UNIVERSITY OF MINNESOTA

Twin Cities Campus

Saint Anthony Falls Laboratory
Engineering, Environmental, Biological
and Geophysical Fluid Dynamics

Department of Civil Engineering
College of Science and Engineering

Mississippi River at 3rd Avenue S.E.
Minneapolis, MN 55414

Dept. Main Office: 612-624-4363
Fax: 612-624-4398

Project Title: Development of a High-Resolution Virtual Wind Simulator for Optimal Design of Wind Energy Projects

Contract Number: RD3-42 **Milestone Number:** 3 **Report Date:** 11/29/10

Principal Investigator: Fotis Sotiropoulos **Contract Contact:** Bridget Foss

fotis@umn.edu 612-624-5571

Congressional District: (Corporate office) Minnesota 5th

Congressional District: (Project location) Minnesota 5th

MILESTONE REPORT

Executive Summary:

This project aims at developing a '*Virtual Wind Simulator*' (VWS) for the prediction of atmospheric boundary layer flow and its interactions with wind turbines and wind farms. The use of the simulator will assist in the improved design of potential wind energy projects by providing more accurate predictions of local and wind turbulence at site and turbine levels. Additionally, the VWS will help increase the level of wind energy utilization and reduce the cost of energy production.

Computational Fluid Dynamics (CFD) methods are used in this project to develop a computational framework for conducting high-resolution simulations of wind turbulence at the meso and micro scales. In particular, the Large-Eddy Simulation (LES) technique will allow for accurate simulations of the turbulent flow at spatial resolutions as small as one to ten meters, and temporal resolutions of just a few seconds. Parameterizations for wind turbine forces will also be developed in the LES framework. In addition, three-dimensional, time-evolving flow fields obtained from LES at any location within a potential wind farm site could then be used as the inflow condition for even more detailed simulations of the turbulent flow around the blades of specific wind turbines using a hybrid Reynolds-Averaged Navier-Stokes (RANS)/LES technique. The SAFL computational models will be coupled to macro-scale regional models to develop a powerful multi-scale computational tool, the VWS. The VWS will integrate the latest advancements in computational fluid dynamics research and provide reliable, high-resolution descriptions of wind turbulence across the entire range of scales that are relevant to wind power production. This information will provide objective, scientifically based criteria that can be used by wind energy project developers for the site-specific, optimal selection and placement (micro-siting) of wind turbines.

As planned, during this reporting period (quarter) activities have been carried out that address three of the specific objectives of the project:

(a) Development of a multi-scale computational fluid dynamics (CFD) framework for accurate simulation of high-resolution wind and turbulence fields and their effects on wind turbine operation and energy output.

(b) Validation of the proposed *Virtual Wind Simulator* using high-resolution wind and turbulence measurements collected in an atmospheric boundary layer wind tunnel.

(c) Testing the *Virtual Wind Simulator* using wind and turbulence measurements collected at an operational wind farm.

Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund.

Technical Progress:

We have made substantial progress in Task 1, Task 2 and Task 3. The progress made in the three tasks is discussed below.

Task 1. Development of the *Virtual Wind Simulator* for high-resolution simulations of wind, turbulence and their effect on energy production

Progress has continued on the development and testing of two of the components of the Virtual Wind Simulator: the Large-Eddy Simulation (LES) code and the RANS/LES code.

Subtask 1.1. LES of the atmospheric boundary layer and turbine models

Large-Eddy Simulation (LES) can potentially provide the kind of high-resolution spatial and temporal information needed to maximize wind energy production and minimize fatigue loads in wind farms. However, the accuracy of LES in simulations of atmospheric boundary layer flow and its interactions with wind turbines hinges on our ability to parameterize subgrid-scale (SGS) turbulent fluxes as well as turbine-induced forces. Below we summarize our most recent efforts to develop and validate a LES framework to simulate atmospheric boundary layer flow and the interaction with wind turbines and wind farms.

(a) Subgrid-scale turbulence modeling

Progress has continued on the improvement, implementation and testing of the state-of-the-art subgrid-scale (SGS) models recently developed by Prof. Porte-Agel’s research group. These include the Lagrangian scale-dependent dynamic models for both momentum and scalar fluxes (*Stoll and Porte-Agel, 2006; Wan and Porte-Agel, 2010*) and the new modulated gradient model (*Lu and Porte-Agel, 2010*). The new models allow for tuning-free simulations and are found to perform better than the existing LES models, including the standard Smagorinsky model and the scale-invariant dynamic model (Germano et al., 1991).

