simulations. We initially analyzed the wind data from the SWiFT site and found that stable and convective conditions predominate [3]. Stable conditions are particularly difficult to simulate due to frequent low-level jets. Low-level jets are phenomena commonly occurring in many locations with rich wind energy resources that can significantly impact wind plant performance due to increased shear as well as turbulence intensity and intermittency across a rotor disk. To accurately reproduce low-level jets in plant scale numerical simulations, it is essential to accurately represent large-scale forcing, in particular the vertical variation of the horizontal pressure gradient, i.e. baroclinity. This can be accomplished only through mesoscale to microscale coupling. Coupling methodologies developed in the previous phase will be essential in achieving high-fidelity simulations of wind plants under low-level jet conditions.

The MMC team's integrated approach to addressing these challenges has been, and will continue to be, grounded in data. The team seeks to leverage DOE-supported field studies, including at the Scaled Wind farm Technology (SWiFT) facility site in Texas and as part of the Wind Forecast Improvement Project 2 (WFIP2) project in the complex terrain of the Pacific Northwest, to select case studies that facilitate

addressing the challenges. Through these case studies, the different approaches can be systematically tested and assessed using metrics specific to wind plant operations [4][5].

Here we discuss methods to spin-up turbulence (section 2), coupling methods (section 3), and wind-energy specific methods of verification and validation (section 4), before summarizing and concluding (section 5). A companion paper [6] details improvements in mesoscale surface modelling to better capture the mesoscale flow that forces the microscale.
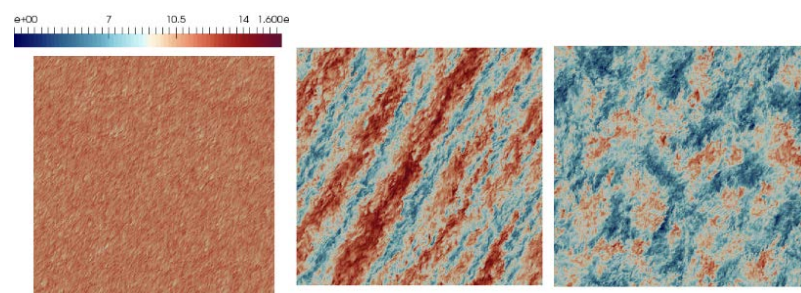
2. Coupling Methodologies

The coupling methodology itself can make a large difference in how microscale models that are typically incompressible respond to a fully compressible mesoscale model. Additionally, the mesoscale models parameterize various physical processes (such as microphysics, radiative transfer, convection, boundary layer processes, and more) in ways that are seldom available in microscale models. Thus, we have found it beneficial to nest from the mesoscale model into its microscale large eddy simulation (LES) range. However, modeling wind plant behaviors, such as those that need blade resolved simulations, require a microscale solver. An open question is how far to nest the Weather Research and Forecasting (WRF) model and/or WRF-LES before handing off to the microscale solver for different use cases. The in-line coupling in WRF is expected to facilitate simulation of meteorological phenomena before passing to the off-line coupling through boundary and internal forcing, such as through forcing with tendencies. This tendency model derives the temporal derivatives of pressure gradient and the mesoscale advection term from the mesoscale model simulation and applies them as forcing functions within the microscale solver, akin to the use of nudging data assimilation in numerical weather prediction [8]. Our efforts showed some success in using this tendency method to simulate non-stationary conditions including diurnal cycles and frontal passages. Currently, the team further is exploring the necessity for such on-line nesting and how to best perform the coupling from both WRF-LES and mesoscale WRF to particular use cases.

The team has continued to develop, test, and evaluate techniques to couple the mesoscale to the microscale. A basic technique is nesting from WRF run in mesoscale mode into the WRF-LES mode. The team also studied offline coupling between WRF-mesoscale model simulations and stand-alone LES models including the Simulator fOr Wind Farm Applications (SOWFA). Two methods to integrate the mesoscale influence into the standalone microscale solver include 1) applying the large-scale advective and pressure-gradient terms extracted from the mesoscale simulation to the governing equations of the microscale solver, and 2) assimilating the mesoscale time-height history of mean wind velocity and potential temperature to generate microscale source terms [4]. Using these methods, the microscale model can dynamically follow transitions at the mesoscale due to diurnal cycles or frontal passages. Snapshots of u-velocity fields at the microscale appear for certain times of day in a diurnal cycle case depicted in Figure 2.

