2014 WIND POWER PROGRAM PEER REVIEW

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

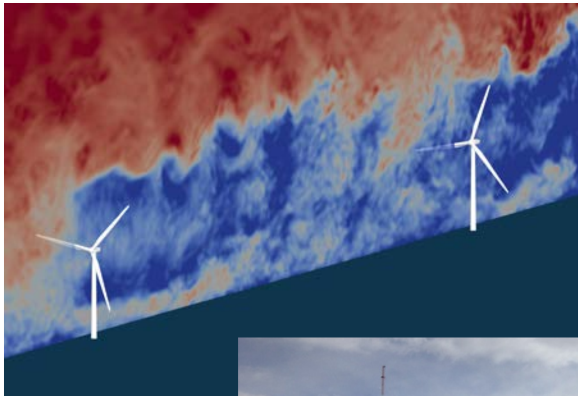
Resource Characterizations

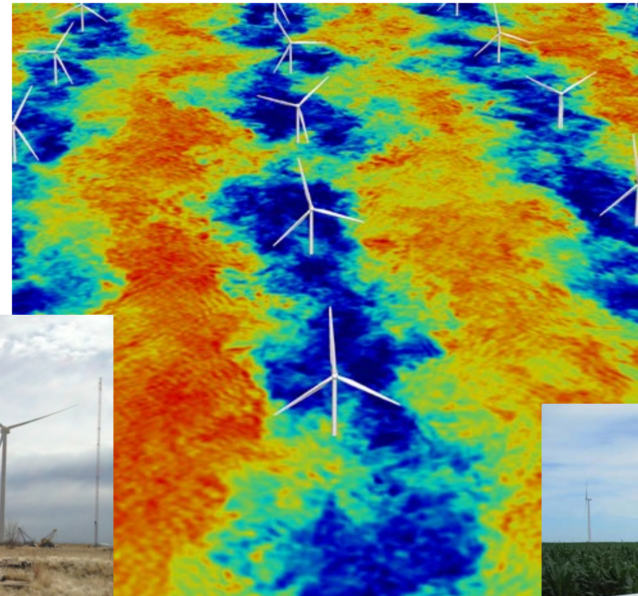
March 24-27, 2014

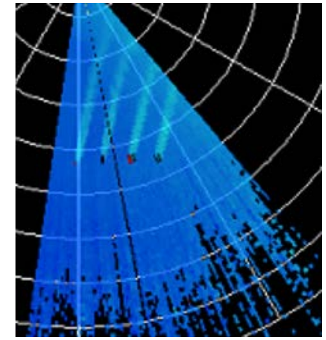
Wind Energy Technologies

PR-5000-62152

Contents







Inflow Characterization Tasks

Patrick Moriarty

NREL

patrick.moriarty@nrel.gov

303-384-7081

March 24, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $2.024M

Total Cost-Share[1]:$0.150M

Problem Statement: A better fundamental understanding of wind behavior across the range scales that influence wind plant operation is required to reduce underperformance and uncertainty.

Impact of Project: A better understanding of the physical interactions between wind plants and their wind environment will reduce energy production and finance costs by improving the tools used for wind plant layout design, energy prediction and operation.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

Observations

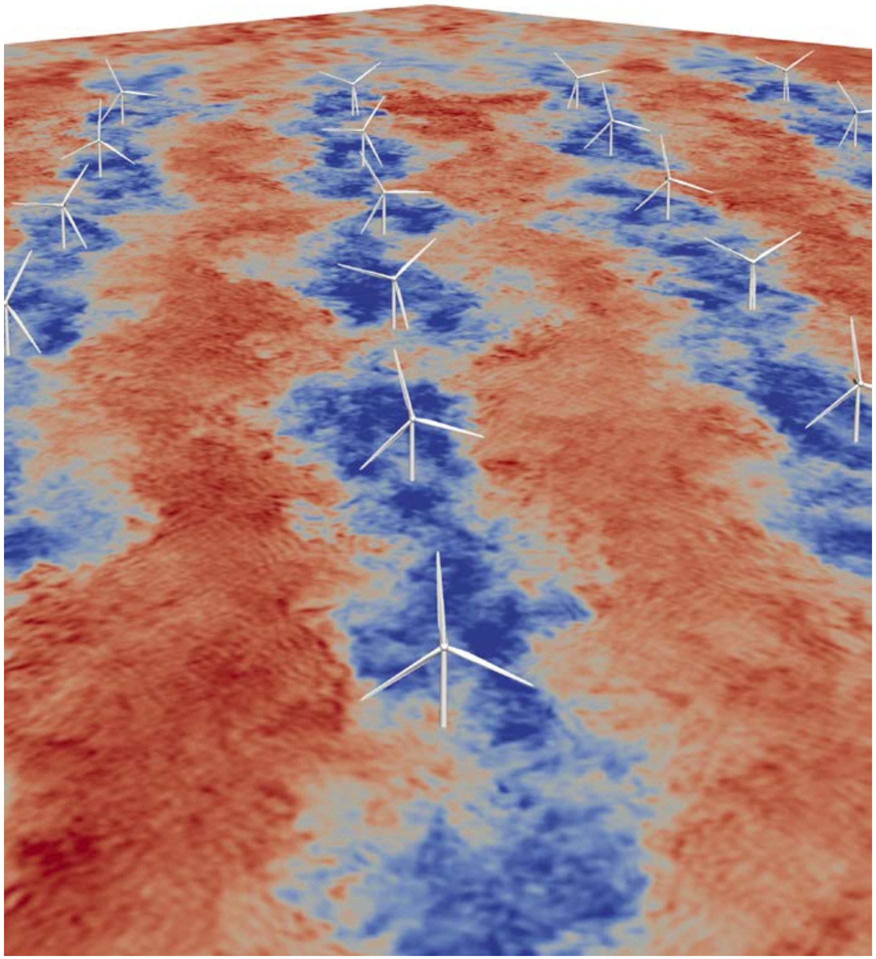
- TWICS
- CWEX
- TODS
- Power curve variation and nacelle transfer functions
- Instrumentation development and analysis

Simulations

- SOWFA
- Wind farm parameterization model in WRF

Stakeholder Engagement and Dissemination

- IEA Best Practice Document
- IEA Task 31
- IEA Task 32
- EWEA CREYAP and AWEA WFME
- IEC Standard 61400-15



Accomplishments and Progress

Turbine Wind and Inflow Characterization Study (TWICS)

- Wake and inflow measurements of 2.3 MW turbine at NWTC
- Influence of complex terrain and stability

Crop Wind Energy Experiment (CWEX)

- Wake measurements
- Impact of changing roughness (i.e. corn) on wind farm performance
- Impact of wind farm on crops

Turbine Outflow Dissipation Study (TODS)

- Measurement of dissipation in turbine wake from DOE 1.5

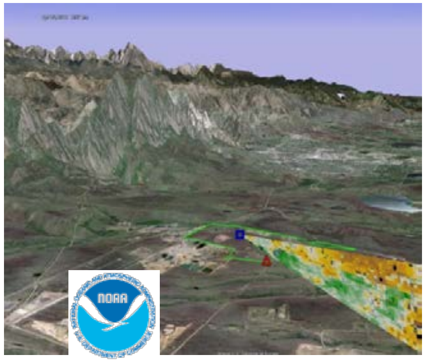
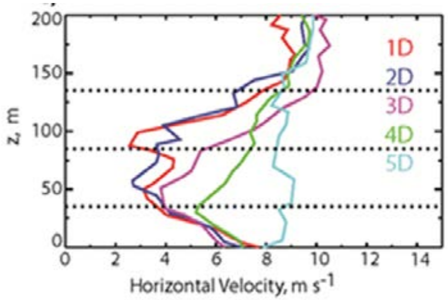
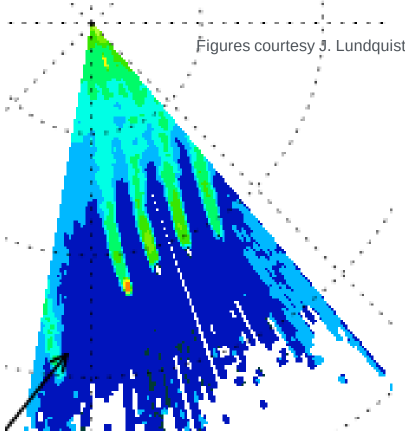


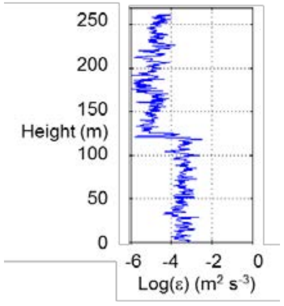
Figure courtesy A. Brewer



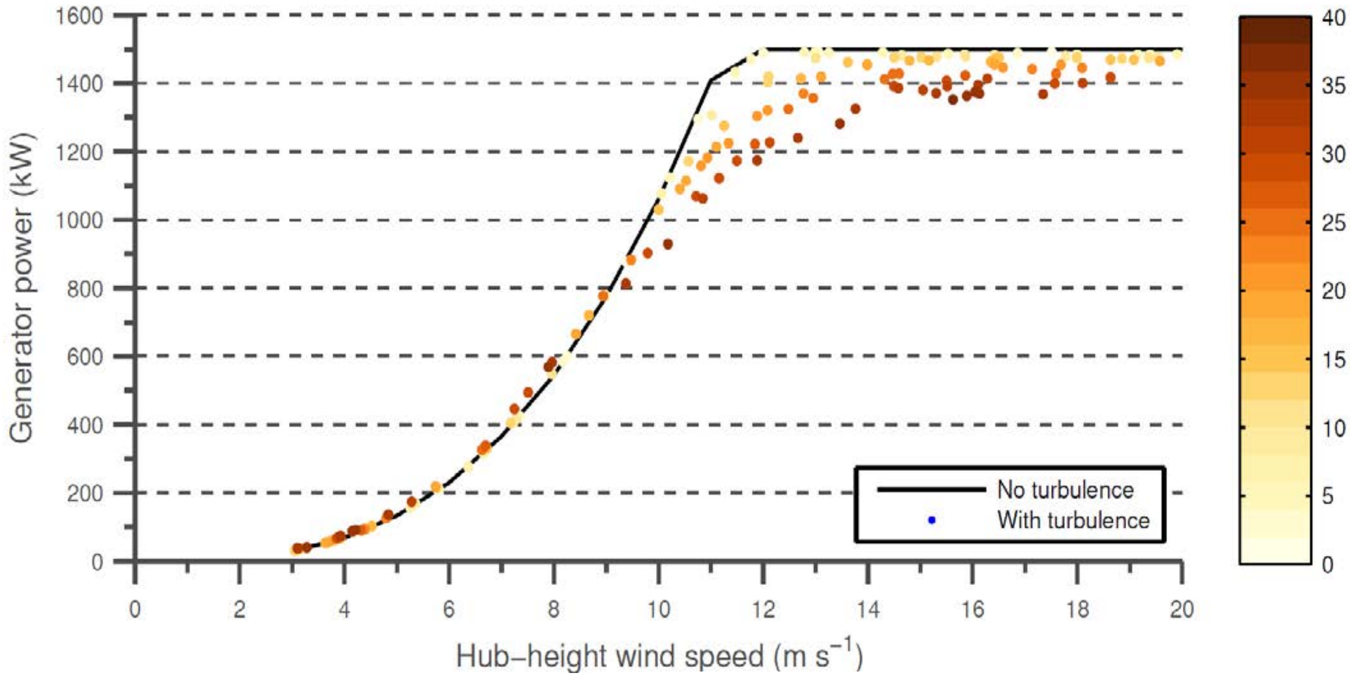
Banta et al. 2013



Figures courtesy J. Lundquist

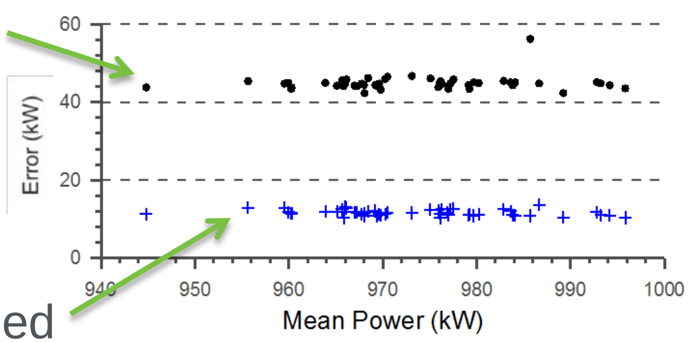


Power curves can deviate in varying atmospheric conditions



Baseline

Power better predicted with more variables



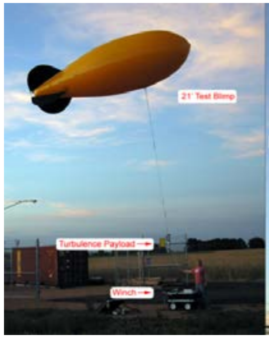
Turbulence included

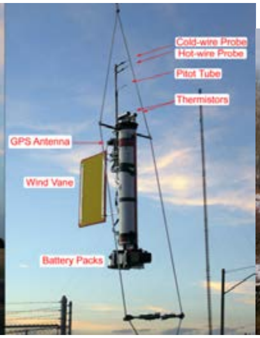
Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Instrumentation Testing

- Tall tower validation
- Wake measurements
- Systems
  - Sodar
  - Lidar
  - Radiometer
  - Tethersonde
  - UAV
- Impacts of complex terrain and unique atmospheric conditions

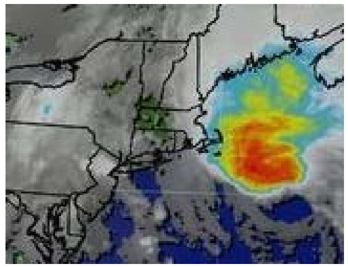




Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

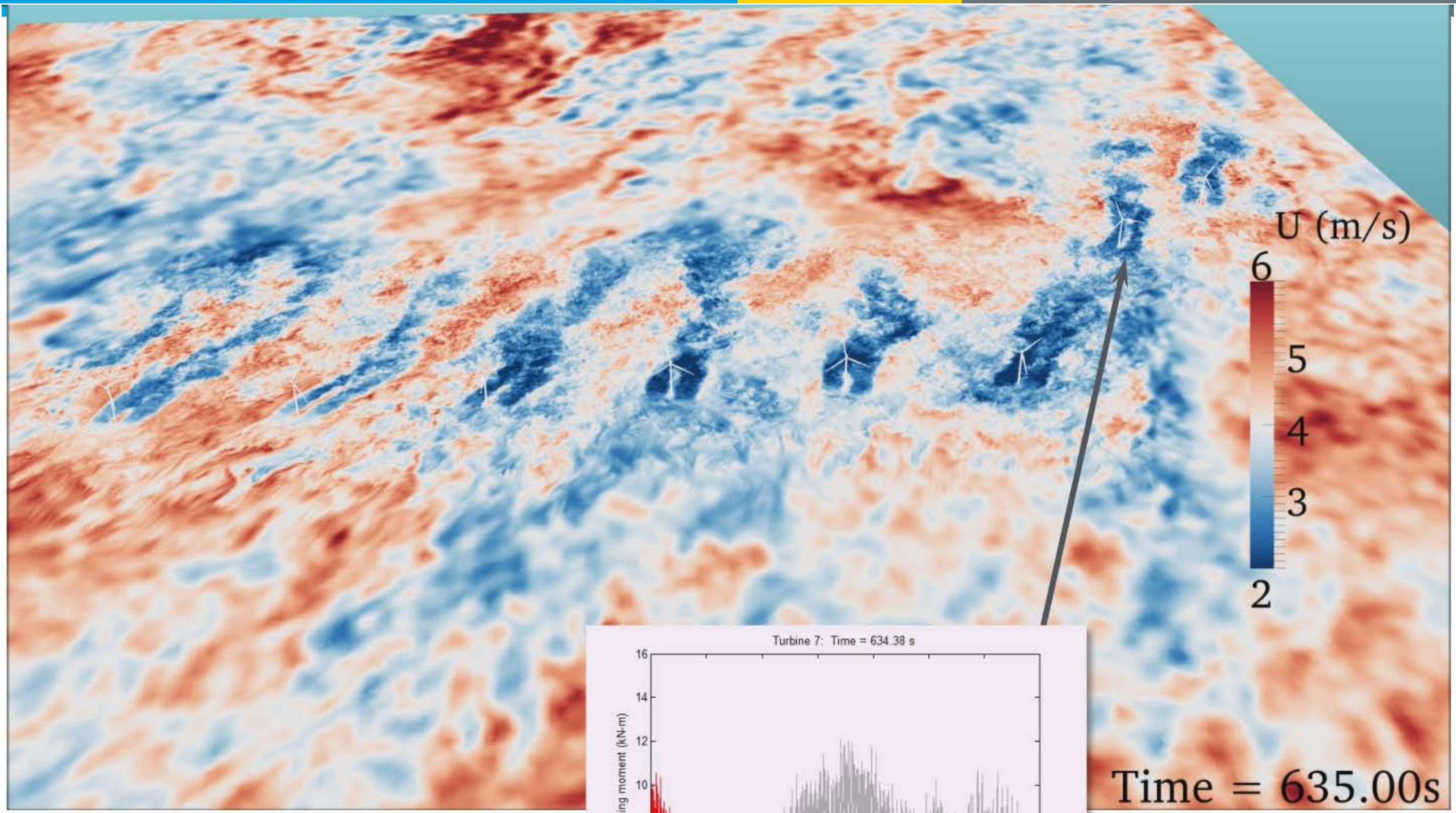
- Simulator fOr Wind Farm Applications (SOWFA)



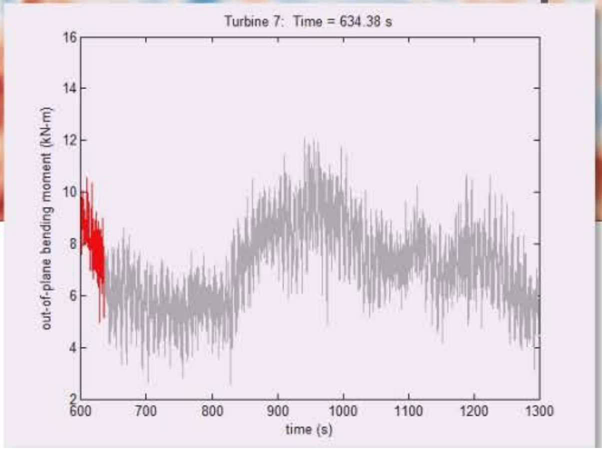
WRF ⟷ OpenFOAM ⟷ FAST

SOWFA

- High performance computing and engineering modules
- Wind farm parameterization model in WRF
- Outcome
  - Improve industry tools
  - Guide experimentalists and understand physics



Blade out-of plane bending



Accomplishments and Progress

- IEA Recommended Practices: Ground-Based Vertically-Profiling Remote Sensing for Wind Resource Assessment
- IEA Task 31: Wakebench
  - Wind flow benchmarks
  - Wake benchmarks
- IEA Task 32: Lidar
  - Calibration and classification of lidar devices
  - Procedures for site assessment
  - Procedures for turbine assessment
- EWEA and AWEA Wind Resource Assessment Exercises
- IEC 61400-15: Siting Standard
  - NWTC Kickoff, February, 2014

iea wind

EXPERT GROUP STUDY ON
RECOMMENDED PRACTICES

15. GROUND-BASED VERTICALLY-PROFILING REMOTE SENSING FOR WIND RESOURCE ASSESSMENT

FIRST EDITION, JANUARY 2013

Submitted to the Executive Committee
of the International Energy Agency Implementing Agreement
for
Co-operation in the Research, Development, and Deployment of
Wind Energy Systems

January 2013

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	2.7.0.2
Project Number	
Agreement Number	2.7

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Inflow Characterization Tasks												
Q1 Milestone: IEA Task 31 Kickoff Meeting												
Q2 Milestone: Public release of SOWFA simulation tool												
Q3 Milestone: Report from TWICS field campaign												
Q4 Milestone: Remote sensing overview and best practice document												
Q2 Milestone: Beta release of SOWFA with advance turbulence models												
Q3 Milestone: CWEX field campaign report												
Q3 Milestone: Publication on power curve variation												
Current work and future research												
AWEA Wind Flow Community Modeling Exercise												
IEA Wind Task 32 meeting for lidar application in wind energy												
Report summarizing SOWFA simluations to CWEX lidar observations												
Advanced methods for mesoscale-microscale coupling												

Comments

- All milestones completed on schedule

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- Subcontractor - University of Colorado, Julie Lundquist (NREL Joint Appt.)
- Collaborators - LLNL, PNNL, NOAA, NCAR, USDA, DTU Wind, CENER, Penn State University, Iowa State University, Indiana University, University of Delaware, WindLogics/NextEra, Iberdrola, GE, Siemens, Vestas
- Instrumentation developers and manufacturers
- IEA and IEC task participants – over 100 combined
- Wind Resource Assessment Exercises – 40+ each

Communications and Technology Transfer:

- 35+ conference and journal publications covering atmospheric science and turbine technology
- SOWFA software and WRF wind farm parameterization open source public release
- IEA Recommended Practices for Remote Sensing for Wind Energy Applications

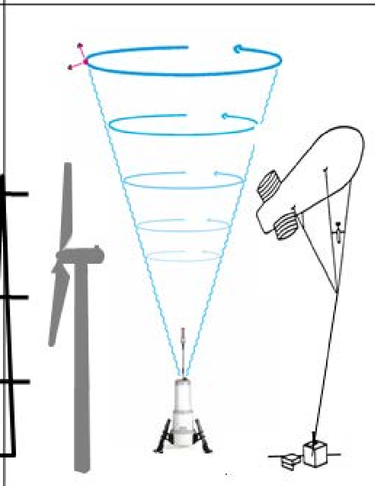
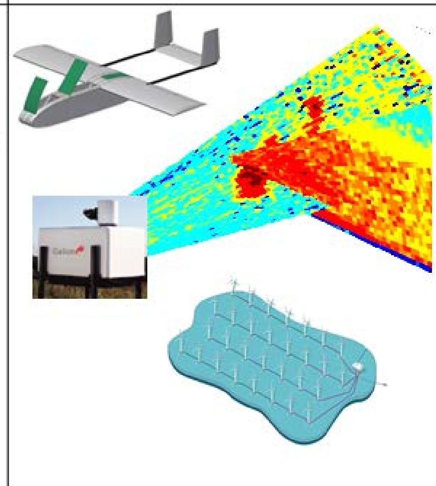
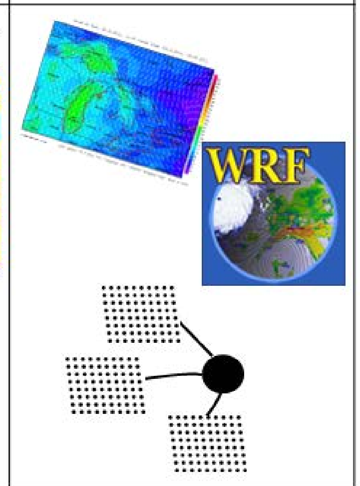
Next Steps and Future Research

FY14/Current research:

- Model validation
  - CWEX13 data analysis combined with model comparison amongst collaborators
  - IEA Task 31
- Mesoscale-microscale coupling
- Power curve variation
- Complex terrain
- Instrumentation development and analysis – IEA Task 32
- IEC standard development

Proposed future research:

- More detailed observations within full scale wind plants including turbine SCADA data and mesoscale inputs
- Interface grid models
- Uncertainty quantification for resource assessment
- Much of the work moving into A2e HFM and Experimental thrust areas

Space-scales	Local/ wind turbine 100's m	Regional/ wind farm 10's km	Mesoscale/ wind farm clusters 100's km
			
Time-scales	←Seconds-minutes	Minutes-hours	Hours-days→

DE-EE0005379

"3D Wind"
An integrated approach to offshore wind energy assessment: Great Lakes 3D Wind Experiment

R.J. Barthelmie
Indiana University
rbarthel@indiana.edu 812-856-5135
24 March 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.466M

Total Cost-Share[1]:$0.328M

Problem Statement: Improve quantification of offshore wind resources and operating conditions via optimal integration of in situ & remote sensing measurements and numerical modeling

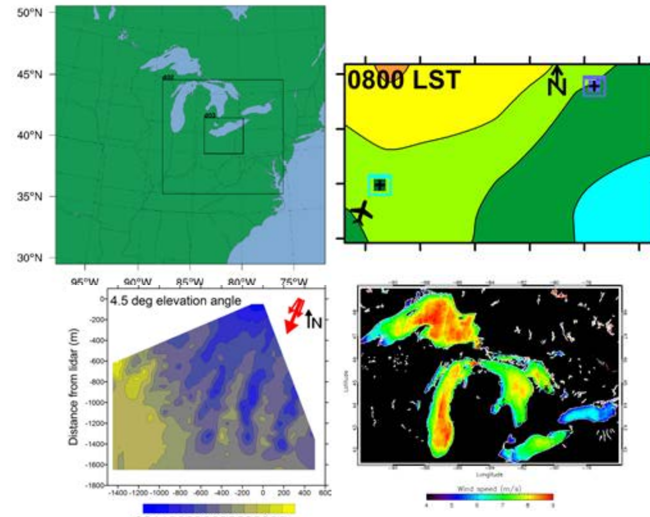
Impact of Project: (i) Optimal methods/best practice for individual measurement platforms & data integration.
(ii) Quantify drivers of offshore wind and turbulence profiles.
(iii) Reduce uncertainty in resource/operating conditions by optimizing data quality & integration, & unique model evaluation.

This project aligns with the following DOE Program objectives and priorities :

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

2012 Field Experiment Indiana	2013 Field Experiments Lake Erie + NREL	2014 Model simulations & data integration



- Objective: Improved accuracy/precision of U(x,y,z,t) & TI(x,y,z,t) for dx/dy: m's to km's, dz: m's to 1 km, dt: seconds to years
- Technical foci: Best practice for new ground-based remote sensing methods & UAV mounted sonic (+ cup/sonics on masts & tethersonde, & satellite winds), WRF & wake models. Key = data integration.
- Scientific foci: Process-level understanding of, and quantification of, 'non-ideal' vertical and horizontal flow fields (gradients, non-equilibrium).

Expanded:

- 3 successful field campaigns (data retrieval > 90%, instrument suite as planned Indiana, extended Lake Erie)
- Improvement in retrievals from vertically pointing and scanning lidar esp. types of scanning geometry, data quality, quantified uncertainty, new algorithms
- Feedback to/Interaction with developers on lidar operation & processing (→ new processing algorithms/software)
- Multiple WRF simulations for 2 experiments (testing optimal parameter settings for PBL & coastal zone)
- New Great Lakes Wind Atlas: Integration of satellite/buoy and in situ data
- Process-level understanding of wind and turbulence profiles e.g. swell & jet impacts
- Unique new data for use in quantifying wind turbine/wind farm wakes

Reduced:

- Deployment of 3D-sonic on UAV (less data obtained than planned, but lessons learned in design & operation)

Awards:

- European Wind Energy Poster Prize 2013
- Distinguished Faculty Research Lecture 2014

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary		Legend
WBS Number or Agreement Number		Work completed
Project Number	DE-EE0005379	Active Task
Agreement Number		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (OND)	Q2 (JFM)	Q3 (AMJ)	Q4 (JAS)	Q1 (OND)	Q2 (JFM)	Q3 (AMJ)	Q4 (JAS)	Q1 (OND)	Q2 (JFM)	Q3 (AMJ)	Q4 (JAS)
Project Name: 3D Wind												
T1.1 Field exp. Coordination. D1.1. Infrastructure report												
T1.2 M1.1 Field Experiment												
T1.3 D1.2 Field experiment report												
T3.1 Offshore experiment M3.1 Offshore experiment												
T3.2 Data coordination D3.1 Report												
T2.0/T4.0/T6.0 Management												
T2.1 /T4.1/T6.1 Project meetings												
T2.2/T2.3/T4.2/T4.3/T6.2/T6.3 Quarterly & annual reports												
T2.4/T2.5/T4.4/T4.5/T6.4/T6.5 Secure & public web site												
Current work and future research												
T5.0 Offshore experiment D5.1 Best practice report												
T5.1 Model simulations and data comparison D5.2 Model report												
NEW EXPERIMENT												

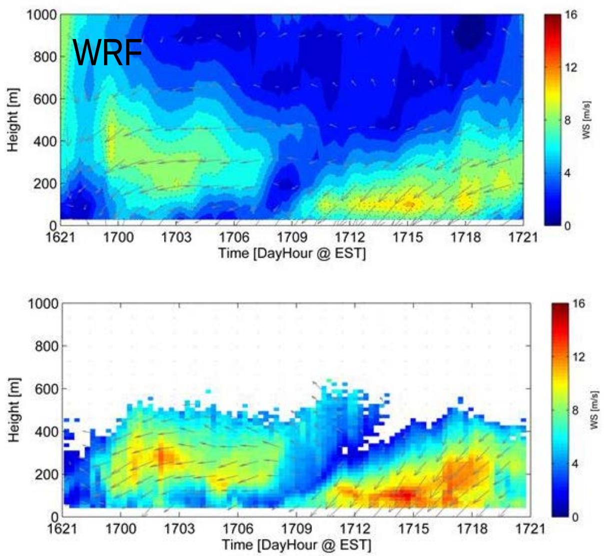
Comments

- Project start Sep 2011, original completion Sep 2014, request extension Sep 2015
- Project to schedule but prospects for new experiment within budget
- Go/no go

Current work

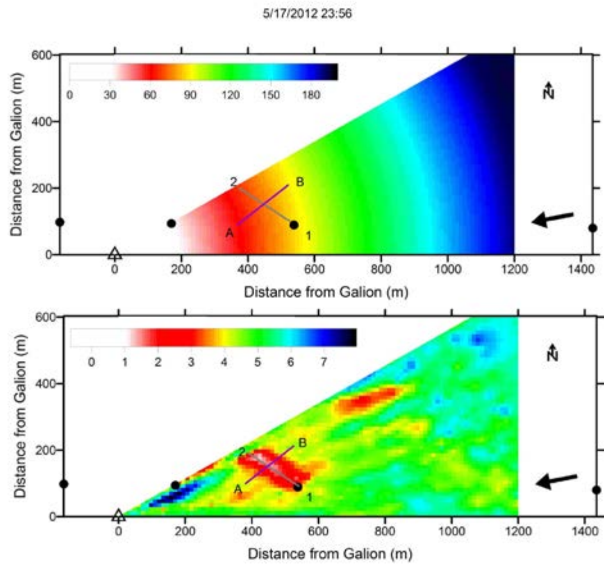
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Lake Erie coastal effects
Collab. IU/CWRU



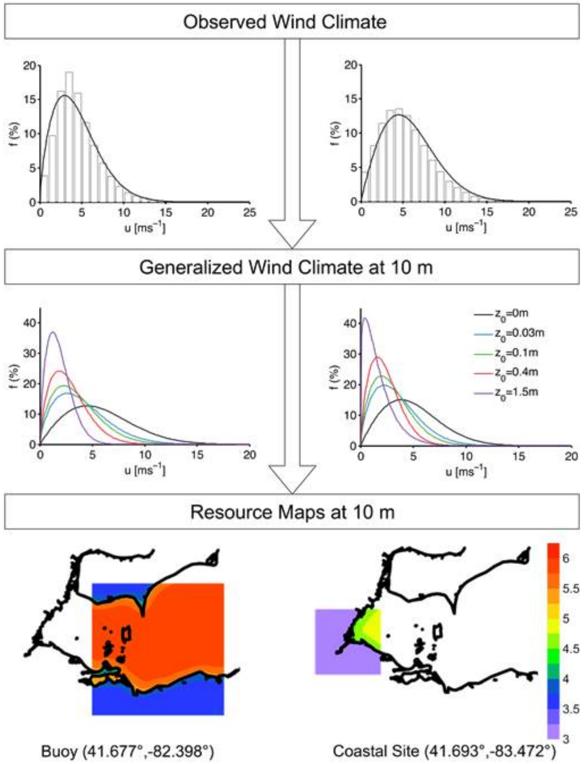
Wang et al. Science of Making Torque from Wind 2014

Lidar analyses
Collab. IU/DTU/Sgurr & NREL



Barthelmie et al. European Wind Energy Conf. 2014

Great Lakes Wind Atlas
Collab. IU/DTU



Doubrawa et al. European Wind Energy Conf. 2014

Research Integration & Collaboration

Partners: **Indiana U**, Case WRU, Clarkson U, Arizona SU
Subcontractors: DTU, SgurrEnergy, Natural Power
Collaborators: NREL

Communications and Technology Transfer:

Refereed journals: 5 Published + 1 in review
Barthelmie et al. (entire 3D wind team) (2014): *Bull. Am. Meteorol. Soc*.; Barthelmie & Pryor (2013): *Appl. Energy*; Barthelmie et al. (2013): *Proc. IEEE*; Smith et al. (2013): *Environ. Res. Lett.*; Wang et al. (2014): *Wind Energy*; Wang et al. (2014) *J. Atmos. Oceanic Technol. (in review)*
Conference papers, posters, presentations: > 30!
2014 Wang (1); Doubrawa (1); Barthelmie (1)
2013 Barthelmie (11); Pryor (1); Wang (2); Valyou (1); Ceruti (1); Grappasonni (1)
2012 Barthelmie (6); Smith (2); Pryor (1); Wang (1)
Example conferences: American Wind Energy Association Conference, American Wind Energy Association: Offshore, European Wind Energy Association Conference, North American Wind Energy Academy Conference, American Geophysical Union Fall Meeting, European Offshore Wind Energy Conference and Exhibition, The Science of Making Torque from Wind ….
Website(s): http://geology.indiana.edu/barthelmie/windFarm/index.html
http://clarksonuniversityuav.blogspot.com/
News stories: > 10 (listed on web site)
Reports: 14 submitted
Technology transfer: Improvements in lidar commercial software & autonomous power supply

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY2014/Current research:

(i) WRF simulations for Lake Erie. Higher resolution + triple nested inner domain (9, 3, 1 km). *Goal: Optimal physics for wind & turbulence profiles.*

(ii) Optimal strategies for data integration

(iii) Data analysis/model comparison for offshore structures and 'non-ideal' profiles (e.g. swell/jets)

(iv) Finalizing Great Lakes wind atlas

(iv) New experiment at Prince Edward Island (within original budget)

Proposed turbine placement for Wind R&D Park

Proposed future research:

(i) Additional experiments focused on "far" offshore

(ii) Additional long-term experiment on wind turbine & array wakes esp. in complex topography

(iii) Further modeling/additional experiments in the near-coastal zone

(iv) Wind energy research with WRF (Improve air-surface coupling/optimal implementation strategies)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Improving Atmospheric Models for Offshore Wind Resource Mapping and Prediction Using LIDAR, Aircraft, and In-Ocean Observations

Dr. Brian A. Colle

Stony Brook University

brian.colle@stonybrook.edu; 631-632-3174

24 March 2014

Budget, Purpose & Objectives

Total DOE Budget[1]: $0.441M

Total Cost-Share[1]:$0.176M

Problem Statement:

- Model Planetary Boundary Layer (PBL) needs more validation and improvement over the coastal ocean.
- Current offshore wind maps were constructed using limited observations at turbine hub height.
- Need to address the uncertainty in offshore winds using ensemble modeling approaches.

Impact of Project: Provide a comprehensive PBL verification over southern New England coastal waters as well as some possible improvements to the PBL parameterizations.

This project aligns with the following DOE Program objectives and

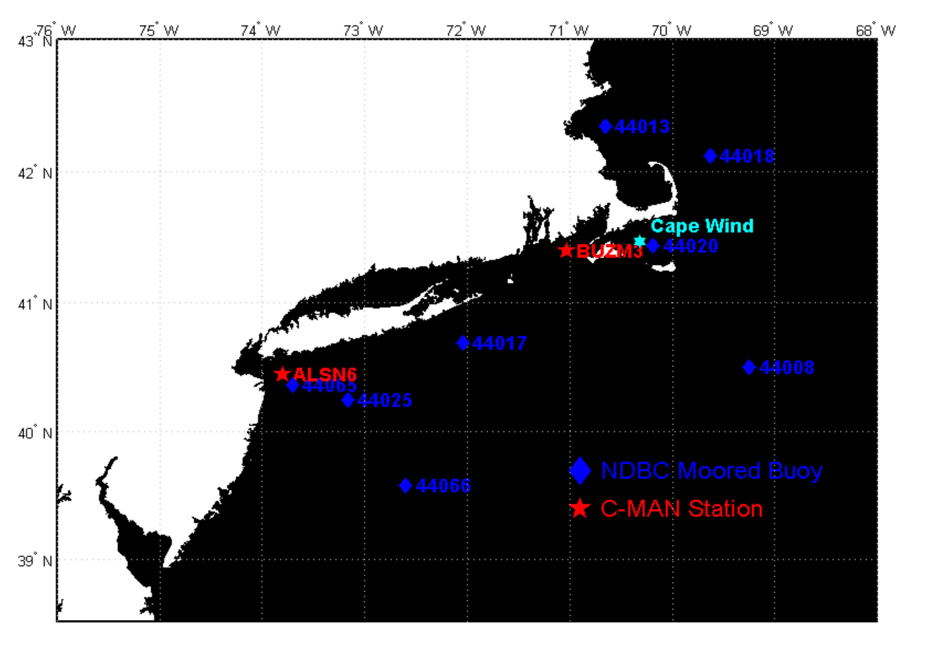
Accelerate Technology Transfer: Lead the way for new high-tech U.S. industries

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

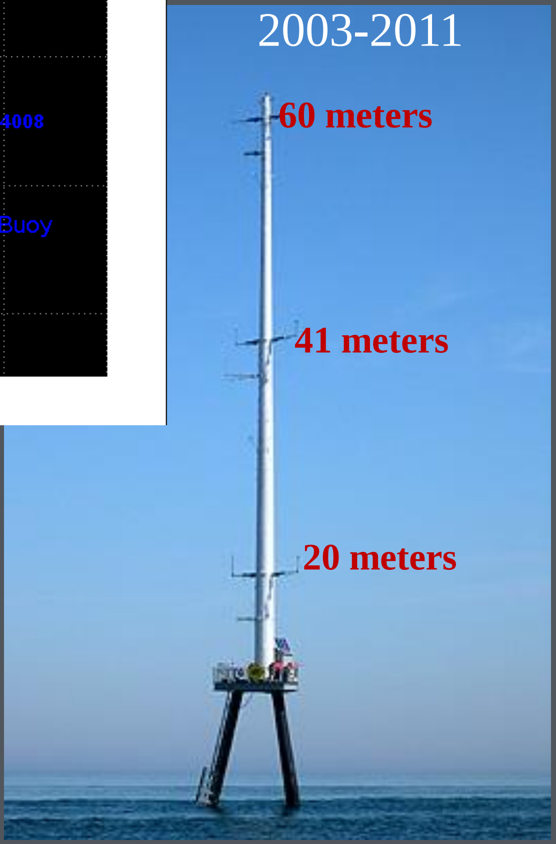
Long-Term Verification Study (2003-2011): Observations for Tasks 2, 4, and 5)



5 meters

NDBC Moored Buoys and C-MAN Stations

Cape Wind Meteorological Mast 2003-2011



60 meters

41 meters

20 meters

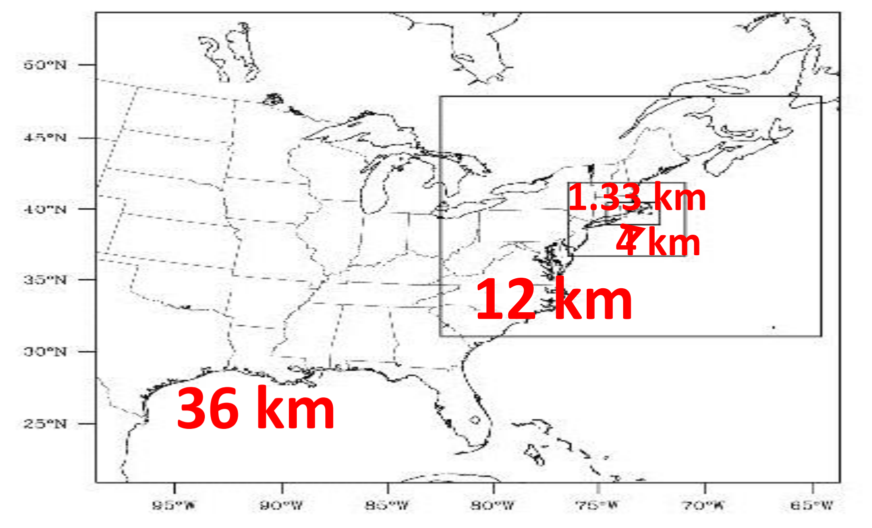
NOAA Buzzard's Bay Tower – 25 m

Technical Approach

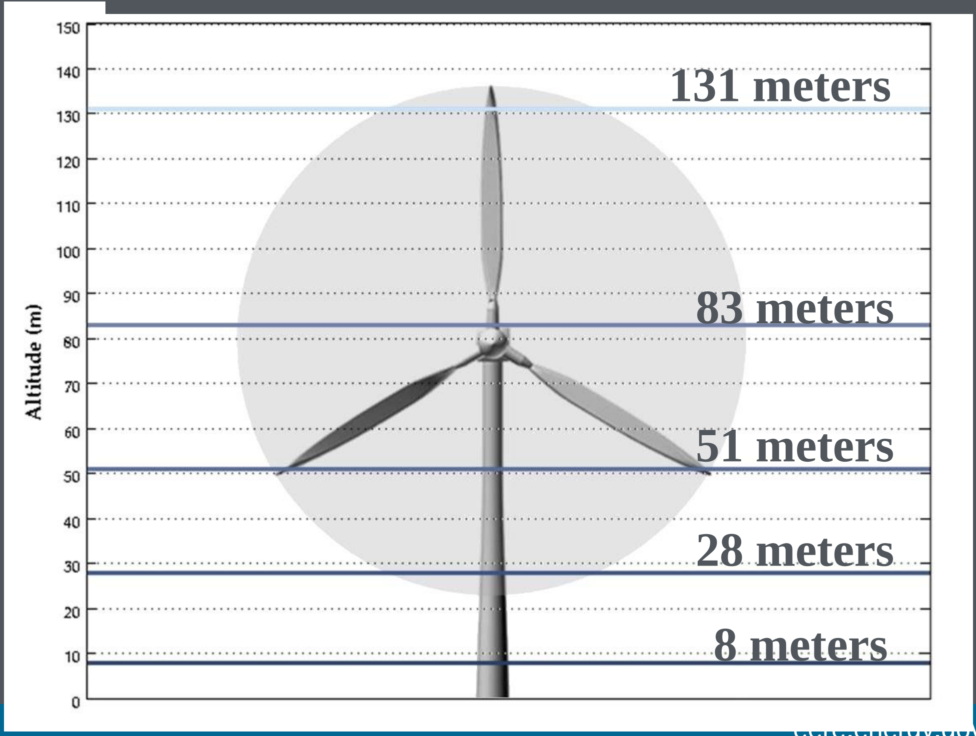
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Task 2: Weather Research and Forecasting (WRF) Model Runs for 2003-2011 (no 1.33 km domain)

- WRF-ARW (version 3.4.1)
- 30-h forecasts 6 PBL schemes
  - Two First-order (YSU, ACM2)
  - Four TKE-order (MYJ, MYNN2.5, BouLac, QNSE)
- North American Regional Reanalysis (NARR) initial and boundary conditions; 0.5° (SST)
- 38 vertical levels
- 110 random runs 2003-2011