(b) Modeling turbine-induced forces in LES

Three models have been implemented to parameterize turbine-induced forces (e.g., thrust, lift and drag) in LES: (a) the `standard' actuator-disk model (ADM-NR), which calculates only the thrust force and distributes it uniformly over the rotor area; (b) the newly developed actuator-disk model with rotation (ADM-R), which uses blade element momentum theory to calculate the lift and drag forces (thus producing both thrust and rotation), and distribute them over the rotor disk based on the local blade and flow characteristics (for more details on this model, see Wu and Porte-Agel, 2010); and (c) an actuator-line model (ALM) that distributes the forces only at the position of the blades. Even though it requires more computational resources, the ALM model is capable of capturing some important flow features such as helicoidal vortices. The three models are currently being used to simulate flow through wind farms, including the Mower County Wind Farm. Figure 1 shows simulation results from a simple neutral atmospheric boundary layer through the SW corner of the wind farm. The flow simulated with the ADM-R and ALM agrees well with the SODAR measurements collected inside the wind farm.

Current efforts are focused on extending the development and validation of the new-generation LES (including new SGS models and wind-turbine parameterizations) to more realistic atmospheric conditions such as stable and unstable conditions as well as wind farm configurations.

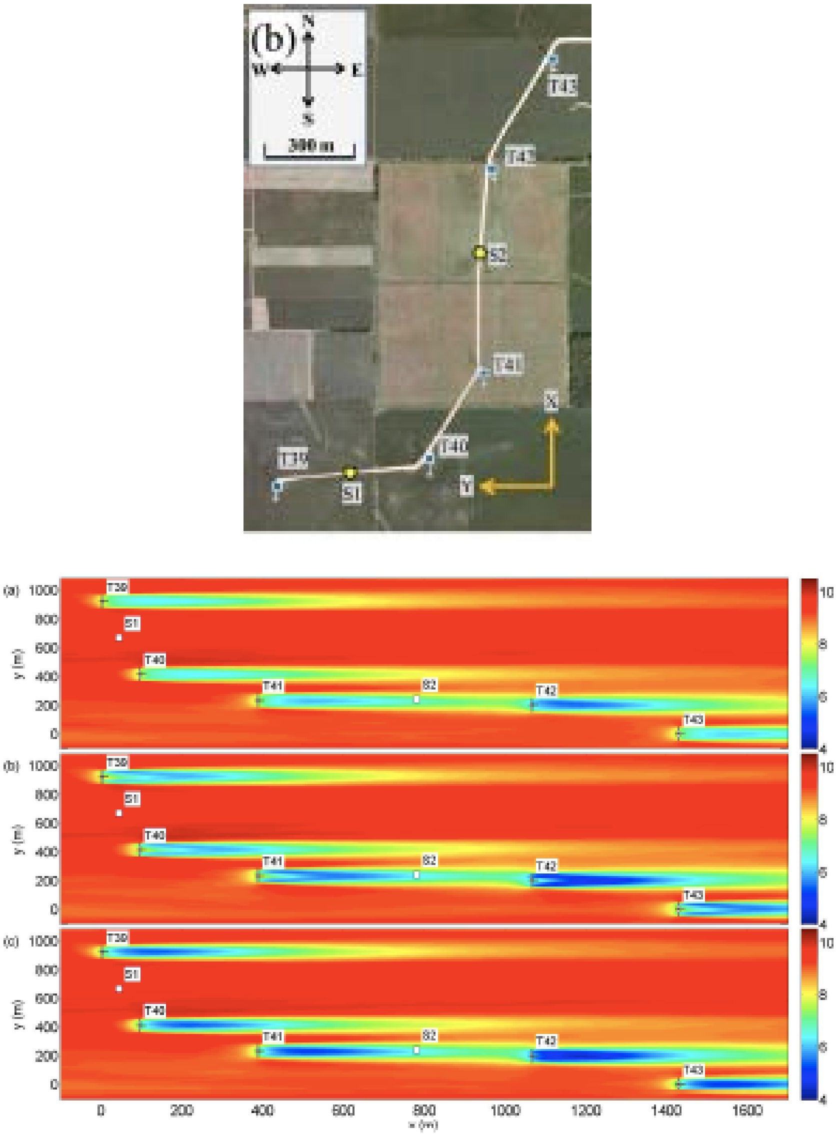

Fig. 1: Left: Layout of the SW the Mower County wind farm and placement of the wind turbines and SODARs. Right: Two dimensional contour plots of the simulated time-averaged streamwise velocity (m/s)

on a horizontal plane at hub height. Comparison between different wind-turbine models: (a) ADM-NR, (b) ADM-R, (c) ALM.