The team has also simulated coupled flow in complex terrain to study the ability of the coupled simulations to capture atmospheric phenomena such as cold pools in valleys, mountain waves, mountain wakes, and drainage flows. To the extent that the mesoscale model captures these phenomena, they can be reproduced in the microscale model. As an example, the team simulated the Biglow Canyon Windfarm region using WRF to force SOWFA. This


Figure 2. Turbulence visible in wind speed at different times in a diurnal cycle. left: stable, middle: developing convective rolls, right: convective cells.

modeling effort has exposed and is leading to solution of several difficult challenges, including microscale domains that include both inflow and outflow, dealing with spurious gravity waves at the

mesoscale-microscale interface, formulating methods to deal with a mismatch in terrain resolution between the mesoscale and microscale, and testing methods to generate realistic turbulence within the microscale domain given that turbulence is not resolved at the mesoscale [9].

3. Turbulence Spin-up

Another challenge is the need to initiate turbulence in the microscale that is not resolved in the mesoscale. Any microscale LES domain receiving inflow data, such as from a mesoscale simulation, that does not explicitly contain all scales of motion resolvable by the microscale mesh, will require a fetch of some distance over which the missing scales of turbulence may develop within that domain. Since that fetch is not useable for computing flow statistics or turbine/airflow interactions, and hence represents wasted computation, methods to accelerate turbulence development within the fetch have been developed and tested during earlier phases of the MMC project. While the most promising of these approaches have been identified and work well within a small number of flow scenarios, those have not yet been generalized and optimized for arbitrary atmospheric and surface conditions, including those featuring significant time variability.

Several turbulence initialization methods have been studied for initializing turbulence at the inflow, including 1) imposing temperature and momentum perturbations via the stochastic cell perturbation method (SCPM; [10][11]), 2) the Veers method [12], 3) the Mann method [13], and 4) velocity perturbations from TurbSim superimposed on WRF-derived inflow, and the Gabor Kinematic Simulation Method [15]. All are found to be effective at generating turbulence at the microscale and comparisons as reported in [16]. Testing of the synthetic methods in non-neutral, heterogeneous and nonstationary applications is ongoing (see Figure 3). That figure indicated that applying SCPM (bottom right panel) produces a flow field much more similar to a periodic LES (bottom left) than does an unperturbed simulation (top right panel).
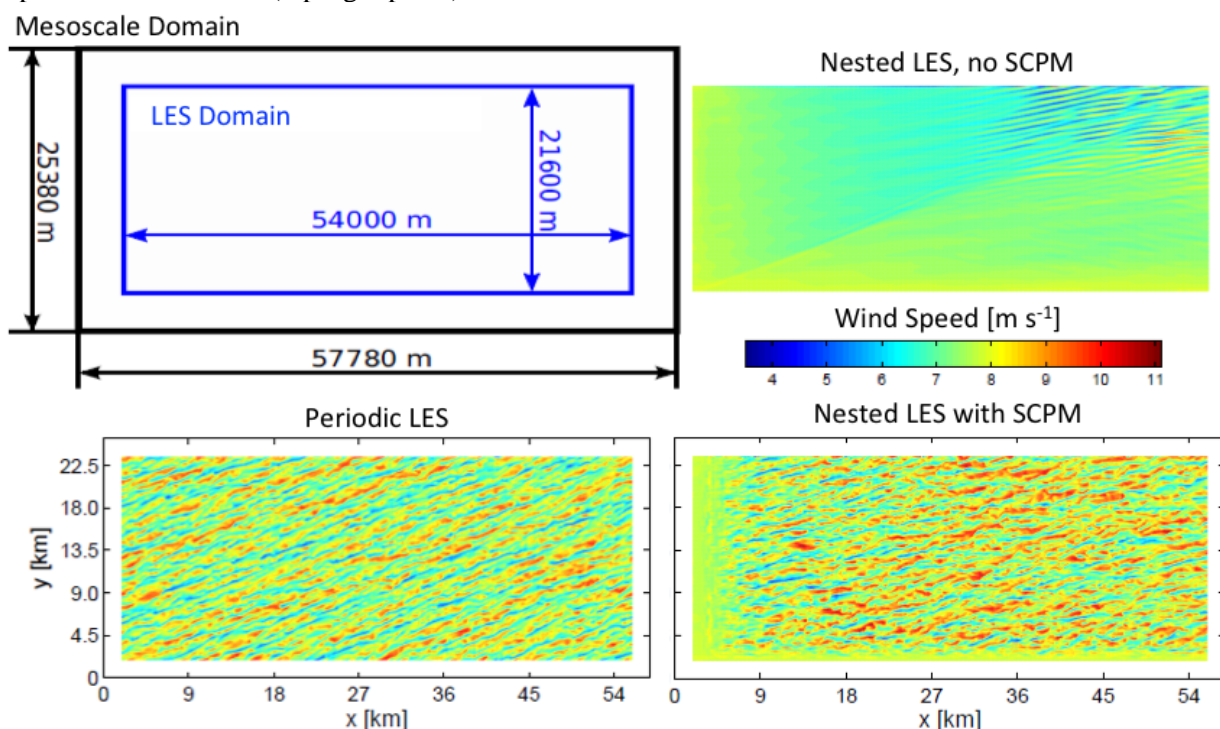
Figure 3. Application of the stochastic cell perturbation method to an LES domain (blue box) receiving inflow from a mesoscale simulation (black box) with no resolved turbulence. Upper and lower right panels show instantaneous wind speed contours at 100 m above the surface depicting, respectively, unperturbed versus perturbed inflow. The lower left panel shows a reference solution from an LES using periodic lateral boundary conditions.