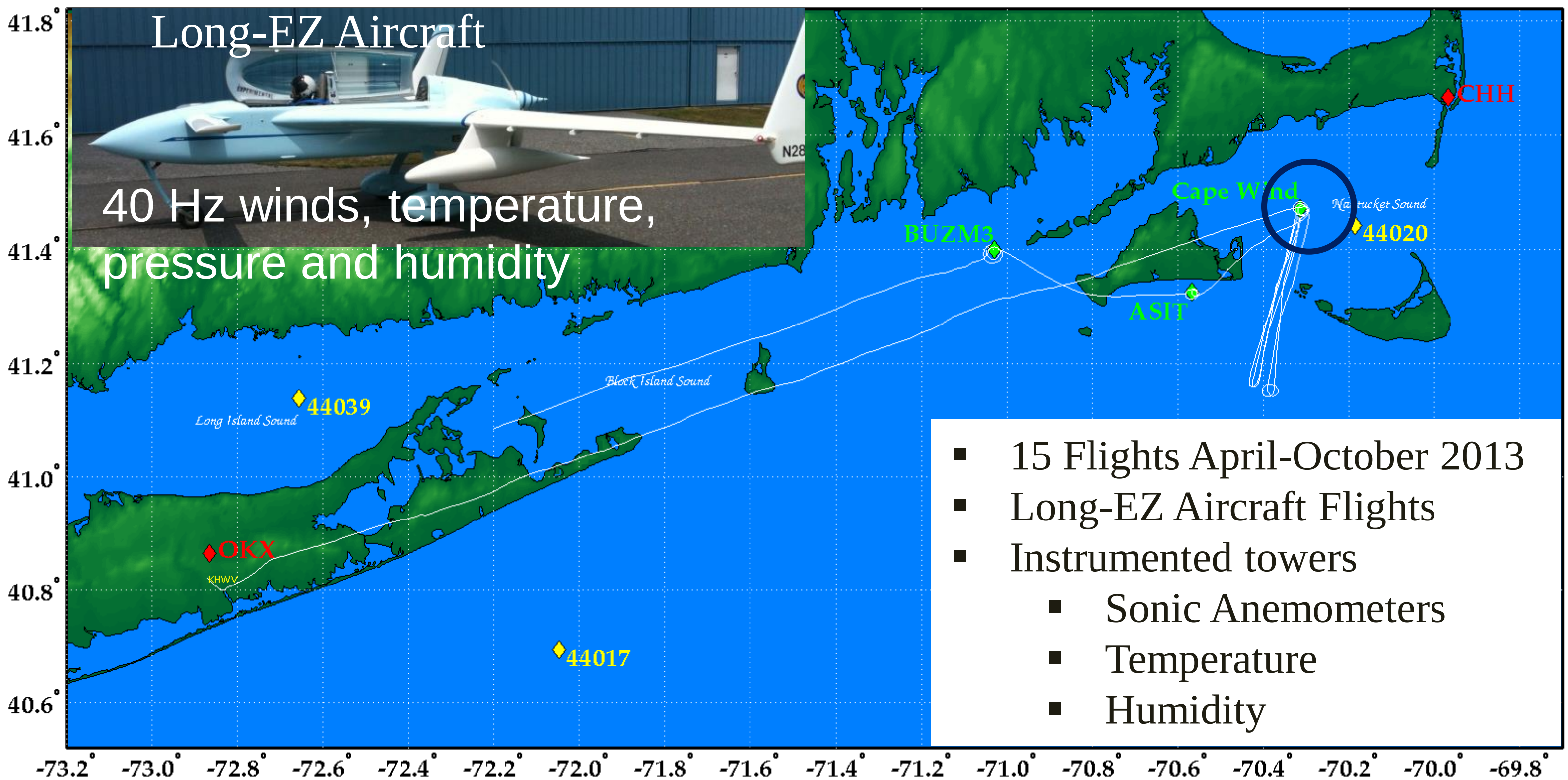


LOWEST MODEL LEVELS RELATIVE TO OFFSHORE WIND TURBINE



IMPOWR Field Campaign (completed 2013: Task 1.2)

Improving the Mapping and Prediction of Offshore Wind Resources

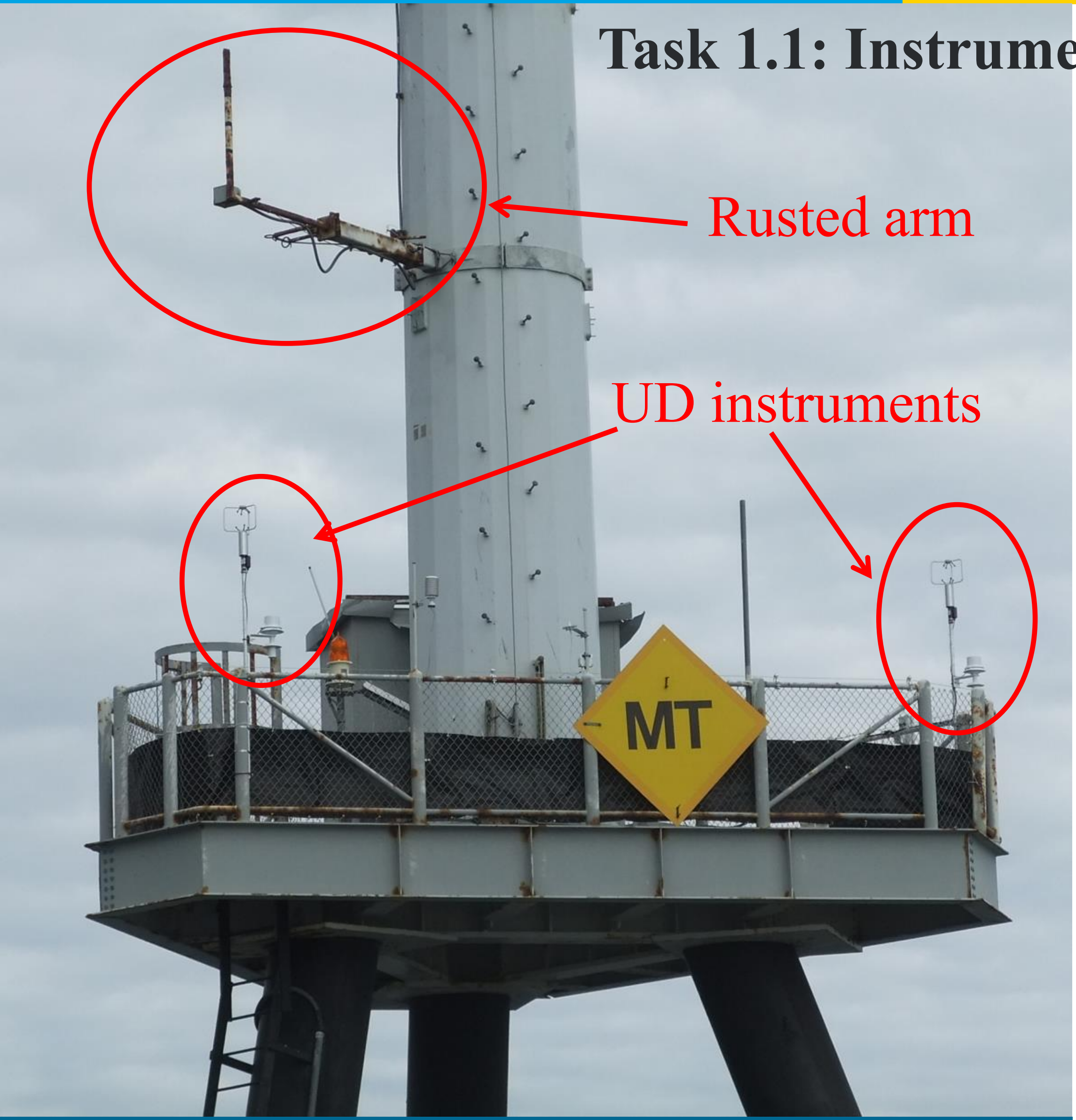


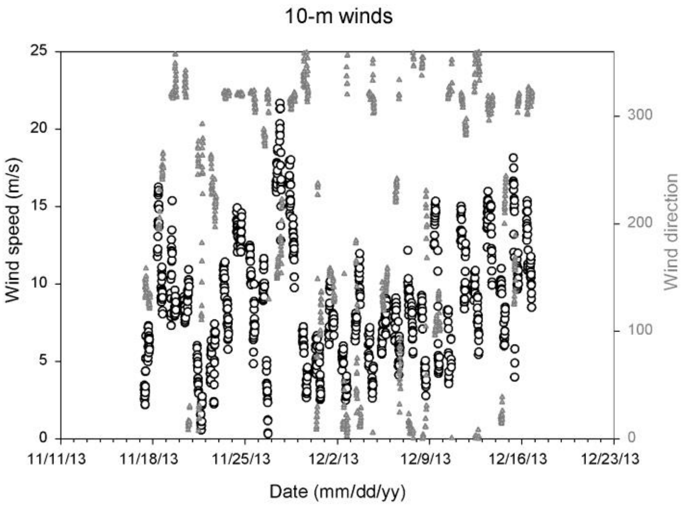
- 15 Flights April-October 2013
- Long-EZ Aircraft Flights
- Instrumented towers
  - Sonic Anemometers
  - Temperature
  - Humidity

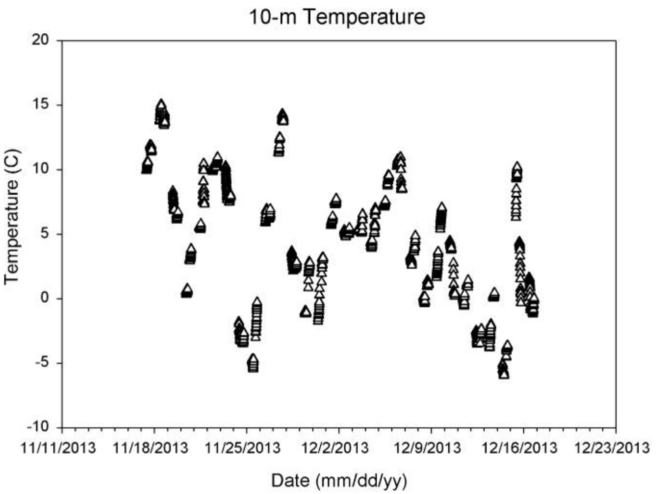
http://dendrite.somas.stonybrook.edu/IMPOWR/impowr.html

Task 1.1: Instrument Cape Wind (completed)

http://capewind.whgrp.com



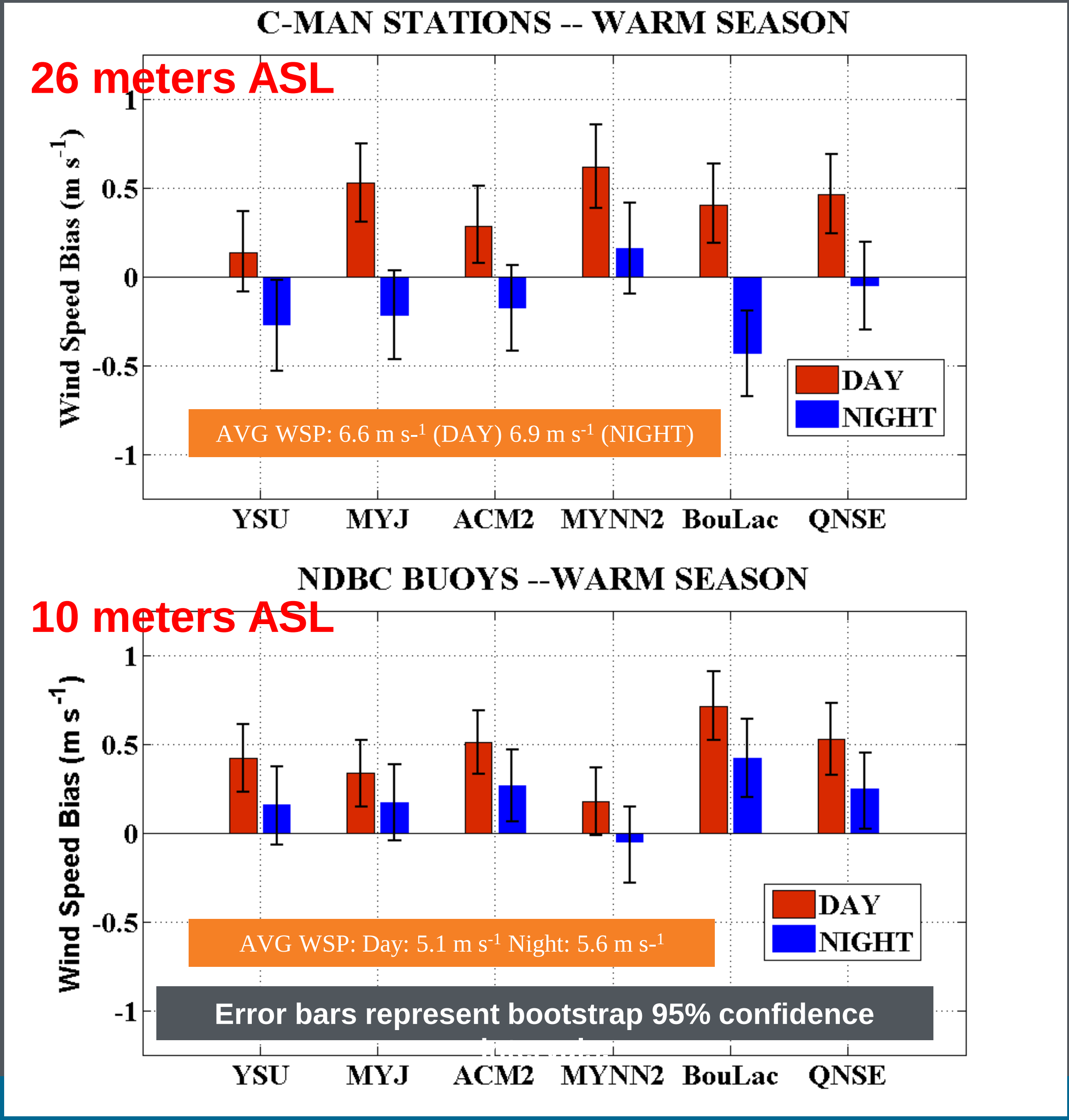




Task 4: Validate Stony Brook PBL ensemble NDBC Station Verification

Wind Speed Biases (Warm Season 2003-2011)

- Positive wind speed biases during the day
- Smaller biases during night at buoys, negative at C-MAN Stations
- Similar MAEs for all schemes/stations/times (1.5-2 m s^{-1})

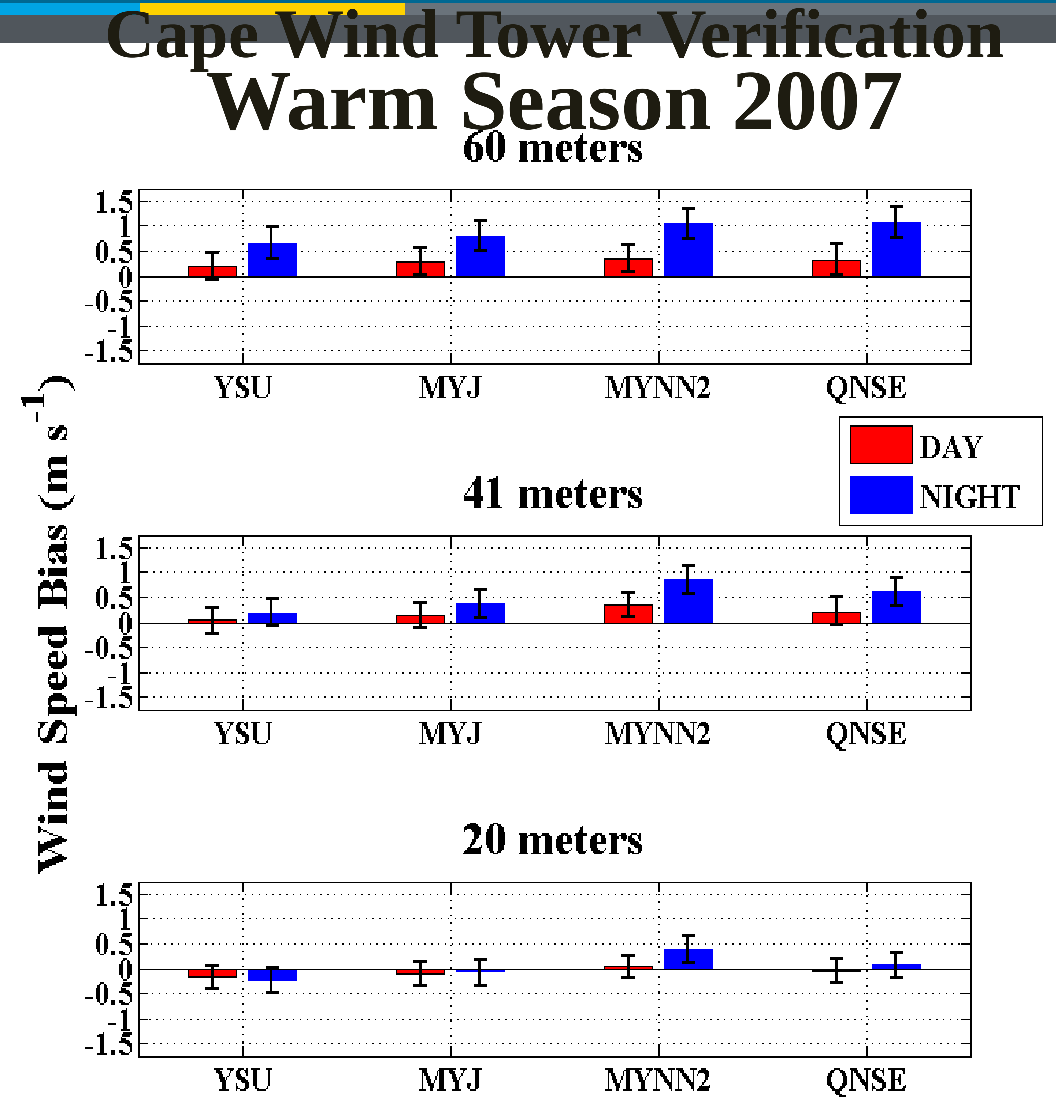


Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Unique: First long-term glimpse of model performance above buoy height (Tasks
- Only CW data from 2007 has been QC'd so far
- 26 Dates from 2007 warm season (May-July) for WRF PBL schemes

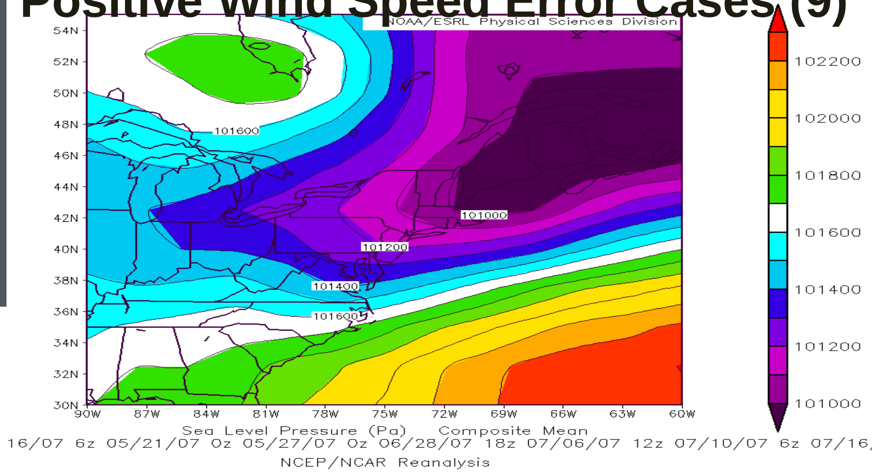
- Too much mixing of higher momentum from aloft to 60 m or too little weaker momentum mixing from below

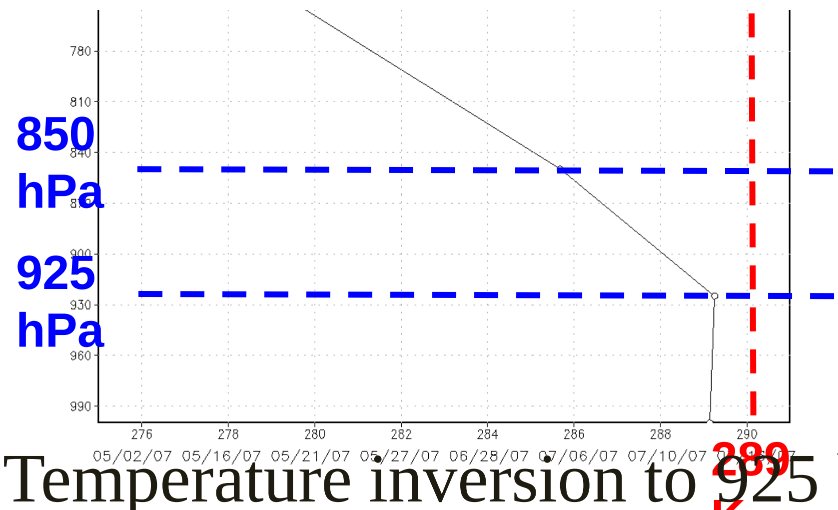


Error bars represent bootstrap 95% confidence intervals.

Positive windspeed errors at 40-60 m are flow dependent Helps understand PBL Errors and Ensenble Calibration (Task 5)

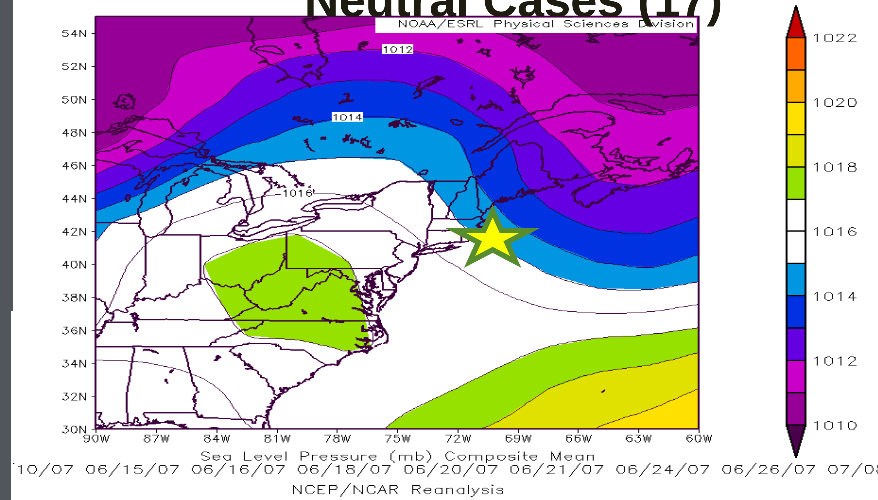
Positive Wind Speed Error Cases (9)

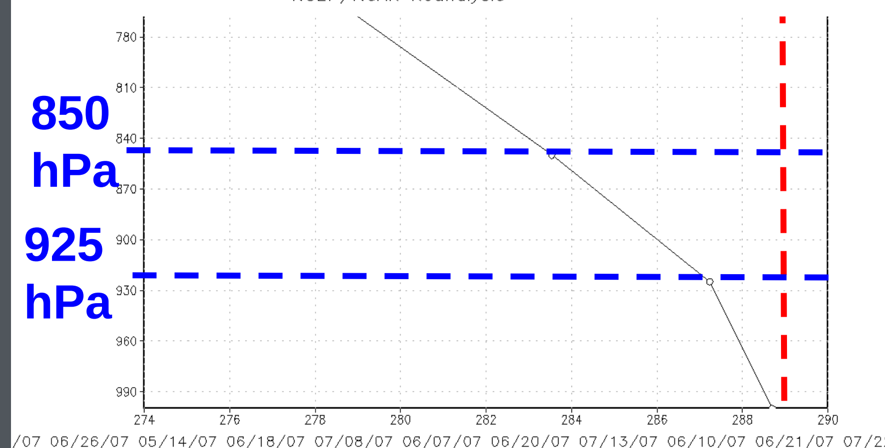




Temperature inversion to 925 hPa

Neutral Cases (17)



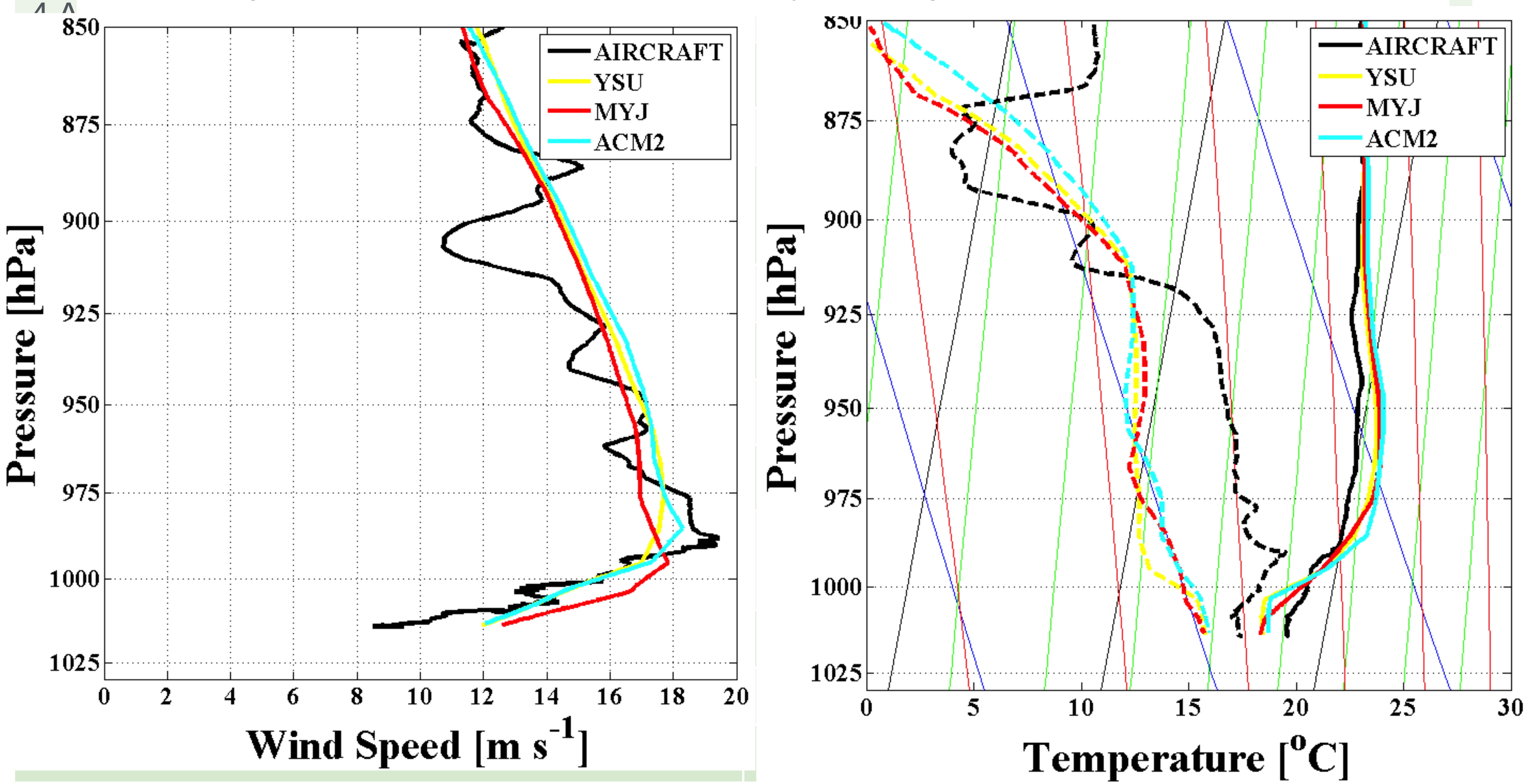


Less stable layer to 925 hPa

15 Flights Completed (Task 1.2) | Weather Conditions

12

Field Study Analysis is under way to better understand processes within the PBL (23 June 2013 summer diurnal jet case)



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	
Project Number: DE-EE0005377	
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q2 Milestone: Archived Data Collection and Instrument Cape Wind Tower (Task 1.1)												
Q3 Milestone: Aircraft calibration and MPOWR Field Campaign (Task 1.2)												
Q2 Milestone: Construct and run 6-member PBL Ensemble (Task 2)												
Q1 Milestone: Validation of Stony Brook Ensemble (buoy and tower analysis, Task 4)												
Current work and future research												
Calibration of ensemble (Task 5)												

Comments

- Start 9/30/2011; Project completion date: 6/30/2015 (might need to be extended another 6 months)
- Start of Year 1 tasks were delayed 6-9 months because of a negotiated Usage Agreement for Cape Wind. Had to wait to following spring (2013) to take field measurements.

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners: University of Delaware (Dr. Cristina Archer, Dr. Dana Veron, Dr. Fabrice Veron, Dr. Willet Kempton)- led efforts for Cape Wind Install, QC Cape Wind data, and Wave modeling).
Subcontractors: Ultra-Pure LLC – aircraft flights; UDel (CW install/data and wave modeling)
Collaborators: Cape Wind LLC (tower), UConn (ASIT tower data), Deepwater and AWS Truewind (2 LIDARs for 2014)

Communications and Technology Transfer: Results presented at AWEA meeting (Oct 2012), UDelaware Symposium on Wind Energy in March 2013 (UDel and SBU led paper in press in Bull Amer Met Soc. about workshop recommendations); SBU grad student presented his WRF PBL verification results at AMS NWP conference (Feb 2014); IMPOWR website:

http://dendrite.somas.stonybrook.edu/IMPOWR/impowr.html

Accomplishments and Progress

Most important technical accomplishments (2012-2013):

* Obtained the first comprehensive field dataset (IMPOWR field study) at hub height to evaluate and improve models along the southern New England coast.

* Used this field dataset (and other convectional data) to quantify model wind and temperature biases within the PBL.

* Illustrated how a federally funded project can collaborate and expand on private sector networks (CW tower, LIDARs, etc…) to help solve a very important problem shared by all parties (improving models over the coastal waters).

Next Steps and Future Research

FY14/Current research:

- Will continue to validate WRF PBL for IMPOWR cases (another 10 flights will be completed in FY14).
- Impacts of waves will be quantified.
- Impact of calibrated ensemble on wind maps will be determined.

Barriers: Obtaining a usable QC'd dataset for all years from CapeWind (still iterating). Power issues on CW tower.

Goals/Milestones: Formal paper on WRF verification.

Proposed future research: Future research: (1) Expand field efforts to include other groups and other resources (floating LIDARs, tall tower, drone planes, …) to get a more additional high resolution data of the PBL around hub height. (2) Use these datasets to collaborate with others to improve the model PBL parameterizations.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Measurement and Analysis of Extreme Wave and Ice Actions in the Great Lakes for Offshore Wind Platform Design

Tony England

University of Michigan

england@umich.edu; (313) 593-5290

24 March 2014

Budget,Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $.459M

Total Cost-Share[1]:$0.152M

Problem Statement: The least understood forces to be experienced by offshore wind platforms in the Great Lakes are those caused by extreme waves and lake ice

Impact of Project: We are measuring extreme wave and ice forces in the Great Lakes and compiling a history of such actions to reduce risk in the design of offshore platforms

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Goal 1 – Measure extreme wave and lake ice actions at an offshore site in the Great Lakes

- Task 1 => Great Lakes Observing Site (GLOS)
  - ➢ Lower Entry Light to Keweenaw Waterway
    - ✓ NE exposure to Lake Superior storms
    - ✓ Significant likelihood of seasonal ice
    - ✓ Reliable cell phone coverage
    - ✓ Convenient access for colleagues at Michigan Tech
  - ➢ Access granted by:
    - ✓ U.S. Coast Guard
    - ✓ State Historical Preservation Office
  - ➢ Demands of GLOS
    - ✓ pv/battery power & autonomous operation
    - ✓ Access only in good weather

Technical Approach

Goal 1 – Measure extreme wave and lake ice actions at an offshore site in the Great Lakes

- Task 2. Develop & deploy a Wave & Ice Sensor Network (WISN) comprised of:
  - Ice Force Measuring System (IFMS) => unique design for this project
  - Wideband Autocorrelation Radiometer (WiBAR) => unique design for this project
  - Acoustic Doppler Current Profiler (ADCP) => commercial instrument
  - Scene Capture System (SCS) => commercial security system
  - Instrument Support System (ISS) => unique design for this project
  - Solar Power System (SPS) => commercial unit

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

An Especially Noteworthy WISN Instrument

Ice Force Measuring System (IFMS)

- A half-ton load cell designed, fabricated, tested, and deployed for this project
- Prof. Dale Karr is lead on this instrument

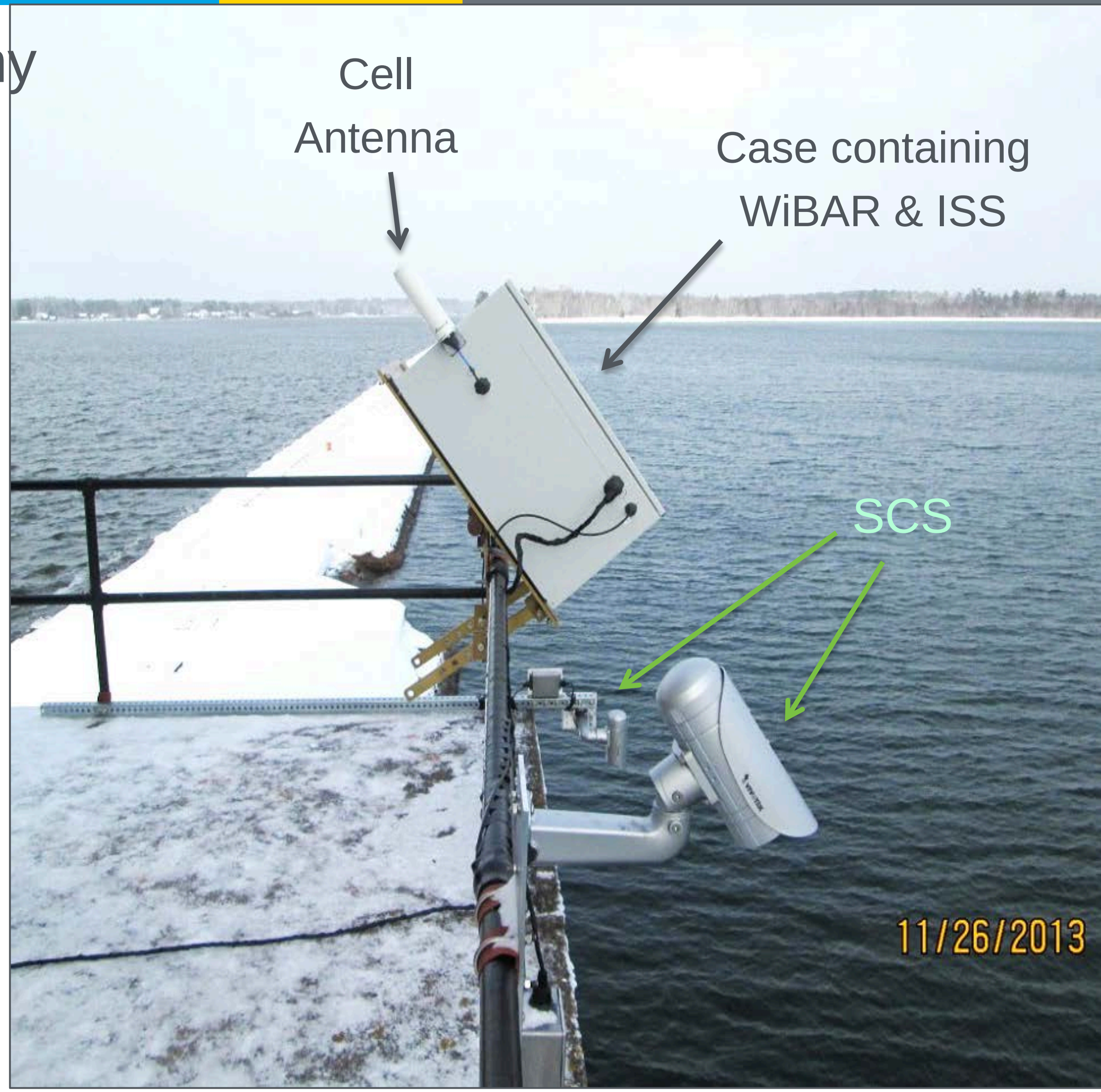
Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

An Especially Noteworthy WISN Instrument

Wideband Autocorrelation Radiometer (WiBAR)

- The first example of an instrument concept invented by the PI
- WiBAR is a passive microwave sensor that provides deterministic measures of freshwater ice and snowpack thickness
- Prof. Tony England is lead on WiBAR



Goal 2 – Compile a spatial and temporal history of extreme wave and ice actions on the Great Lakes => Work on this goal has been deferred to the last year of the project

Ice Cover on Lake Superior, Winter 2013-2014

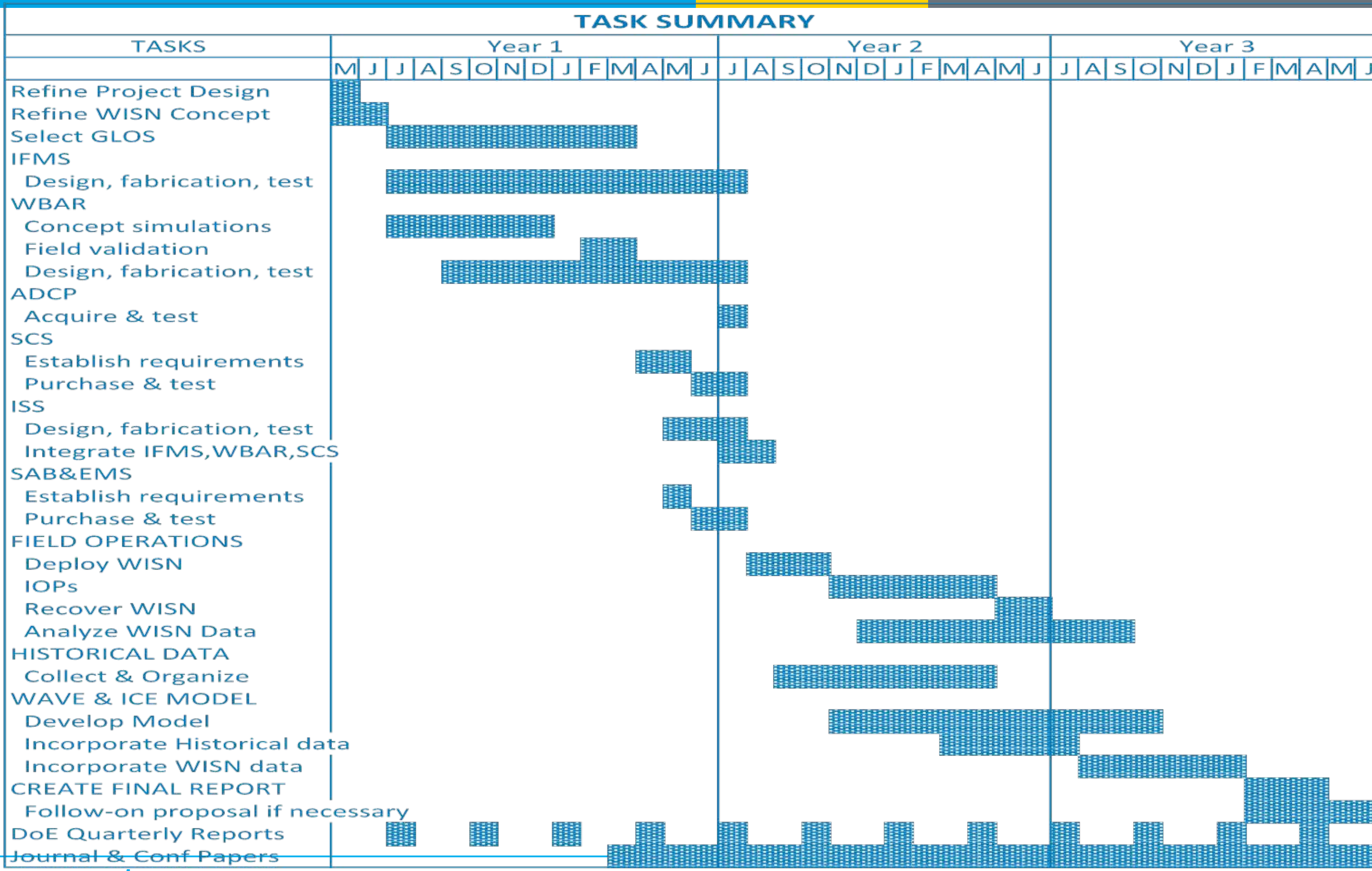
Accomplishmentsand Progress

Accomplishments:

- A Great Lakes Observing Site (GLOS) has been established
- Our Wave & Ice Sensor Network (WISN) has been designed, fabricated, tested, and deployed
- We are receiving data from WISN through our cell phone link
- The system is poised to record ice breakup on Lake Superior following a record year of ice formation
- We have published one journal paper, submitted another journal paper, and published two conference papers on the concept, lab & field proof-of-concept, and implementation of WiBAR

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Comments

- Project duration is May 2012 through June 2015
- Historical Data and Wave & Ice Modeling will slip to year 3

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Subcontractor: The Great Lakes Research Institute at Michigan Technological University has been an essential contributor to this Project. They manage the GLOS field site, and Prof. Guy Meadows, Director of the Institute, serves as lead on the ADCP. Members of the Institute visited the GLOS several times in challenging weather to make critical adjustments to WISN.

Communications and Technology Transfer: Talks: NOAA Climate Change Workshop, Muskegon, MI, Aug 27-29, 2012; and 70th Annual Eastern Snow Conf., Ontario, CA, June 4-6, 2013. Publications:

England, A.W.; Wideband autocorrelation radiometric sensing of microwave travel time in snowpacks and planetary ice layers, IEEE Trans. Geosci. Remote Sensing, 51, pp. 2316 - 2326, 2013.

Nejati, H., S.Y.E. Wong, R.D. DeRoo, L. van Nieuwstadt, K. Sarabandi, G.A. Meadows, and A.W. England; Design, Modeling, and Implementation of Wideband Autocorrelation Radiometry for Snowpack/Lake Ice Thickness Detection, Submitted to IEEE Trans. Geosci. Remote Sensing, May 2013.

Nejati, H., S.Y.E. Wong, R. DeRoo, L. van Nieuwstadt, and A.W. England; Design, Optimal Operation, and In-situ Verification of Wideband Autocorrelation Radiometer (WiBAR), MicroRad Conference, March 24-27, 2014, Pasadena, CA; to be archived in J. Selected Topics in Applied Earth Observations and Rem. Sens. (JSTARS).

Negati, H., R.D. DeRoo, L. Van Nieuwstadt, K. Sarabandi, and A.W. England; Design and modeling of a Wideband Autocorrelation Radiometer (WiBAR) as Snowpack Thickness Sensor, Submitted to IGARSS’14, Quebec City, Canada, July 13-18, 2014.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research: Assuming continued success of our field experiment, the final year of the project will be devoted to data analysis, integrating that data in lake ice models, compiling temporal and spatial records of extreme wave and ice actions in the Great Lakes, and reporting our findings to the DOE and in the literature.

Proposed future research: We would like to validate our ice force models either during an additional season at the current GLOS, or at another site that might be of particular interest to DOE.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Improved wind modeling through studying the underlying surface-atmospheric physics of rotor-disk flow

Role of Energy Fluxes for WRF Wind Modeling

Sonia Wharton

Lawrence Livermore National Laboratory

wharton4@llnl.gov; 925-422-9295

March 24, 2014

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344. LLNL-PRES-650569

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $.150M

Total Cost-Share[1]:$0.000M

Problem Statement:

- Prior work has shown that wind power is dependent on wind shear and turbulence (Wharton & Lundquist 2012).
- Surface energy exchange largely drives daytime mixing in the lower PBL which in turn influences the shear and turbulence characteristics of rotor-disk flow.
- Are these surface-atmosphere processes accurately represented in WRF?
- How important is the accuracy of these processes in the land surface model (LSM) within WRF for modeling flow related to wind power?

Impact of Project:

- Recommendations to the wind industry on the importance of choice of the land surface model (LSM) for a rapidly expanding U.S. wind power region (northern Oklahoma).
- Increased insight into the underlying surface physics which control rotor-disk wind shear *could lead to improved wind forecasting.*

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)

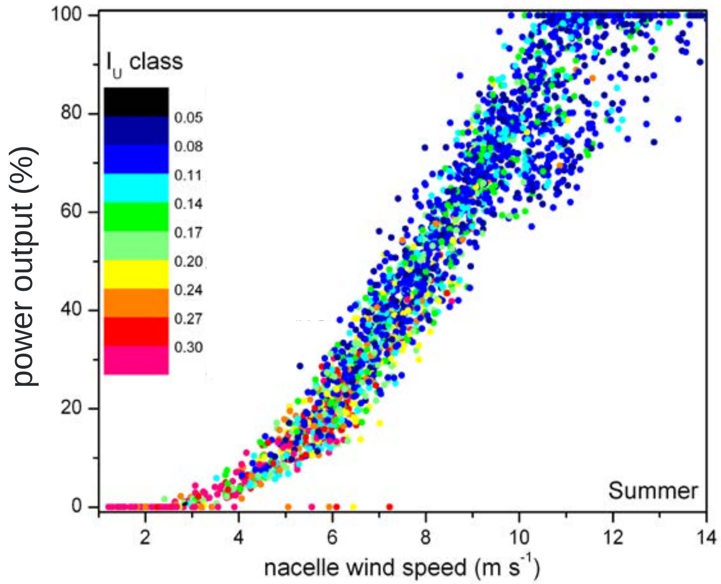
[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

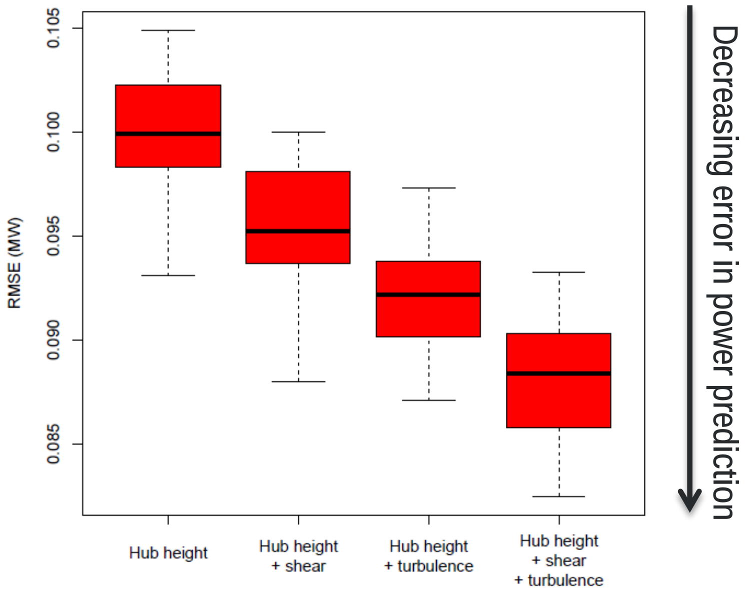
surface energy exchange → atmospheric mixing → rotor-disk shear and turbulence → power

Power is a function of atmospheric stability: EERE Tall Turbine Project (FY2009-2011)



Wharton & Lundquist (2012)

Including shear and turbulence in statistical models decreases error in predicted power: LLNL Funded Project



Courtesy of Vera Bulaevskaya, LLNL

Includes: Gaussian Process Model, Altamont Pass Wind Farm Lidar and SCADA data.