Subtask 1.2 URANS/LES model for wind turbine flow

We have developed a computational framework that enables us to perform high resolution simulations of a wind turbine on a complex terrain. To accomplish this we have generalized our fluid/structure interaction curvilinear/immersed boundary (FSI-CURVIB) method [Borazjani et al., *J. Comp. Phys.* **227**, 7587-7620, 2008] to incorporate overset (CHIMERA) grids to increase grid resolution locally near complex immersed boundaries, such as topographic features and multiple turbine rotors. The computational domain (say a section of a wind farm) can be discretized with a Cartesian grid within which a complex topography and/or multiple turbine rotors can be treated either as sharp-interface immersed boundaries. We have developed novel interpolation techniques for satisfying mass conservation in the resulting composite grids in conjunction with an efficient fractional step method. The numerical methodology has been generalized to include both inertial and non-inertial frame formulations as well as to enable simulations with hybrid formulations. We have implemented dynamic subgrid scale model for large-eddy simulations (LES) and k-ω model for unsteady Reynolds Averaged Navier-Stokes (URANS) simulations.

We have carried out turbulent as well as inviscid simulations for the two-blade NREL phase VI wind turbine rotor rotating at 72 rpm and wind velocity 7 and 15 m/s. A coarse and a fine overset grid arrangements with 8.6 and 12.5 million grid nodes, respectively, has been used for these simulations. We compare the simulation results against the NREL phase VI experiments in terms of pressure coefficient distribution on the blades as shown in Fig 3. Fig 4 shows the kinetic energy in the LES wake in the midplane of the blade. Fig 5 and 6 show the 3D wake structure visualized by the iso-surfaces of q-criteria for the instantaneous and averaged flow fields obtained from LES.

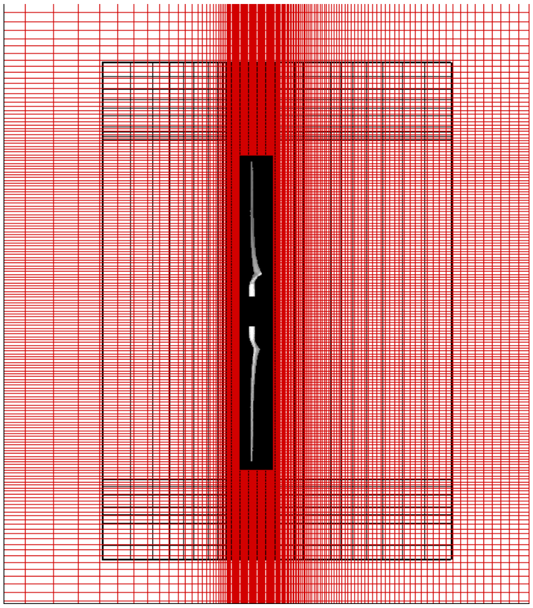

Fig. 2. Blade-geometry-resolving LES.