While each of the approaches studied provides a correlated turbulence flow field at the inflow, some fetch may be still be required within the microscale domain for further development and equilibration of the turbulence field due to inexact matching between extant forcing and simulation parameters, and those used in the construction of the synthetic turbulence field.

## 4. Validation and Uncertainty Quantification

Rather than merely assessing the hub-height wind prediction according to average mean absolute or root mean square errors, the team has been applying metrics that are more relevant to wind plant operation and grid integration.

4.1. Wind Turbine Specific Validation

To validate MMC methods, first one needs to define quantities of interest (QOI). Because MMC is the coupling of two atmospheric scales, using atmospheric QOIs for validation is a logical starting point. Atmospheric QOIs include vertical profiles of wind speed, wind direction, temperature, and humidity of the atmospheric boundary layer; turbulence spectra; and spatial coherences. Figure 4 shows examples of comparing profiles and turbulence spectra. This type of analysis is able to disern differences in shear across the diurnal cycle (left panel) and the underprediction of turbulence by WRF without use of perturbations (right panel). Because the ultimate goal of the A2e MMC project is to apply MMC methods to the wind-plant problem, we have enhanced our set of validation QOIs with wind-plant-specific quantities, such as:

- Time-dependent vertical profiles of wind speed, variances, covariances, direction, and temperature over the rotor diameter.
- Low-pass filtered wind speed, direction, and temperature
- Root mean square, standard deviation, variances, covariances of high-pass filtered wind data.
- Spectra of high-pass filtered wind data.
- Inflow turbulence spatial correlation information

Finally, the team is also using the wind turbine power output as a metric where available. This innovative metric allows us to correlate the predictions with the output that is most meaningful for the plant operator – the actual production from the turbines. This also allows very turbine-specific analysis that includes details of the micrositing, impact of upwind turbines, and differences for differing wind directions.
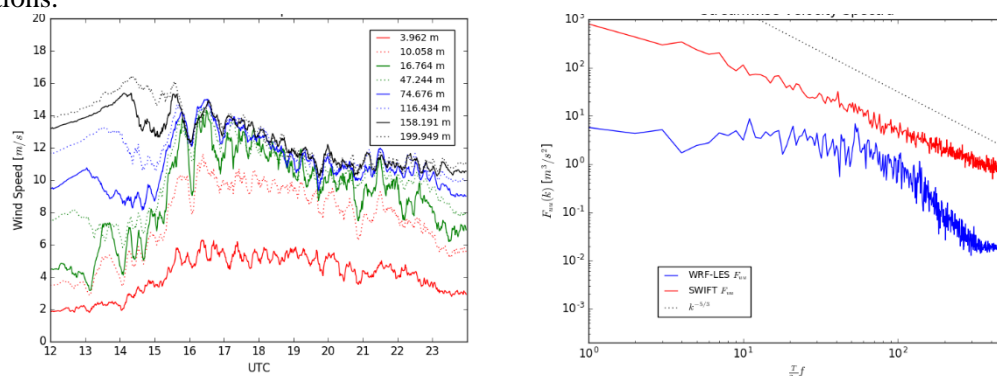

Figure 4. Left: Wind Speed - diurnal case based on observations on November 8, 2013 – WRF-LES. Right: Comparison of measured (red) and simulated (blue) streamwise velocity frequency spectra under unstable stratification produced using WRF-LES.

4.2. Uncertainty Quantification

The relevant processes for wind generation operate on a wide range of timescales and some of the finer-scale processes need to be parameterized. Each of those parameters has a range of plausible values, but even slight variations in those parameters within their corresponding ranges can lead to large variations