Technical Approach

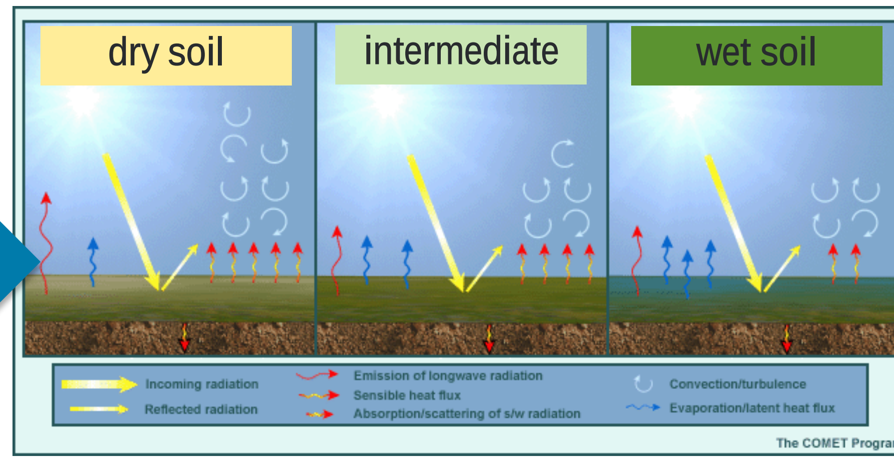
Motivation: Greater understanding of the atmospheric physics governing wind speed, shear and turbulence should lead to better forecasting of rotor inflow and power production.

Science Question: To what extent are wind conditions at turbine height affected by the LSM?

Approach: Measure and analyze Wind Cube Lidar wind profile data for 8 months in 2012-2013. Utilize concurrent flux measurements. Archived flux and Halo Lidar were used for 2011. Run WRF with multiple LSMs for case studies.

Surface flux tower (LBNL) and Lidar (LLNL) at SGP ARM. Surface energy flux exchange in part determines daytime turbine shear and turbulence inflow as measured by the Lidar.

Data gives us information about the underlying physics of shear profiles

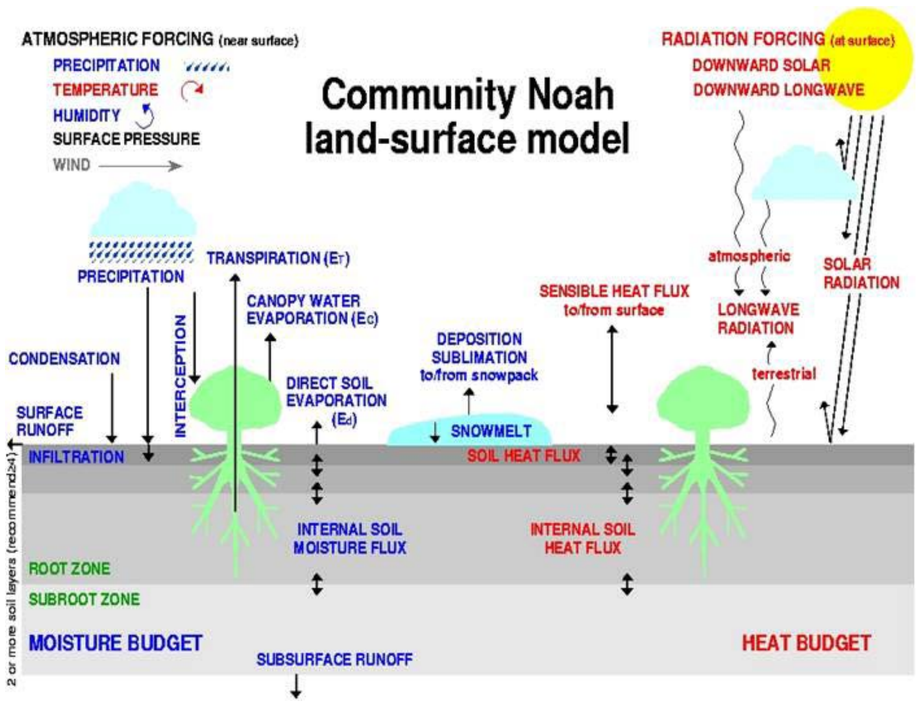


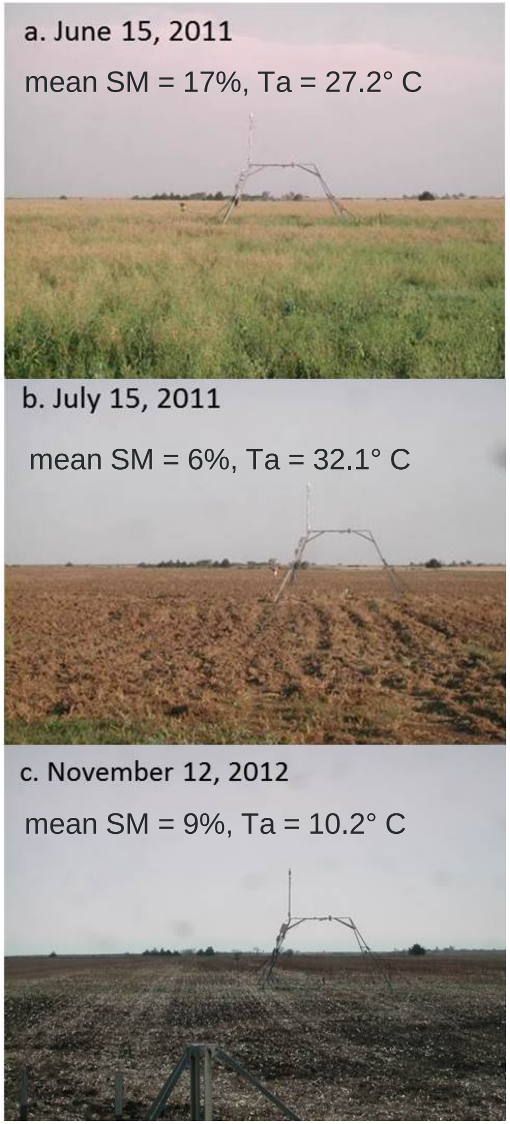
Higher H, lower LE
More mixing
Lower shear

Less H, higher LE
Less mixing
Greater shear

WRF was run with 8 LSM configurations during 3, 2-week periods of different canopy cover, soil moisture, temperature, and radiation conditions.

➢ Land surface fluxes provide a lower boundary condition for the PBL scheme: influences vertical transport, rotor disk flow.





Case 1: high available energy, warm temps (Ta), moderate soil moisture (SM), active crop

Case 2: high available energy, hot temps, very low soil moisture, no crop

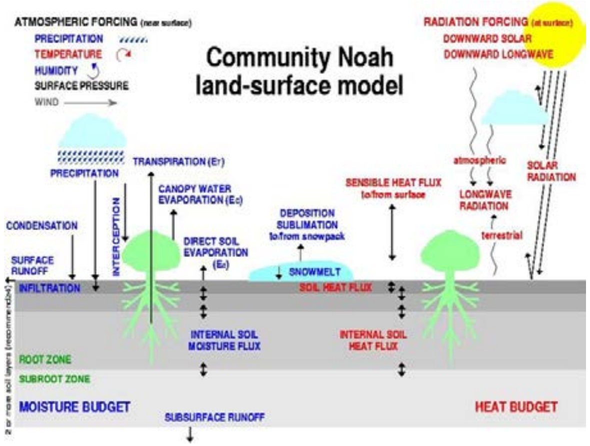
Case 3: low available energy, cool temps, low soil moisture, no crop

Technical Approach

LSMs differ in their sophistication in dealing with:

1. Soil thermal and moisture fluxes
2. Vegetation, root and canopy effects

➢ These should lead to differences in the partitioning of surface energy fluxes



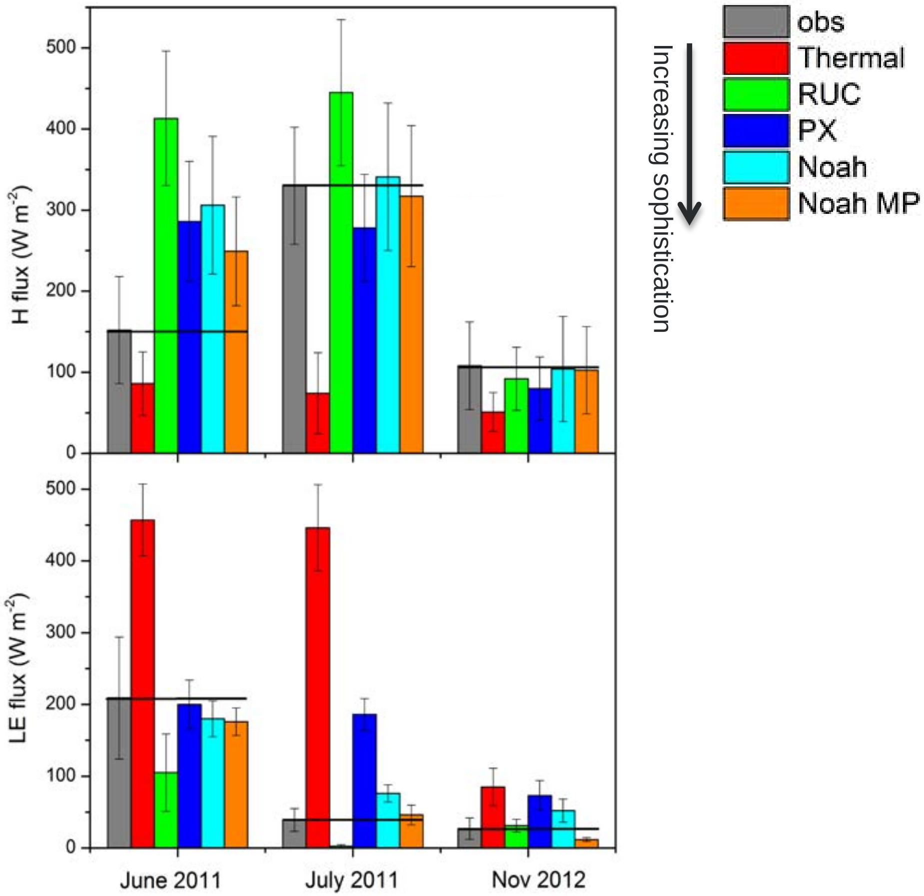
WRF land surface model (LSM) ensemble members in order from least to most sophisticated. All use MYJ PBL and M-O surface layer scheme.

Member	Name	Vegetation	Drivers of soil moisture	Soil Layers	Drivers of water flux exchange
1	Thermal	None	LUC	5	Soil surface
2	RUC	Extension of soil	LUC + evap	6 or 9 layers, 3m max	Air temperature, relative humidity
3	Pleim-Xiu	1-layer from LUC	LUC + evap + roots	2 layers, 1m max	Soil surface + plant transpiration
4	Noah	1-layer from LUC	LUC + evap + roots + drainage	4 layers, 2m max	Soil surface + plant transpiration
5-8	Noah-MP	2-layer from multiple LUC	LUC + evap + roots + drainage + runoff + storage *	Variable layers, 8m max	Complex soil-plant feedbacks *

LUC = land use category
* variable options

Accomplishments and Progress

- Found significant differences in the modeled energy fluxes – the least sophisticated LSMs tended to be less accurate.
  - Thermal underestimated the buoyant H flux
  - RUC tended to overestimate H
- Model performance varied by surface condition.
  - H was the most problematic during the wet, growing crop June case
  - LE was the most problematic during the dry, no crop July case
  - The "control case" November had the smallest errors in both H and LE

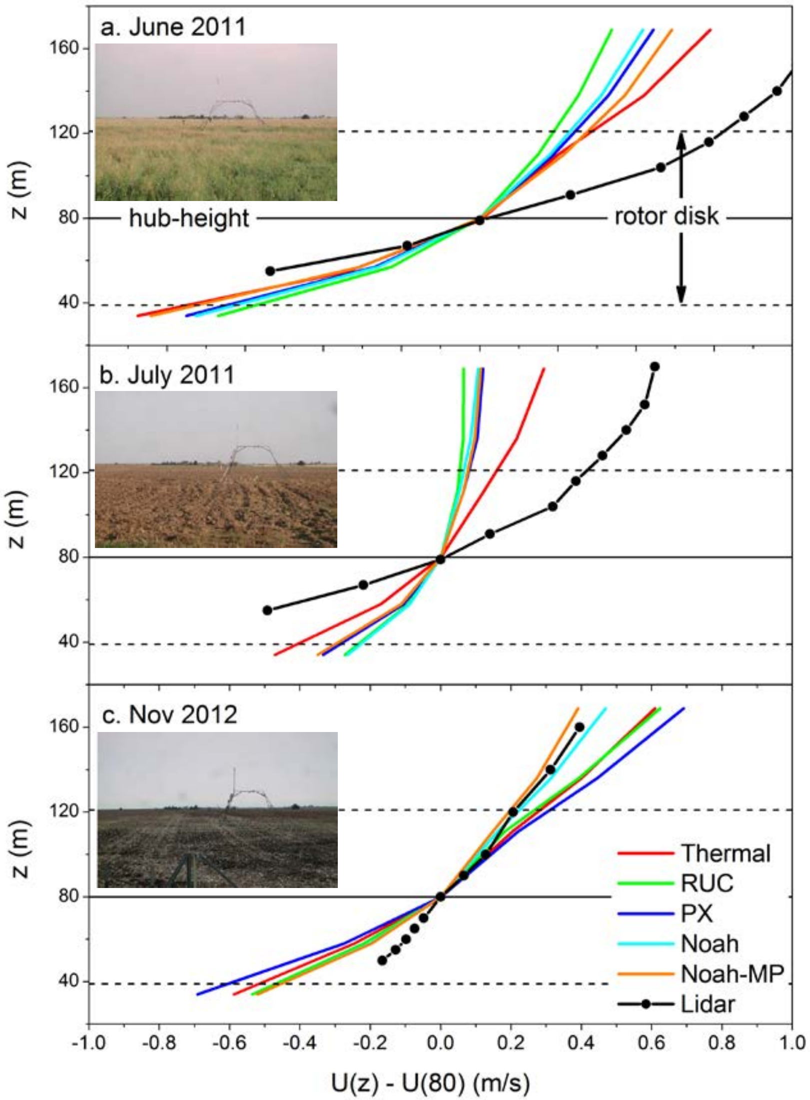


Accomplishments and Progress

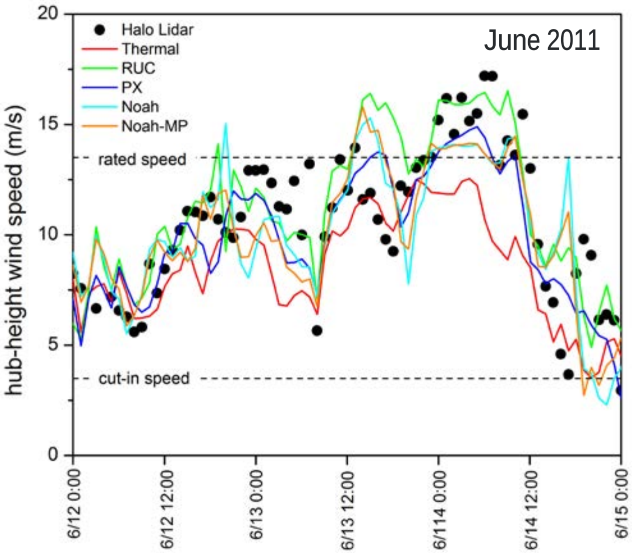
- The LSMs modeled significantly less shear during the dry July case compared to the wetter June case. A smaller shear trend is seen in the observations.
  - Validation was difficult as the Halo Lidar observations were instantaneous snapshots and not continuous measurements.

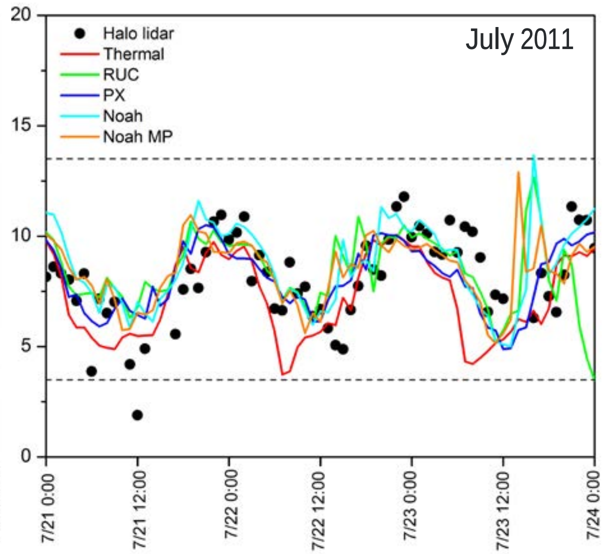
- The more sophisticated LSMs modeled the most accurate shear compared to the high temporal resolution Wind Cube Lidar data at least above 80m (November 2012 case).

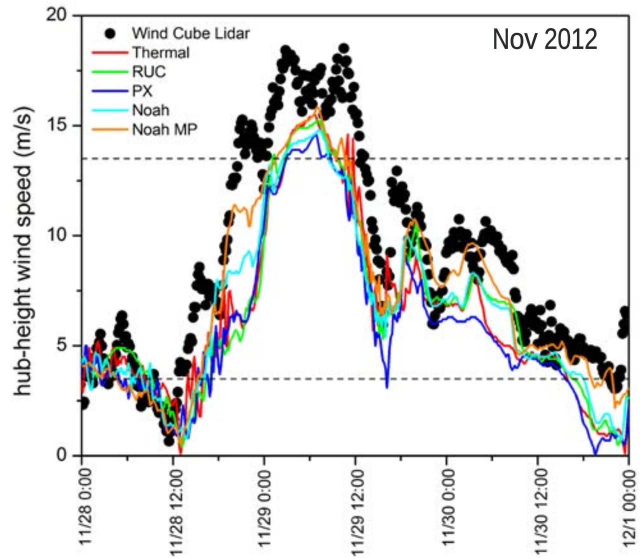
Average midday wind shear



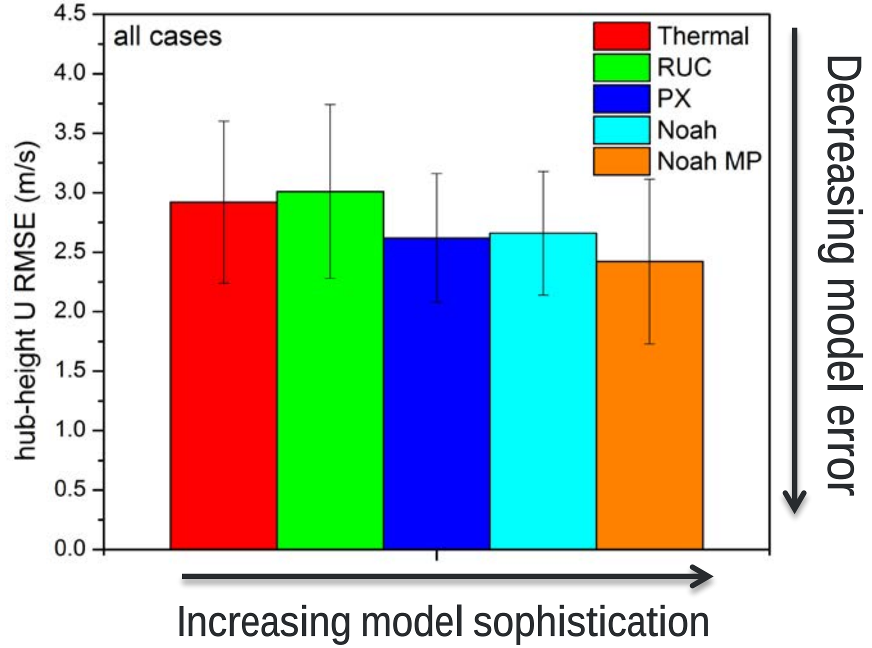
- LSM differences carried over to hub-height wind speed
  - ➢ Significant hub-height U differences between the LSMs.
  - ➢ Errors evident during both day and night.
  - ➢ Error evident during both synoptic and locally driven events.







- Conclusions:
  - Modeling wind flow at rotor-disk height is sensitive to choice of LSM at this site.
  - Modeled wind accuracy is appears to be linked to LSM sophistication in surface-atmosphere energy exchange processes.
  - The importance of LSM choice during different land surface conditions needs further investigation as our case studies did not show clear trends.
  - Need for additional test sites: more locations would provide insight into LSM importance for modeling other wind power regions of the country.



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	WE 7.0
Project Number	7.1.4
Agreement Number	22541

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Deploy Wind Cube to SGP ARM												
Q2 Milestone: Execute LSM simulations in WRF for selected case studies.												
Q3 Milestone: Complete validation of LSM simulations for selected case studies.												
Q4 Milestone: Finish writing the technical report.												
D1: Technical report (LLNL-TR-643914) delivered to DOE Wind Program.												
Current work and future research												

Comments

- Decided to use SGP ARM as the test site instead of Site 300 to remove topographical influences on flow.
- Journal manuscript in prep.

Research Integration & Collaboration

Collaborators:

- LLNL – Matthew Simpson, Jessica Osuna (post-doc)
- LBNL – Sebastien Biraud, Marc Fischer
- ARM/PNNL – Rob Newsom
- U Oklahoma – Jennifer Newman (grad student)

Communications and Technology Transfer:

- Technical report: LLNL-TR-643914 (DOE Information Bridge: http://www.osti.gov/scitech/biblio/1097768
- Presentations:
  - American Geophysical Union (AGU) Weather-Driven Renewable Energy Session ePoster on-line: https://live.blueskybroadcast.com/bsb/client/_new_default.asp?action=SEARCH&Client=483862
  - Traversing New Terrain in Meteorological Modeling, Air Quality and Dispersion Conference, UC Davis
- Industry Partnerships:
  - This project led to a new partnership with Enel Green Power and GE to measure and model inflow and wakes and do statistical power curve modeling for Enel's nearby 235 MW wind farm.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Proposed future research:

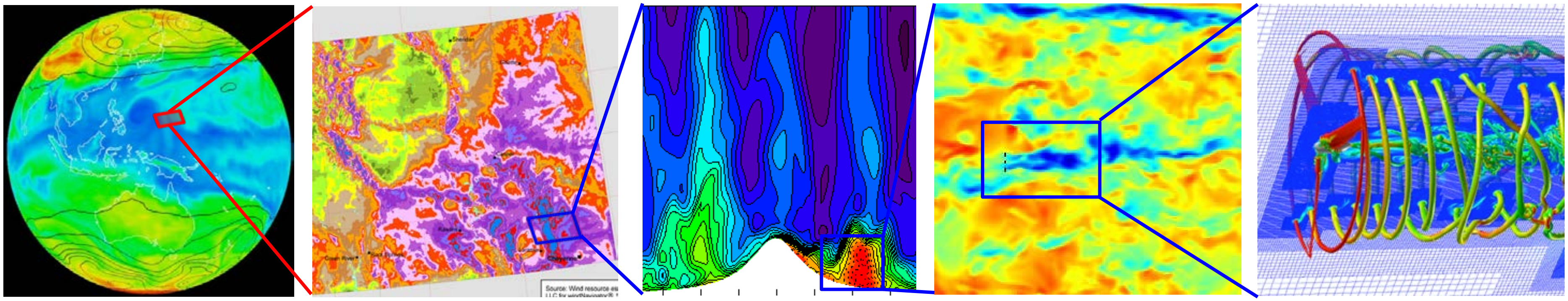
- Use SCADA power data (currently available) from the nearby wind farm to validate statistical power curve models for this site using:
  - Modeled wind flow with multiple LSMs in WRF
  - Inflow Lidar data (currently available)

  ➢ This would tell you how important the LSM choice is on predicted power generation in the Northern Oklahoma wind region and give you a range of uncertainty estimates.

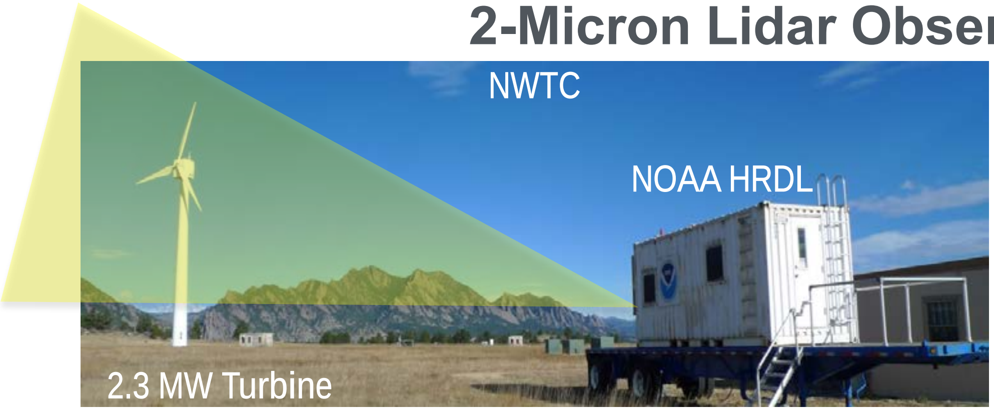
- Replicate and expand experiment in other wind power regions by taking advantage of concurrent Wind Program funded campaigns:

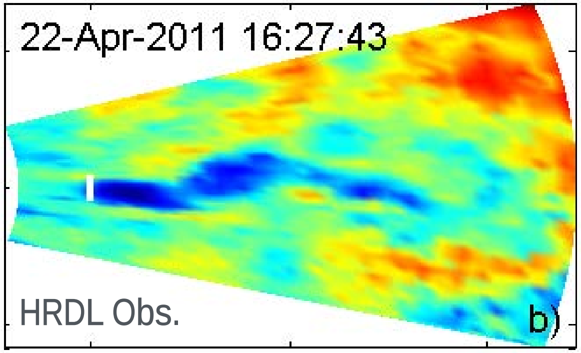
  ➢ This would tell you how region-specific or site-specific the results are. Is getting the LSM correct important in other wind areas of the country, in complex terrain, etc.?

Multiscale Atmospheric Modeling



2-Micron Lidar Observations





1. Characterization of Turbine Inflow Conditions using Multiscale Atmospheric Modeling
2. Integration of Turbine Inflow and Wake Observations from a 2-Micron Lidar into a Wind Energy Forecasting Model

Jeff Mirocha

LLNL

jmirocha@llnl.gov, 925-422-4627

Monday, March 24, 2014

Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL PRES-650632

Budget, Purpose, & Objectives

Multiscale Atmospheric Modeling

Total DOE Budget[1]: $.275M

Total Cost-Share[1]:$0.000M

Problem Statement:

- Contemporary simulation tools do not capture the multiple scales of atmospheric motions required for many wind turbine/wind farm studies
- Absence of adequate tools has hindered progress in many key areas of wind energy R&D and operations

Impact of Project:

- Completed significant background R&D to enable high-fidelity, multiscale atmospheric simulation for wind energy applications
- Multiscale simulation will enable advances in critical R&D areas:
  - Siting, fatigue mitigation, reliability, power capture, inflow for CFD
- Development within the open-source WRF model provides this capability to a large and diverse user base

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Multiscale Atmospheric Modeling

Technical Approach:

- Identify errors using standard tools in various nesting setups
  - Provided knowledge to guide development efforts
- Implement new subroutines into WRF for improved simulation
  - Advanced turbulence models for nested LES
  - Newly developed algorithms to seed turbulence at nest inflow boundaries
  - Benchmarking of new approaches in simulations of increasing complexity
- Establish practical guidelines for users

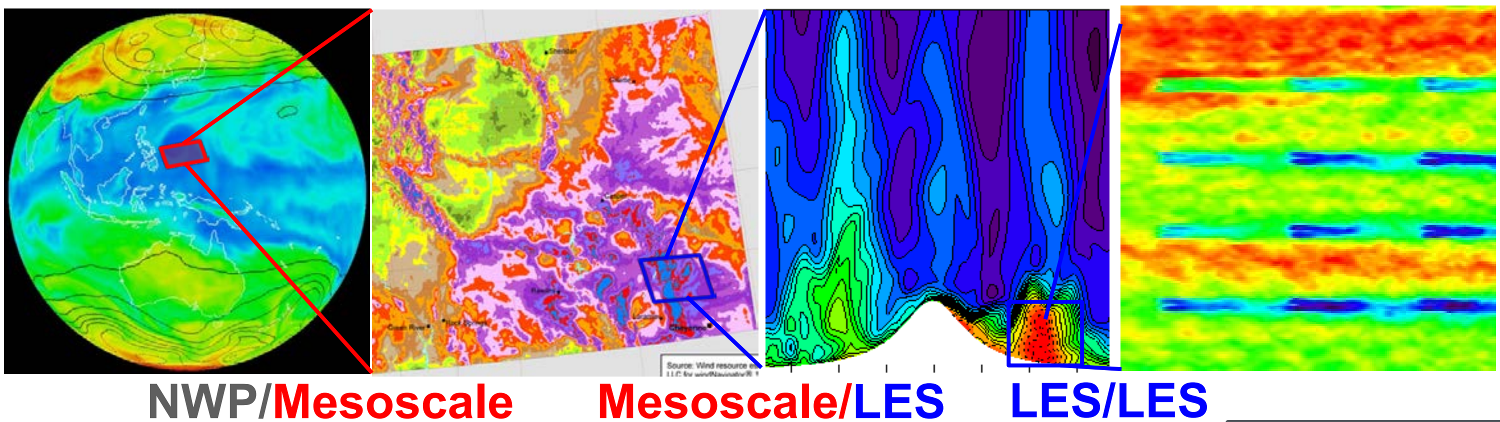
Unique aspects:

- Few quantitative studies of downscaling issues, especially in WRF
- Developed novel turbulence seeding approaches
- Implemented new codes within a widely-used community model

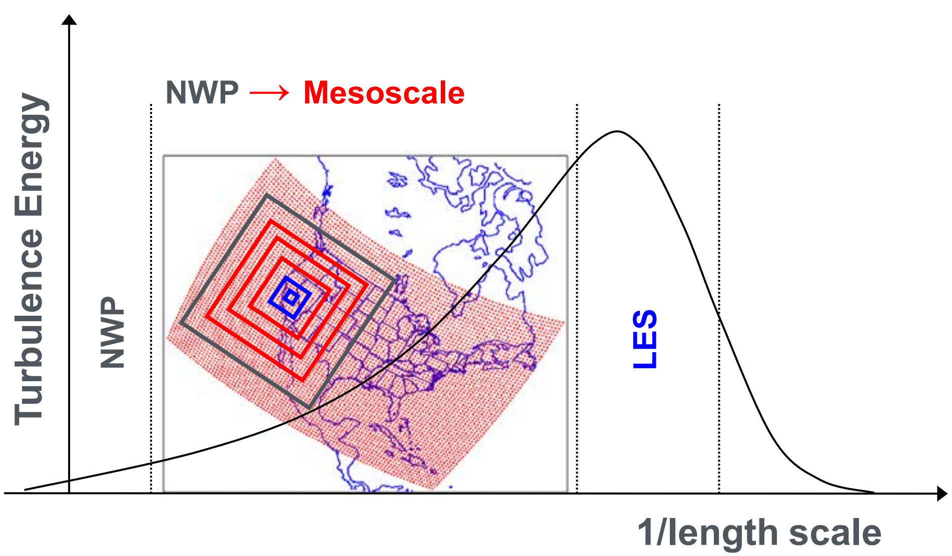
Technical Approach

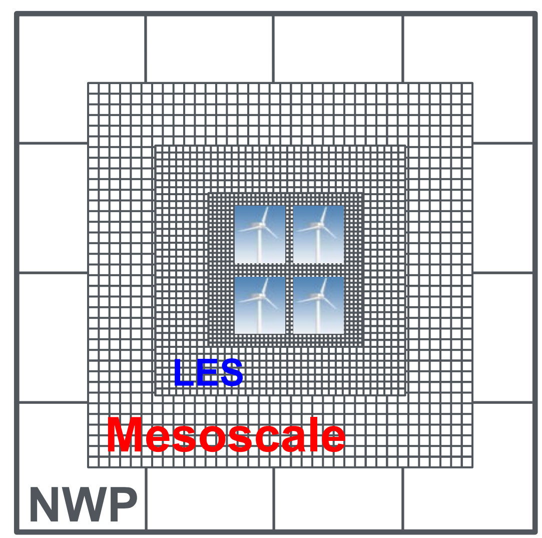
Multiscale Atmospheric Modeling

Technical Approach:
Examination of errors in various nesting strategies



Grid nesting: Bounding domains provide boundary conditions for higher resolution domains nested within





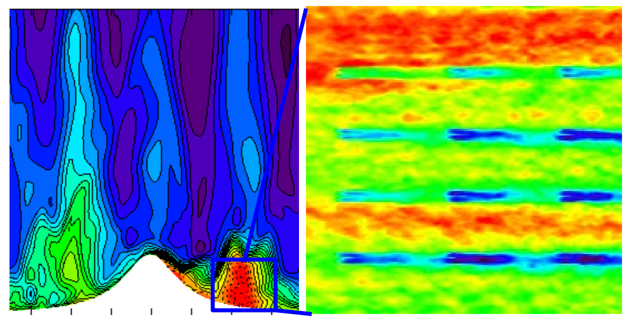
Multiscale Atmospheric Modeling

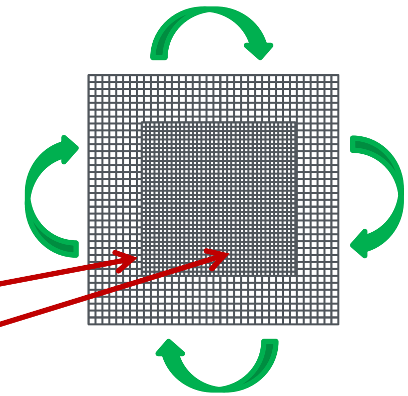
Technical Approach:

Examination of errors in various nesting strategies: **LES/LES**

Idealized Setup:
Flat terrain, z_0=0.1m;
Geostrophic wind,
Ug=10 m s^{-1}

Results presented in 2 journal articles

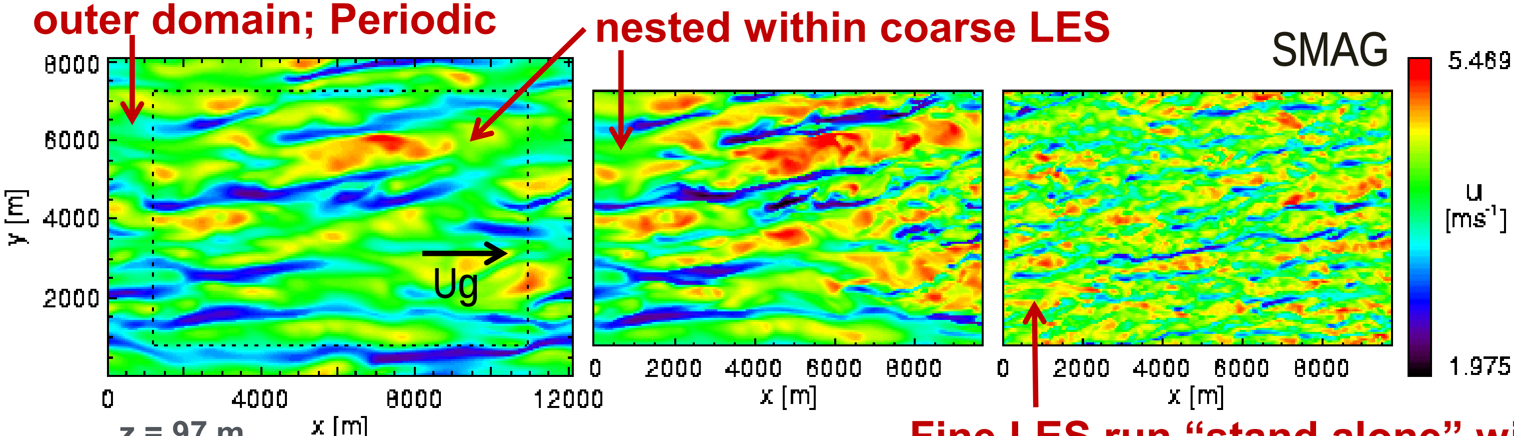


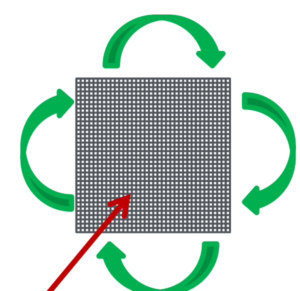


Periodic lateral boundary conditions

Coarse LES (Δx=99 m) outer domain; Periodic

Fine LES (Δx=33 m) nested within coarse LES





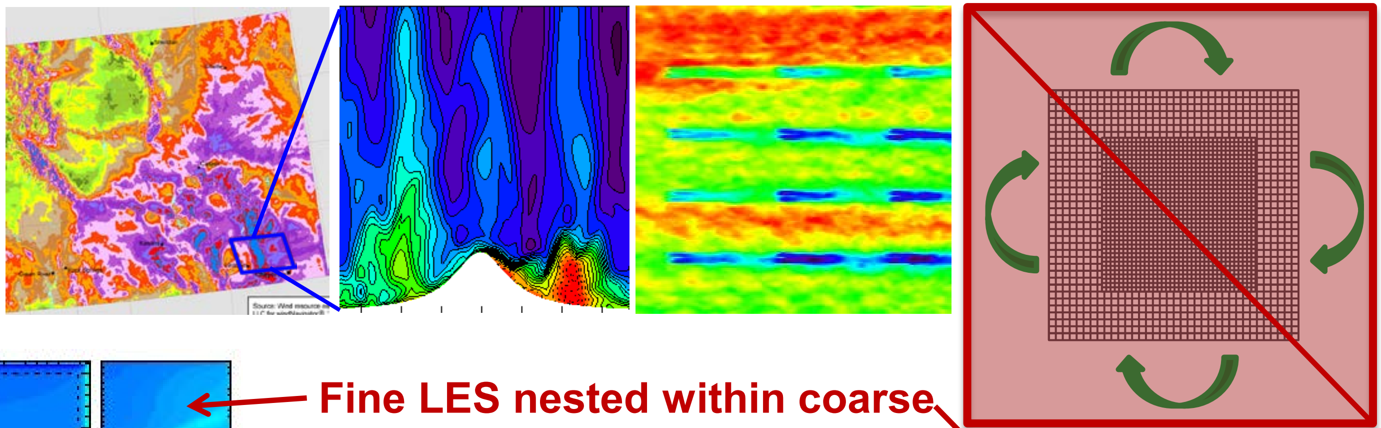
Fine LES run "stand alone" with periodic B.C.

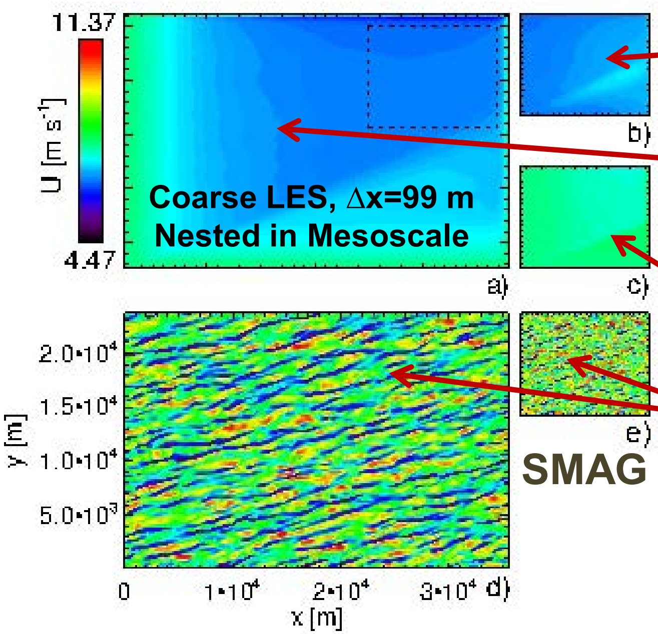
Multiscale Atmospheric Modeling

Technical Approach:

Examination of errors in various nesting strategies: **Mesoscale/LES**

Idealized Setups:
Neutral, convective & stable conditions,
Flat & hilly terrain



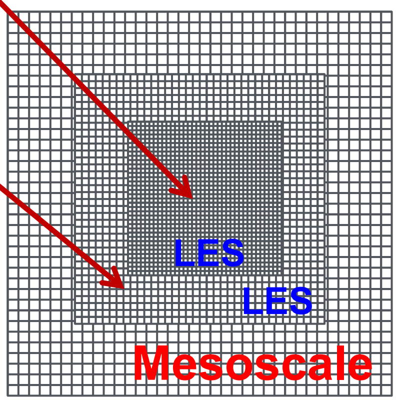


Fine LES nested within coarse LES, nested within mesoscale

Coarse LES nested within mesoscale

Fine LES nested directly within mesoscale

Coarse and fine "stand alone" LES with periodic B.C.