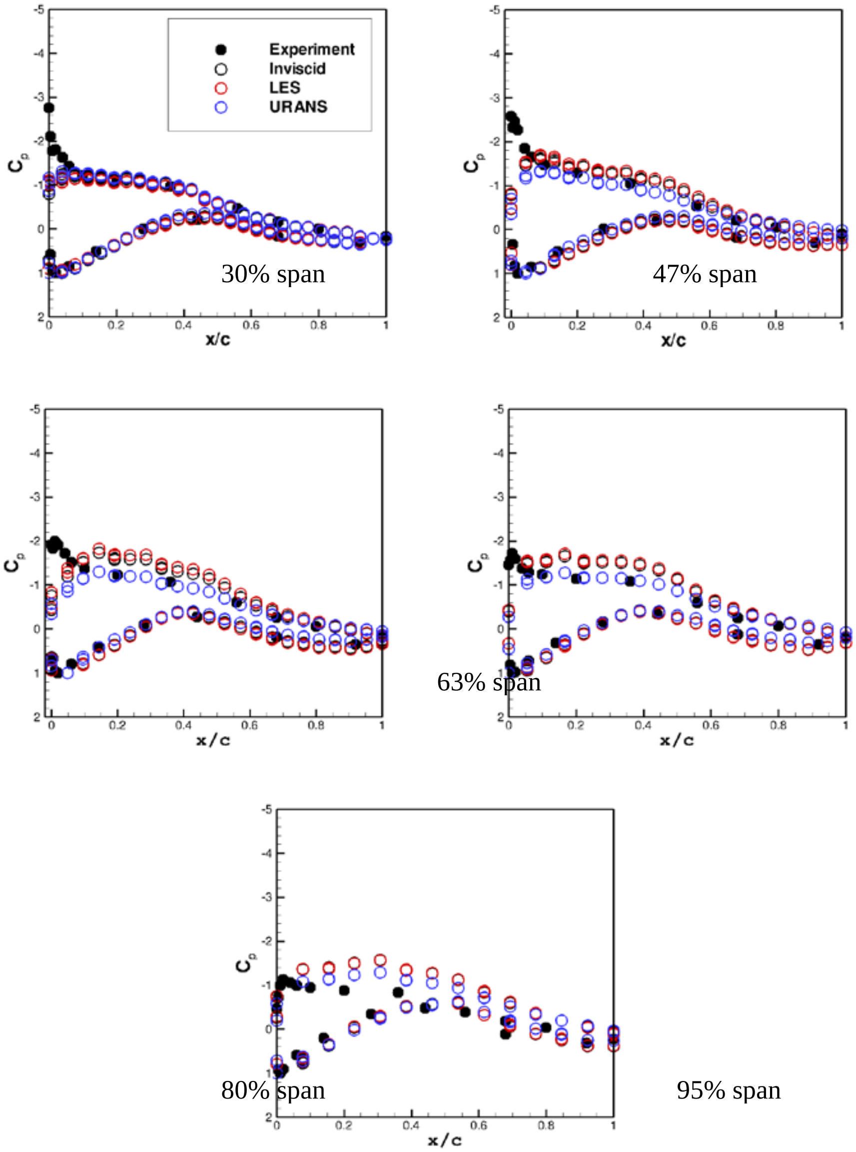

Fig. 3. Pressure coefficient on different airfoil cross sections at different span locations for wind speed 7m/s.

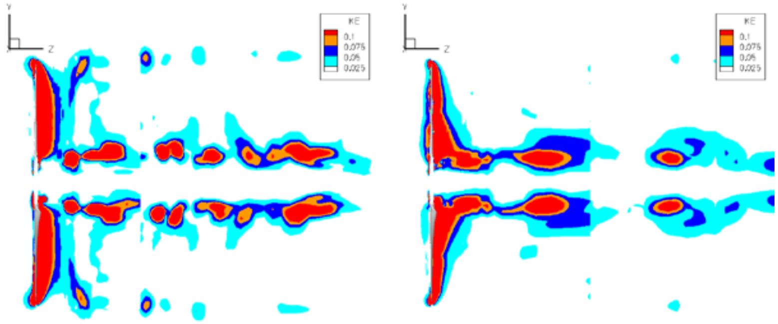

Figure 4. Non-dimensional kinetic energy in the midplane of the blade in the LES wake for wind speed 7m/s (left) and 15m/s (right).