in generated wind power (Figure 5), leading to uncertainty. Reducing these uncertainties requires formal study using uncertainty quantification (UQ) methodology. During the MMC project, we are using UQ to address several aspects of a single key question: Using an MMC framework, how do structural uncertainties, parametric uncertainties, and changing boundary conditions (time-evolving inflow) affect the accuracy of our estimates of the turbulent inflow to the wind plant? UQ will provide the community with information for robust decision support to improve the integration and reliability of the wind plant.
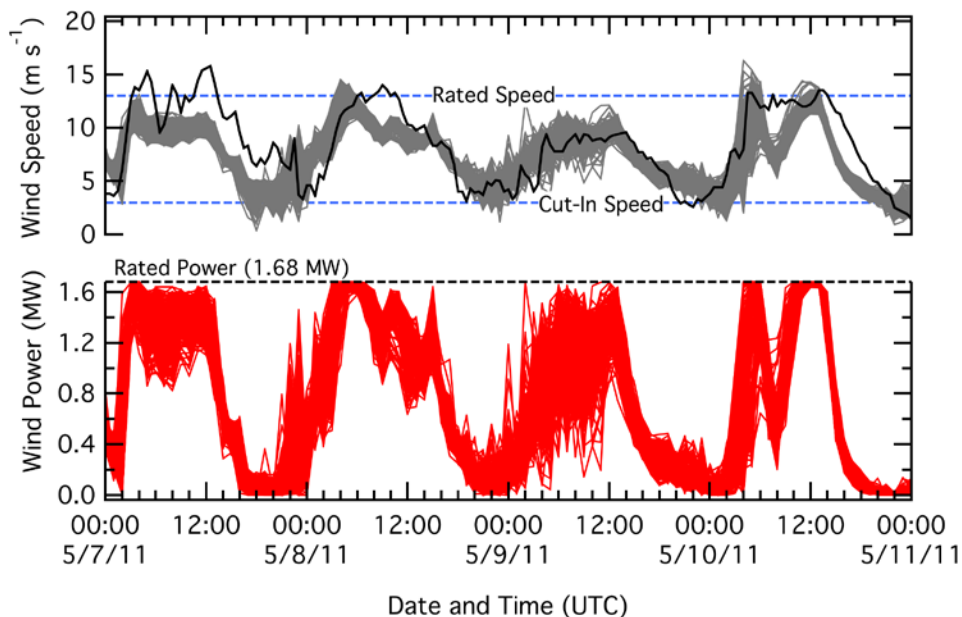
Figure 5. Uncertainty ranges in simulated wind speed (gray, top), observed wind speed (black, top) and generated wind power (bottom) for an ensemble of simulations with perturbed parameter values from Yang et al. [15]. Small variations in plausible parameter values can have dramatic impacts on predictions of power generation.

Structural uncertainty deals with uncertainties introduced by the components of the model. How might a model change if a previously missing process is included? How does model behavior change when two different, equally plausible boundary-layer schemes are applied? How important is a land surface model that resolves the forest canopy? Questions along these lines are essential to address because they are directly related to the appropriateness of the chosen modeling framework to quantify wind plant inflow. We are also addressing issues such as: Which processes are most important to include to properly represent wind plant inflow? Under what meteorological conditions are some processes more important than others? At what horizontal resolution does including these representations affect the results? These questions will be addressed individually in WRF and WRF-LES and in the multi-model coupled system.

Parametric uncertainty deals with the fact that, for any given parameter, there is a range of plausible values that are supported by observations under a particular set of atmospheric conditions. However, even slight changes in some parameters within those ranges can have profound impacts on the resulting forecasts of wind speed or power. In each individual model (WRF, WRF-LES, and SOWFA), we identify a set of parameters to be investigated, as well as their plausible ranges. These are of particular importance for coupled model systems, as inflow for a finer-scale model is provided by the coarser model. These parameters, in combination with parameters specifically related to inter-model coupling (e.g., coupling frequency) are perturbed to determine the changes.

Different meteorological conditions (e.g., unstable convective versus low-level jet) have different inflow characteristics, affecting wind power generation. The effects of different meteorological

conditions will also vary depending upon the location (e.g., simple terrain, offshore flow, complex terrain, or channeled flow, such as in the Columbia River Gorge). It is important to note that this category focuses on inflow into the coupled mesoscale-microscale system. The inflow from the mesoscale model into the microscale model is also a boundary condition for the microscale model, but such concerns are incorporated into structural and parametric uncertainty.

5. Summary

The DOE-funded MMC project seeks to develop, test, refine, validate, and disseminate specific mesoscale to microscale coupling strategies and technologies as well as to provide basic research results and enable low order modelling. The team is building new high-performance-computing-based multiscale wind plant simulation tools that couple a broad range of scales, including interactions across scales, which will enable the optimization required to ensure efficient, reliable production and integration of wind power. These tools will be applicable for diverse locations (both on- and off-shore) and operating conditions, as required to support wind energy integration at high penetration levels. Data and results of the modeling are being archived using the A2e Data Archive and Portal (DAP). The tools undergo thorough verification and validation and the uncertainty is being quantified. This is being accomplished via a series of observation-based case studies with increasing complexity in terms of nonstationarity, terrain, offshore influences, and inclusion of actual wind plant field data.

A key component of the MMC project is the development of a suite of test cases that can be downloaded, compiled, and run by members of the community. Evaluation code is archived on github as Jupyter notebooks that can be utilized to judge the comparative value of each simulation. This work will culminate in producing well-validated tools with the uncertainty quantified as well as validation cases that will be useful to industry.

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