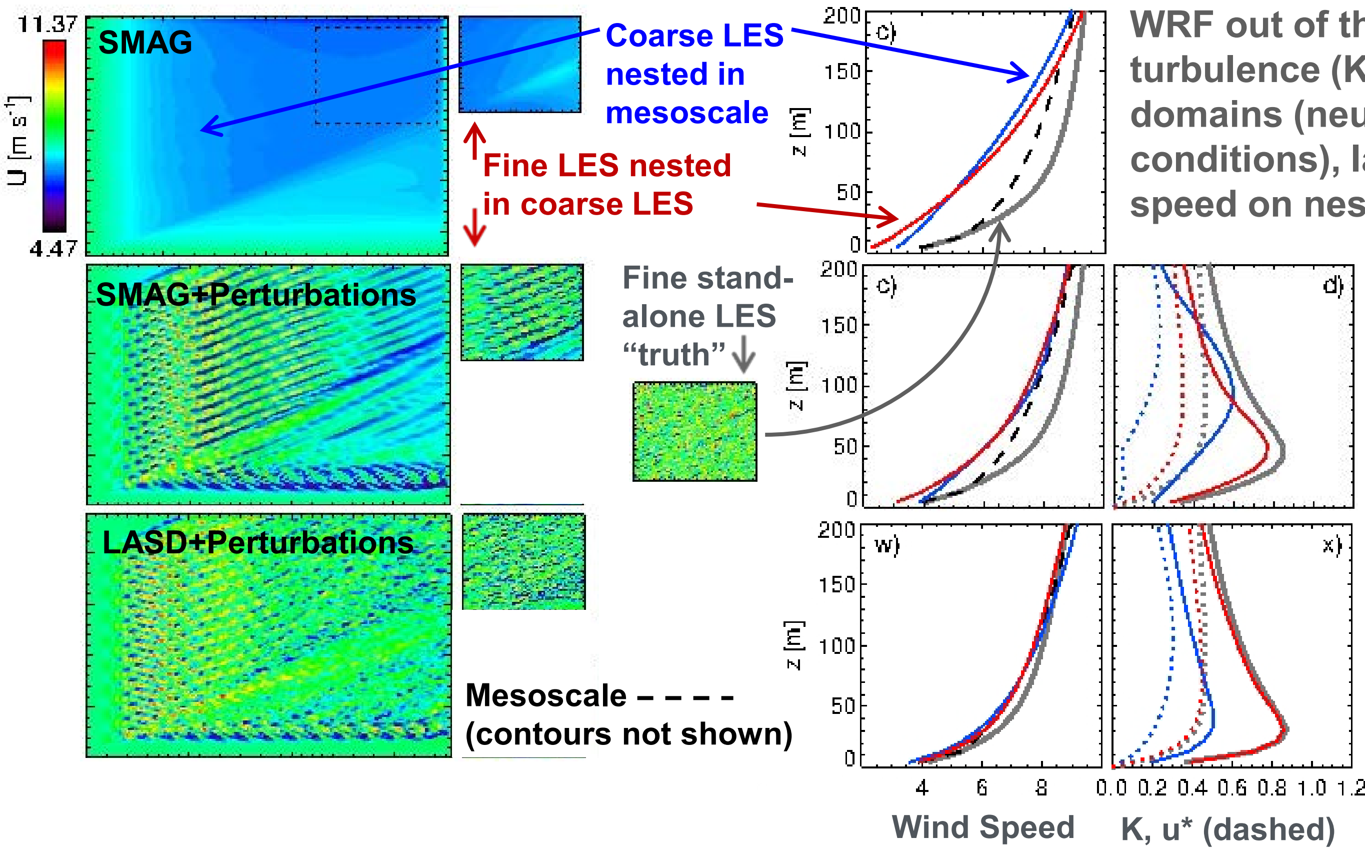


Multiscale Atmospheric Modeling

Technical Approach:

Examination of errors in various nesting strategies: **Mesoscale/LES**

Perturbations lead to significant improvements for all SFS stress models → realistic wind speed, turbulence profiles on nested LES domains



WRF out of the box: SMAG. No turbulence (K or u*) on nested LES domains (neutral and stable conditions), large errors in wind speed on nested LES

SMAG+Perturbations: Improved agreement of U, K and u* on fine LES nested domain

LASD+Perturbations: Good agreement of U, K and u* on fine LES nested domain

Good results also from modified NBA+Perturbations

Results presented in 2 journal articles

Accomplishments and Progress

Multiscale Atmospheric Modeling

Most important technical accomplishments 2012-2013:

- Identified errors/issues in nested LES
- Developed new algorithms for improved simulation
- Established guidelines for both LES to LES and Mesoscale to LES Nesting

Awards/recognition:

Excerpt from anonymous review of Mirocha et al. 2014 Mon. Wea. Rev. manuscript:

"This is a very well-written and thoroughly analyzed study that follows up on previous studies by the co-authors where they test new SGS models in WRF and analyze the model's performance in nested setups. The study analyzes default options in WRF and proposes improvements. Given that the number of papers using WRF and doing a-posteriori assessment of the model is at this point staggering (though more in mesoscale mode), and given the dearth of more basic analyses of the model like this study, the paper certainly qualifies as a significant contribution to the meteorological literature …"

Project Plan & Schedule

Multiscale Atmospheric Modeling

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Numbers: 7.1.1 (Multiscale) and 7.1.3 (2-Micron Lidar)	
Project Number	
Agreement Number: 22541	

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Multiscale simulation												
Q1 Milestone Original: Multiscale simulation of real data case over complex terrain												
Q3 Milestone Original: Multiscale simulation of real data case with low level jet												
Q4 Milestone Original: Analysis and macnuscript submission for each case study												
Q1 Milestone Actual: Multiscal simulations with idealized terrain, neutral and unstable												
Q2 Milestone Actual: Mustiscale simulations with idealized stable conditions												
Q4 Milestone Actual: Anaysis complete and 2 papers submitted to journals												
Current work and future research												
N/A												

Original initiation: FY11Q1; Planned completion: FY12Q4

Milestones rescoped due to unforseen technical complexities requiring additional time; delivered during FY13

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Multiscale Atmospheric Modeling

Partners, Subcontractors, and Collaborators:

Collaborated with Princeton, U.C. Berkeley, NCAR and von Karman Institute

Communications and Technology Transfer:

- 4 journal articles (3 published, 1 in review):
  - Kirkil, G., J. D. Mirocha, E. Bou-Zeid, F. K. Chow, and B. Kosović, 2012: Implementation and Evaluation of Dynamic Subfilter-Scale Stress Models for Large-Eddy Simulation using WRF, *Mon. Wea. Rev.*, **140**, 266-284, doi:10.1175/MWR-D-11-00037.1
  - Mirocha, J. D., G. Kirkil, E. Bou-Zeid, F. K. Chow, and B. Kosović, 2013: Transition and equilibration of neutral atmospheric boundary layer flow in one-way nested large-eddy simulations using the Weather Research and Forecasting model, *Mon. Wea. Rev.*, **141**, 918-940, doi:10.1175/MWR-D-11-00263.1
  - Mirocha, J. D., B. Kosović, and G. Kirkil, 2014: Resolved turbulence characteristics in large-eddy simulations nested within mesoscale simulations using the Weather Research and Forecasting model, *Mon. Wea. Rev.*, **142**, 806–831, doi:10.1175/MWR-D-13-00064.1
  - Muñoz-Esparza, D., B., Kosović, J. D. Mirocha, and J. van Beek, Bridging the transition from mesoscales to microscale turbulence in atmospheric models, *In review at Boundary-Layer Meteorology*
- 1 technical report:
  - Multiscale simulation of boundary-layer flow over complex terrain using the Weather Research and Forecasting model, LLNL-TR-645827
- Conferences: American Geophysical Union and American Meteorological Society

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Impacts of Stratification and Non-Equilibrium Winds and Waves on Hub-Height Winds

Edward (Ned) Patton

National Center for Atmospheric Research

Email: patton@ucar.edu, Phone: 303-497-8958

March 24, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $.468M

Total Cost-Share[1]:$0.117M

Problem Statement:

- Wind farm deployments reside in coastal zones where the atmospheric boundary layer is in disequilibrium with the surface
- Current boundary layer models presume equilibrium

Impact of Project:

- Physically-based representation of disequilibrium wave state and stratification impacts on hub-height winds incorporated into the freely available Weather Research and Forecast (WRF) model
- Improved resource assessment and weather forecast skill resulting in reduced O&M costs

This project aligns with the following DOE Program objectives and priorities:

- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

- Use **turbulence-resolving simulation** and **analysis of available observations** to construct a model to extrapolate buoy-observed winds to the turbine layer
- Incorporate physical understanding of non-equilibrium wave states and stratification into the model
- New model implemented as a WRF physics package option
  - Stand-alone single column mode tests
  - Three-dimensional simulations
  - Compare against observations
- Inclusion in the WRF-repository ensures availability for the international user community

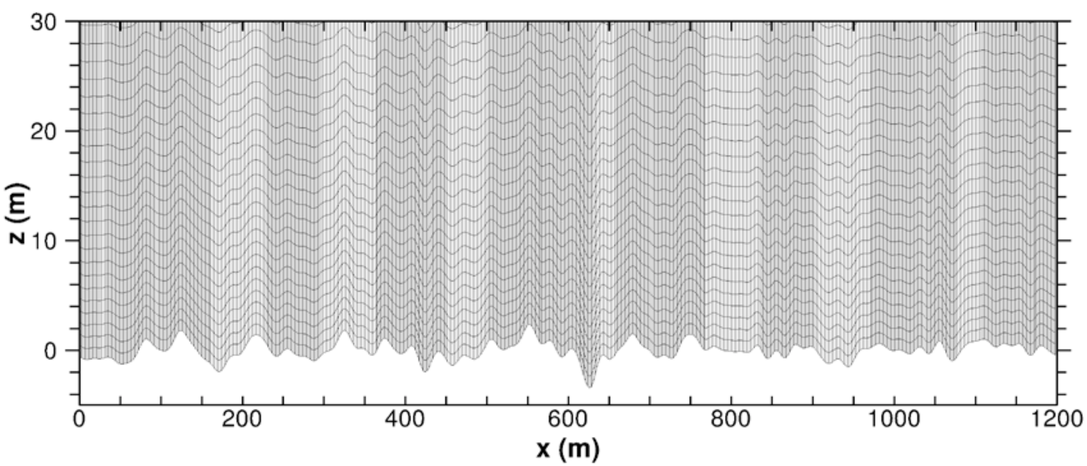
Observational data analysis:

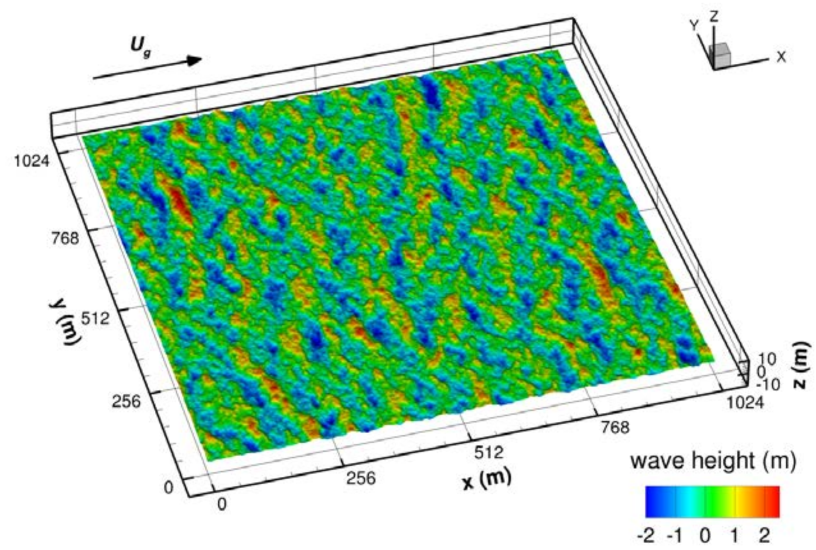
CBLAST-LOW
July-August 2001

FINO1-3
North/Baltic Sea
2006 onward

Turbulence- and wave-resolving simulation

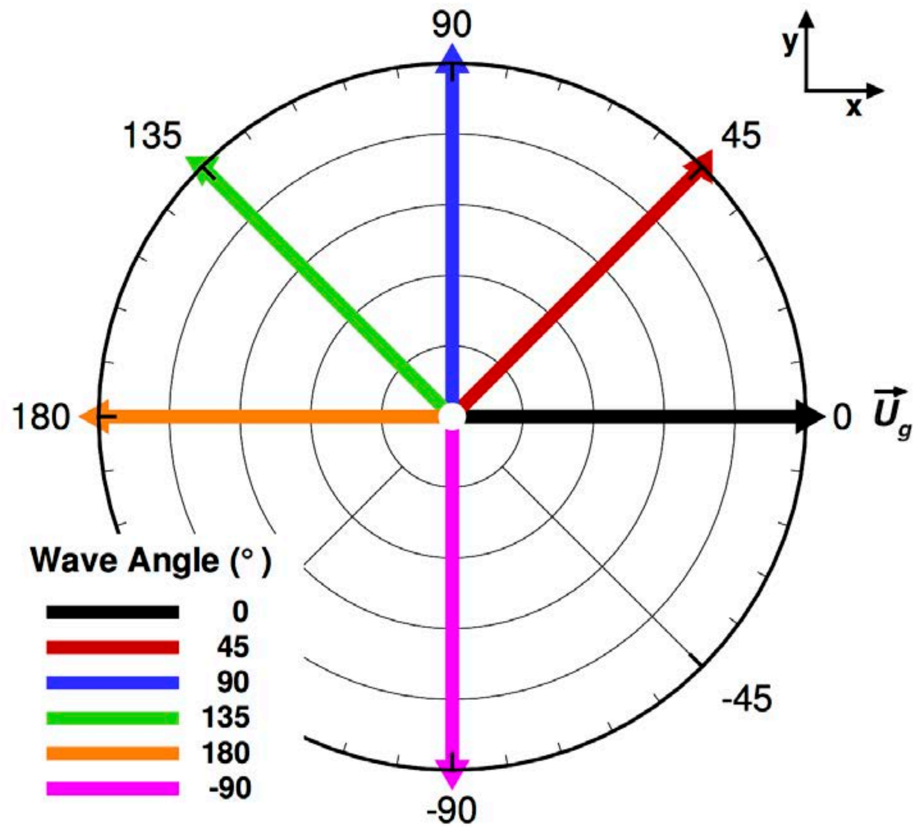
- Resolve surface waves of height *h*(*x*,*y*,*t*)
- Coordinate transformation maps physical space coordinates onto computational coordinates
- Surface wave amplitudes match Donelan's (1985) measured wave spectra
- Waves are linear modes with random phase
- Caveat: Waves are imposed



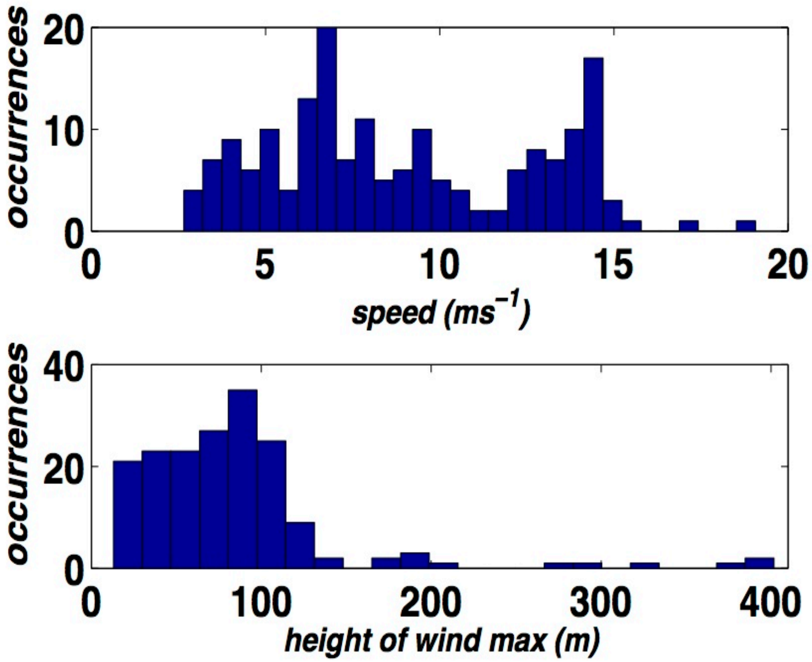


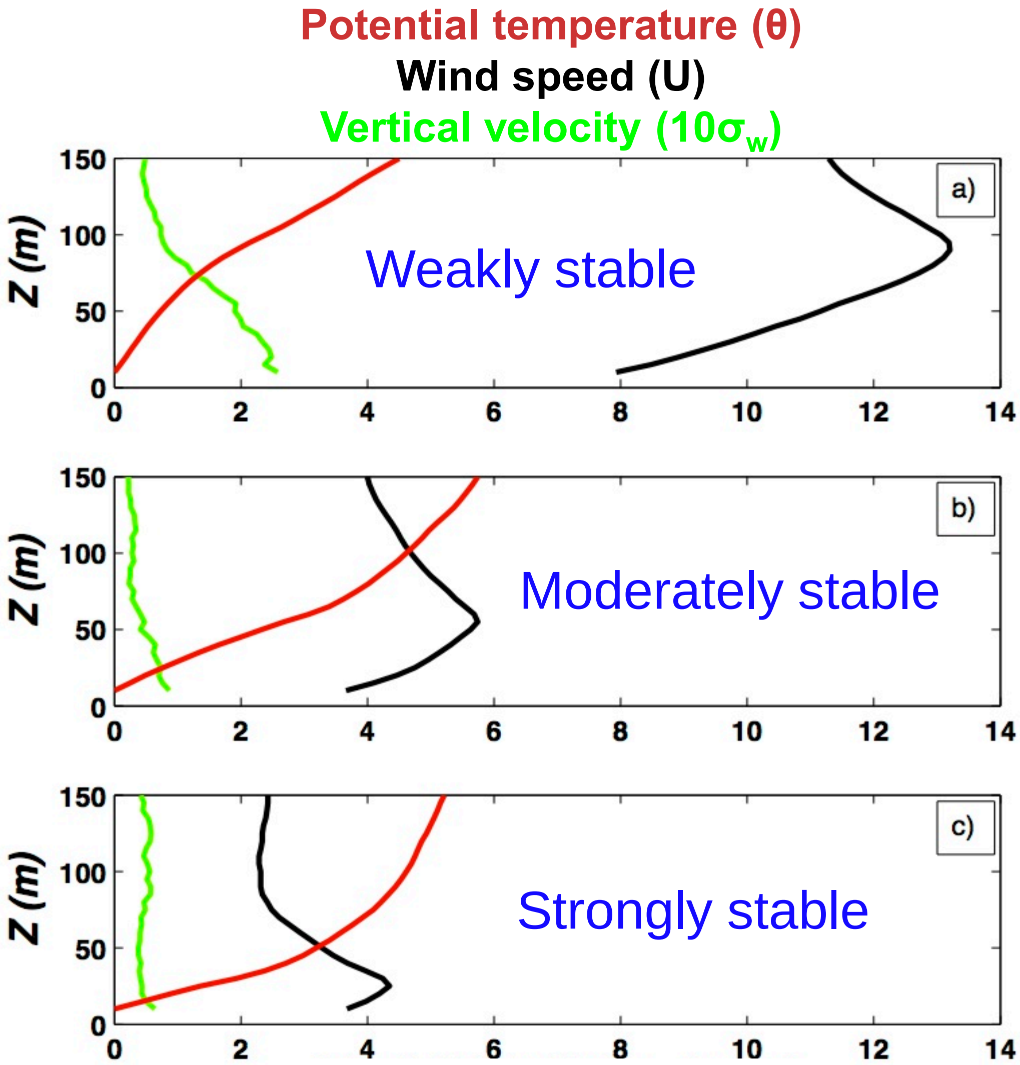
Turbulence- and wave-resolving simulation

- Atmosphere driven with a pressure gradient (U_g)
- Investigate:
  - Impact of wind-wave mis-alignment
  - Range of wave-age (young vs. old waves)
  - Range of atmospheric stability (i.e. buoyancy/shear forcing)



CBLAST-LOW



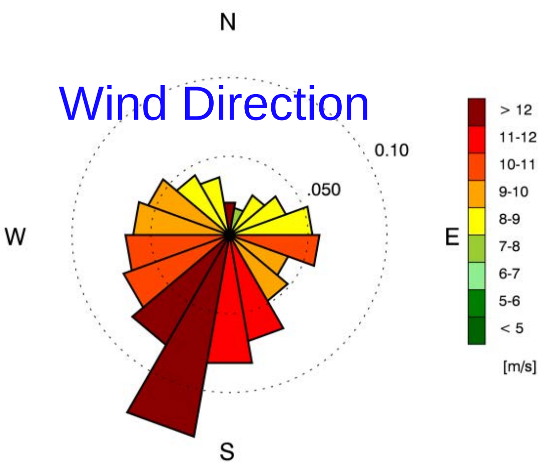


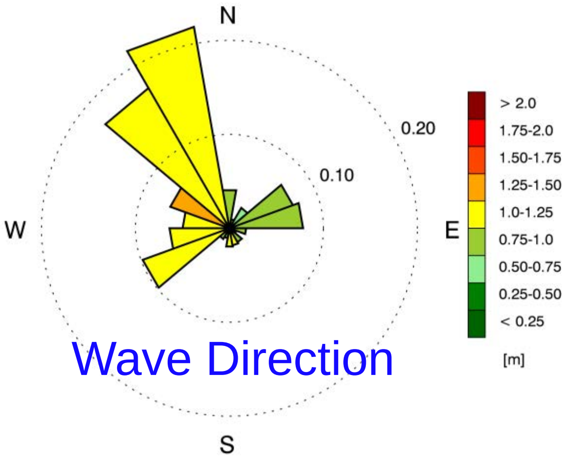
Composite averages over 20+ soundings

Key findings:

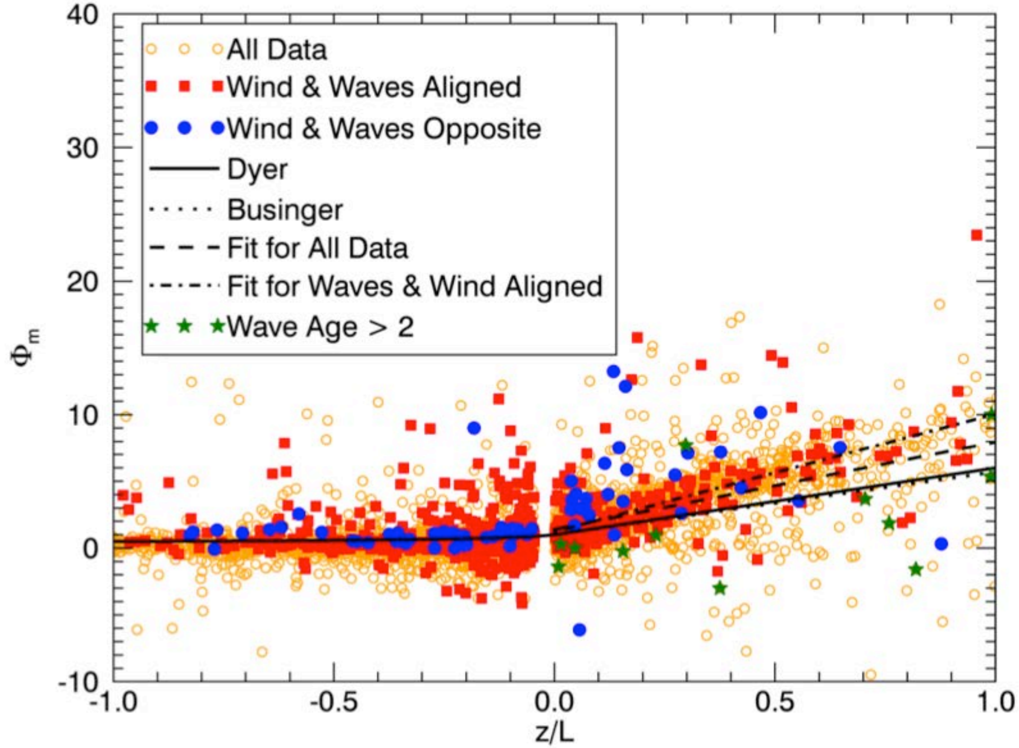
- Low-level wind maxima are common
- Can be quite low (20 m)
- Non-stationary on time scales < 1hr

FINO-1 2006





Non-dimensional wind shear

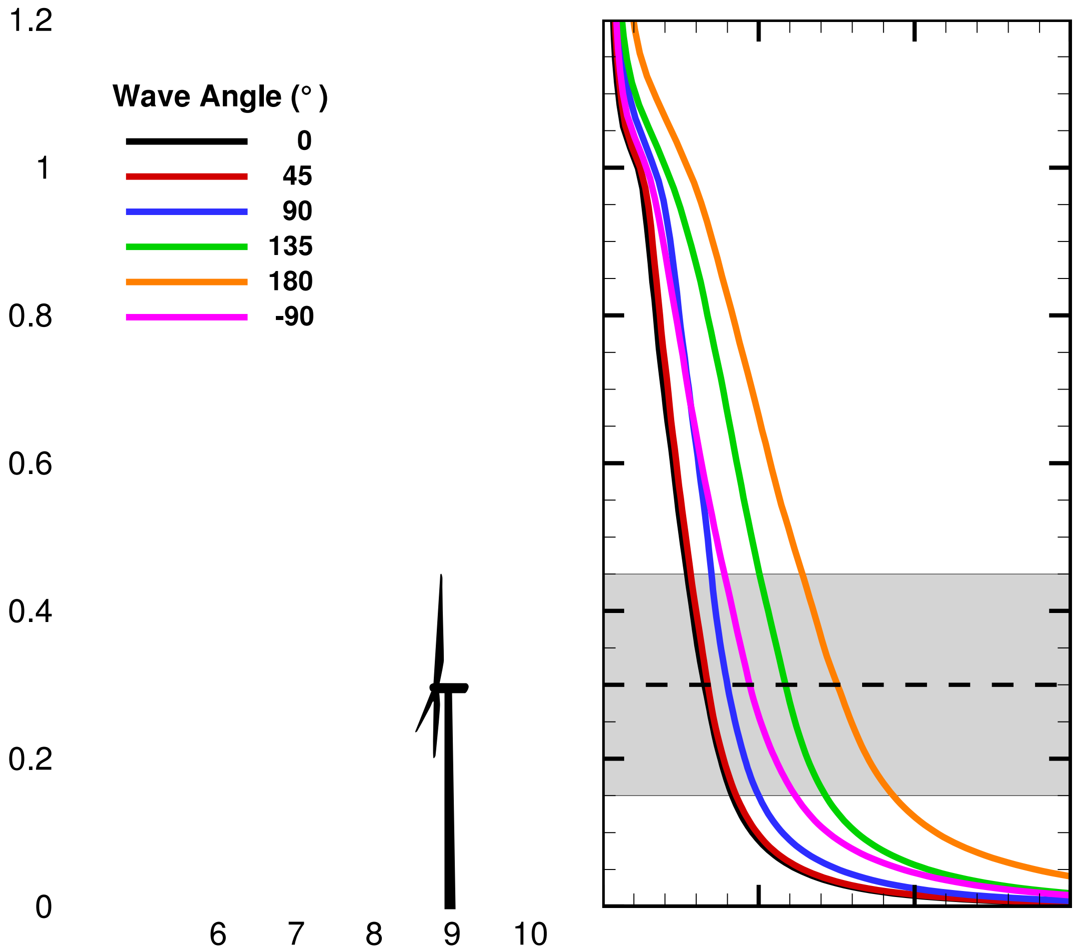


Stable stratification:

$$\phi_M = \frac{kz}{u_*}\frac{\partial u}{\partial z} = \left(1 - c\frac{z}{L}\right)$$

	c
Businger et al. (1971)	4.7
Dyer (1974)	5
FINO (all alignments)	7.8
FINO (aligned)	8.8

Turbulence and wave-resolving simulation



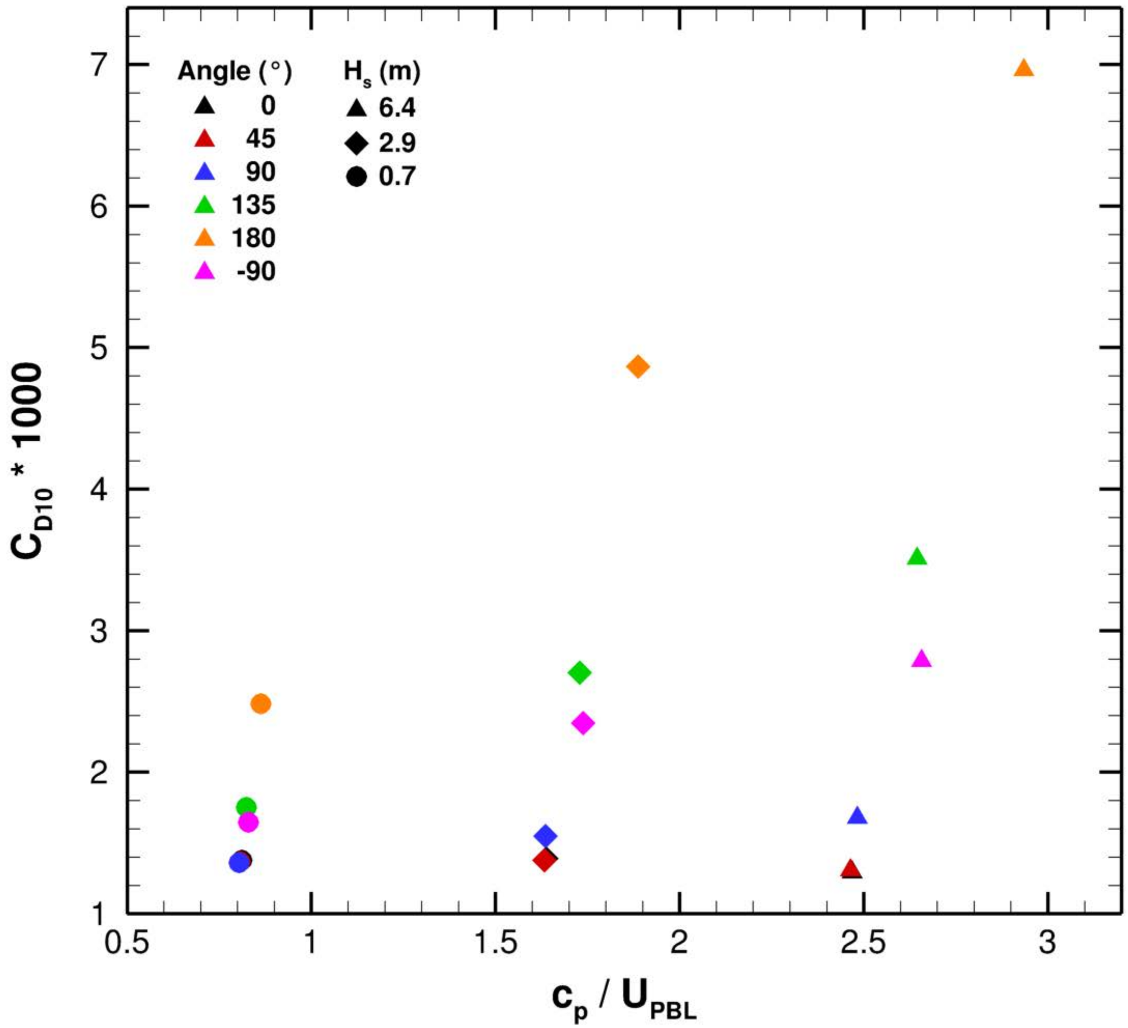
- For the simulated wind/wave regime:
  - Increased PBL growth rates
  - Reduced wind speeds (up to 15%)
  - Increased turbulence intensity (up to x2)
- Non-equilibrium winds/waves induce pressure drag that varies with wind-wave alignment
- To upscale buoy measurements to hub-height you need:
  - winds, temperature
  - *wave state*
- Key information for optimizing turbine deployment decisions

Turbulence and wave-resolving simulation

Impact of wave age on drag coefficient:

$$C_{D10} = \overline{u'w'_{10}} / U_{10}^{2}$$

- Matches Donelan's (1998) observations for aligned waves
- (Linear?) increased drag coefficient with bulk wave age (up to a factor of 5 for 180°)



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	Legend
WBS Number: 7.0 Wind Resource Characterization	Work completed
Project Number: DE-EE0005373	Active Task
Agreement Number: DE-EE0005373	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Impact of stratification and non-equilibrium winds and waves on hub-height winds												
Task 1: Select and analyze off-shore experimental data												
Task 2: Analyze wind extrapolation algorithms and PBL schemes												
Task 3: Setup idealized LES, execute and analyze results												
Task 4: 3D baseline simulation with WRF using off-shore experimental data												
Milestone: Analyzed off-shore experimental data												
Task 5: Setup and execute LES based on selected offshore data												
Task 6: Develop an algorithm for extrapolation of offshore surface winds to hub-height												
Task 7: Implement and validate modified offshore PBL scheme within WRF-SCM												
Task 8: Write manuscript												
Milestone: Analyze LES results												
Milestone: Developed a modified off-shore PBL scheme												
Current work and future research												
Task 9: Implement and validate the modified PBL scheme in WRF												
Task 10: Refine analysis of LES results												
Task 11: Refine PBL-scheme												
Task 12: Write manuscript												
Task 13: Include offshore PBL scheme in WRF repository at NCAR												
Milestone: Implemented and validated modified off-shore PBL scheme in WRF												

Comments

- Six month delay resulting from lengthy negotiations with our cost-share partner. We received a six month no-cost extension for BP1.
- All Go/No-Go decision points have been met.

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- National Center for Atmospheric Research:
  - Branko Kosovic, Peter Sullivan, Jimy Dudhia, Luca Della Monache
- Northwest Research Associates:
  - Larry Mahrt
- Vestas Wind Systems A/S:
  - Mark Zagar, Line Gulstad
- Nacional Renewable Energy Centre of Spain
  - Javier Sanz Rodrigo

Communications and Technology Transfer:

- Presentations:
  - Kosovic, B. et al., *AWEA Offshore*, Virginia Beach, VA, October 2012
  - Kosovic, B. et al., *NAWEA Symposium*, Boulder, CO, August 2013
  - Patton, E. G. et al., *International Conference on Future Technologies for Wind Energy*, Laramie, WY, October 2013
  - Patton, E. G. et al., *EWEA Offshore*, Frankfurt, Germany, November 2013
- Manuscripts:
  - Mahrt, L., et. al., 2014: *J. Appl. Meteorol. Climatol*. doi:10.1175/JAMC-D-13-0170.1, in press
- WRF available at www.wrf-model.org. Over 30,000 downloads since 1998

Next Steps and Future Research

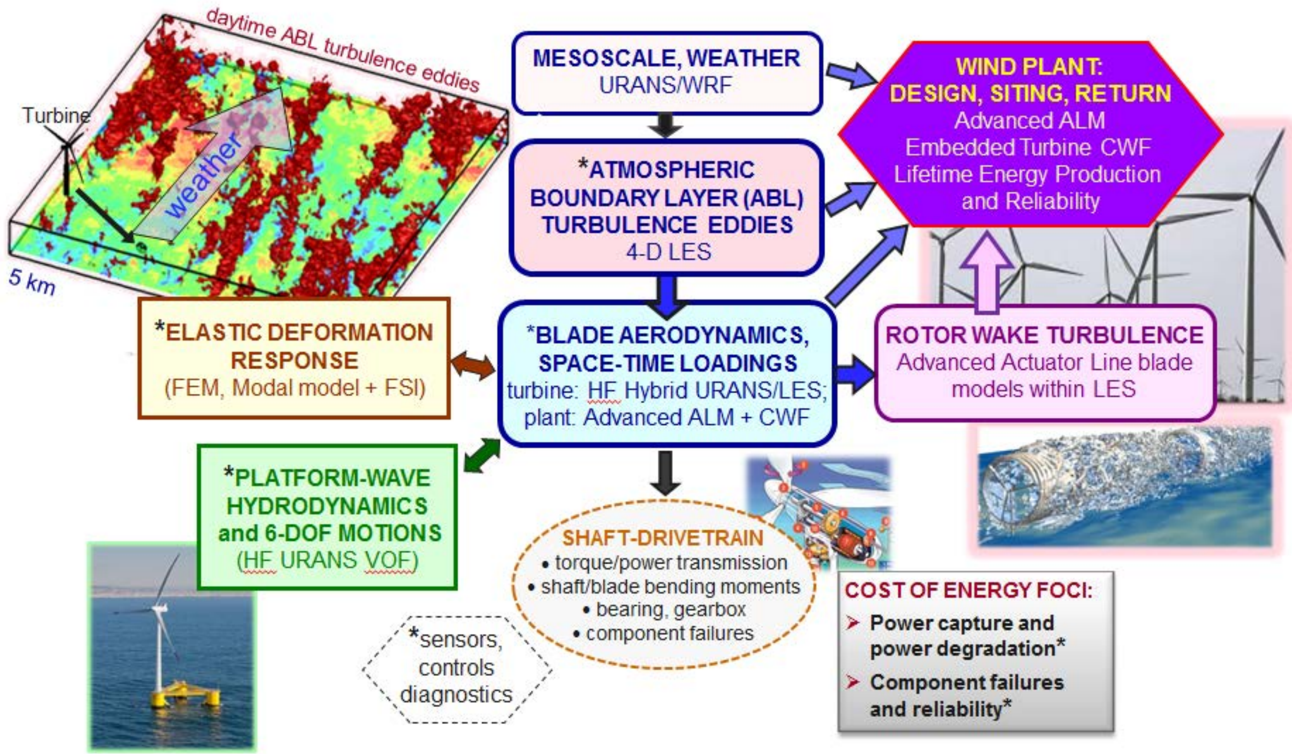
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

- Additional simulations mapping out broader parameter space of wave age and buoyancy influence on air-water coupling
- Implement parameterization in WRF
- Test parameterization and iterate improvements using WRF single column mode; compare against observations
- Integrate parameterization into WRF-repository

Proposed future research:

- Wave/stability influences on offshore turbine wakes
- Wave/stability influences on wind park layout optimization



CYBER WIND FACILITY (CWF)

- INTEGRATING FOCUS**:** Nonsteady loading responses to space-time varying winds from the passage of most-energetic atmospheric eddies.
- EXTREME MULTISCALE COUPLING**:** Meso-scale-driven atmospheric turbulence eddies ⇒ near-blade separating boundary layer dynamics ⇒ blade and rotor wakes.
- EXPERIMENTAL TESTBED**:** Generation of extreme-resolution multi-use 4-D cyber data for discovery and technology development.
- Elastic blade response to space-time atmospheric turbulence forcing.
- 4-D wake simulations: Advanced ALM using CWF and high-fidelity wind park simulation, with embedded CWF turbines.
- Offshore**:** Coupled wave-platform interactions with turbine motions with atmospheric turbulence.
- Selectable Fidelity**:** Advanced design-level models (BEM) for nonsteady response**.**

A HPC "Cyber Wind Facility" Incorporating Fully-Coupled CFD/CSD for Turbine-Platform-Wake Interactions with the Atmosphere and Ocean

James G. Brasseur

Pennsylvania State University

brasseur@psu.edu, (814) 865-3159

24 March 2014

Budget, Purpose, & Objectives

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$.070M

Problem Statement:

Problems: Consequences of nonsteady loading responses to repetitive space-time varying atmospheric eddy passage to groupings of wind turbines within wind plants.

Challenges: Develop, validate (and distribute) an open-source "Cyber-Wind Facility" (CWF) for land/offshore extreme fidelity simulation – with swappable low fidelity models – that couple atmospheric turbulence eddy passage with:
1) blade boundary layer dynamics, 2) wake turbulence and turbine interactions, 3) blade elastic deformation, 4) offshore platform hydrodynamics and motions.

Knowledge Gaps: Effective ways to reduce power degradation and component failure in wind plants arising from variabilities in wind turbulence with changes in atmospheric stability.

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

Purpose & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Impacts of Project:

Extendable HPC Test Environment: Extreme multiscale HPC experimental testbed with swappable components to develop design-level models for time-dependent response to atmospheric eddies.

Technical Advances: 1) in HPC, actuator line, and lower order model strategies for nonsteady blade and wake response, 2) offshore platform CFD and 3) for blade deformation FSI models.

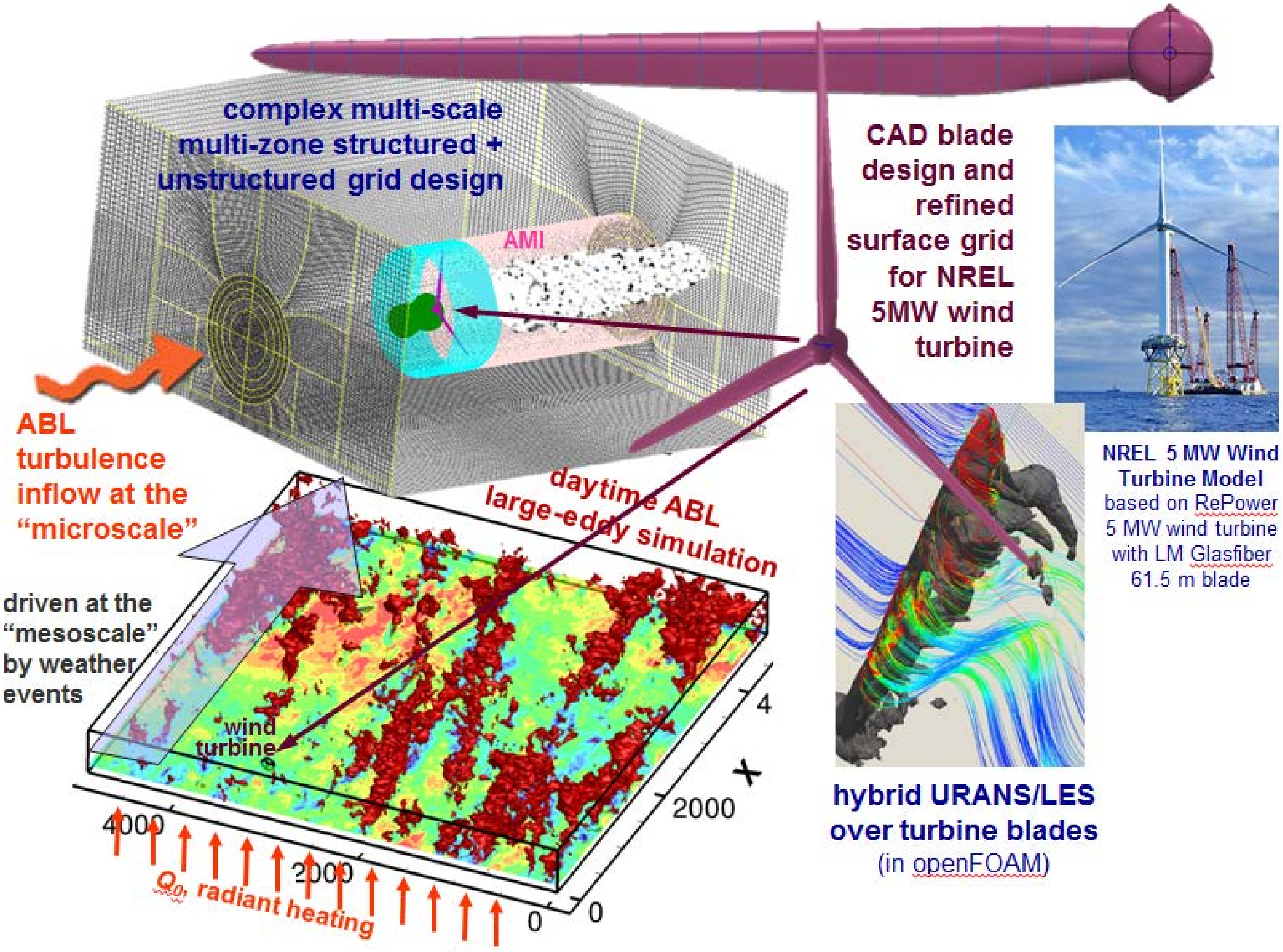
Final Product: Hierarchical modeling strategies for prediction of atmosphere-forced wind plants to develop new design and control concepts to enhance power capture and reduce component failure.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant LCOE.
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities.
- **Modeling & Analysis:** Focus technology development and identify key drivers/hurdles.

THE CORE DESIGN of multi-scale CWF

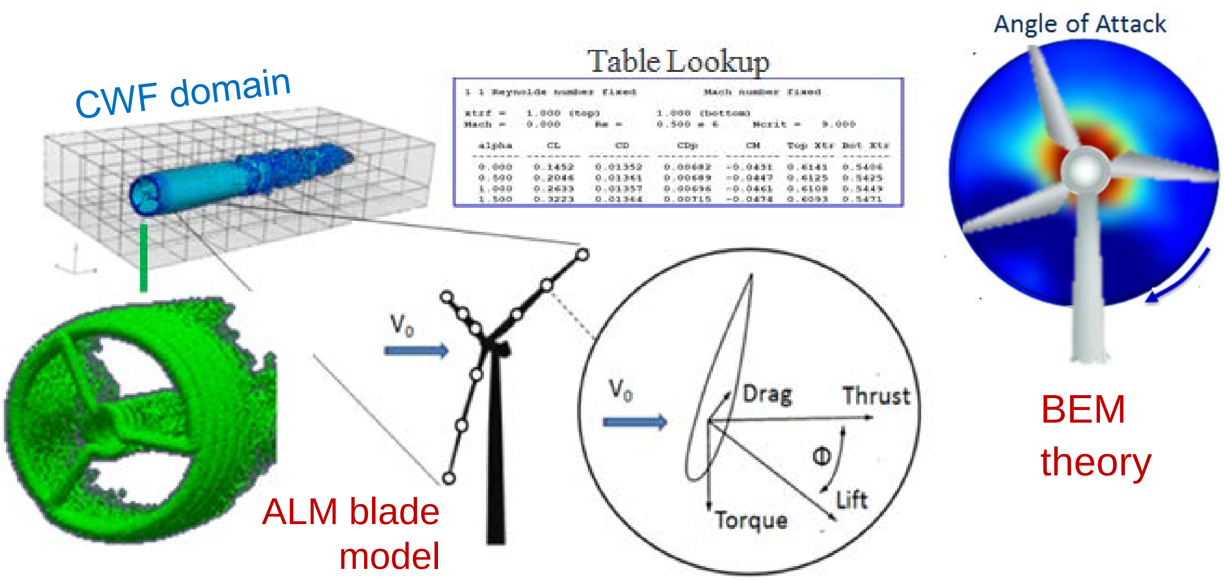
- Precurser spectral LES of the ABL.
- Finite volume CWF domain built on carefully designed multiscale grid that resolve near-blade viscous layers.
- Coupled hybrid URANS-SAS-LES models for accurate prediction of dynamically separating blade boundary layers in response to ABL eddy passage.