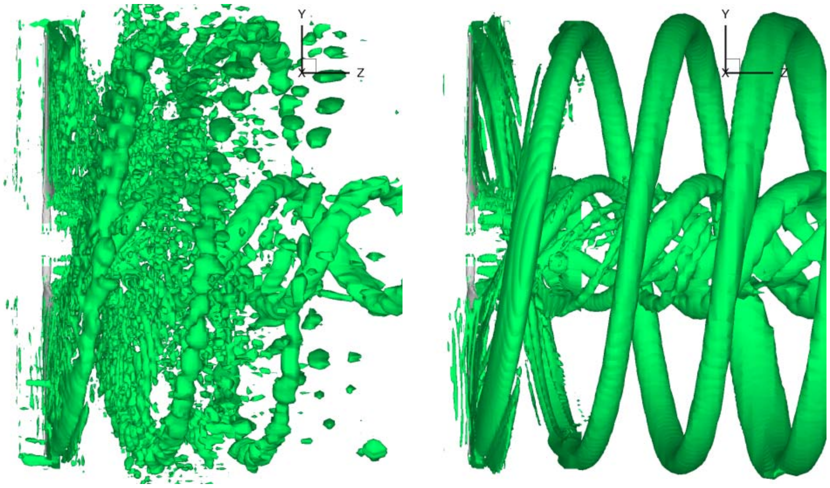

Figure 5. Instantaneous wake (left) vs. averaged wake for speed 7m/s (LES).

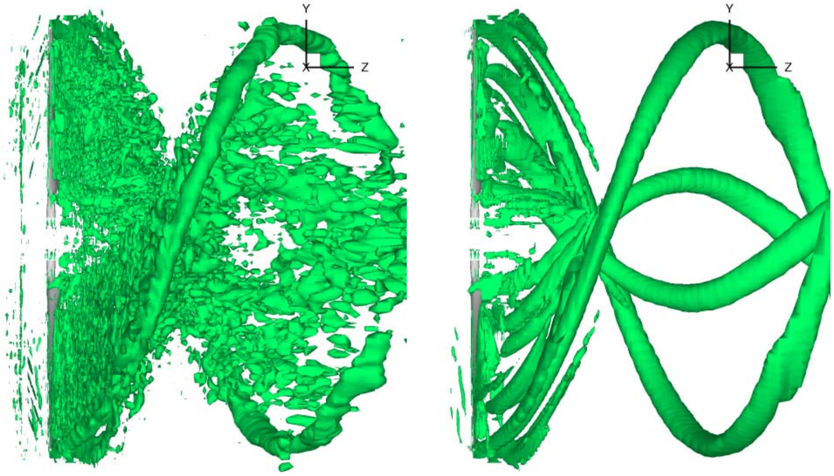

Figure 6. Instantaneous wake (left) vs. averaged wake for speed 15m/s (LES).

Task 2. Validation of the *Virtual Wind Simulator* using wind tunnel measurements

Wind tunnel experiments

Progress has continued on the fundamental understanding of the turbulent flow properties around wind farms. In particular, we have performed wind tunnel experiments to study fundamental properties of the turbulent flow around a perfectly aligned wind farm placed in a boundary layer flow. Main flow properties of the turbulent flow within and above the aligned wind farm will be compared with the case of a staggered wind turbine array to infer the effect of the layout on the overall wind farm efficiency.

High-resolution spatial and temporal fields of velocity and turbulence statistics, collected at different locations (see Fig. 7) using a hotwire sensor anemometer have been used to characterize the wind-turbine wake and guide the development of parameterizations of wind turbines in computational fluid dynamic models (e.g., Fig. 8, 9). Particle Image Velocimetry (PIV) experiments are being planned to complement the current information obtained with the hotwire and 3-wire data.

Results suggest that the turbulent flow in a wind farm (under an align configuration) can be characterized in two broad regions. The first, located below the turbine top tip height, has a direct effect on the performance of the turbine. The mean flow statistics appear to reach equilibrium as close as the third to fourth row of wind turbines independent of the layout, but turbulence statistics showed dependence with the wind farm configuration. In the second region, located right above the first region, flow adjusts slowly. There, two layers were found: an internal boundary layer where flow is affected by the wind turbine array and an equilibrium layer, where flow statistics are adjusted. The role of these layers on the overall power production in the wind farm will be analyzed.

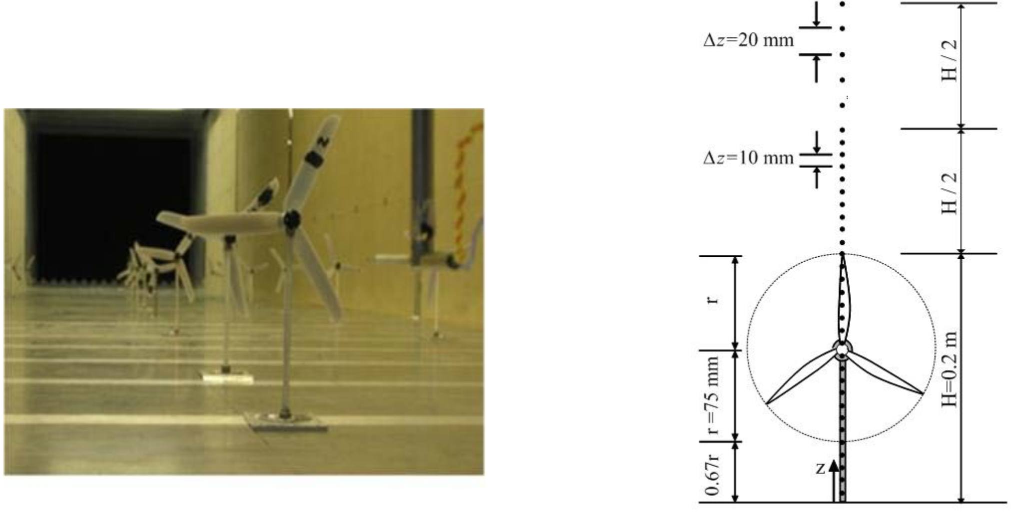

Fig. 7: Photograph of the test section with the model wind turbines (left) and measurement locations right).

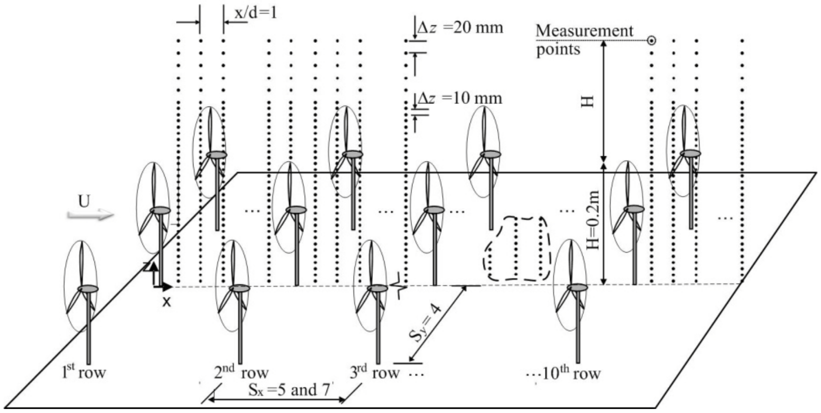

Fig. 8: Miniature wind farm (align configuration) placed in a turbulent boundary layer flow at the SAFL wind tunnel. Measurement locations.

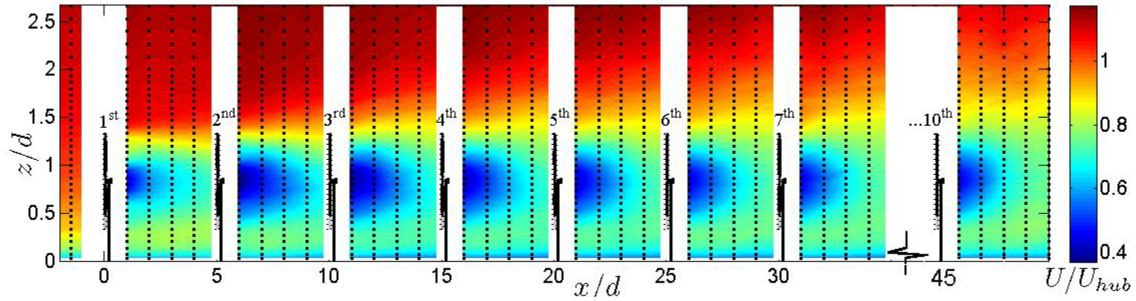

Fig. 9. Non-dimensional velocity distribution in the wind farm (Δx/d=5).