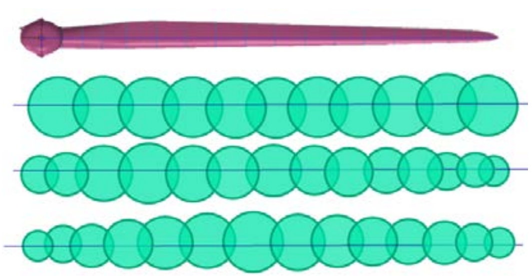


Hierarchy of Lower-order Modeling strategies: Improvement and Analysis

Analysis of Actuator Line and BEM Modeling

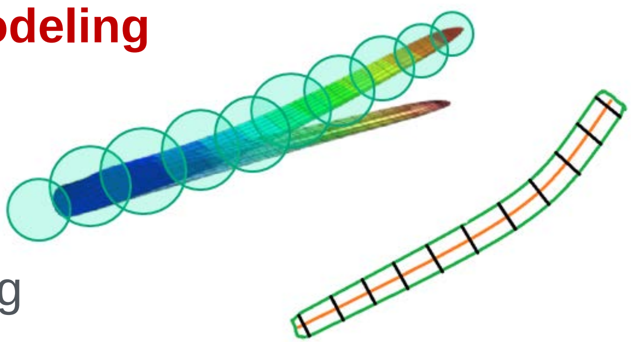
- In same domain as CWF for one-on-one comparison
- Embedded within LES of atmospheric boundary layer
- Seek improvements in high-fidelity predictions of:
  - ➢ ALM: wake turbulence
  - ➢ ALM & BEM: blade loadings





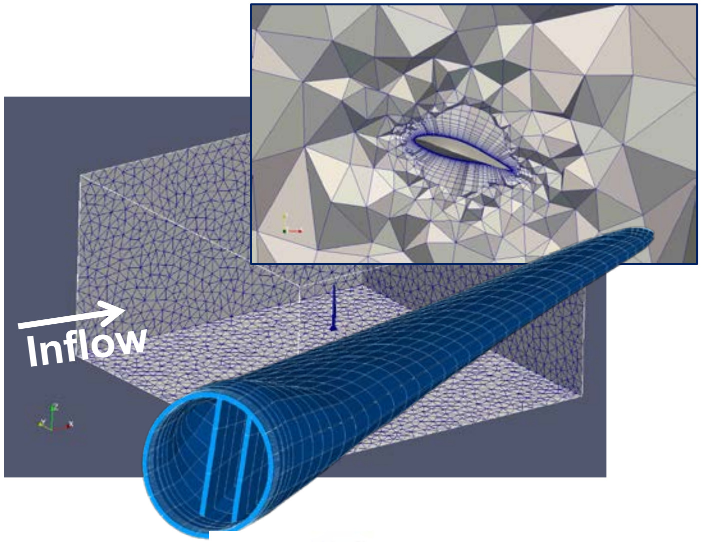
Advanced Actuator Line Modeling

1) Improving and Optimizing Current ALM methods.
2) Advanced ALM method: Actuator Curve Embedding - for deforming blades



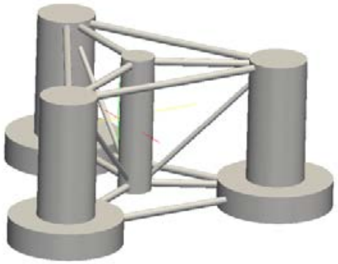
Blade Elastic Deformation and FSI

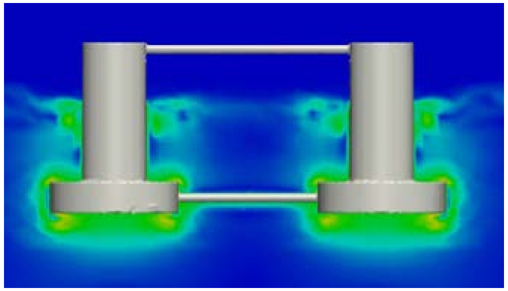
- Validated fluid-structure interaction (FSI) approach
- For linear/small displacements (modal decomposition) and nonlinear/large displacements (FEM).
- In-house FSI solver with a body fitted mesh to support sub-layer resolved modeling.
- Developed software to be placed in public domain.



Offshore Platform and 6-DOF Module

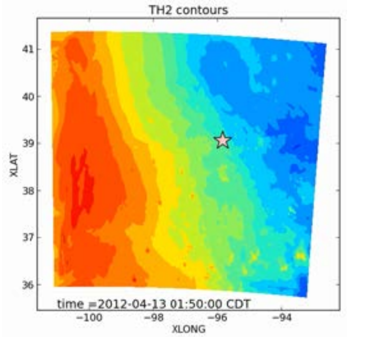
- Fidelity open-source multiphase CFD/HPC
- Efficient and stable algorithms for coupled wave motion, hydrodynamic platform loads, mooring-line loads, and 6-DOF platform motions with turbine.
- V&V for benchmark and OC4 problems
- High fidelity simulation coupled with to-be-developed LES of the marine ABL with waves.

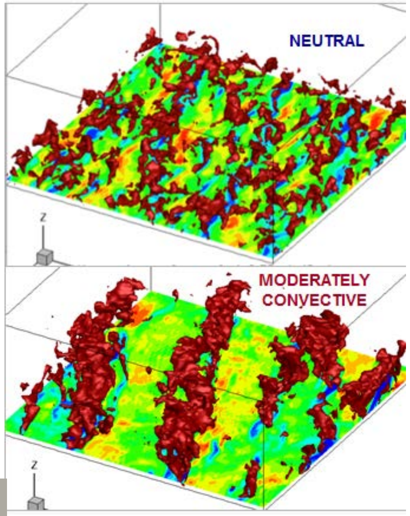




Classes of Atmospheric Boundary Layer Turbulence with Large-eddy Simulation

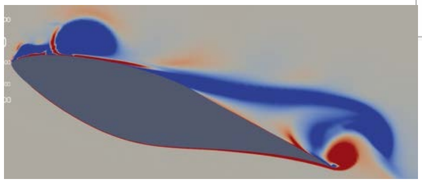
- Change in ABL turbulence eddying structure with atmospheric stability state
- Atmospheric boundary layer forced by weather events at the mesoscale





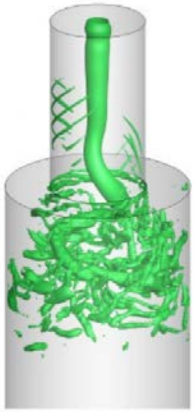
Role of Transition on Turbine Blades in Presence of Large Changes in Angle-of-attack

- Validation of Langtry-Menter transition model
- Analysis of oscillating S809 airfoil
- Application to a CWF study with transition.



Validation Study with GE Global Research

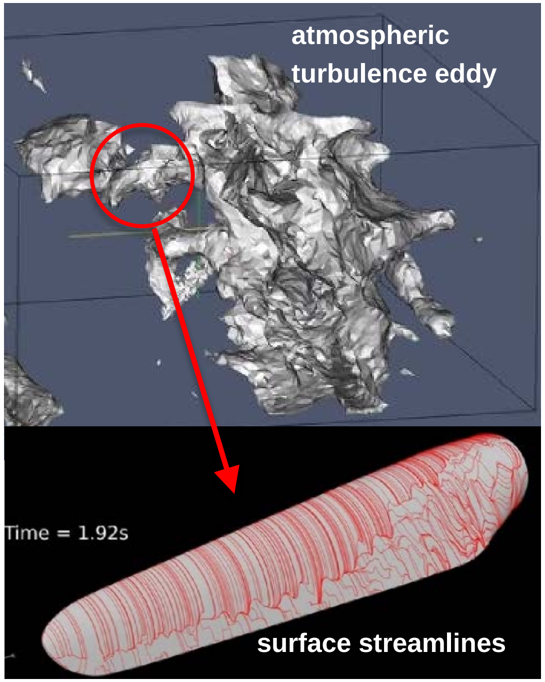
- Analysis of data from a 2008 GE field test with concurrent met, blade and shaft data.
- Will develop a CWF simulation for analysis and validation



Improved hybrid URANS-LES Models

- For accurate turbine-blade boundary layer separation response to atmospheric turbulence.

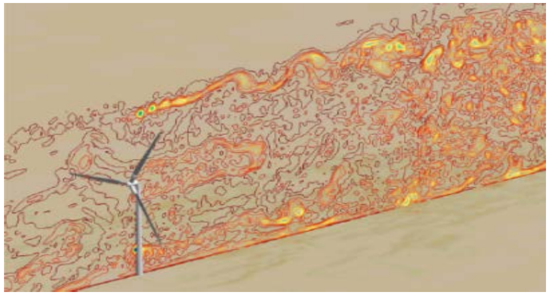
Technical Accomplishments



Cyber Wind Facility Development

- Much gridding/regridding, solver evaluations, validation experiments on airfoils, parked/rotating blades.
- CAD model developed, grid resolution studies completed.
- Successful in-house blending method implemented to couple URANS-SAS and LES turbulence models.
- Simulations: single blade rotating in atmosphere (SRBiA) on coarse (9M cells) and fine (58M cells) grid ; 3-bladed rotor CWF simulation on fine grid (158M cells) initiated.

Advanced Actuator Line Methods and Wake Prediction Analyses



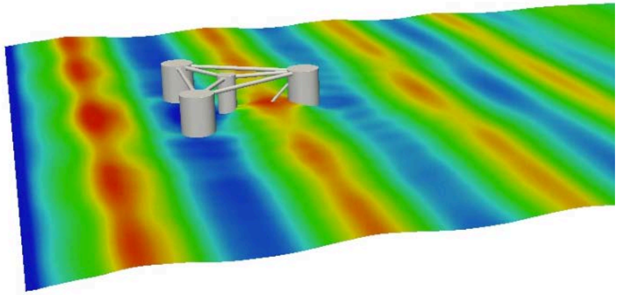
- Improved accuracy of current Actuator Line Method accomplished through modified Gaussian spreading.
- Quantified the effect of ALM modifications on wake turbulence in turbine-turbine interaction problem.
- Developed a new “vortex embedding” actuator line method.

Blade Elastic Deformation Module

- Structural-dynamics model of the NREL 5 MW rotor blade completed and validated against Sandia model results. Canonical interior blade structure and material properties identified and applied to blade structural-dynamics model.
- Actuator Line Model solver was augmented with for aeroelastic deformation.
- FSI simulation of parked blade with body-fitted fluid mesh was completed with uniform inflow and coarse fluid mesh to assess mesh motion solver performance
- Initial integration of FSI technology with CAD module complete.

Offshore Platform Module

- Development of new multiphase-CFD/6DOF solver which overcomes added-mass instability.
- Application to OC4 platform for free-decay and in waves. Excellent agreement with engineering models.
- Cyber experiments with hybrid RANS/LES for platform drag, inertia, and wave-excitation model coefficients.



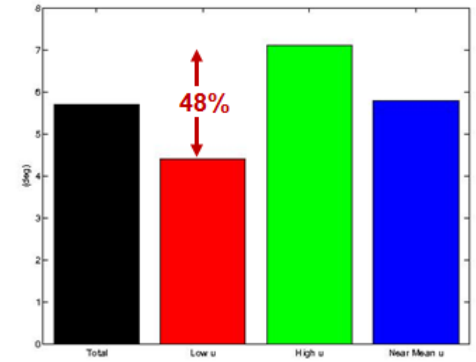
Contours of wave elevation for OC4 semi-submersible platform in waves

Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Lower-Order Model Analyses

- A major study using BEM embedded within LES of the ABL was completed which identified variability in AoA as major contributor to loading transients. Publication.
- A one-on-one comparison with CWF simulation is under way.



Variability in Angle of Attack (AoA) from different Atmospheric Turbulence Eddies

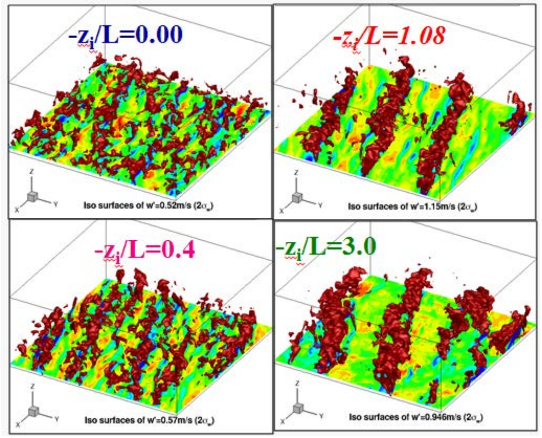
Wind Turbine Boundary Layer Transition Study

- Langtry-Menter transition model extensively studied and validated on flat plate and airfoils. We found it necessary to modify the model.
- Currently studying oscillating airfoil to mimic atmospheric nonsteady winds.

GE Validation Study

- Completed transfer of data, NDA, evaluation of met fields, and choice of analysis periods where atmospheric conditions can be simulated with LES.
- Completed full characterization of the data and preliminary analysis.
- Developed CAD model of GE wind turbine.

Atmospheric Boundary Layer Turbulence



- Completed an important study of changes in ABL turbulence eddying structure with daytime stability from neutral to moderately convective.
- The changes in structure are dramatic and will have major impacts on time-dependent wind turbine loadings

Meso-scale Weather Forcing of the ABL

- Worked with Sue Haupt & Tyler at NCAR; chose two frontal weather events to force ABL simulations observe response. We have analyzed/validated the WRF runs.
- We have developed the meso-micro coupling method and are implementing.

Awards and Recognition

- Schmitz, Brasseur, Paterson: Organ com., OpenFOAM Symp Wind Energy 2014.
- Paterson: Invited Speaker: Princeton, Notre Dame; Keynote Speaker: Open Source CFD, Germany; Marine & Offshore Enginrg, Kuwait; Host for NAWEA 15.
- Brasseur: Invited Speaker at NREL/NWTC, NCAR, U Colorado, NOAA, GE, Texas Tech, Sandia Nat. Labs, DOE, VA Tech, U Wyoming, U Minn, Frontiers Fluid Dyns, Puerto Rico, DTU-Risø, Keynote speaker: NTU Workshop, Singapore. Argonne Nat. Lab; Invited lecturer at von Karman Institute for Fluid Dynamics.

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	
Project Number:	DE-EE0005481
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project: A HPC "Cyber Wind Facility" Incorporating Fully-Coupled CFD/CSD for Turbine-Platform-Wake Interactions with the Atmosphere and Ocean												
Subtask 1.1: Atmospheric Boundary Layer Large-Eddy Simulation Module												
Subtask 1.2: Aerodynamic Loadings Computational Aerodynamics Module												
Subtask 1.3: Platform Computational Hydro Dynamics Module												
Subtask 1.4: Wake Actuator Vortex Embedding Module												
Subtask 1.5: Aeroelasticity Computational Solid Dynamics with FSI Module												
Current work and future research												
Complete MABL development												
Platform module												
Wake Actuator Vortex Embedding Module												
Aeroelastic module with FSI												

Research Integration & Collaboration

Partners and Collaborators: Dominic Von Terzi, Stefan Kern, Andreas Herrig from GE Global Research (industry partner); Matt Churchfield and Pat Moriarty from NREL-NWTC.

Communications and Technology Transfer: Too numerous to list all in detail. Representative examples:

- AIAA SciTech 2014, National Harbor MD (6 papers); AIAA Nashville,TN 2012 (3 papers), AIAA Orlando FL (1 paper)
- 7th OpenFOAM Workshop, Darmstadt, Germany, 2012 (1 paper)
- The Science of Making Torque from Wind: 2012 Germany (1 paper) 2014 Denmark (1)
- Two presentations at GE GR in Münich Germany (2012, 2013)
- 2nd Symposium on OpenFOAM in Wind Energy, Boulder, CO, 2014 (4 papers)
- Int. Conf. on Future Technologies for Wind Energy, WY (2 papers)
- APS Division of Fluid Dynamics meetings 2013, 2012 (8 papers)
- Many presentations (>25) at universities & national labs (see "Awards & Recognition")
- American Helicopter Society Meetings Wind Energy track (3 papers)
- Brasseur was keynote speaker and contributor to the organization of the Argonne National Lab, Workshop on Atmospheric Modeling at LES Scales, Sept 2013.

The overall outcome has been a great deal of interest in the CWF effort.

Next Steps and Future Research

FY14/Current research:

- Complete SRBiA and CWF computations and carry out several extensive analysis to quantify correlations between space-time winds and time-varying loads.
- Develop one-on-one comparisons between CWF, ALM and BEM and use to develop methods to improve lower order models for nojnsteadines.
- Implement generalized Actuator Line Embedding method; set up test harness.
- Complete mooring-line model, integration of ALM and aggressive application.
- Complete FSI model development, develop and carry out a cyber experiment.
- Complete transition study & hybrid modeling improvements; Implement in CWF.
- Complete meso-micro scale interaction analysis and consequences to WT loading.
- Deliverables: codes, test-cases, papers, student theses.

Proposed future research: (1) Expand CWF as part of HFM thrust area in a2E program; (2) Integrate CWF with ALM wind plant (WP) models and (3) use to develop advanced control strategies to enhance power capture while mitigating deleterious time-dependent loadings; (4) Apply CWF to continue development of a improved hierarchical model formulations specific to time-depending loadings for advanced design and control of WPs and WTs, (5) Apply CWF to the Virginia Offshore Wind Technology Application Program; (6) Apply CWF to aeroacoustics driven by time-dependent interaction between atmospheric and blade.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

High-resolution modelling of offshore wind turbines and farms: Model development and validation

Fotis Sotiropoulos
St. Anthony Falls Lab., University of Minnesota
fotis@umn.edu, 612-624-2022

Kelley Ruehl
Sandia National Laboratories

3/27/2014

Budget, Purpose, & Objectives

Total DOE Budget [1,2]: $0.00M

Total Cost-Share[1]:$.069M

Problem Statement: To develop novel high-fidelity, wave/atmosphere/turbine interaction computational tools for advancing design and optimization of offshore wind technologies

Impact of Project: Developed the offshore and multi-resolution version of the Virtual Wind Simulator (**VWiS**), which can simulate floating wind turbines in realistic ocean wave environments accounting for the coupling between waves, atmosphere and turbine dynamics. VWiS can help the industry take advantage of high-performance computing in designing efficient and reliable offshore turbines and optimizing turbine array performance.

DOE Program objectives and priorities

Optimize Wind Plant Performance: Reduce Wind Plant Levelized Cost of Energy (LCOE)

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

[2] *Project remained active using DOE funds received prior to FY2012*

Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

TASK 1: Develop the offshore, multi-resolution VWiS

Task 1.1: Virtual Wind Simulator (VWiS) @ Turbine-scale

- Curvilinear immersed boundary method for complex turbine geometry
- Large-eddy simulation (LES)
- Level set for free surface with Fluid-Structure Interaction (FSI)
- Wave generation method: apply surface pressure coupled with level set mehtod
- Coupling with large scale ocean wave model
- Low dimensional modeling of floating turbine dynamics
- Validation with floating platform experiment

Task 1.2: VWiS @ Farm-scale

- Actuator disk and actuator line models
- Prescribed waves and turbine motions or FSI level set simulation
- Coupling with large scale ocean wave model

Task 1.3: VWiS - Coupling across scales

- One-way coupling with mesoscale simulation: Inflow + Synthetic turbulence
- Multi-resolution capability via manual/adaptive mesh refinement (AMR) model

Task 2: Massively parallel implementation of VWiS

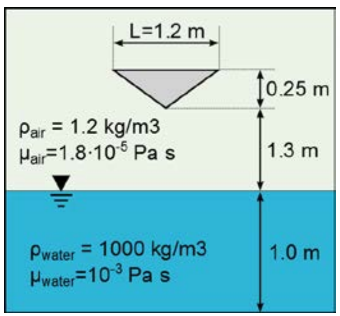
- I/O optimization and I/O parallel implementation
- Algorithm restructuring for data locality and cache reuse
- Performance optimization on heterogeneous systems

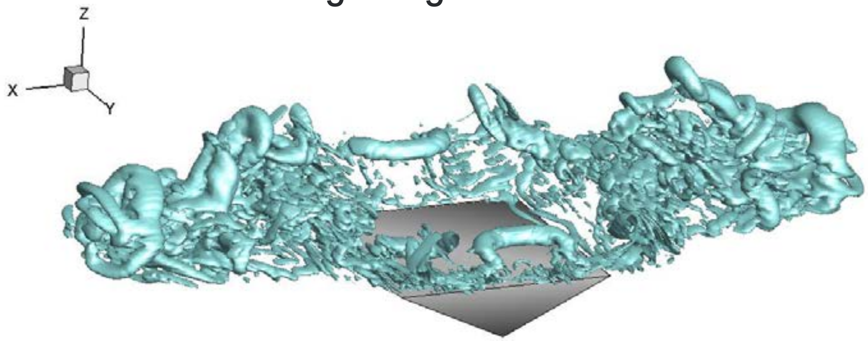
Task 3 Physical Model Experiment

- Turbine/wave interactions experiment
  - SAFL main channel
  - Air flow is neglected
- Wave dynamics of oscillating turbine
  - SAFL wind tunnel
  - Apply oscillatory motion to the model wind turbine
- Kinematic and performance of downwind turbines
  - Elastically mount set of turbine on the wind tunnel surface

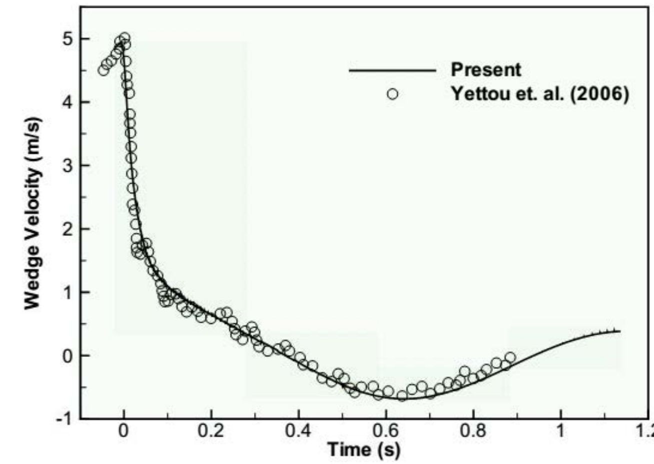
VWiS @ Turbine scale : FSI of floating structures

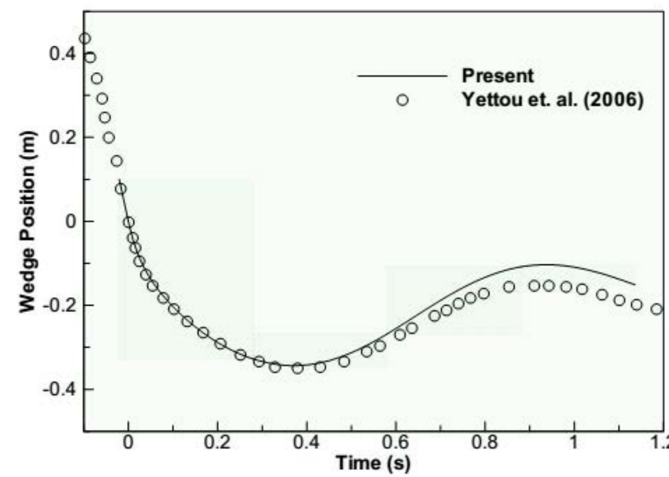
- Novel Level-Set Two-Phase Flow Solver with FSI
  - Simulate complex floating structures in 6 DOF
  - LES with wall modeling for turbulent flows
  - Validation with benchmark numerical and experimental such as free falling wedge

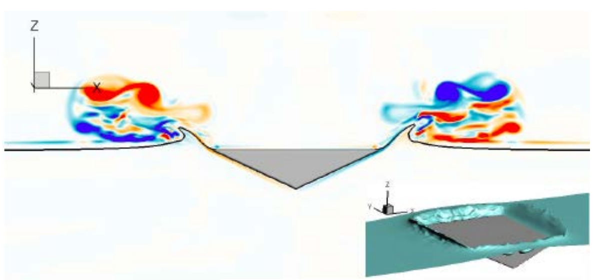




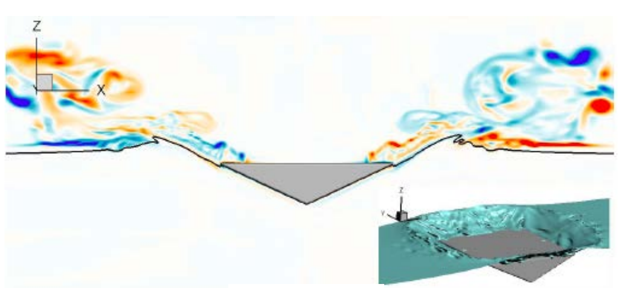
3D coherent structures in the air phase induced by the breaking wave







A

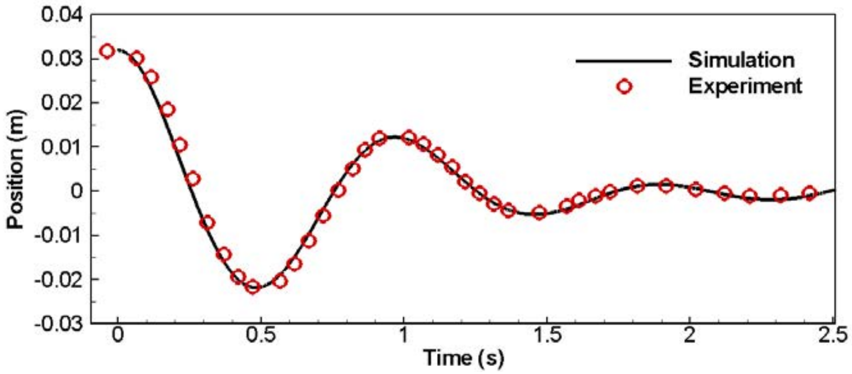


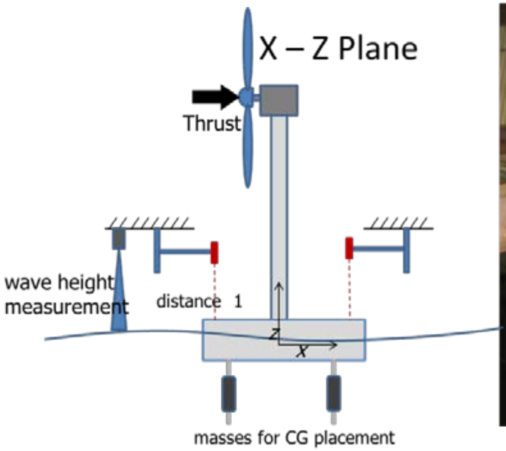
B

VWiS @ turbine scale: Validation of floating platform FSI with SAFL experiments

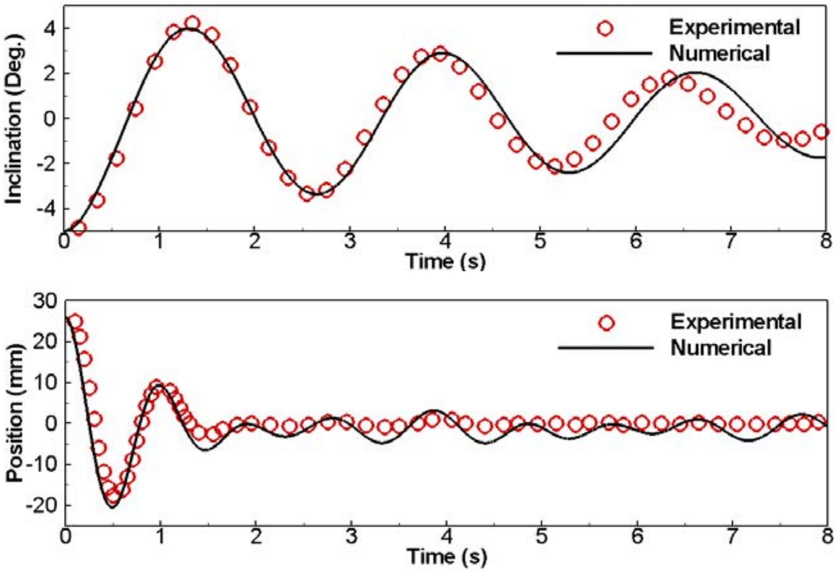
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Free heave decay test

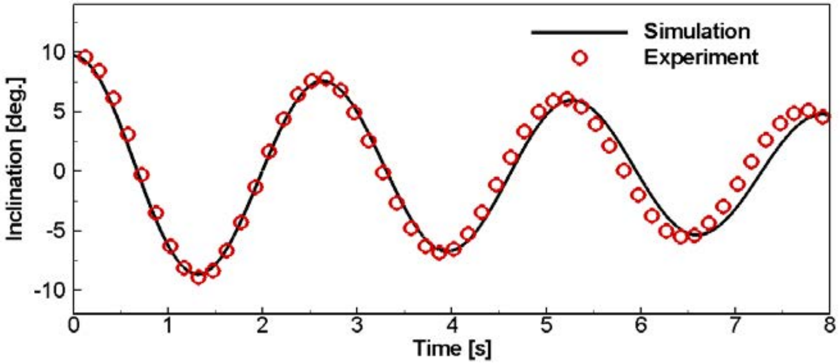




- Free heave and pitch decay test



- Free pitch decay test

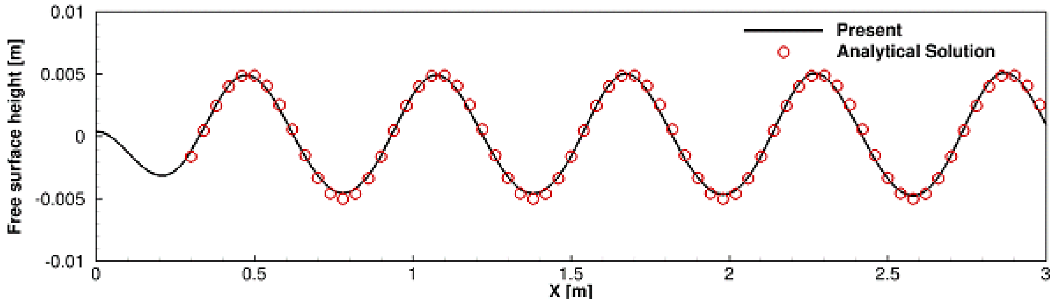


VWiS with level sets: Generating waves by applying pressure at the free surface

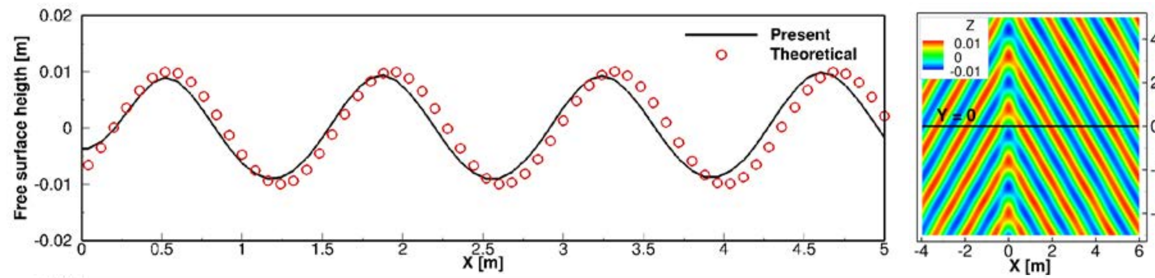
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Monochromatic wave
  - Wave length L=0.6m

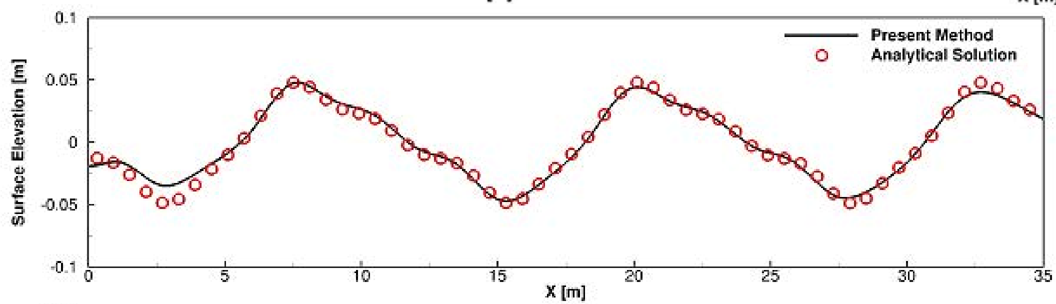
Lines: VWiS with level sets
Points: Potential wave theory



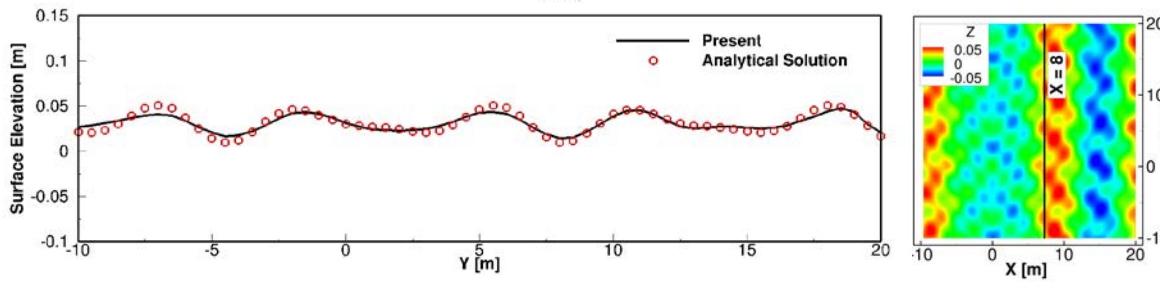
- 3D directional wave
  - L=1.2
  - Direction: 30deg.



- Superposition of waves
  - Incorporated from far-field
  - L_1=12.5, L_2=6.2 L_3=1.5 [m]



- Superposition of 3D directional wave
  - Incorporated from far-field
  - L_1=12.5, L_2=4.5, L_3=2.5 [m]
  - Directions: 0, 45, -30 [deg.]

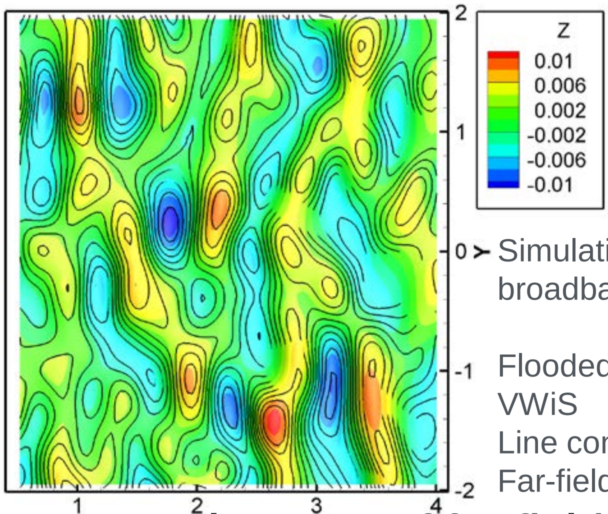


VWiS @ Turbine scale: Floating turbine FSI driven by ocean waves

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- **Far-field/near-field coupling**

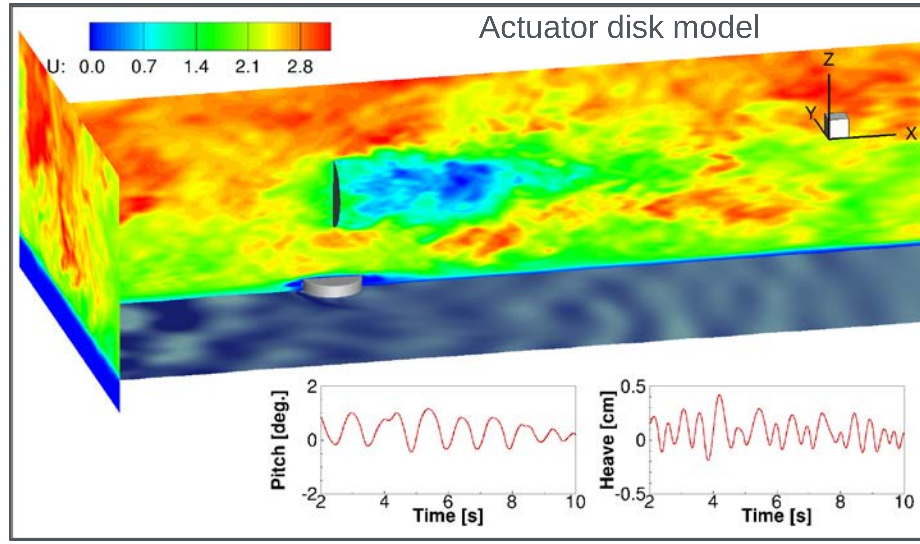
  Apply far-field model to obtain pressure at the free surface and prescribe this pressure field as input to the VWiS with level sets to simulate near-field waves



Simulation of broadband waves

Flooded contours: VWiS
Line contours: Far-field wave model

- **2 DOF FSI simulation of floating turbine under real-life ocean waves**



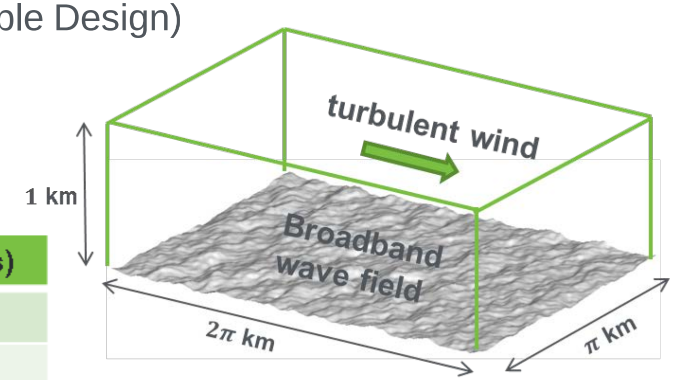
- **Development of far-field wind/wave conditions for full turbine simulation**
  - SNL 13.2 Floating wind turbine (based on OC4 Semi-Submersible Design)
  - Wind and wave conditions representative of Maine Climate

Parameters for wind field:

Water depth(m)	T_{peak} (s)	λ_{peak} (m)
110	12.75	251.33

Parameters for wave field:

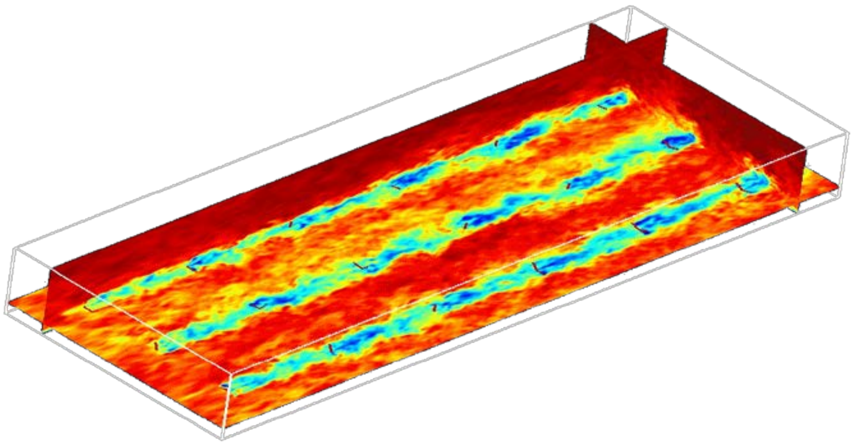
$u_{z=5m}$ (m/s)	$u_{z=133.5m}$ (m/s)	$u_{z=1000m}$ (m/s)
6	7.95	9.14
10	13.24	15.23



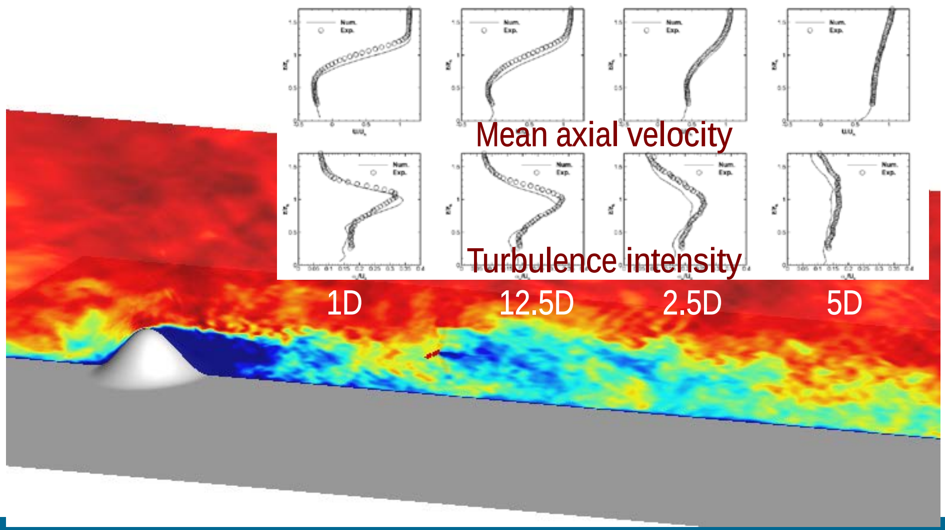
VWiS @ Wind farm scale: Application and validation for land-based wind farms

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

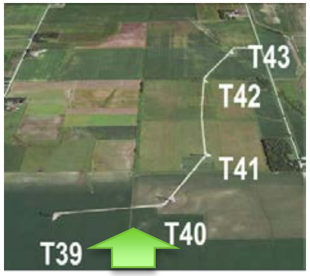
- Wind tunnel experiments
  - Single turbine & turbine arrays



  - Complex topography: Turbine/hill interaction

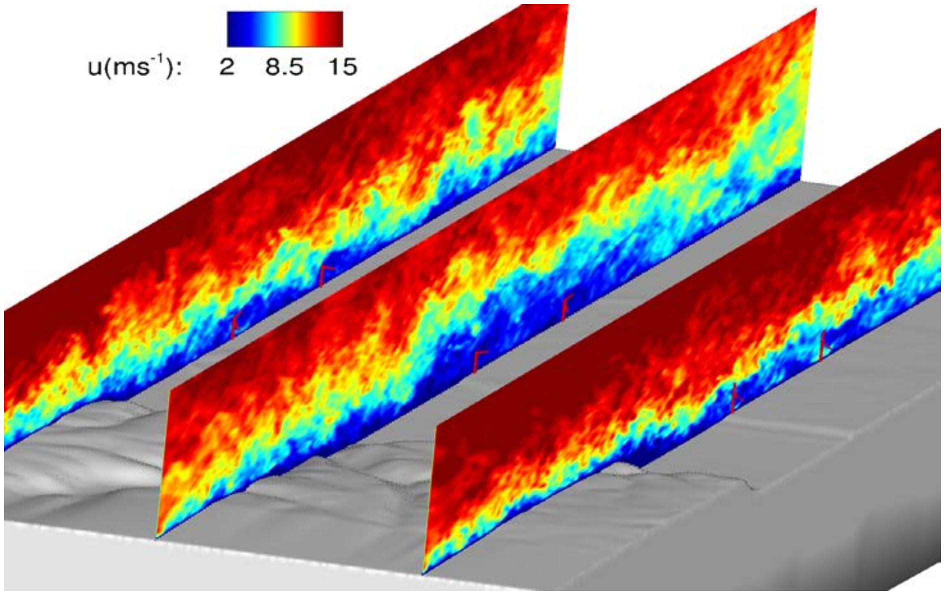


- Wind farm in Mower County, MN



Power (MW)	T40	T41	T42	T43
Measured	**2.15**	**2.15**	**1.86**	**1.85**
VWiS	**2.15**	**2.12**	**1.27**	**2.03**

- Complex terrain: Prairie Island, MN



Multi-resolution VWiS: VWiS with Manual/Adaptive Mesh Refinement

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Motivation…

- ✓ Resolve real life problems
- ✓ Multi-resolution numerical simulations
- ✓ Manual / adaptive grid refinement
- ✓ Low CPU cost accurate calculations

Features of the AMR solver…

- ✓ Strong coupling between different levels of refinement
- ✓ 2nd order temporal and spatial parallel discretization
- ✓ The fractional step method ensures mass balance
- ✓ DNS calculations coupled with the Actuator Line Model

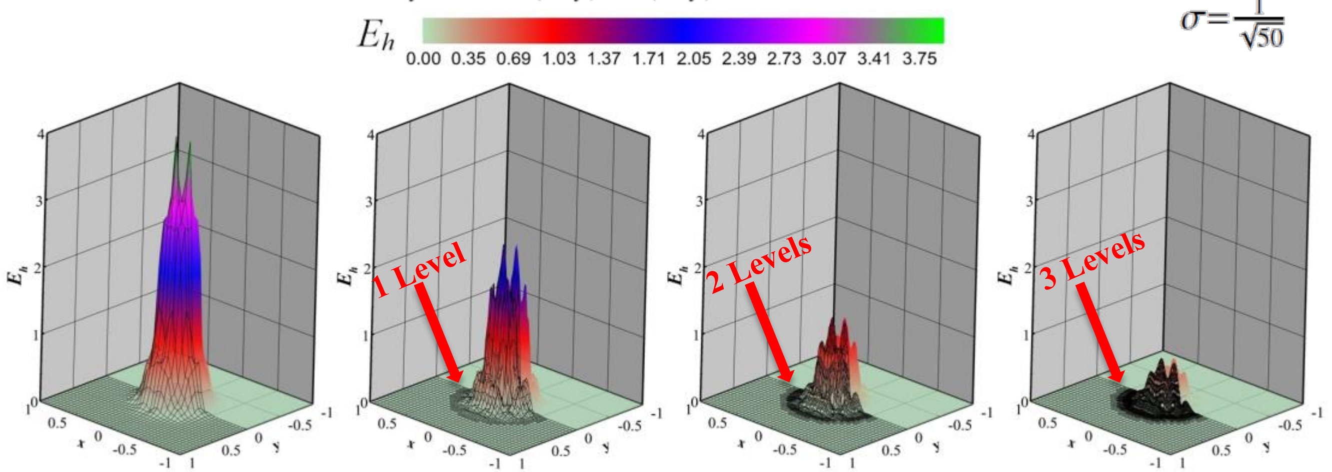
Validating the discretization procedure…

- ✓ Solution of the Poisson equation with AMR (Circular Gaussian function modulated by sinusoidal fluctuation)

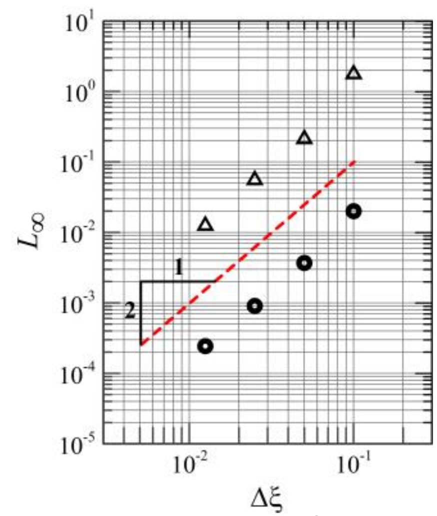
$$\nabla^2\varphi = S(x,y) \qquad \varphi(x,y) = A\exp\left(-\left((x-x_0)^2+(y-y_0)^2\right)/2\sigma^2\right)$$

$$S(x,y) = -100Ae^{-B} + 50^2x^2Ae^{-B} + 50^2y^2e^{-B}A - 500\pi xAe^{-B}\cos(5\pi x)\sin(5\pi x)$$
$$-500\pi yAe^{-B}\sin(5\pi y)\cos(5\pi y) - 50\pi^2e^{-B}$$

$$A = \sin(5\pi x)\sin(5\pi y)$$
$$B = 25x^2 + 25y^2$$
$$x_0 = y_0 = 0$$
$$\sigma = \frac{1}{\sqrt{50}}$$



Distribution of the energy of the error (primary grid 40x40).