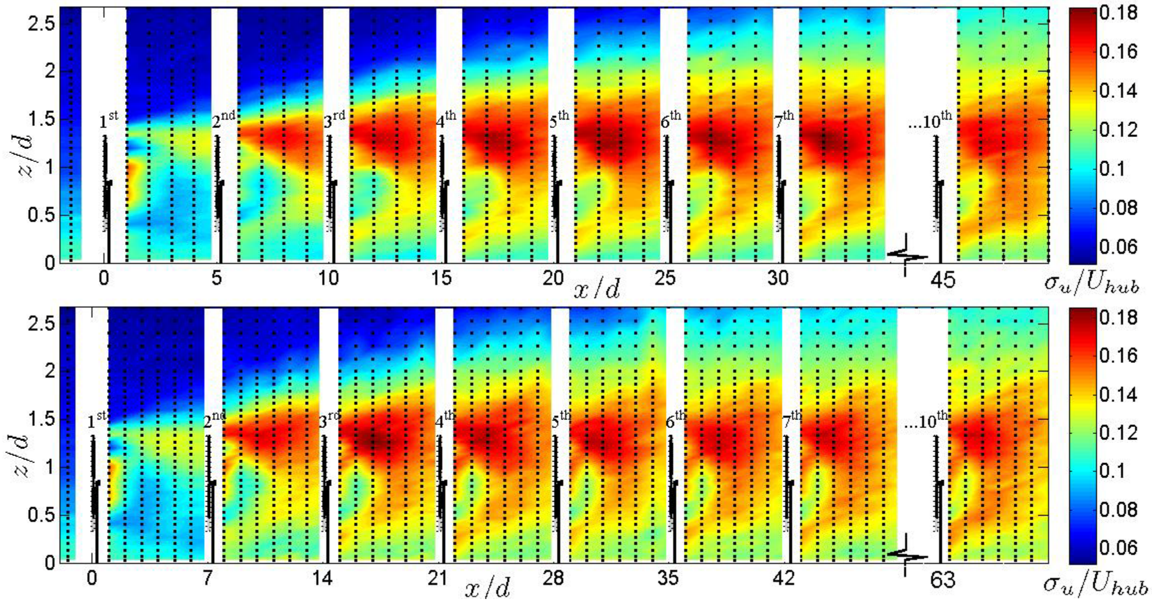

Fig. 10. Turbulence intensity distribution around the wind farm. Inter-turbine separations of 5 (top) and 7 rotor diameters.

Task 3. Testing the *Virtual Wind Simulator* using wind and turbulence measurements collected at an operational wind farm

Field experiments

Measurements continue in collaboration with our partners from WindLogics, Inc. and Barr Engineering in a wind farm located in Mower County. Two Sodars provided by WindLogics have collected three months of data, which complete the current phase of experiments. A new LiDAR has been purchased and will be used to support the current filed campaign.

Field campaign (WindLogics activities) included further data analysis of the SODAR and SCADA data collected from the Mower County wind farm during the summer of 2010 and refinements of quality control and quality assurance procedures for the SCADA data. The sodar data were composited to form turbine wake cross sections. Prior analyses formed the composite cross-sections for all data in the sampling period, but the more recent analyses categorize the cross sections according to atmospheric stability. The data collected during the Summer 2010 has added samples from the set of profiles from which the composites are constructed, allowing for better composites to be calculated. Fig. 11 shows the cross section of the ratio of the waked sodar wind speed to the free stream (upstream from the turbine wake) wind speed and vertical velocity for stable conditions during summer 2010. All three sodars at the site have collected data that are capable of resolving the rotation of the flow within the turbine wake. In Fig. 11, the vertical velocity is upward to the left of the wake centerline (Y=0) and downward to the right of the centerline. These results are qualitatively consistent with large eddy simulations that have been conducted.

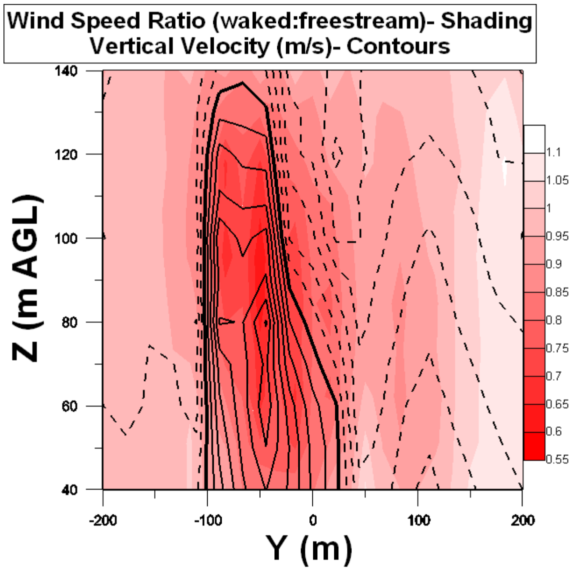

Fig. 11. Y-Z cross section of turbine wake measured by the Triton sodars for stable atmospheric conditions during summer 2010. Shading indicates the ratio of wind speeds of the waked to unwaked sodar (the waked sodar is downstream from Turbine 41), and the contour lines show vertical velocity (contour interval of 0.05 m/s, dashed lines are negative, zero line is bold).

Barr continued to monitor and QA/QC data from Barr ASC Sodar unit deployed at Mower County, post data on project web site, and coordinate analysis with WindLogics.

In July and August, final monitoring adjustments for Mower County site, including Natural Power Lidar and ASC Sodar relocations to new sites within the wind farm were performed. Barr coordinated final high-resolution data burst from ASC SoDAR at Mower County site, retrieved ASC SoDAR for review and re-deployment at Prairie Island complex terrain site.

In mid-September, Barr installed the meteorological tower and associated equipment near the Prairie Island Indian Community Treasure Island Casino, in preparation for monitoring at complex terrain site. Data collection from that site is ongoing. Plans for lidar, SoDAR, and CSAT-3 deployment at Prairie Island site were also developed in September, 2010.

Fig. 12. Wind Farm in the Mower county area (top) and LiDAR in operation in the wake of a wind turbine (bottom).

Additional Milestones:

Work is in progress towards Milestone 4.

Project Status:

The project is ahead of schedule due to the fact that work on the project started before the contract was finalized.

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Appendix:

List publications

Papers in Refereed Journals

1. Chamorro, L.P., Arndt, REA and Sotiropoulos F. 'Turbulent flow properties around a staggered wind farm'. *To be submitted*.
2. Chamorro, L.P., Arndt, REA and Sotiropoulos F. 'Reynolds number dependence of turbulence statistics in the wake of wind turbines'. Under Review.
3. Chamorro, L.P., and F. Porté-Agel, 2010. 'Thermal stability and boundary-layer effects on wind turbine wakes. A wind tunnel study'. *Boundary-Layer Meteorology*, 136: 489-513.
4. Lu, H., and F. Porté-Agel, 2010. 'A modulated subgrid-scale model for large-eddy simulation: Application to a neutral atmospheric boundary layer'. *Physics of Fluids*, in press.
5. Wu, Y.-T., and F. Porté-Agel, 2010. 'Large-eddy simulation of wind-turbine wakes: Evaluation of turbine parameterizations'. *Boundary-Layer Meteorology*, in press.
6. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbines wakes: Boundary-layer turbulence and surface roughness effects'. *Boundary-Layer Meteorology*, 132: 129-149.

Conference Presentations

1. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2008. 'Development of a high-resolution Virtual Wind Simulator for optimal design of wind energy projects'. E3 -Energy, Economic and Environmental- Conference. Minneapolis, MN.

2. Chamorro, L.P., and F. Porté-Agel, 2008. ‘A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects’. American Geophysical Union. San Francisco, CA.
3. Wu, Y.-T.., H. Lu, and F. Porté-Agel, 2008. ‘Large-eddy simulation of wind-turbine wakes’. American Geophysical Union. San Francisco, CA.
4. Chamorro, L.P., and F. Porté-Agel, 2009. ‘A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects’. European Geophysical Union. Vienna.
5. Porté-Agel, F., Y.-T. Wu, Y.-T.., H. Lu, 2009. ‘Parameterization of turbulent fluxes and wind-turbine forces in large-eddy simulation’. European Geophysical Union. Vienna.
6. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2009. ‘Development of a high-resolution Virtual Wind Simulator for optimal design of wind energy projects’. E3 -Energy, Economic and Environmental- Conference. Minneapolis, MN.
7. Chamorro, L.P., and F. Porté-Agel, 2009. ‘A wind tunnel investigation of wind turbine wakes’. American Physical Society Meeting. Minneapolis, MN.
8. Porté-Agel, F., Y.-T. Wu, and H. Lu, 2009. ‘Large-eddy simulation of wind-turbine wakes’. American Physical Society Meeting. Minneapolis, MN.
7. Chamorro, L.P., R.E.A. Arndt and F. Sotiropoulos, 2010. ‘Turbulence characteristics around a staggered wind farm configuration. A wind tunnel study’. American Physical Society Meeting. Minneapolis, Long Beach, CA.