L_∞ error; **o** - uniform grid, **Δ** - 3 level refinement.

Multi-resolution VWiS: VWiS with Manual/Adaptive Mesh Refinement

AMR solver coupled with actuator line model

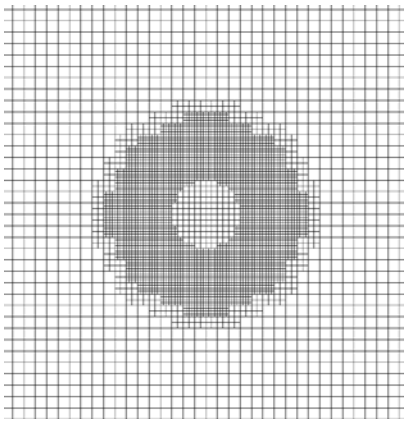
Uniform inflow

2 Level Annular Refinement:

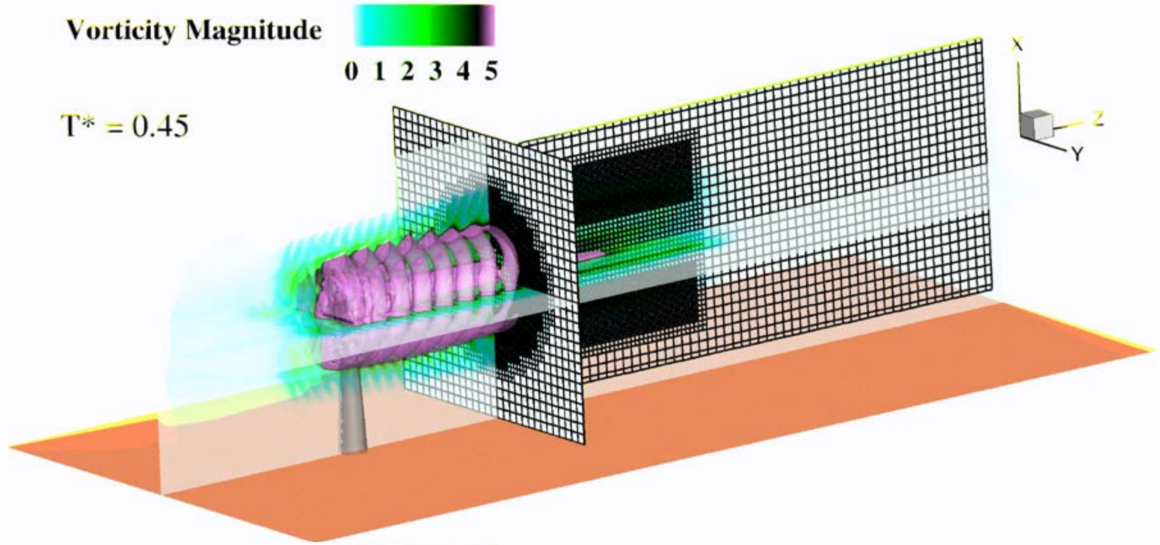
- Around the tip vortex region
- Around the blades to increase the numerical accuracy (ACL model)

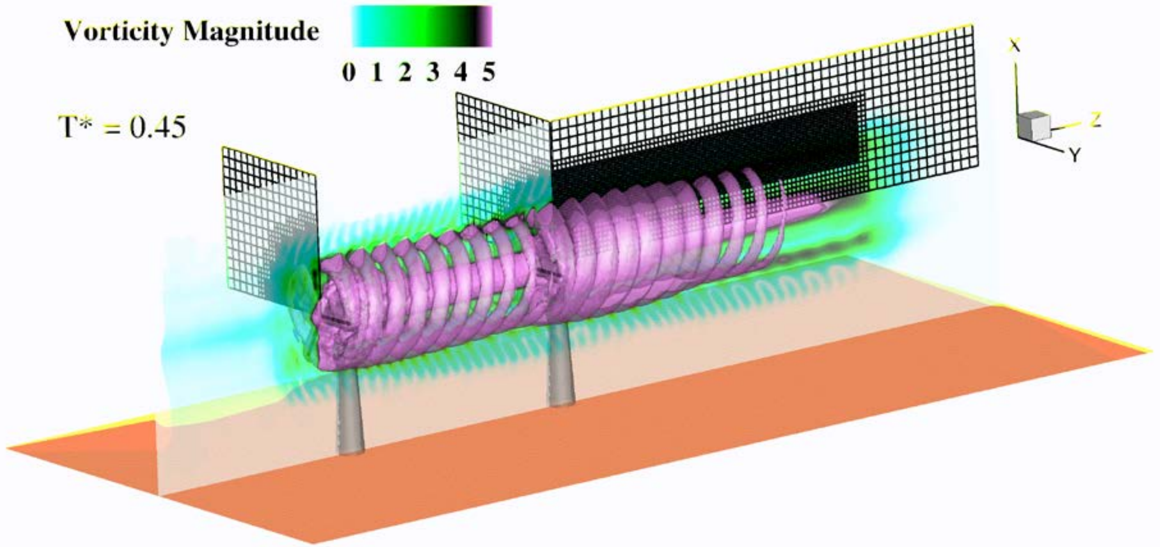
Unstructured grid : 1 M cells

Equivalent uniform grid : 16 M cells



2 Level annular refinement.





VWiS Scalability Studies on Sandia Supercomputers

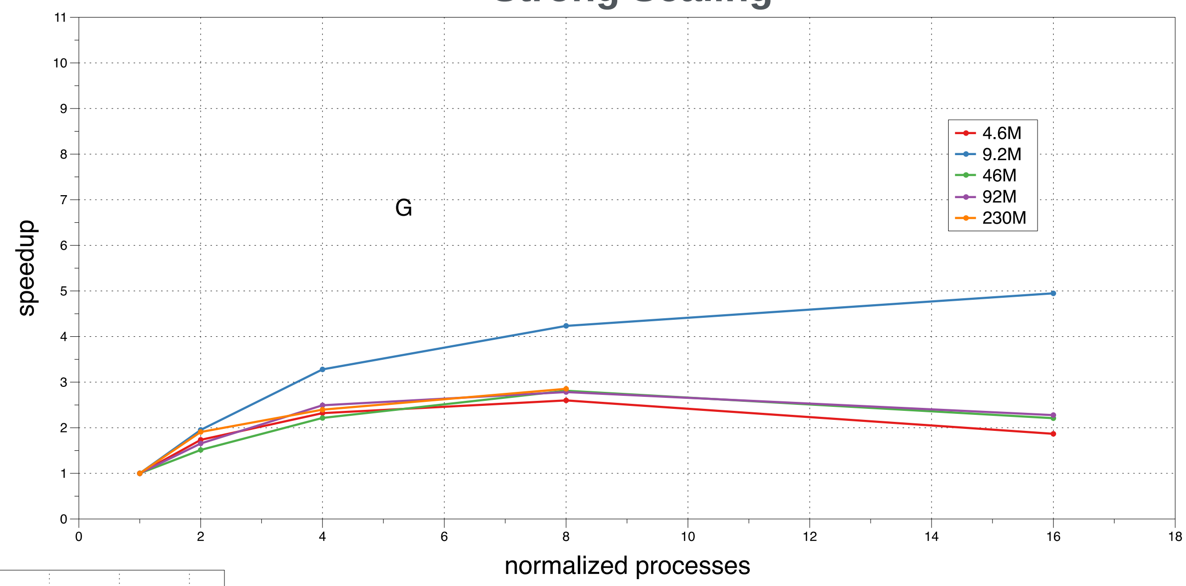
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Motivation…

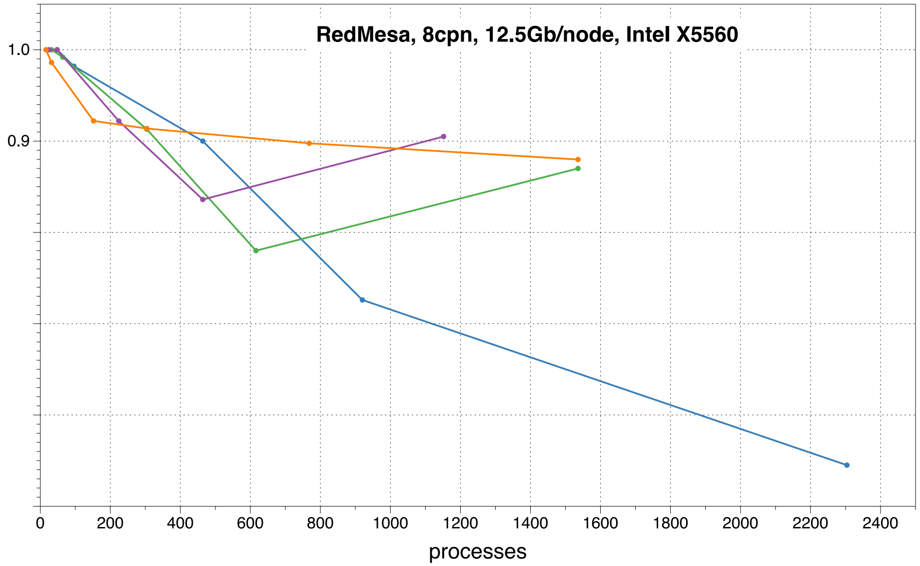
In order to efficiently utilize Sandia's supercomputers, RedSky and RedMesa, VWiS should show good strong and weak scaling.

Strong Scaling: a measure of simulation turnaround time (quickness)
Weak Scaling: a measure of the ability to handle larger problems with many cores (efficiency)

Strong Scaling



Weak Scaling



Progress…

Dedicated Application Time on RedMesa enabled us to test scaling up to 14,000 cores.

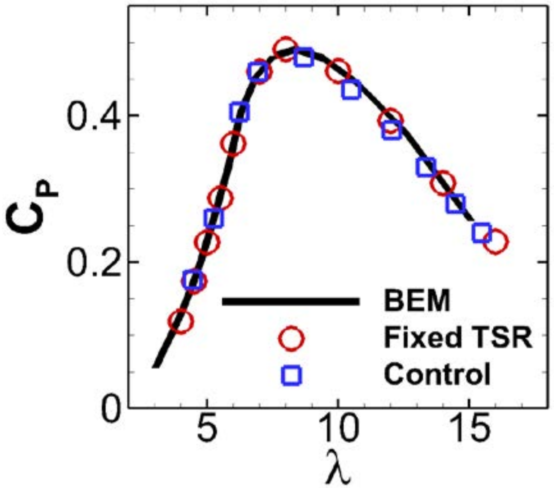
Strong scaling was improved from 20-30% to 40-50%. Further improvement expected as intranode communication addressed and software tuned for hardware.

Weak scaling shows about 85-90% efficiency up to 1,500 cores. Typical simulations run about 200k grid points/core.

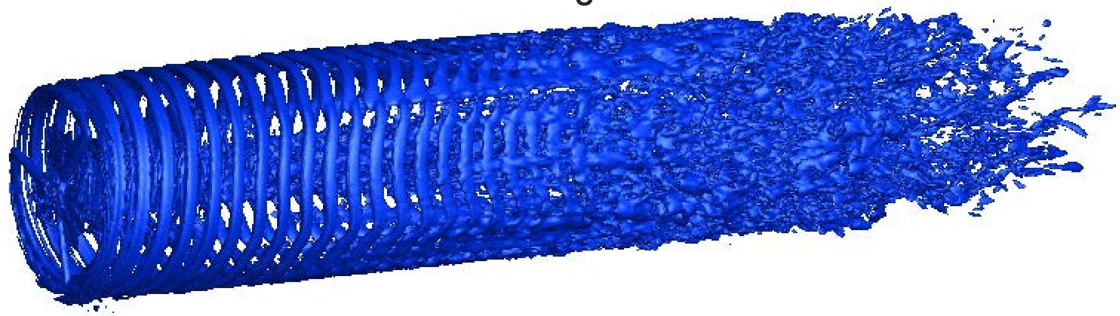
VWiS simulations of full-scale wind turbines using Sandia Supercomputers

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

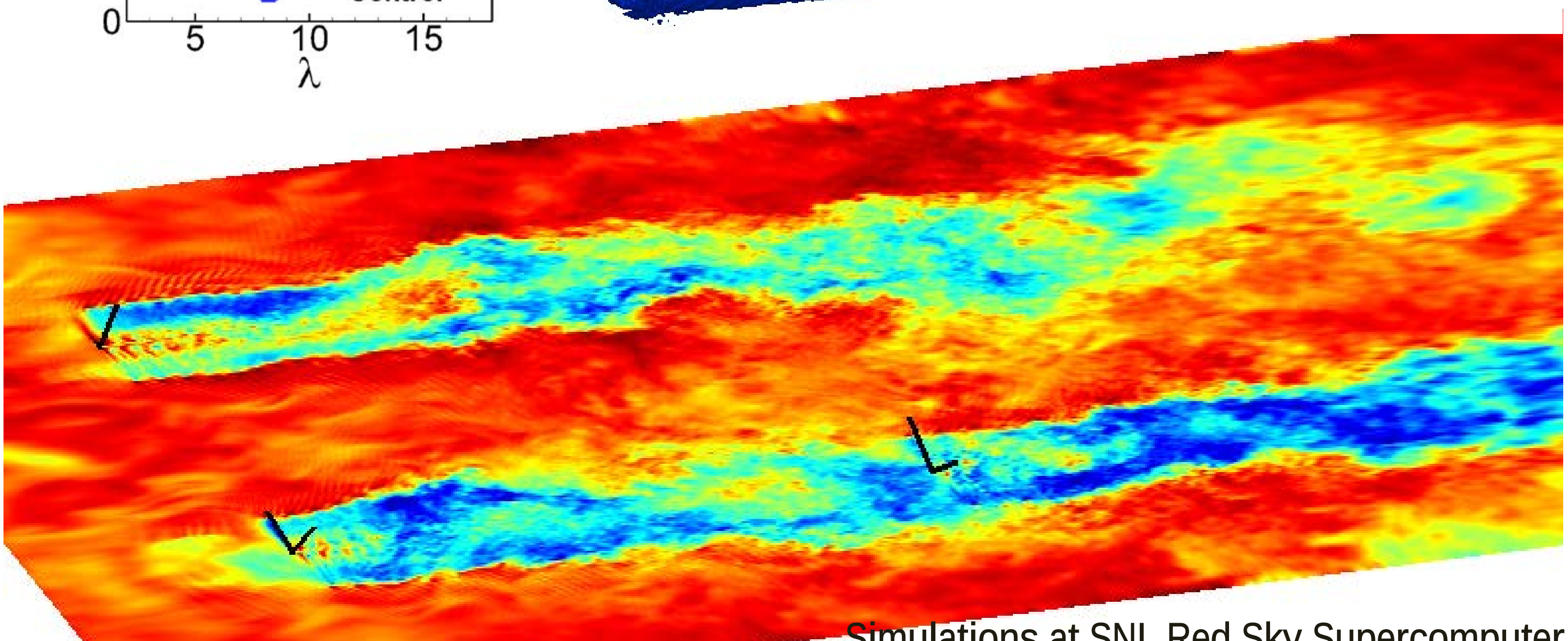
EOLOS turbine



Simulation of the University of Minnesota 2.5MW EOLOS turbine with various turbine control strategies



SWiFT turbines



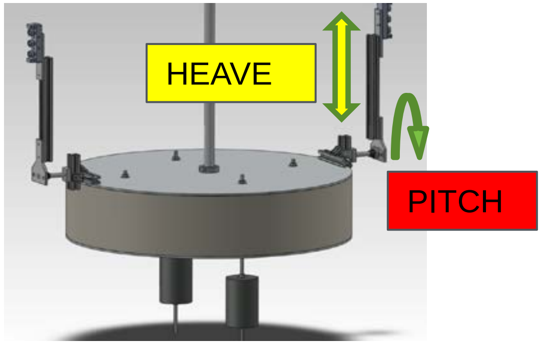
Simulations at SNL Red Sky Supercomputer

Laboratory experiments for VWiS validation

Floating turbine model:
1:100 scaled in Froude similarity, with respect to the 13.2MW concept turbine (SNL)

Available degree of freedom: 2D heave + pitch

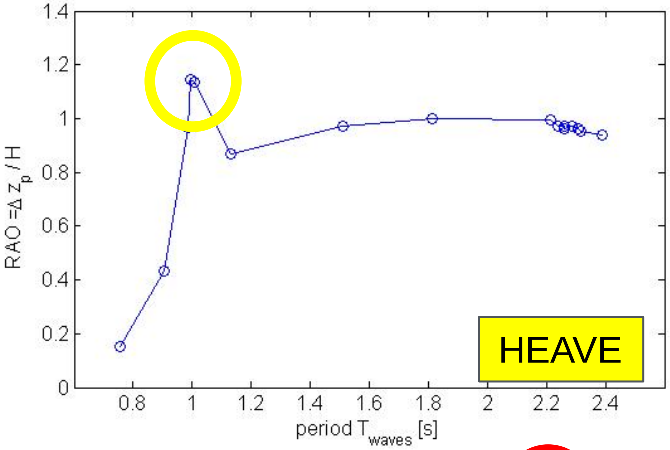
Moment of inertia, destabilizing and restoring moments (gravity, buoyancy and thrust) accordingly scaled

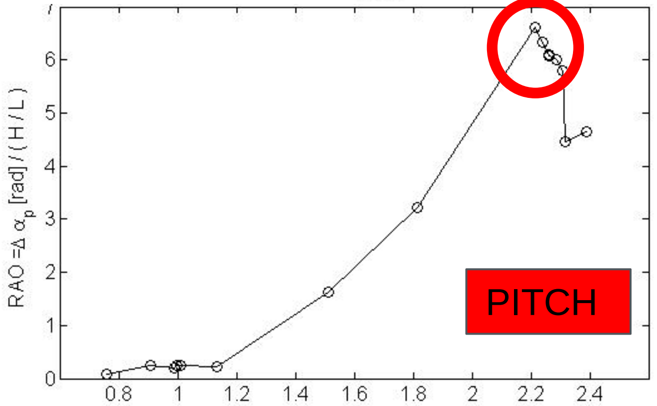


Wave characteristics:
Scaled waves using buoy data from the Pacific Ocean Oregon coast
Thrust force controlled by turbine rotor angular velocity (calibration required)

New wave maker facility, operating on a 65m long 3m wide channel

Response amplitude operator

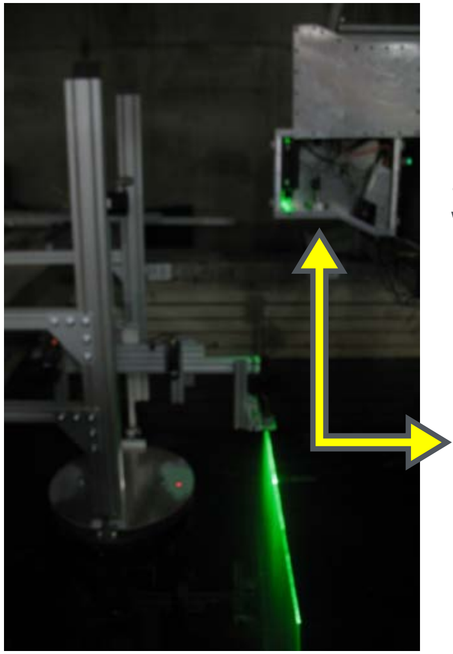




Results:
pitch and heave time series were recorded under different waves and thrust reproducing the following cases: wind without waves, waves with constant wind, variable wind gusts, waves without wind

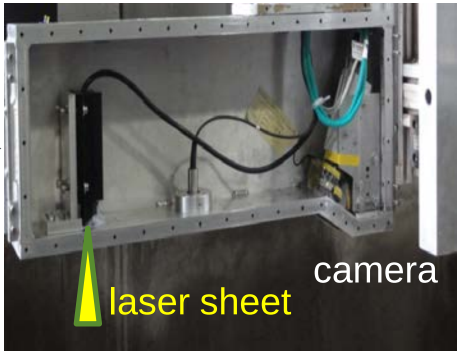
Laboratory experiments for VWiS validation

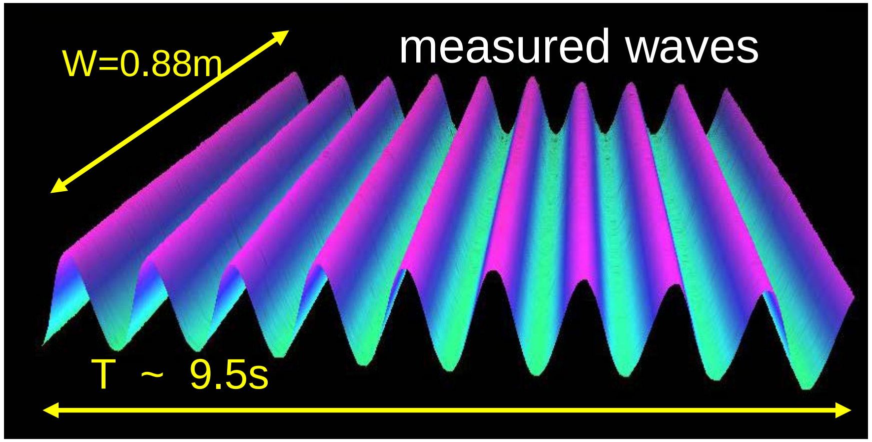
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



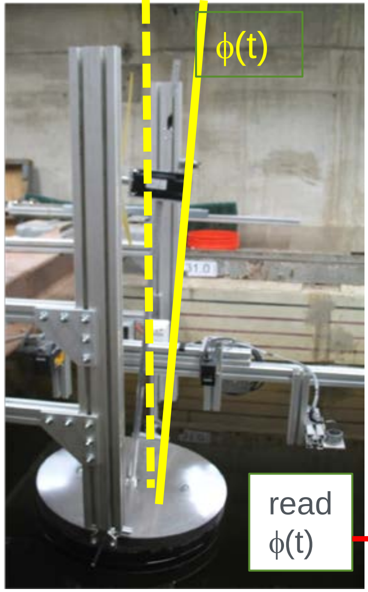
Laser wave scan

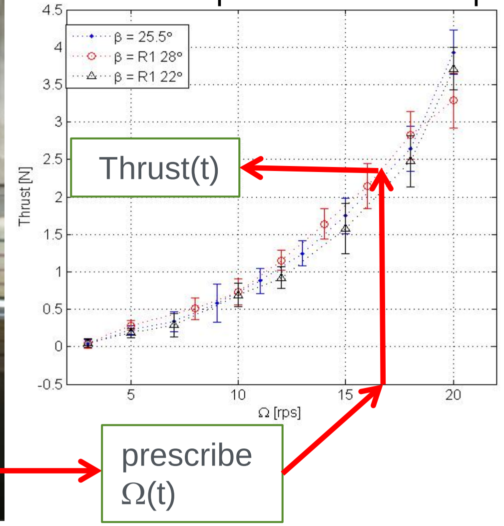
2D Spatio-temporally resolved waves z=z(y,t) using floating biodegradable particle tracers

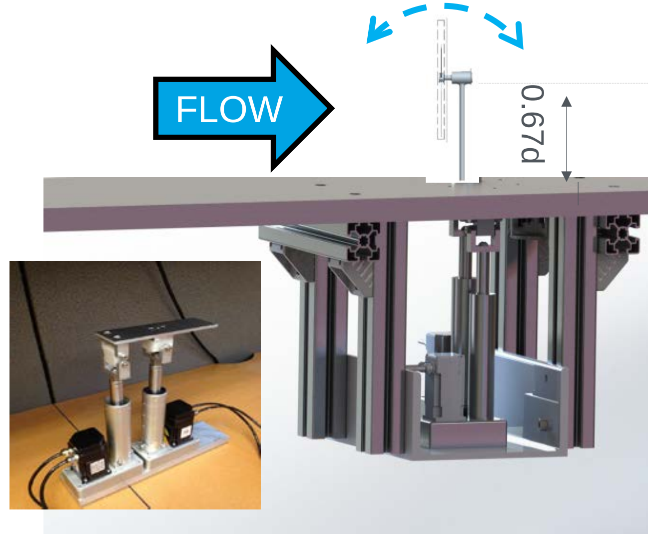




Pitch mitigation strategy
via closed loop control of rotor speed







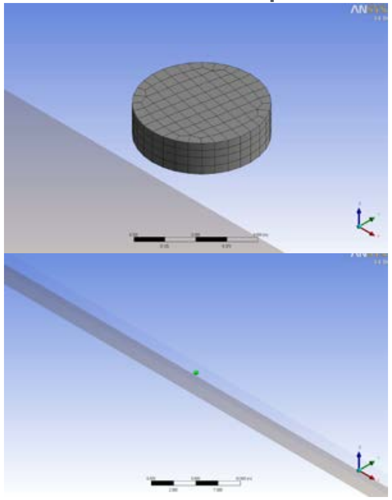
Next phase: wind tunnel measurements with induced pitch & heave motions

Validation of low-dimensional model of floating platform dynamics

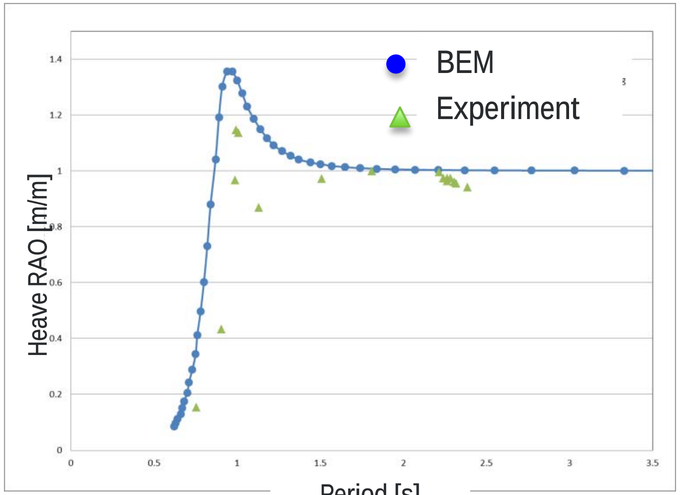
Boundary Element Method (BEM) low resolution simulations of wave tank experiments

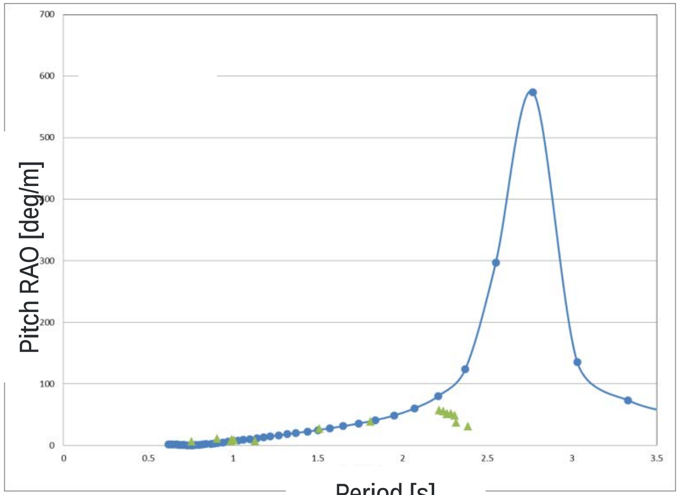
- ANSYS-AQWA frequency-domain model
  - BEM results do not include drag or viscosity
- Simulations capture structural trend of response, but are *highly* inaccurate near resonance
- Results reiterate the need for higher order models that include full physics

Cylindrical Platform Model Setup



Experimental Data Comparison





Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Task	Task Name	FY 2012 Q1 (Oct–Dec)	FY 2012 Q2 (Jan-Mar)	FY 2012 Q3 (Apr-Jun)	FY 2012 Q4 (Jul-Sep)	FY 2013 Q1 (Oct–Dec)	FY 2013 Q2 (Jan-Mar)	FY 2013 Q3 (Apr-Jun)	FY 2013 Q4 (Jul-Sep)	FY 2014 Q1 (Oct–Dec)	FY 2014 Q2 (Jan-Mar)	FY 2014 Q3 (Apr-Jun)	FY 2014 Q4 (Jul-Sep)
1,0	**Development of computational models for offshore farms and turbines**												
1,1	**Development of the turbine geometry resolving model**												
1.1.1	CURVIB-FSI model for floating structures												
1.1.2	Develop the 3D underwater foundation and floating platform model												
1,1,3	Wave generation method and coupling with large scale model												
1.1.4	Application of the model to simulate a complete floating offshore turbine												
1.1.5	Validation of the model with laboratory experiments												
1,2	**Development of the wind-farm scale model**												
1.2.1	Develop actuator disk and actuator line parameterizations for wind turbine												
1.2.2	Develop low dimensional aero-elastic and floating platform models												
1.2.3	Development of coupled wave model for wind farms												
1.2.4	Validation with the proposed laboratory experiments												
1,3	**Coupling of models across scales**												
1.3.1	Develop an AMR model for coupling LES models across scales												
1.3.2	Use AMR to couple wind farm-scale LES model with WRF and ROMS												
1.3.3	Apply LES-WRF model to multi-scale simulations of floating wind farms												
2,0	**Massively parallel implementation of the computational models**												
3,0	**Experiments for model validation**												
3,1	**Turbine/wave interactions without airflow**												
3,2	**Wake dynamics of an oscillating turbine**												
3,3	**Kinematics and performance of an elastically mounted wind farm**												
4,0	**Project management and reporting**												

Legend	
	Work Completed
	Actual Work
	Milestones & Deliverables (Original Plan)

Partners, Subcontractors, and Collaborators:

University of Minnesota:

Fotis Sotiropulos, Michele Guala, Lian Shen
Xiaolei Yang, Dionysios Angelidis, Xin Guo
Antoni Calderer and Christopher Feist

Sandia National Laboratories:

Kelley Ruehl, Todd Griffith

Journal Publications & Presentations:

Calderer, A., & Sotiropoulos, F., "Level set Immersed Boundary Method for Coupled Simulation of Air/Water Interaction with Complex Floating Structures," submitted *J. Comp. Physics*, 2014

Kang, S., Yang, Y., & Sotiropoulos, F. "On the onset of wake meandering for an axial flow turbine in a turbulent open channel flow," in press, *J. Fluid Mechanics*, 2014.

Yang, X., Sotiropoulos, F. et al., "Large-eddy simulation of turbulent flow past wind farms in complex terrains: The Virtual Wind Simulator (VWiS)," in revision, *Wind Energy*, 2014.

Yang, X., Kang, S., and Sotiropoulos, F., "Computational study and modeling of turbine spacing effects in infinite aligned wind farms," *Phys. of Fluids* **24**, 115107, 2012.

- 3 Presentations, 66th Annual Meeting of APS Division of Fluid Mechanics, November 2013 Pittsburgh
- Presentation and conference paper at the ERCOFTAC Symposium on UNSTEADY SEPARATION IN FLUID-STRUCTURE INTERACTION, June 2013, Greece
- 2 presentations, 65th Annual Meeting of APS Division of Fluid Mechanics, November 2012 San Diego.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

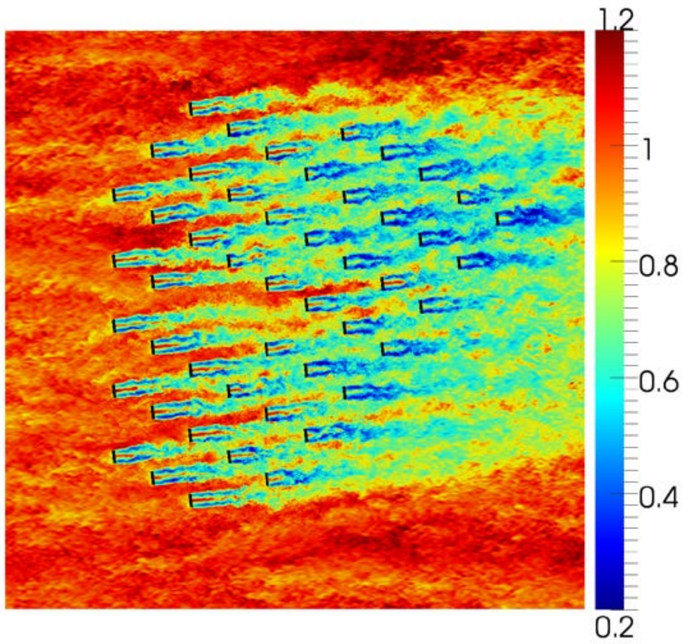
FY14/Current research:

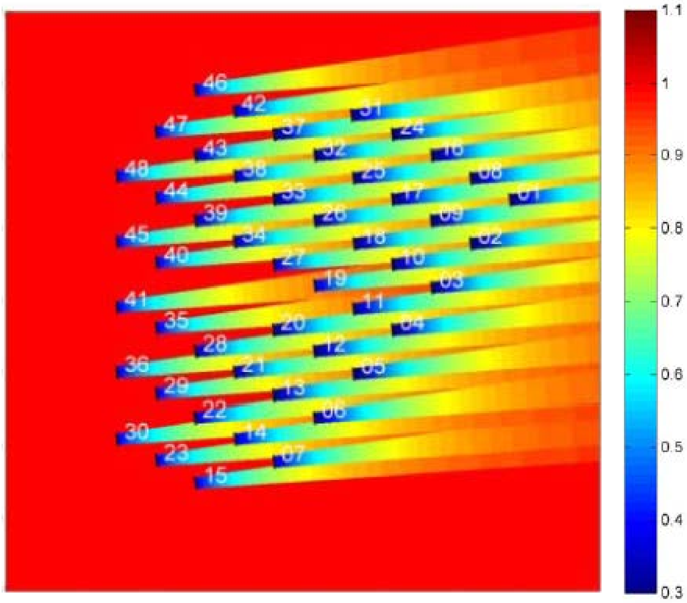
- Finalize validation of turbine scale model and simulate several full turbine configuration cases.
- Implement LES in the AMR solver.
- Scalability and optimization of the code
- Complete wind tunnel physical model experiments.

Proposed future research:

- Incorporate torque and pitch control algorithms in VWiS for floating wind farms.
- VWiS validation with field data
- Prepare documentation for and package the VWiS code to make it available in an open source environment

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





Simulator for Plant Applications

Patrick Moriarty

NREL

patrick.moriarty@nrel.gov

303-384-7081

March 24, 2014

Budget, Purpose, & Objectives

Total DOE Budget [1,2]: $0.00M

Total Cost-Share[1]:$.255M

Problem Statement: Industry wind plant layout and development tools fail to model important physics and are not able to predict turbine structural loading. Wind plant control represents a paradigm shift in control design.

Impact of Project: Improved and validated industrial wake models will lead to more accurate prediction of energy losses and turbine loading within wind plants. Wind plant control has the potential to increase plant energy capture and reliability.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

[2] *Project remained active using DOE funds received prior to FY2012*

Technical Approach

Engineering Wake Model Development

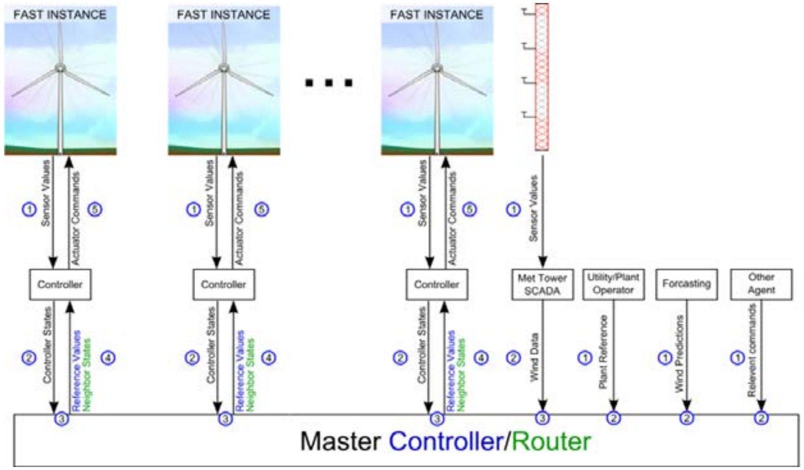
- Dynamic Wake Meandering (DWM) model development
- FLOw Redirection and Induction in Steady-state (FLORIS) model

Wind Plant Data Analysis and Validation

- Access to offshore wind plant data including structural loading from two turbines

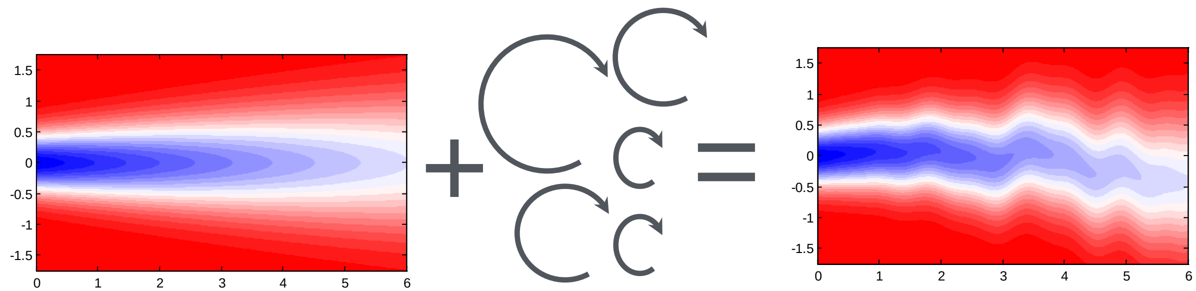
Wind Plant Control

- Studies of axial flow control and wake steering
- HPC model usage and engineering model development
- Wake tracking



Dynamic Wake Meandering Model

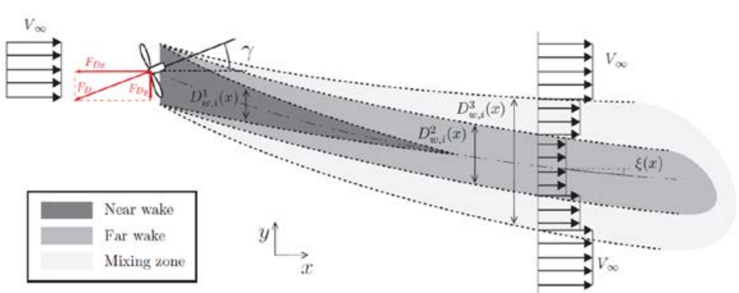
- Added to NREL FAST 8.0 Framework
- Compares well to SOWFA HPC code and power loss data
- Validation of structural loads ongoing



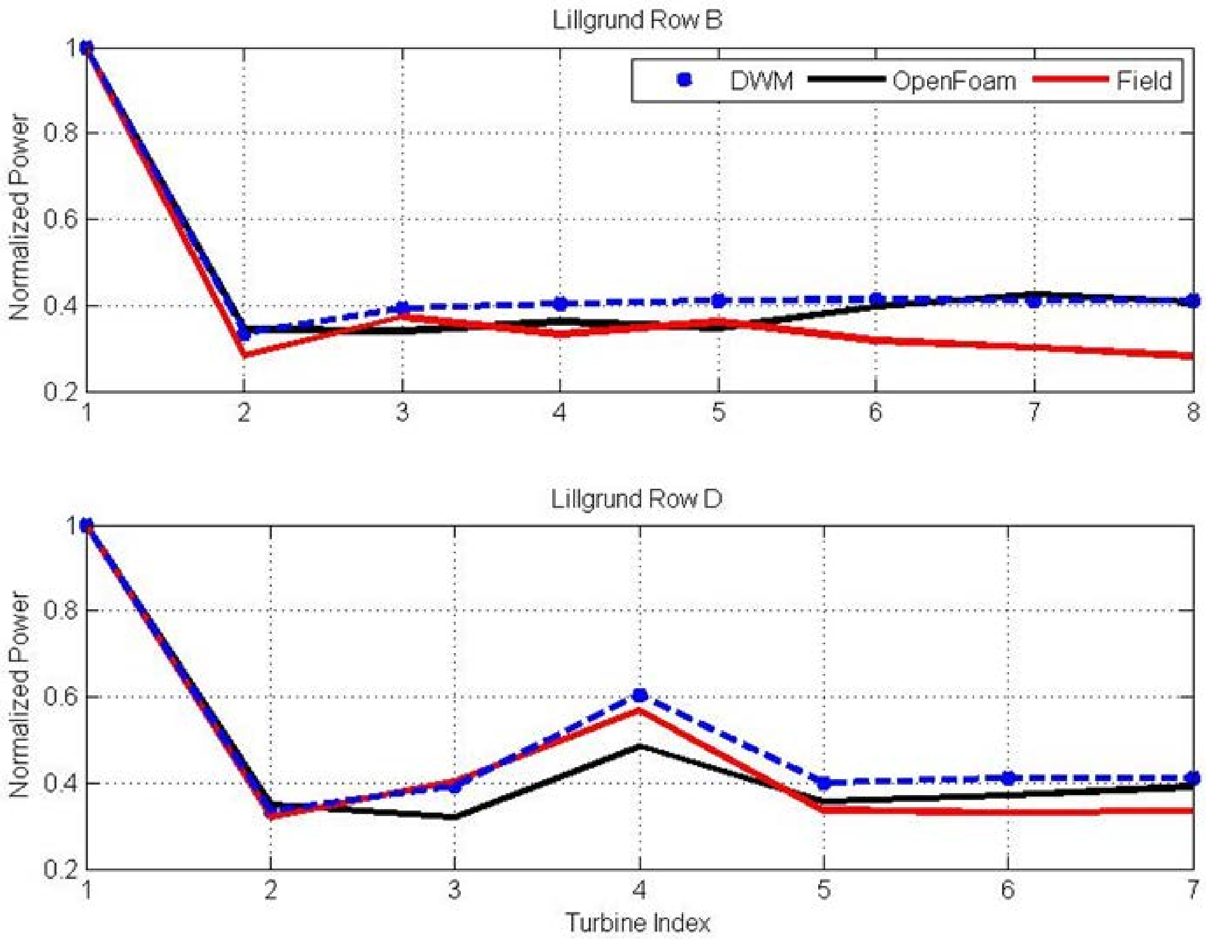
Base Wake Turbulence DWM (snapshot)

FLORIS Model

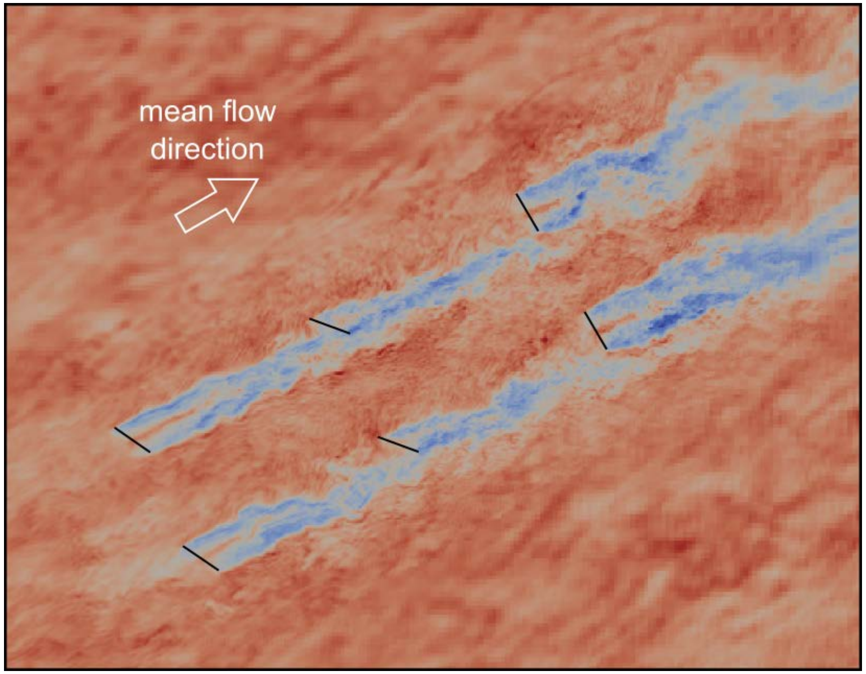
- Wind plant control with wake steering
- Power only
- TUDelft collaboration

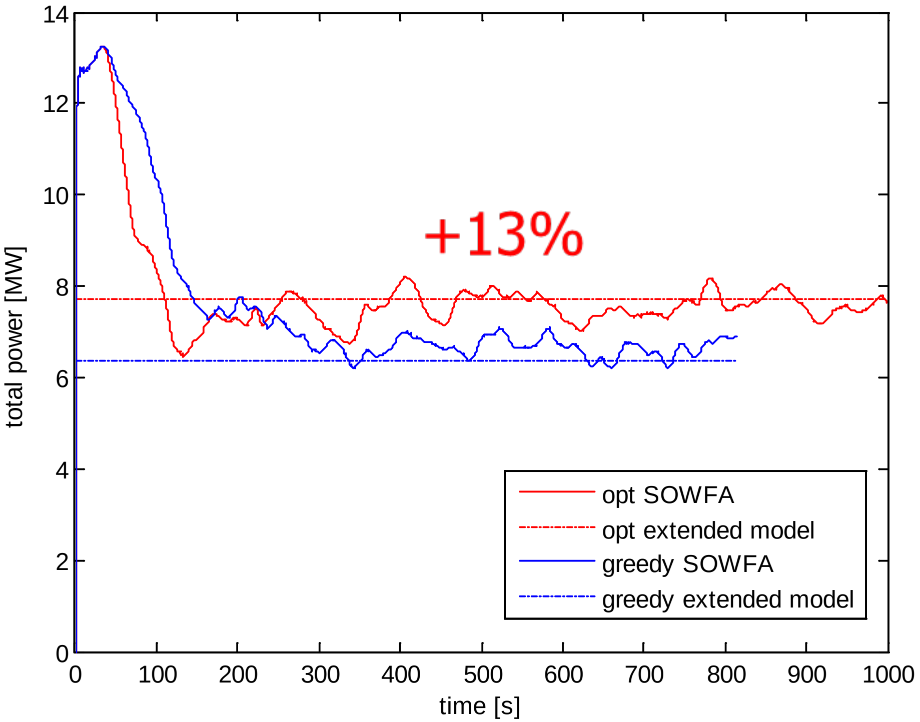


DWM validation from operating wind plant SCADA data



Wind Plant Control





Need to test at full scale

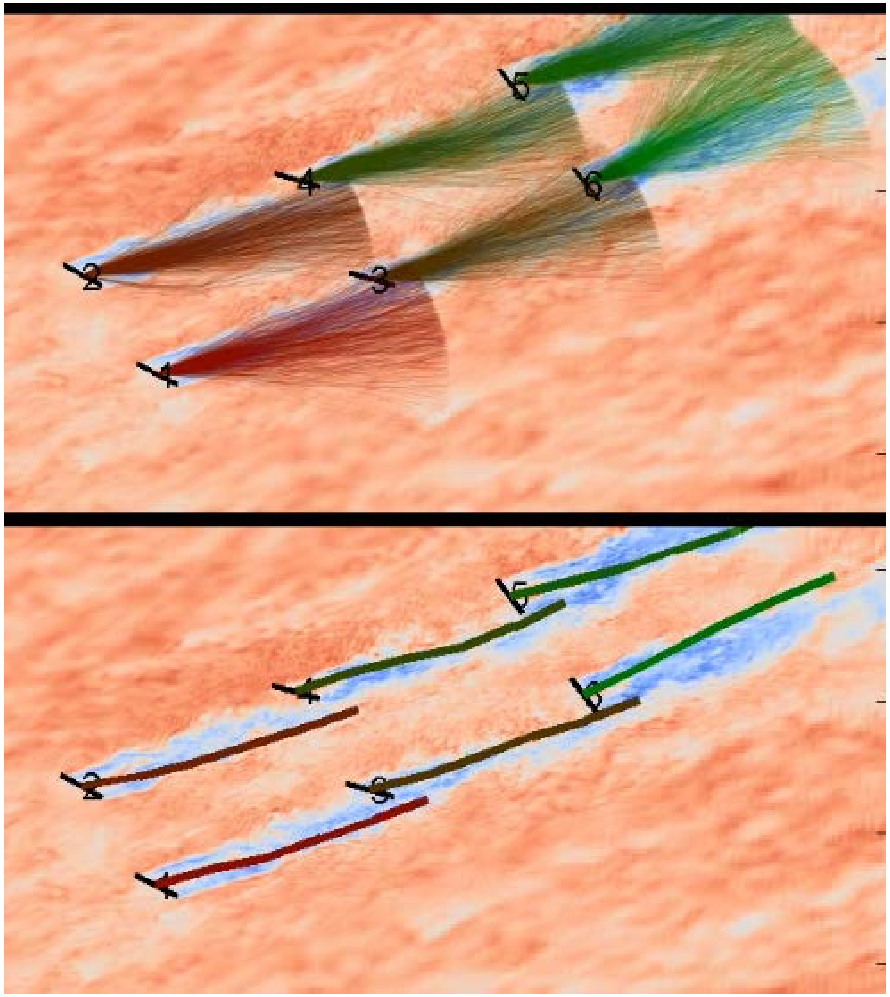
TU Delft

University of Colorado Boulder

Accomplishments and Progress

Wake tracking

- Particle Filtering
- Use only existing turbine channels:
  - Nacelle wind speed
  - Nacelle wind direction
  - Yaw angle
  - *Optionally: Blade bending moment (strain)*



Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	2.5.0.10
Project Number	
Agreement Number	2.5

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

Task / Event	FY2012				FY2013				FY2014			
	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Simulator for Plant Applications												
Q2 Milestone: Complete agreement for offshore wind plant data exchange												
Q4 Milestone: Dynamic Wake Meandering model incorporated into FAST												
Q1 Milestone: Complete System ID study of wind plant to enable control studies												
Q2 Milestone: Initial analysis report for offshore wind plant data												
Q4 Milestone: Publish multiple paper on wind plant control												
Current work and future research												
Further data analysis of offshore wind plant												
Further plant control studies and publication												
Model validation and final report												

Comments

- Project original initiation date – October 1, 2011
- Project planned completion date – September 30, 2014
- All milestones met on schedule

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

Subcontractors

- University of Massachusetts – Matt Lackner
- University of Colorado – Julie Lundquist (NREL Joint Appt.)
- Colorado School of Mines – Katie Johnson (NREL Joint Appt.)
- Indiana University – Rebecca Barthelmie

Collaborators

- Vestas – Dick Veldkamp
- DTU Wind – Gunner Larsen
- TUDelft – Jan-Willem van Wingerden
- ECN – Bernard Bulder

Communications and Technology Transfer:

- Dynamic Wake Meandering model – 2 conference papers, 2 journal papers
- Wind plant control – 6 conference papers, 3 journal papers
- SOWFA with super-controller and user manual publicly released
- FAST 8.0 DWM module publicly released

Next Steps and Future Research

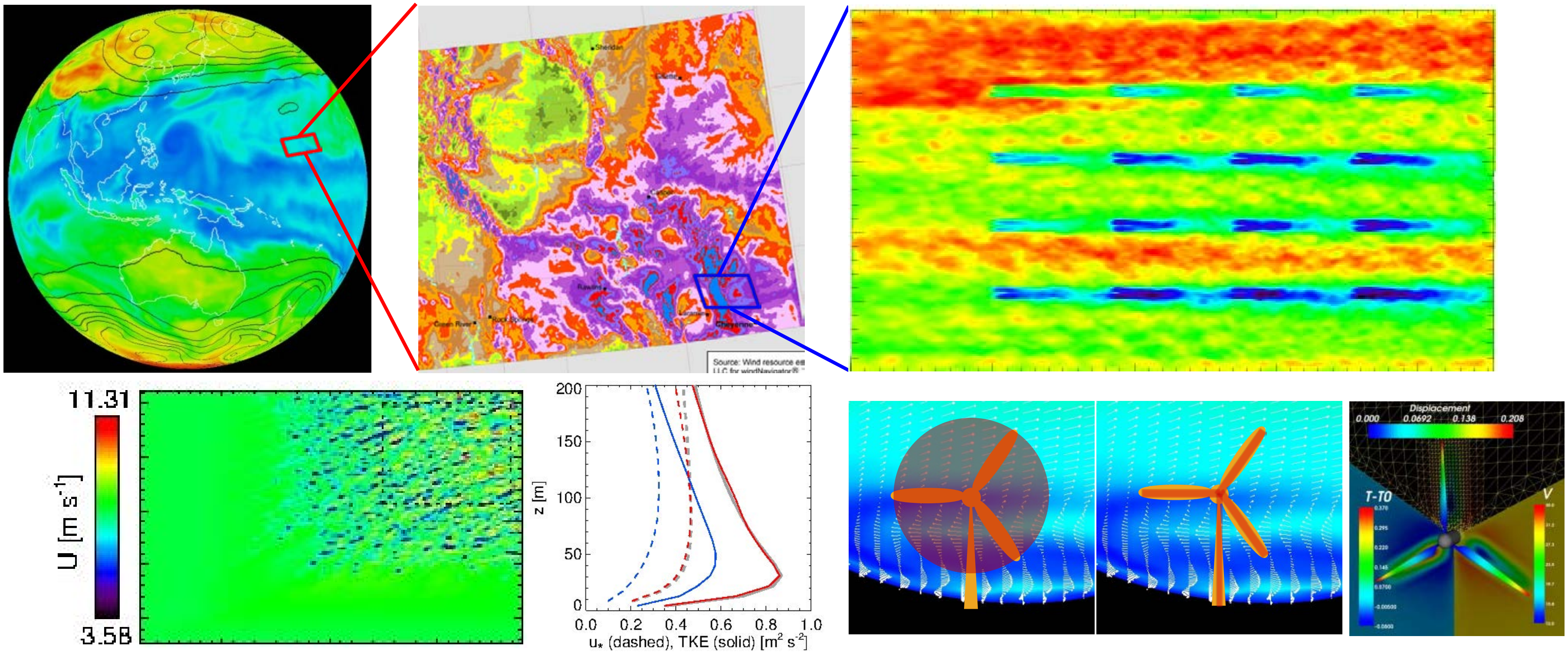
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

- Further analysis of offshore wind plant data, focus on atmospheric stability
- Maturation of Dynamic Wake Meandering and FLORIS models
- Validation of SOWFA modules particularly structural loading
- Further wind plant control studies

Proposed future research:

- Wake merging
- Combine best features of DWM and FLORIS model
- Full and subscale testing of wind plant control concepts
- Closed loop plant control in changing wind conditions



Wind Plant Modeling and Validation

Prepared by LLNL under Contract DE-AC52-07NA27344.
LLNL-PRES-650633

Jeff Mirocha

LLNL
jmirocha@llnl.gov, 925-422-4627

Monday, March 24, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $.200M

Total Cost-Share[1]:$0.000M

Problem Statement:

- Neither atmospheric or engineering CFD models capture the entire range of scales and processes important for many wind plant studies
- Absence of appropriate tools hinders progress on many R&D issues
- Coupling of weather and engineering CFD codes progressing slowly
- WRF provides ready platform for seamless integration of atmospheric simulation and engineering tools applicable to many R&D issues

Impact of Project:

- Provide a flexible toolkit to wind industry in widely used WRF model
- Broad applicability: turbine impacts on boundary layer physics, wake and load predictions, turbine siting, wind farm layout and operations
- Provide data to engineering CFD for higher-fidelity applications

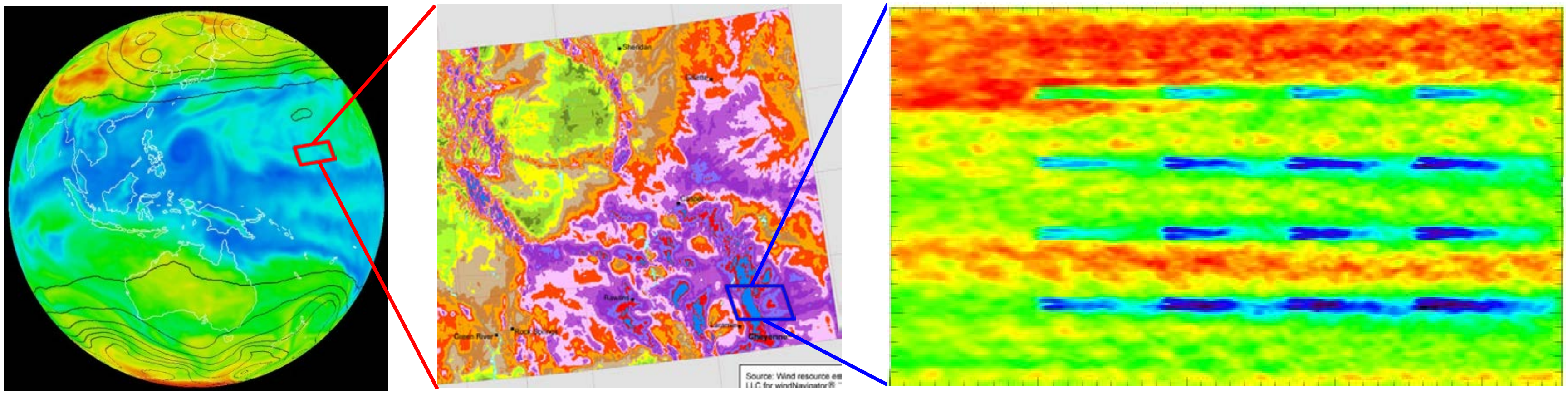
This project aligns with the following DOE Program objectives and priorities:

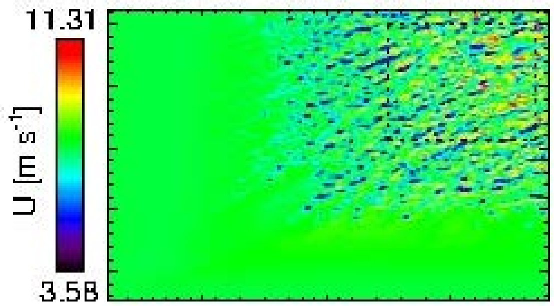
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)

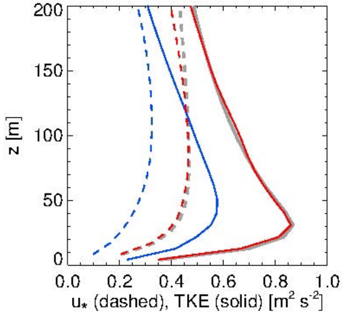
[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

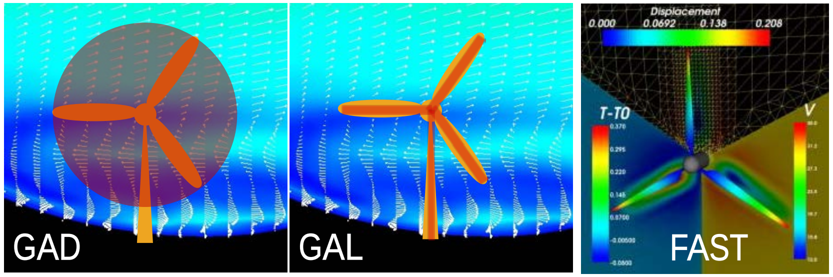
Technical Approach:

- Integrate engineering CFD tools with WRF model
  - Generalized Actuator Disk (GAD) and Line (GAL) Models
  - FAST Aeroelastic response model
  - Integration with advanced turbulence models and downscaling algorithms



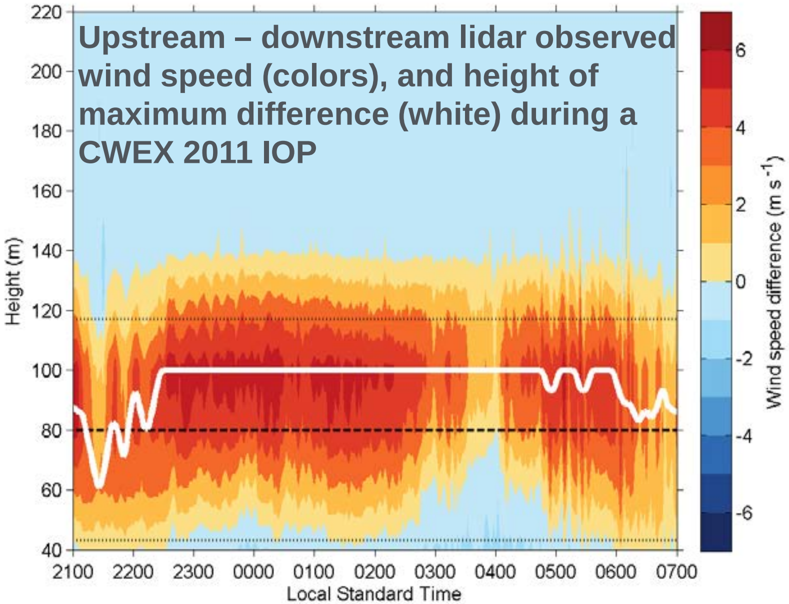


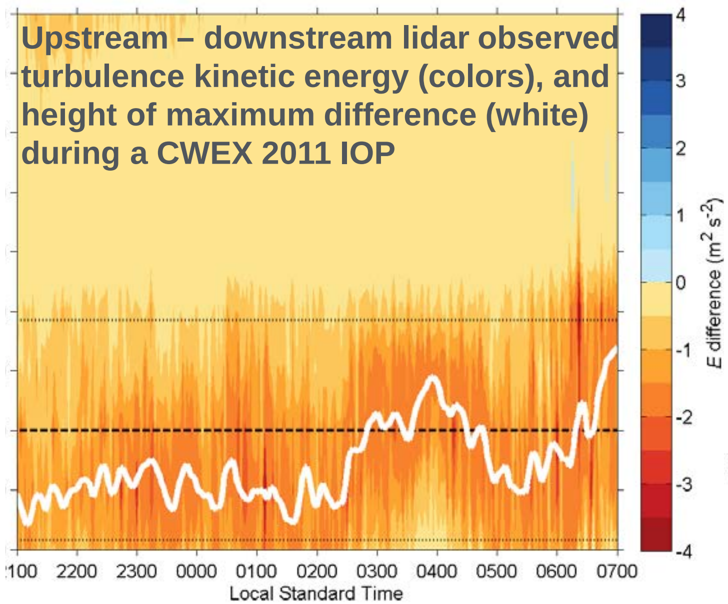


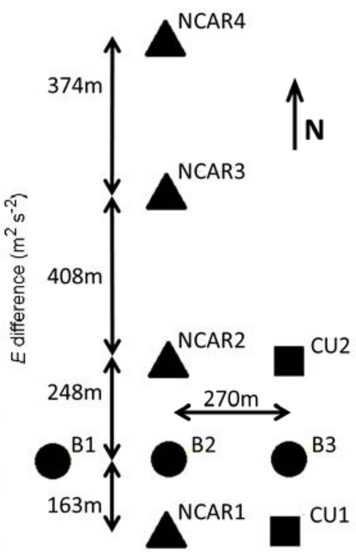


Technical Approach:

- Integrate engineering CFD tools with WRF model
  - Generalized Actuator Disk (GAD) and Line (GAL) Models
  - FAST Aeroelastic response model
  - Integration with advanced turbulence models and downscaling algorithms
  - Benchmarking of new approaches in simulations of increasing complexity







From: Rhodes, M. E., and J. K. Lundquist. 2013: The Effect of Wind Turbine Wakes on Summertime Midwest Atmospheric Wind Profiles, *Boundary-Layer Meteorology,* **149**, 85-103.

CWEX 2011 Instrumentation near turbines B1, B2 and B3.

Technical Approach

Technical Approach:

- Integrate engineering CFD tools with WRF model
  - Generalized Actuator Disk (GAD) and Line (GAL) Models
  - FAST Aeroelastic response model
  - Integration with advanced turbulence models and downscaling algorithms
  - Benchmarking of new approaches in simulations of increasing complexity
- Establish practical guidelines for users

Unique aspects:

- Integrated atmospheric and engineering tools in one framework
- Implemented within a popular, widely-used community model
- Extends wind plant simulation to general atmospheric conditions

Project Plan & Schedule

Summary	Legend
WBS Number or Agreement Number: 7.1.3	Work completed
Project Number	Active Task
Agreement Number: 22541	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

Task / Event	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Wind Plant Modeling and Validation								
Q1 Milestone: Implement line version of generalized sctuator disk model into WRF								
Q2 Milestone: Implement real-time YAW algorithm								
Q3 Milestone: Validate wake sensitivity to turbulence model/atmospheric stability								
Q4 Milestone: Integrate FAST aeroelastic response model into WRF/GAL								
Current work and future research								
Extending GAD to Generalized Actuator Line (GAL) model								
Settimg up case studies from CWEX 2011 to assess stability impacts on wake properties								
Validating WRF-GAD with advanced LES turbulence models								

Comments

- Project initiation:FY13Q4; Planned completion FY16Q4
- Order of milestones rearranged to accommodate student working on project
- Proposed Go/no-go decision points: if difficulties with GAL or FAST integration

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

Collaborations with NREL, PNL, NCAR, U.C. Berkeley, and U. Colorado

Communications and Technology Transfer:

Work scheduled for presentation at:

- American Meteorological Society's 21st Symposium on Boundary Layers and Turbulence, June 2014, Leeds, UK
- The Science of Making Torque From Wind, June 2014, DTU, Copenhagen, DK

Next Steps and Future Research

FY14/Current research: Finished Ongoing

- Computational streamlining
- Consistency of turbine computations across decomposed domains
- Option for automatic real-time yaw
- Verification of proper wake forces for arbitrary turbine orientation
- Extension of actuator disk (GAD) to line (GAL) version
- Validation of GAD with advanced turbulence models
- Validation of GAD with variable atmospheric stability
- Validation of GAL with advanced turbulence models
- Validation of GAL with variable atmospheric stability
- Integration with FAST model

Deliverables:

- Report validating GAL implementation
- Paper using GAD with advanced turbulence models to assess wake characteristics under different atmospheric stabilities
- Report validating FAST integration

Next Steps and Future Research

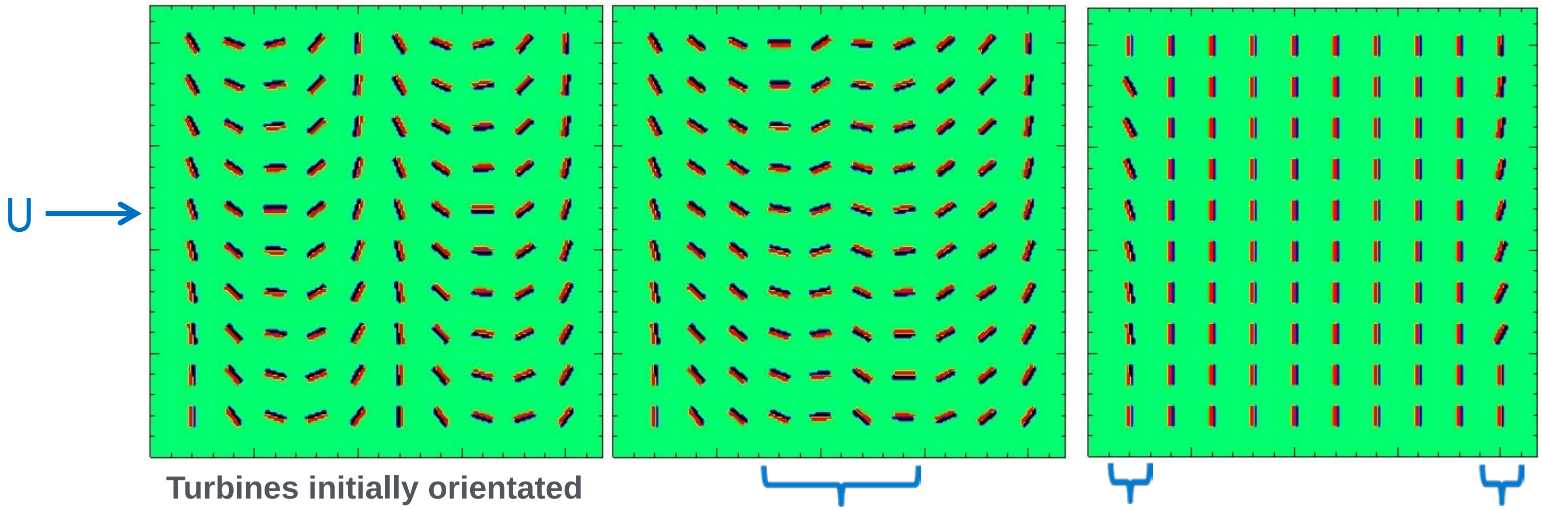
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

- Option for automatic real-time yaw

After a user-specified accumulated yaw error is reached, turbine yaws at a user-specified rate to face into the wind direction averaged over a user-specified time window.

10X10 array of GADs in WRF. Red/blue shows front/back of turbines.

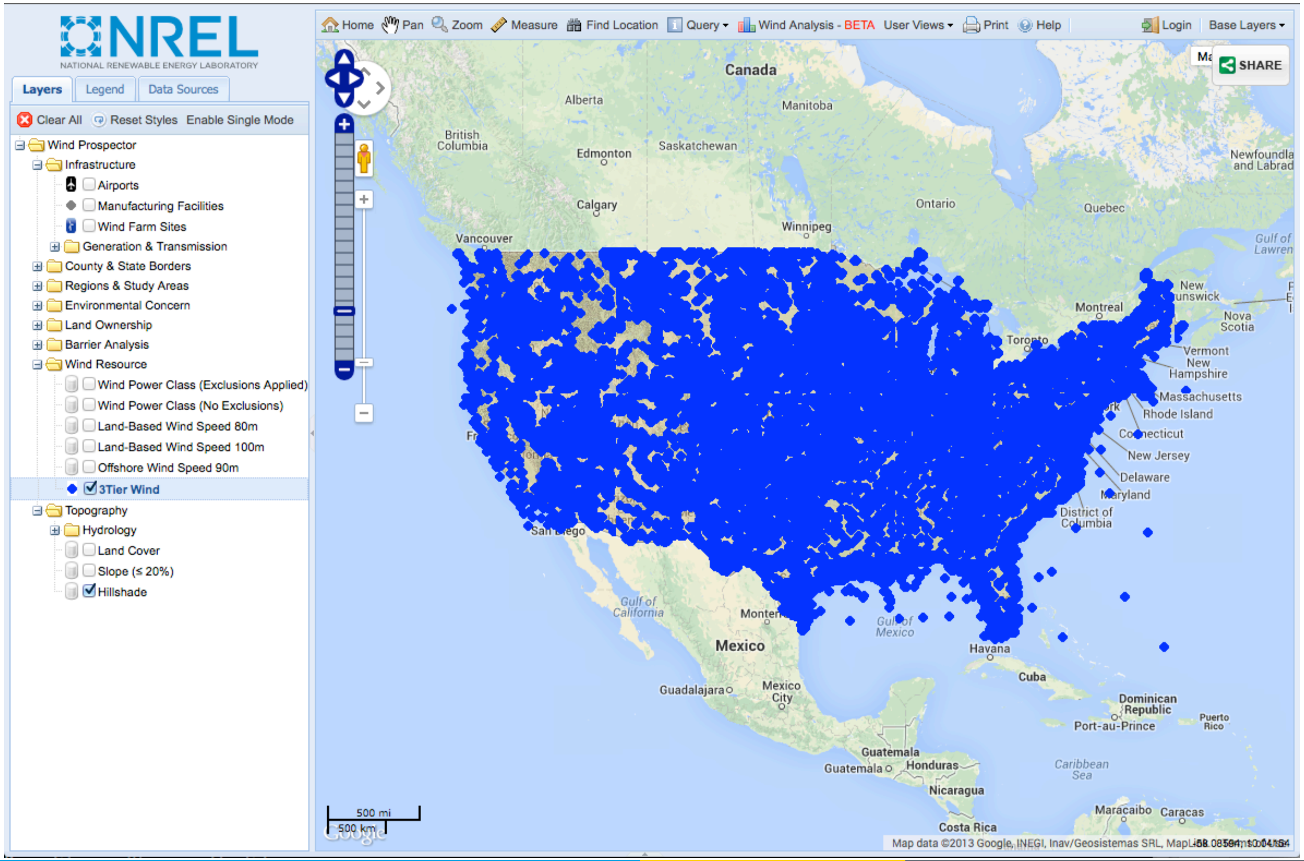


Turbines initially orientated at 3.6 degree increments.

Turbines furthest out of alignment begin yawing first.

Turbines nearly aligned are the last to yaw.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Mesoscale Datasets (WIND Toolkit) and Forecasting using Analogs

Patrick Moriarty

NREL

patrick.moriarty@nrel.gov,

303 384-7081

March 24, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $2.872M

Total Cost-Share[1]:$0.000M

Problem Statement: Need for improved wind resource and power data to be used in wind integration studies using state-of-the-art modeling techniques.

Impact of Project: This data allows for stakeholders to better understand grid interactions and wind resource data, thus fostering large penetrations of wind deployment. This data also allows for operational changes in the electric sector.

This project aligns with the following DOE Program objectives and priorities:

Advanced Grid Integration: Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

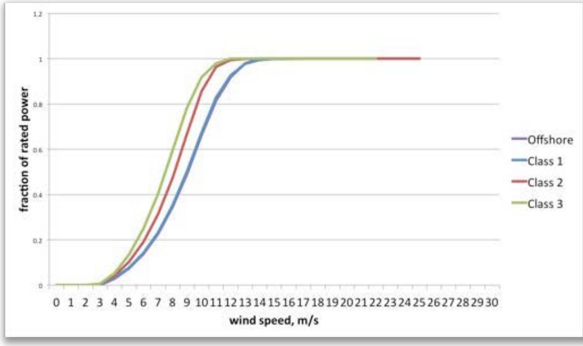
Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Run a numerical weather prediction model to create meteorological data
  - Weather Research and Forecasting (WRF) model
  - 2 km x 2 km and 5 minute resolution
  - 6 complete years: 2007 – 2012
  - Avoid “seams” issues from other datasets
  - Computationally expensive

WRF Modeling Domain

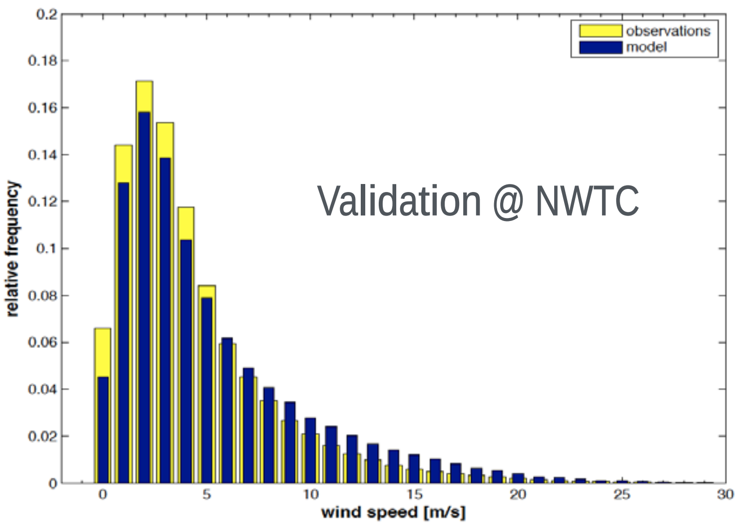
- Select wind sites
  - 126,000 sites throughout continental US and offshore
- Convert wind speed to power
  - 3 onshore and 1 offshore turbine power curves
- Forecast studies
  - Synthetic using 3Tier data
- Analog ensembles



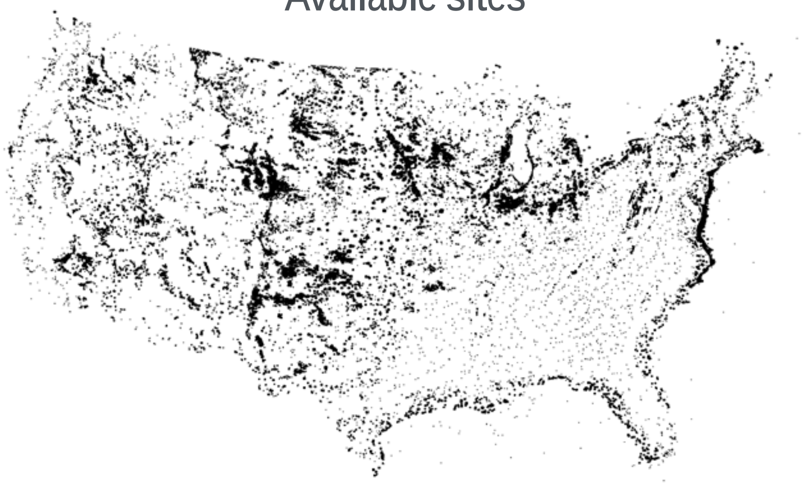
Wind Toolkit Power Curves

Accomplishments and Progress

- Meteorological datasets are complete
  - Currently being transferred to NREL (~0.5 Petabytes)
  - NREL validation underway
- Power datasets
  - Validation complete, report forthcoming
  - Publicly available soon
  - Data extraction tool completed



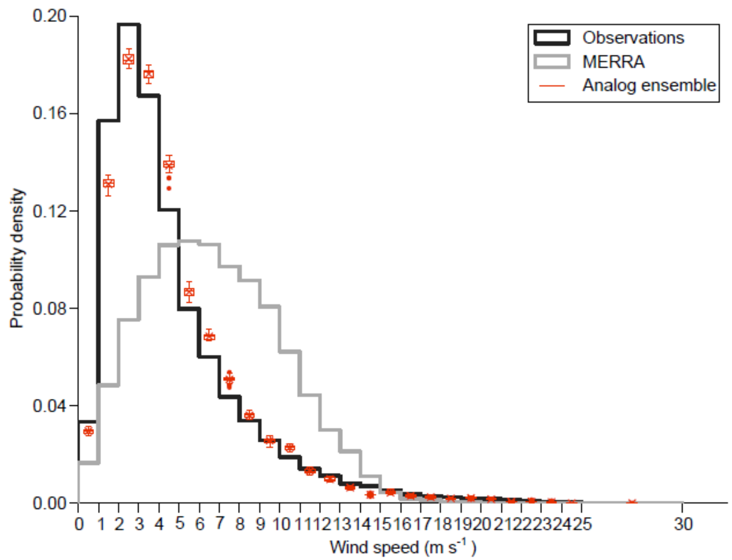
Available sites

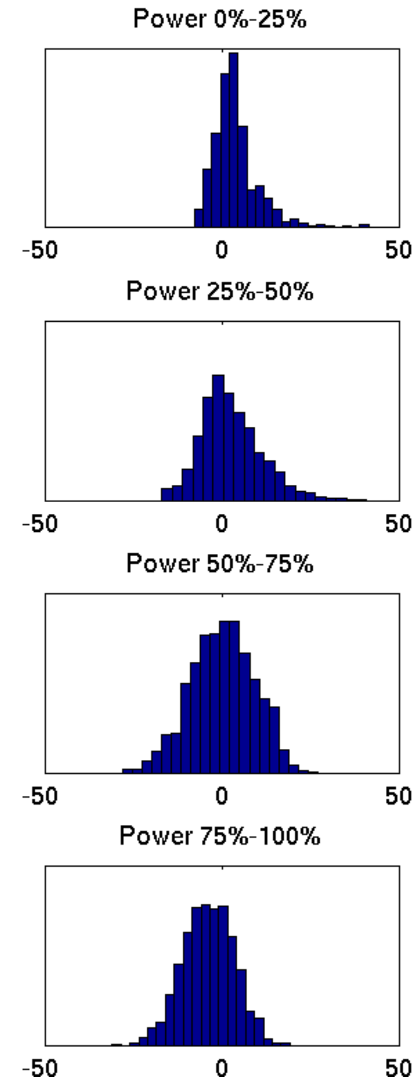


Accomplishments and Progress

- Forecasting datasets
  - 3Tier validation underway
  - Includes site-specific probabilistic information
  - Analogs can provide uncertainty bounds
- Analogs also useful for resource assessment
- Technical Review Meetings
  - Key stakeholder input received

Analog ensembles @ NWTC





Forecast error by power regime

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	2.7.0.1
Project Number	
Agreement Number	2.7

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Mesoscale Datasets (WIND Toolkit) and Forecasting using Analogs												
Q1 Milestone: Release RFP to generate mesoscale datasets												
Q2 Milestone: Finalize subcontract with awardee												
Q4 Milestone: Complete and deliver mesoscale datasets												
Q2 Milestone: Complete the site selection for 126,000 for mesoscale datasets												
Q3 Milestone: Complete wind power production profiles												
Q4 Milestone: Complete data extraction tool												
Q3 Milestone: Complete analog filtered datasets												
Q4 Milestone: Final report on analog filtering techniques												
Current work and future research												
Validation of meteorological dataset												
NREL report and journal publication on WIND Toolkit												

Comments

- Project original initiation date: October 1, 2011
- Project planned completion date: September 30, 2014
- Delays in subcontracting process in FY12 for mesoscale datasets and FY13 for analog filter subcontract
- Computing issues and data transfer limitations delayed completion of mesoscale datasets

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- 3Tier - primary mesoscale subcontractor
    - Performed simulations using the WRF model on NREL supercomputing systems
    - Validation of results and forecasts
- Jack King (independent consultant) involved in validation
- NCAR subcontractor on analog ensembles

Communications and Technology Transfer:

- Paper and Presentation at 12th Wind Integration Workshop
- Presentations
    - EWEA Forecasting Workshop
    - American Geophysical Union Conference
    - American Meteorological Society Meeting
    - IEA Technical Experts Meeting
- Power data will be made publically available via web-interface
- Meteorological data will eventually be made available

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

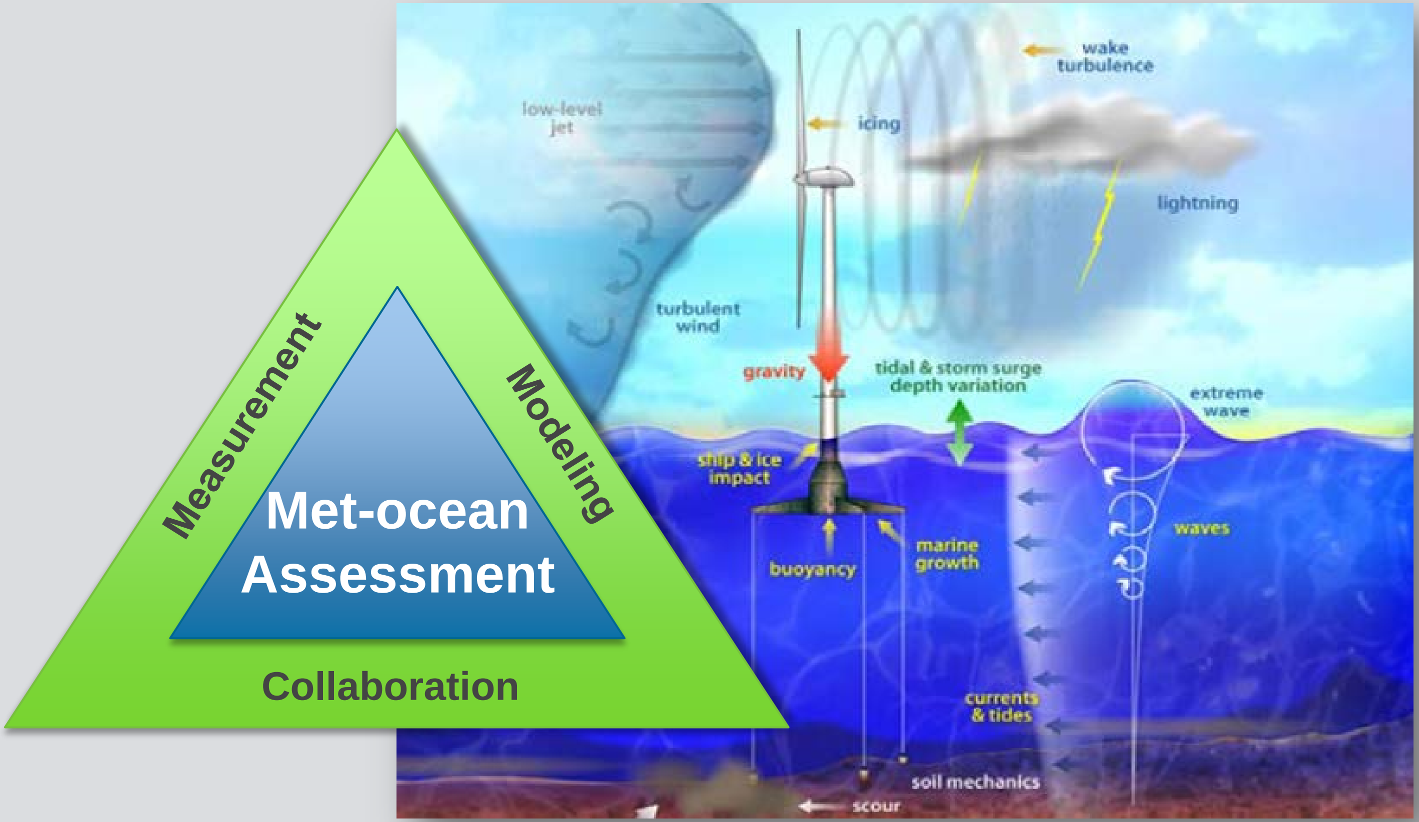
FY14/Current research:

- Meteorological, power, and forecast data validation
- File transfer from 3Tier to NREL
- Permanent storage for the dataset is being procured
- Data extraction tool development
- New IEA Task on Forecasting is in discussion stages

Proposed future research:

- Comparisons with statistical techniques that are less computationally expensive - next generation of data could be created at a fraction of the cost
- Grid integration studies with derived data sets
- Additional simulation years and further validation
- Application to wind resource assessment activities

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



National Offshore Wind Energy Resource and Design Condition Data Campaign

Bruce H. Bailey

AWS Truepower LLC

bbailey@awstruepower.com; 518-213-0044

March 24, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $0.519M

Total Cost-Share[1]:$0.000M

Problem Statement: Coordinated efforts are needed to mitigate or eliminate data-related offshore wind technical/market barriers through a process involving public-private collaboration that addresses offshore resource assessment, design condition definition, and operational industry needs.

Impact of Project: This project will provide a comprehensive, consensus definition of relevant met-ocean resource assets, needs, accepted modeling approaches, and standards designs, together with recommended pathways for addressing data data and fulfilling project certification requirements.

This project aligns with the following DOE Program objectives and priorities:

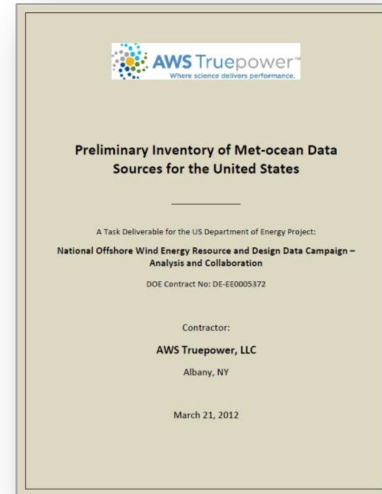
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

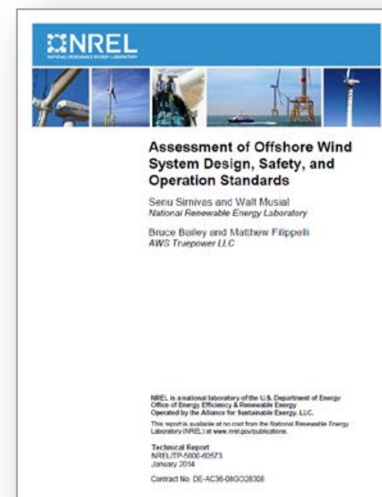
[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach (1)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

1. Assess & Catalog National Datasets/Capabilities
   - Inventory of met-ocean data sources & metadata
   - Atmospheric, surface & subsurface parameters
   - Definitive reference for offshore wind-related efforts
2. Analyze Gaps in Data & Modeling Capabilities
   - Develop matrix of needs by parameter category, user, project phase, model type
   - Establish priorities
3. Evaluate Wind System Design and Operation Standards
   - Review existing and pending standards relating external met-ocean conditions to design & safety
   - Type Certification, IEC, API, GL, DNV, ABS
   - Assess relevance to design conditions in US
   - Recommendations for revisions & gap filling





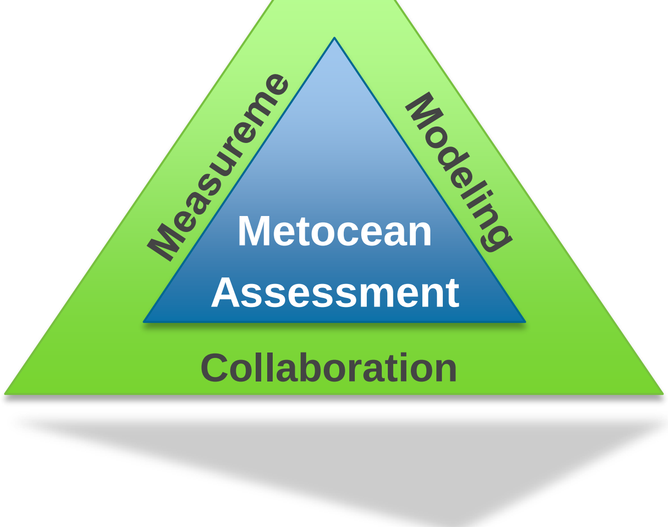
Technical Approach (2)

4. Recommend Near-Term Measurement Strategies
   – Identify opportunities where limited resources can be applied through leveraging of existing field programs
   – Concepts for data sharing vs confidentiality
5. Establish Infrastructure for Industry Collaboration
   – Define industry segments, user types, and associations as vehicles to achieve project objectives
   – Networking, consensus building, publications
   – Dedicated website & other outreach activities
6. Conduct Long-Term Planning for Data Gathering & Research
   – Roadmap for improving offshore data networks
   – Recommend topical priorities, target regions, timelines, approaches, partnerships

Met-Ocean Data Users

Enterprise-Wide Collaboration

- Coordination with National and Regional Groups with Overlapping Goals
- Consensus Building on Metocean Needs and Solutions
- Joint Publications
- Dedicated Web Site for Inventory of Offshore Metocean Data Sources



Sample of Collaborators

Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Inventory of Met-Ocean Data Sources for US
  - Identified multiple stakeholders with similar data objectives
- Near-term measurement concepts for DOE planning
- Draft Standards report
  - *“Assessment of Offshore Wind System Design, Safety, and Operation Standards”*
- Outreach to Trade/Technical Organizations & Agencies
  - e.g., OffshoreWindDC, AWEA, AMS, IOOS, BOEM, NOAA
  - Joint reports & white papers with consensus recommendations
  - Emerging consensus on strategies to address knowledge gaps
- Website & Project Portal: www.usmodcore.com
  - US Met-Ocean Data Center for Offshore Renewable Energy

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	
Project Number	
Agreement Number	DE-EE0005372

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: National Offshore Wind Energy Resource and Design Data Campaign												
Task 1: Assess & Catalog National Datasets and Capabilities												
Task 2: Analyze Gaps in Data & Modeling Capabilities												
Task 3: Assess Wind System Design and Operation Standards												
Task 4: Provide Analysis on Potential Near-Term Measurement Strategies												
Task 5: Industry Collaboration and Outreach												
Task 6: Long-Term Planning for Data Gathering and Future Research												
Current work and future research												
Task 3 Standards Report Release												

Comments

- Project Period: 30 Sept 2011 – 30 Sept 2014
- For Task 2, interim joint industry reports have deferred the final report.

Partners, Subcontractors, and Collaborators:

- National Renewable Energy Laboratory
- National Lab. for Sustainable Energy at the Technical Univ. of Denmark

Communications and Technology Transfer:

Publications:

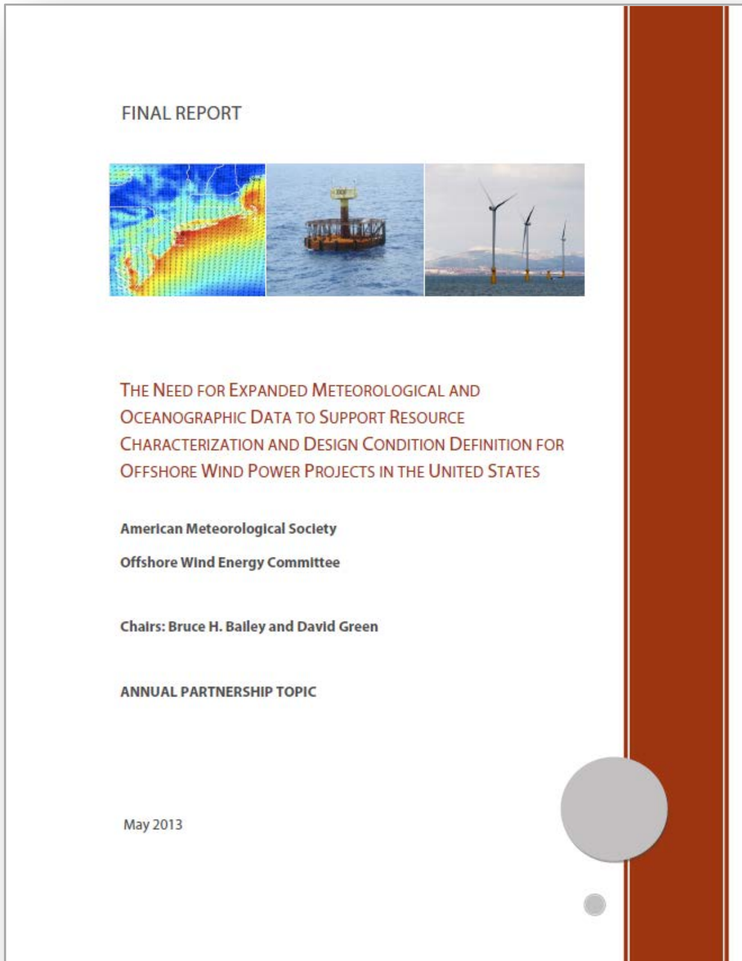
2012: *Preliminary Inventory of Met-ocean Data Sources for the United States*. **Task 1 Project Report**, 33 pp.

2012: *The Need for Improved Met-Ocean Data to Facilitate Offshore Renewable Energy Development*. **IOOS Summit** whitepaper

2013: *The Need for Expanded Meteorological and Oceanographic Data to Support Resource Characterization and Design Condition Definition for Offshore Wind Power Projects in the US*. **Amer. Meteor. Soc.**, Committee Co-Chair B. Bailey, 34 pp.

2014: *Assessment of Offshore Wind System Design, Safety, and Operation Standards*. Tech. Report **NREL**/TP-5000-60573. 51 pp.

2014: *Meteorology for Coastal/Offshore Wind Energy in the United States: Recommendations and Research Needs for the Next 10 Years*. **Bulletin of the American Meteorological Society**, March issue.



FINAL REPORT

THE NEED FOR EXPANDED METEOROLOGICAL AND OCEANOGRAPHIC DATA TO SUPPORT RESOURCE CHARACTERIZATION AND DESIGN CONDITION DEFINITION FOR OFFSHORE WIND POWER PROJECTS IN THE UNITED STATES

American Meteorological Society

Offshore Wind Energy Committee

Chairs: Bruce H. Bailey and David Green

ANNUAL PARTNERSHIP TOPIC

May 2013

Outline

1. Introduction
2. Overview of Offshore Wind Energy Opportunities & Challenges in the US
3. Role of Metocean Data in Addressing Project Planning, Design & Operational Needs
4. Sources of Existing Measured/Modeled Data
5. Data Gaps and Strategies to Address Them
6. Conclusions and Recommendations

Communications and Technology Transfer:

Presentations/Webinars:

2012: **AWEA Windpower 2012 Conf**., Atlanta, GA. *The Role of Public-Private-Academic Collaboration to Prioritize Met-Ocean Data Needs for Offshore Wind Energy*, B. Bailey

2012: Webinar for the benefit of the **Integrated Ocean Observing System** (IOOS) and regional associations. *The Role of Public-Private-Academic Collaboration to Address Met-Ocean Data Needs for Offshore Wind Energy*, B. Bailey presenter.

2012: **AWEA Offshore Windpower Conf**., Virginia Beach. *Evolving Standards and Industry-Accepted Applications of Measurements and Modeling*, M. Filippelli presenter.

2013: **Symposium on the Importance of Meteorology to Wind Energy**, Univ. Delaware. *Metocean Data and Modeling to Advance Offshore Wind Energy: Challenges and Opportunities*, B. Bailey presenter.

2013: **UVIG meeting**, Salt Lake City, Project Overview. J. Freedman presenter.

2014: **5th Conf. on Weather, Climate and the New Energy Economy**, Atlanta, GA, American Meteorological Soc., *Addressing the Metocean Data Needs of the US Offshore Wind Energy Industry to Enable Accelerated Project Deployment,* B. Bailey presenter.

Project Website: www.usmodcore.com

Next Steps and Future Research

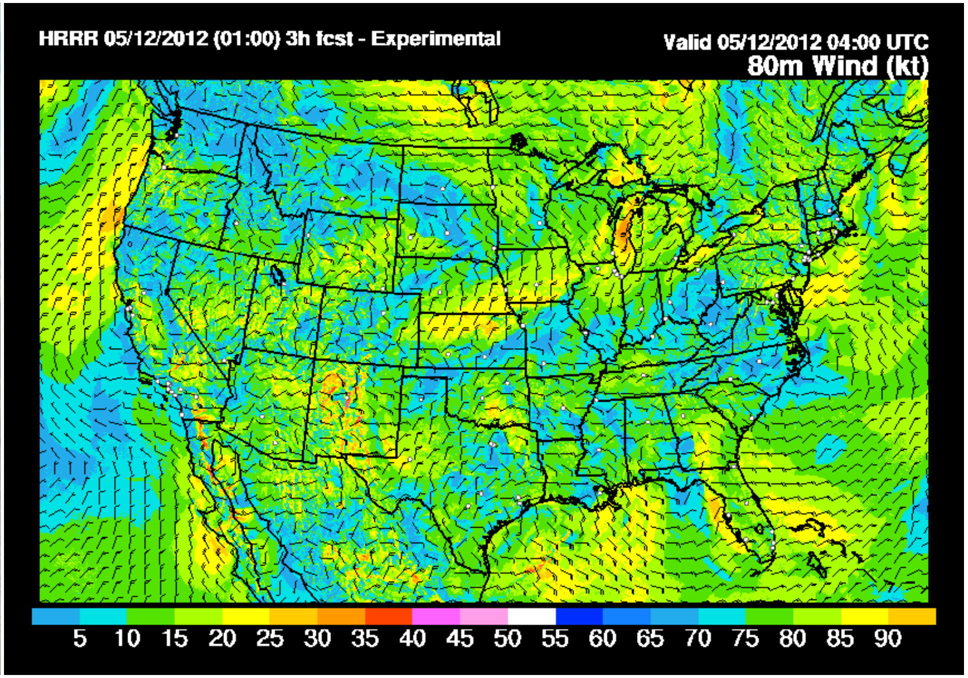
FY14/Current research:

- Standards report release (Jan 2014)
- 2-day standards workshop in DC area (June 2014);
  – Coordinated with BOEM; ~150 invitees
- Report on met-ocean data gaps analysis and recommended strategies
- Input to Wind Vision Task Force
- Stakeholder Collaboration
  – peer reviewed article on offshore wind research needs authored by 10 organizations in BAMS (March 2014)

Proposed future research:

- Continue organized collaboration and outreach program
  - *Accelerated traction likely when first projects built*
- Develop frameworks for collaborative private-public data sharing & research
  - *Document case studies & draft sample legal agreements*
- Spur industry development of best practices/standards for met-ocean data measurement, QA and assimilation
- Develop multi-year research and industry benefits agenda for government-sponsored offshore measurement facilities such as RFORE
  - *Collaborate with industry on priorities and applications*
  - *Accelerate field testing & acceptance of floating lidar & radiometer*
  - *Incentivize state- and utility-sponsored measurement initiatives*
  - *Establish national offshore data archive (e.g., PNNL)*
  - *Advance model development for resource and boundary layer characterization, wakes, forecasting*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Wind Forecast Improvement Project: WFIP

James Wilczak

NOAA/Earth System Research Laboratory

james.m.wilczak@noaa.gov (303) 497-6245

March 25,2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $1.210M

Total Cost-Share[1]:$1.140M

Problem Statement: Can power forecasts be improved through better numerical weather prediction models and data assimilation, leading to more efficient power grid operation? Is there value in sharing proprietary data from the wind industry with NOAA for the purposes of improving wind energy forecasts?

Impact of Project: More accurate forecasts will help reduce grid integration costs and wind curtailments.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid

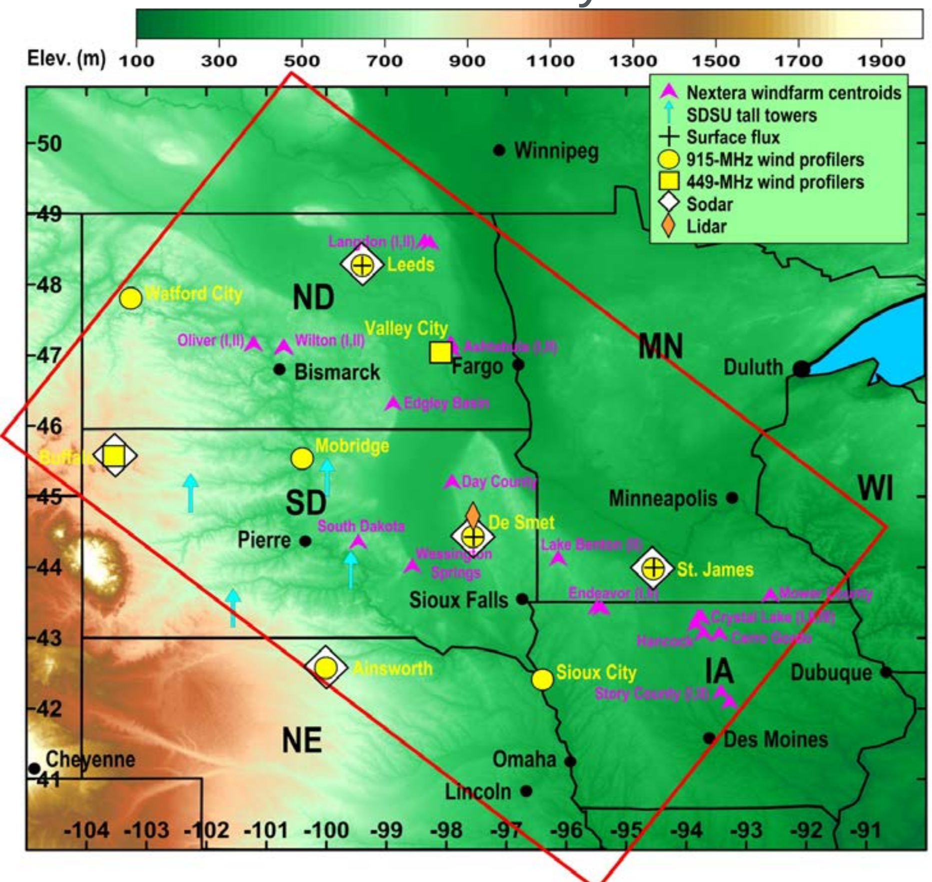
[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

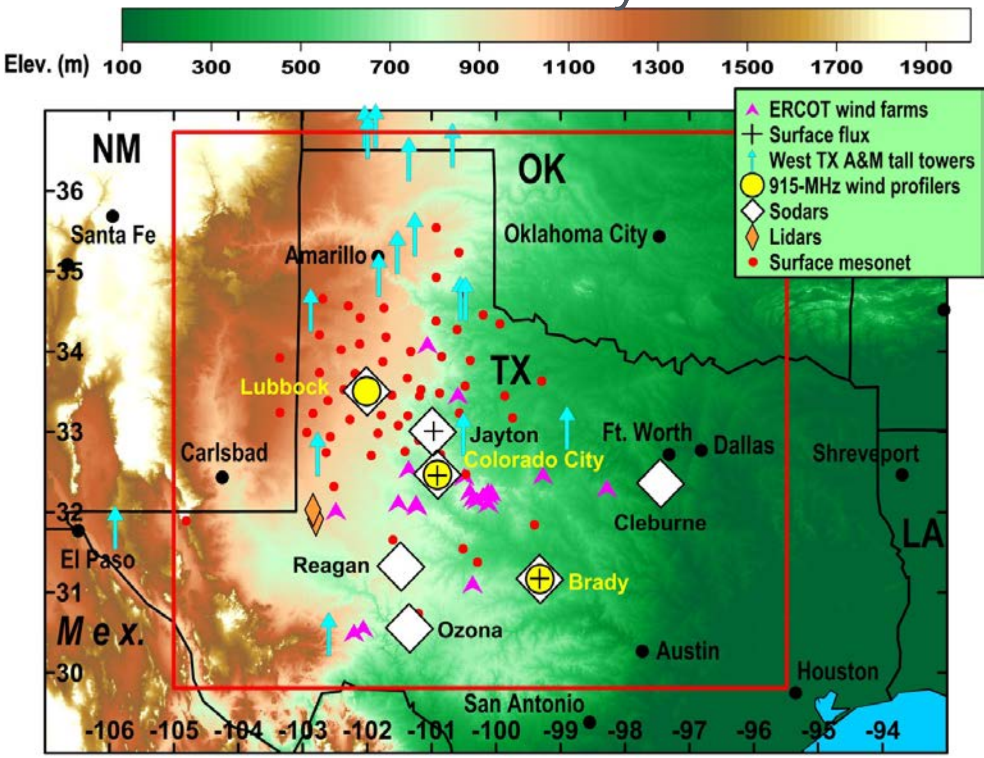
- Deploy meteorological instrumentation and collect new high quality observations.
- Assimilate these into weather prediction models.
- Improve fundamental physics in weather models.
- Develop wind ramp metric tool.
- Evaluate impact of better models and assimilation of new observations.

Technical Approach

Northern Study Area



Southern Study Area



NOAA responsible for data integration and management.

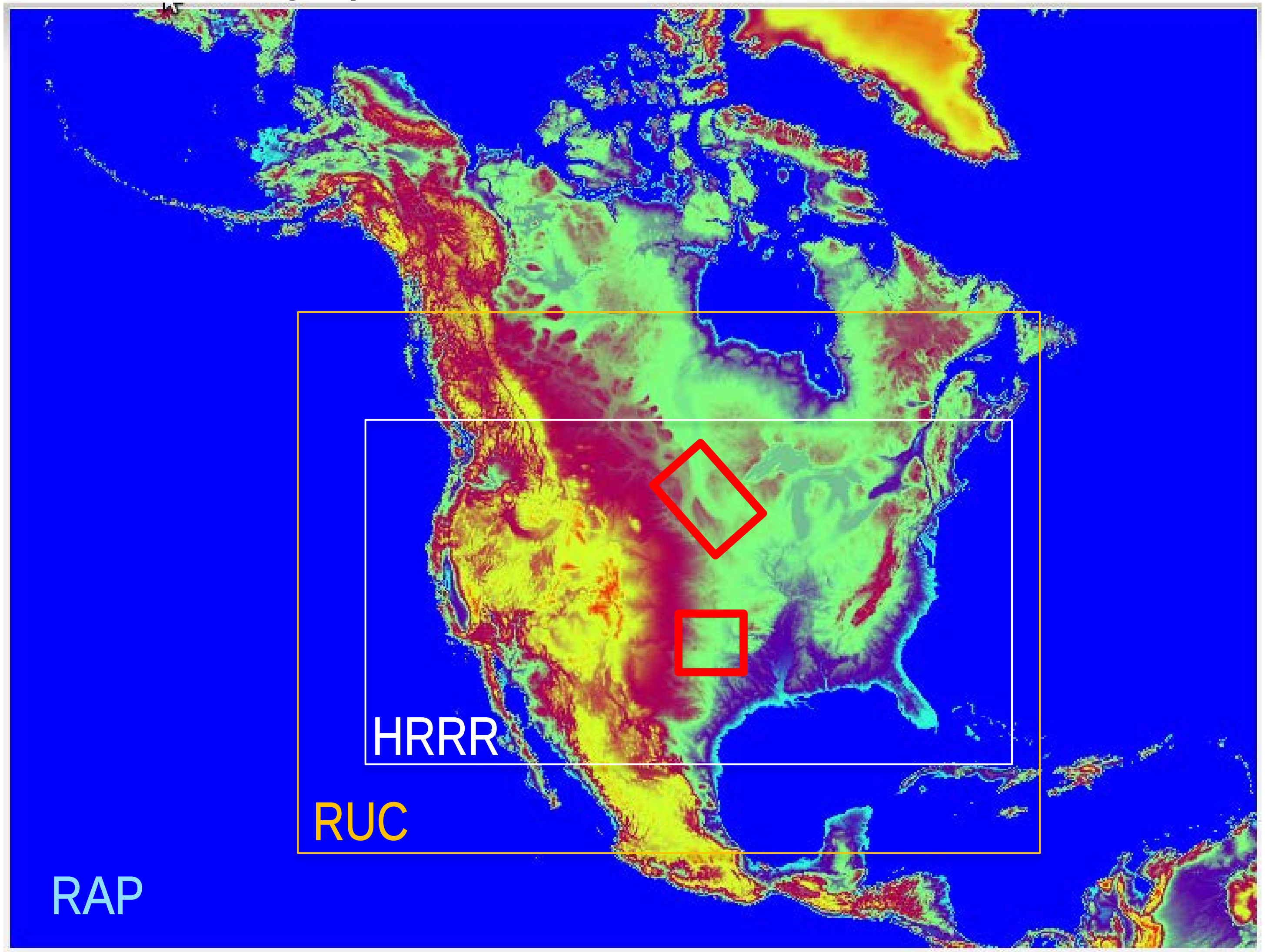
Real-time obs/model web site.

12 wind profiling radars
441 nacelle anemometers
71 surface met stations

12 sodars
184 tall towers
1 lidar

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

NOAA hourly updated models



RUC (Rapid Update Cycle)
13km resolution
No WFIP obs assimilated

RAP (Rapid Refresh)
13km resolution
WFIP obs assimilated

HRRR (High Res Rapid Refresh)
3km resolution
WFIP obs assimilated

Model Improvements:
Data assimilation
PBL parameterization

Accomplishments and Progress

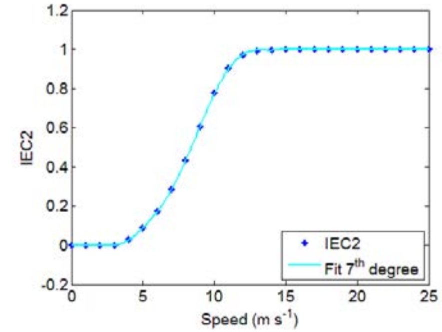
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

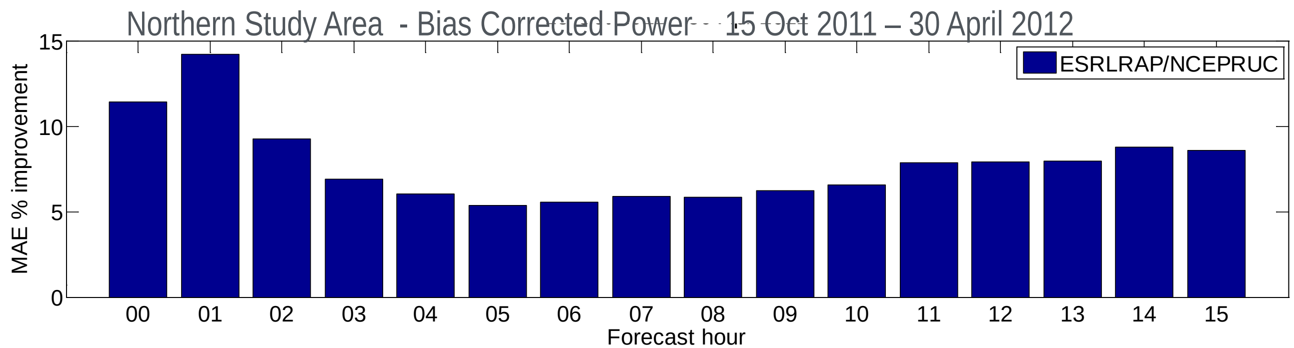
Old operational model (RUC) no WFIP obs assimilated

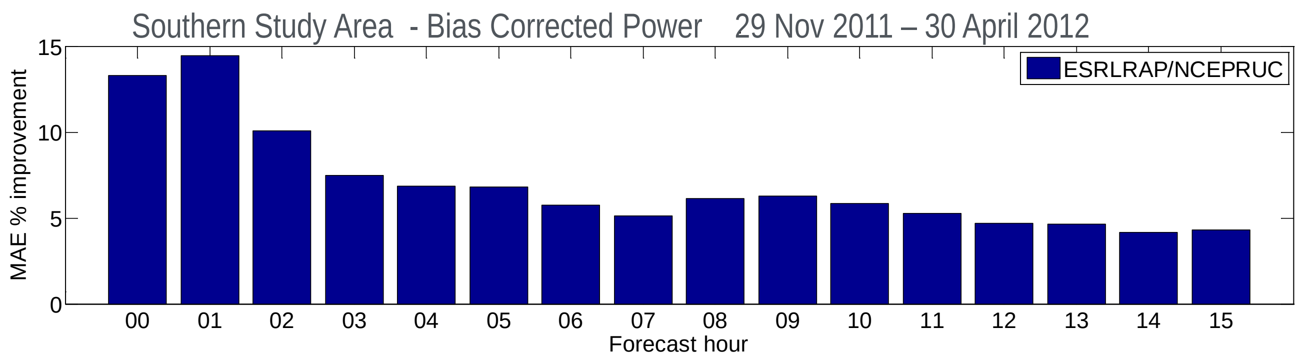
vs

New research model (RAP) with WFIP obs assimilated

% Improvement MAE Power
~6 months of data







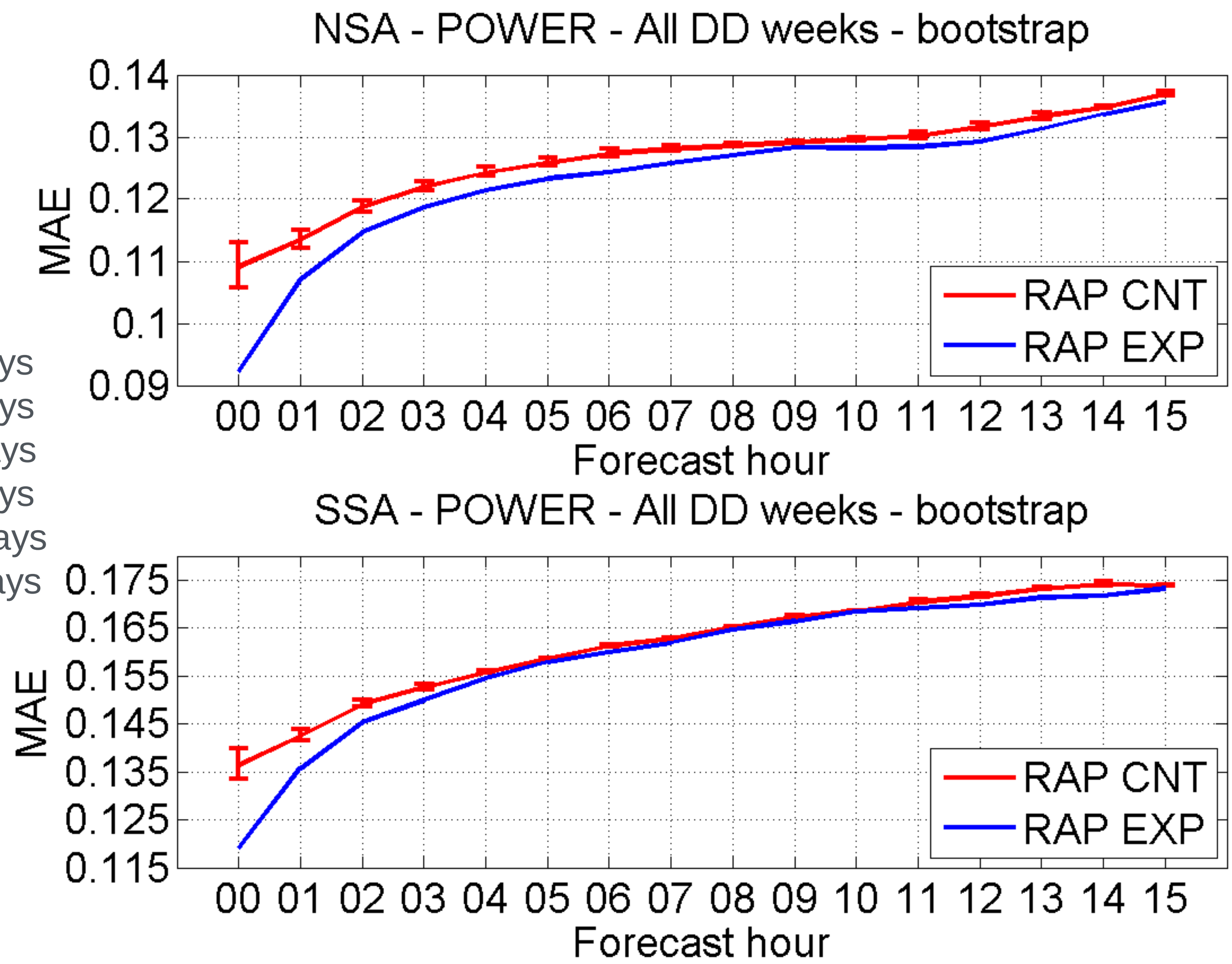
<u>Combined</u> effects of new model and assimilation of WFIP obs

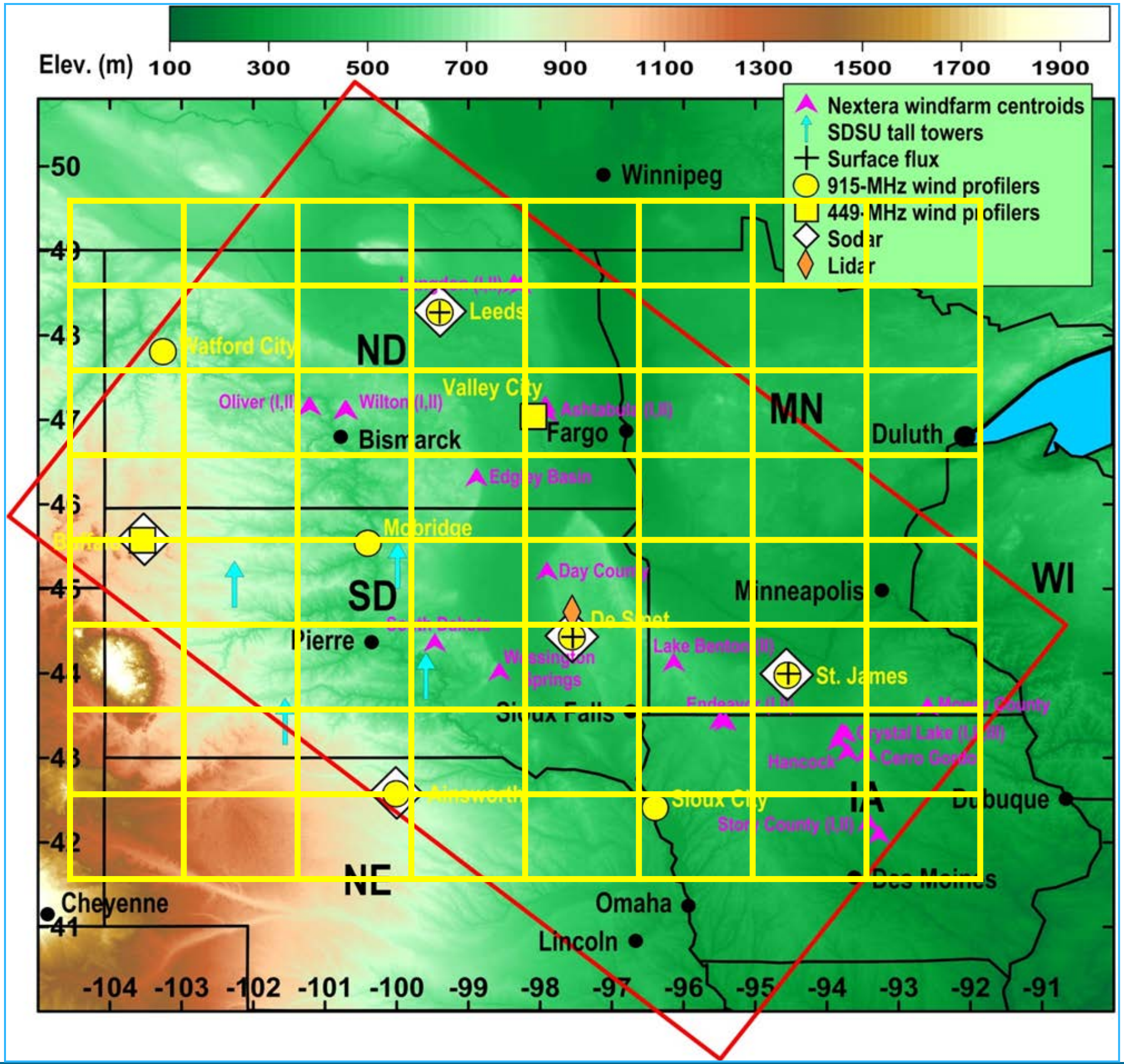
Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

RAP data denial simulations (56 days)

30 Nov – 6 Dec 2011	7 days
07 Jan – 15 Jan 2012	9 days
14 Apr – 25 Apr 2012	12 days
09 Jun – 17 Jun 2012	9 days
16 Sep – 25 Sep 2012	10 days
13 Oct - 20 Oct 2012	9 days





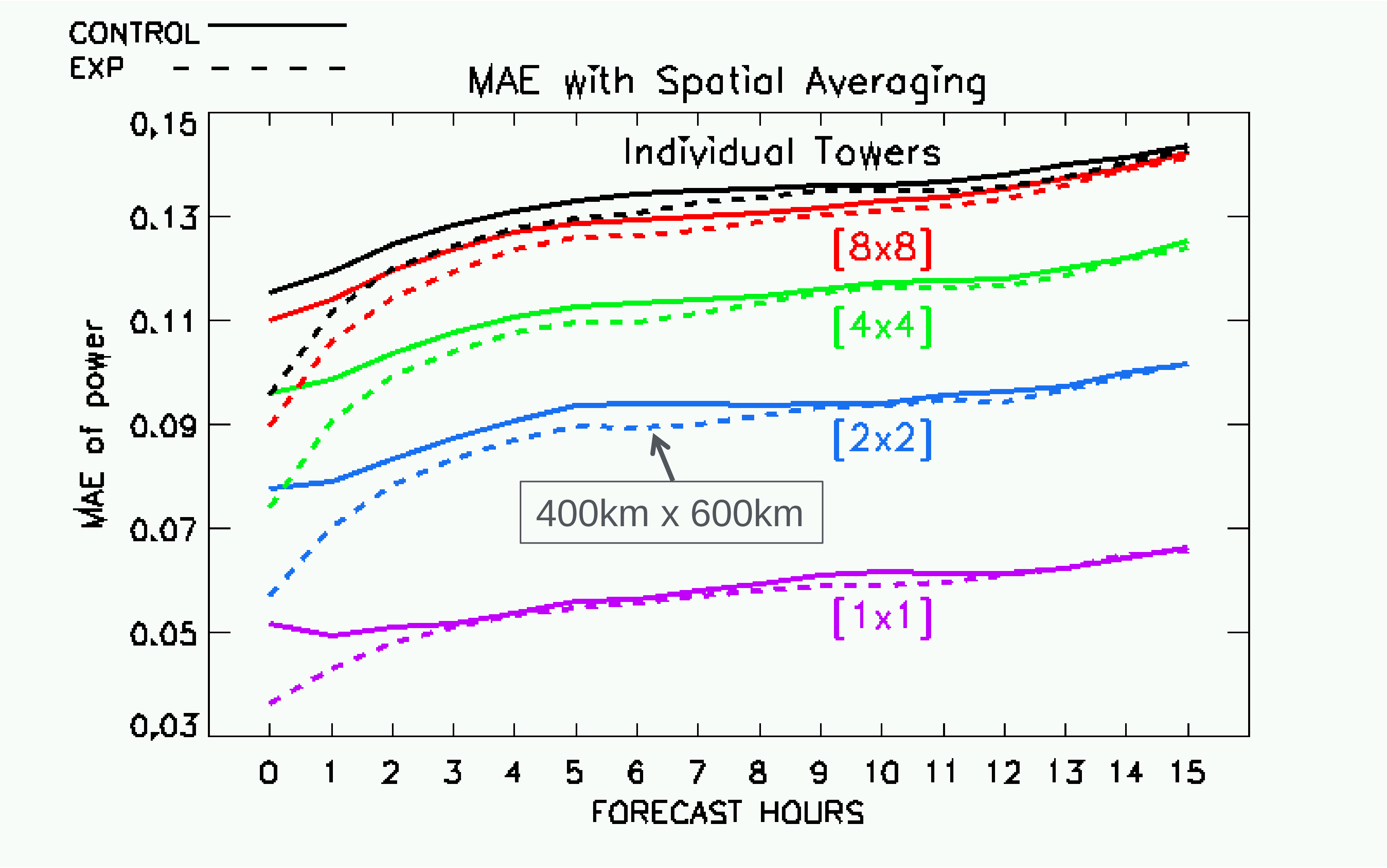
Effects of Spatial Aggregation

8x8 boxes
100km x 150km

4x4 boxes
200km x 300km

2x2 boxes
400km x 600km

1x1 box
800km x 1200km


CONTROL
EXP
MAE with Spatial Averaging
Individual Towers
[8x8]
[4x4]
[2x2]
[1x1]
400km x 600km
MAE of power
0.15
0.13
0.11
0.09
0.07
0.05
0.03
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
FORECAST HOURS

Wind Ramp Metric Community Tool

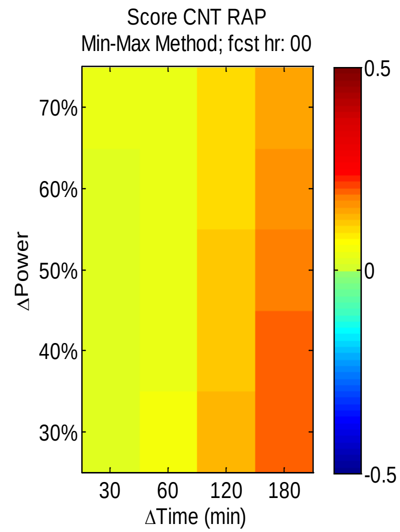
1. Ramp definition
2. Matching forecast and observed ramps
1. Skill score calculation

Skill has <u>phase</u> and <u>amplitude</u> components

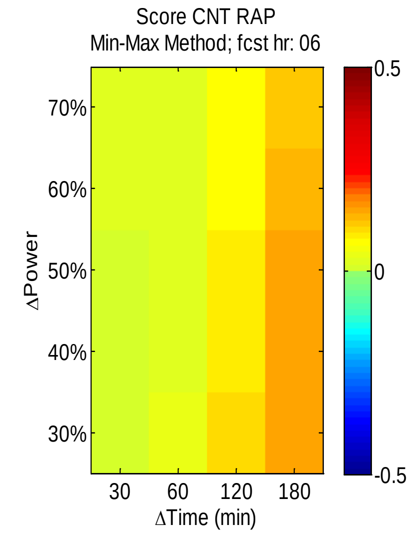
Skill = A * (Phase score) + B * (Amplitude score)

Skill is continuous in time and amplitude, giving partial credit for decent but imperfect forecasts:

Skill is computed over a weighted matrix of ramp lengths and amplitudes

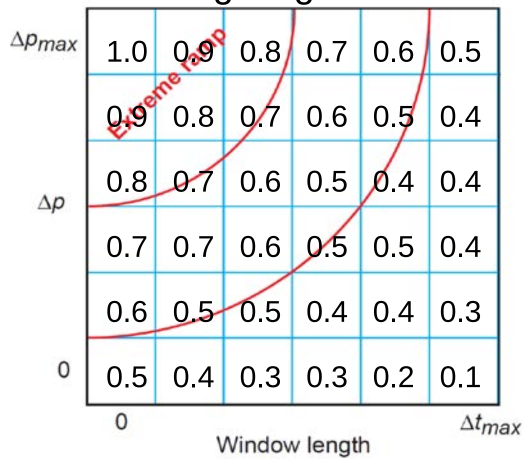


h 00

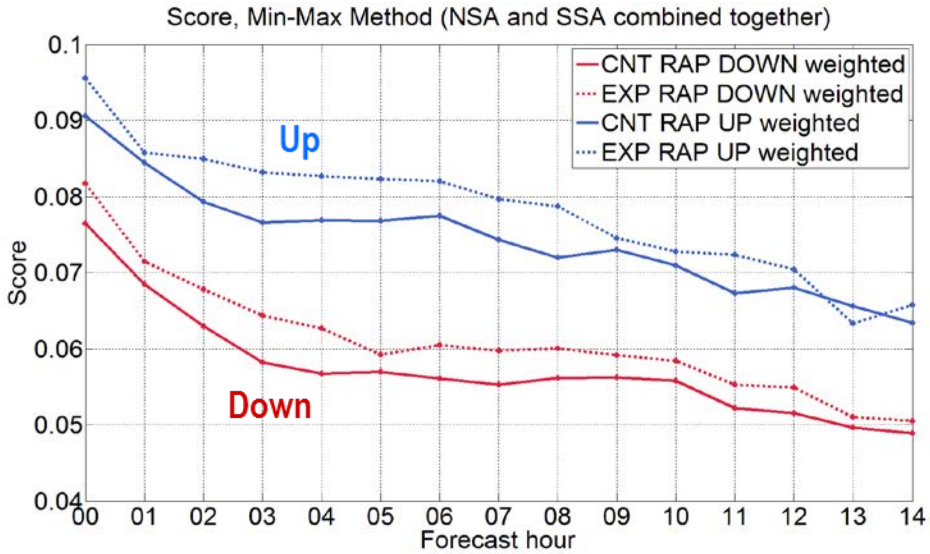


h 06

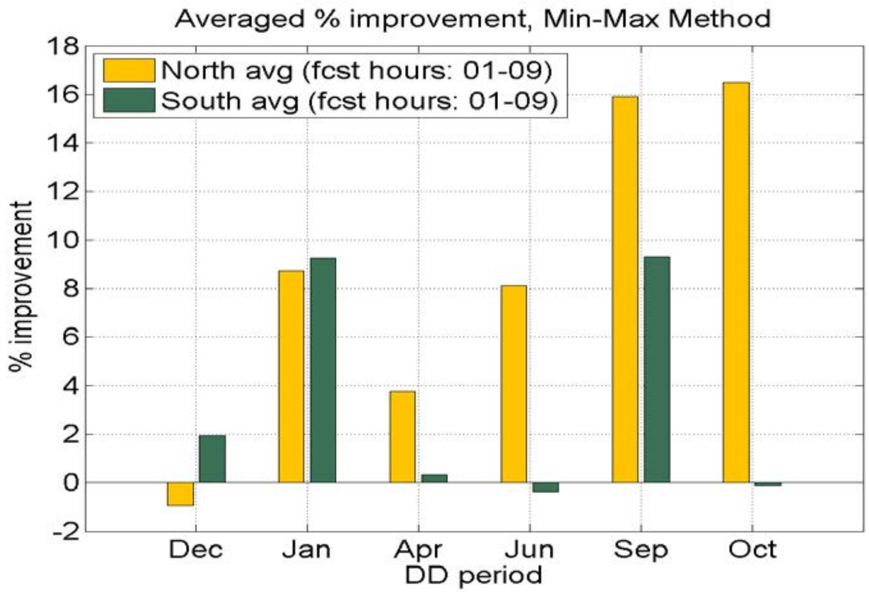
Weighting Matrix



Wind Ramp Metric Community Tool



Skill score for observed up and down ramps and improvement due to assimilation of WFIP obs



Ramp MAE percent improvement averaged for forecast hours 01-09, for NSA and SSA, for each data denial episode,

Scientific Results Summary:

- NOAA's operational model upgrade from the RUC to the WRF model resulted in a significant increase in wind energy forecast skill.
- Assimilation of the special WFIP observations reduces forecast error (6% forecast hour 01, 1-2% at hour 15).
- Improvements are larger in the NSA than SSA where there were more observations spread over a larger area.
- The improvement is larger for ramp events and lasts for greater time (~7% MAE improvement 1-9h, both areas combined).
- Spatial aggregation reduces the forecast error. Even with spatial aggregation forecast skill improved by assimilating new observations.

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	
Project Number	DE-EE0003080
Agreement Number	DE-EE0003080

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Forecasting and field campaigns continue												
Q4 Milestone: Forecasting and field campaigns end												
Q2 Milestone: Forecasting performance, data analysis continue												
Q2 Milestone: Devlopment of Ramp Tool												
Q4 Milestone: Forecasting performance, data analysis continue												
Q4 Milestone: Forecasting performance, data analysis completed												
Q2 Milestone: Draft Technical Report												
Current work and future research												

Comments

Project original initiation date: 1 February 2011

Project planned completion date: 31 October 2013

Explanation for slipped milestones and slips in schedule: delay in execution of leases; data assimilation issues; economic analyses questions.

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators: Project Team Members: AWS Trupower, LLC; WindLogics, Inc./NextEra Energy Resources; Department of Energy National Laboratories (NREL, ANL, PNNL, LLNL); Energy Reliability Council of Texas (ERCOT); Midcontinent Independent System Operator (MISO); other AWS Truepower and WindLogics sub-contractors.

Communications and Technology Transfer: WFIP presentations given at Utility Variable Generation Integration Group 2011, 2012, 2013, 2014; American Meteorological Society 2012, 2013, 2014; Danish Technical University 2012, 2013; NAWEA, 2013; Technical paper to be submitted to the Bulletin of the American Meteorological Society.

WFIP model evaluation website available at:
www.esrl.noaa.gov/psd/psd3/wfip/

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

1) Impact of different observation types. Preliminary results show that industry tall towers and nacelles have a significant positive impact.
2) Forecast busts. What meteorological phenomena lead to the greatest forecast errors?

Proposed future research:

1) How do model and observations/data assimilation improvements translate to a region of complex terrain?

WFIP: Northern Study Area

Wind Forecast Improvement Project

Cathy Finley

WindLogics

cfinley@windlogics.com (651) 556-4283

March 25, 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.135M

Total Cost-Share[1]:$0.187M

Problem Statement: Improving wind energy forecast accuracy will facilitate integrating more wind energy into the electric grid. Since wind energy forecasts use NOAA weather forecast models, wind energy forecasting will improve as we improve foundational weather models through enhanced data assimilation, improved model physics, and better model grid resolution.

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Purpose & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Impact of Project: Reducing forecast errors will reduce barriers to integrating wind onto the electric grid through more efficient power grid operation. It will also demonstrate the value of sharing proprietary data from the wind industry with NOAA for the purposes of improving wind energy forecasts.

This project aligns with the following DOE Program objectives and priorities:

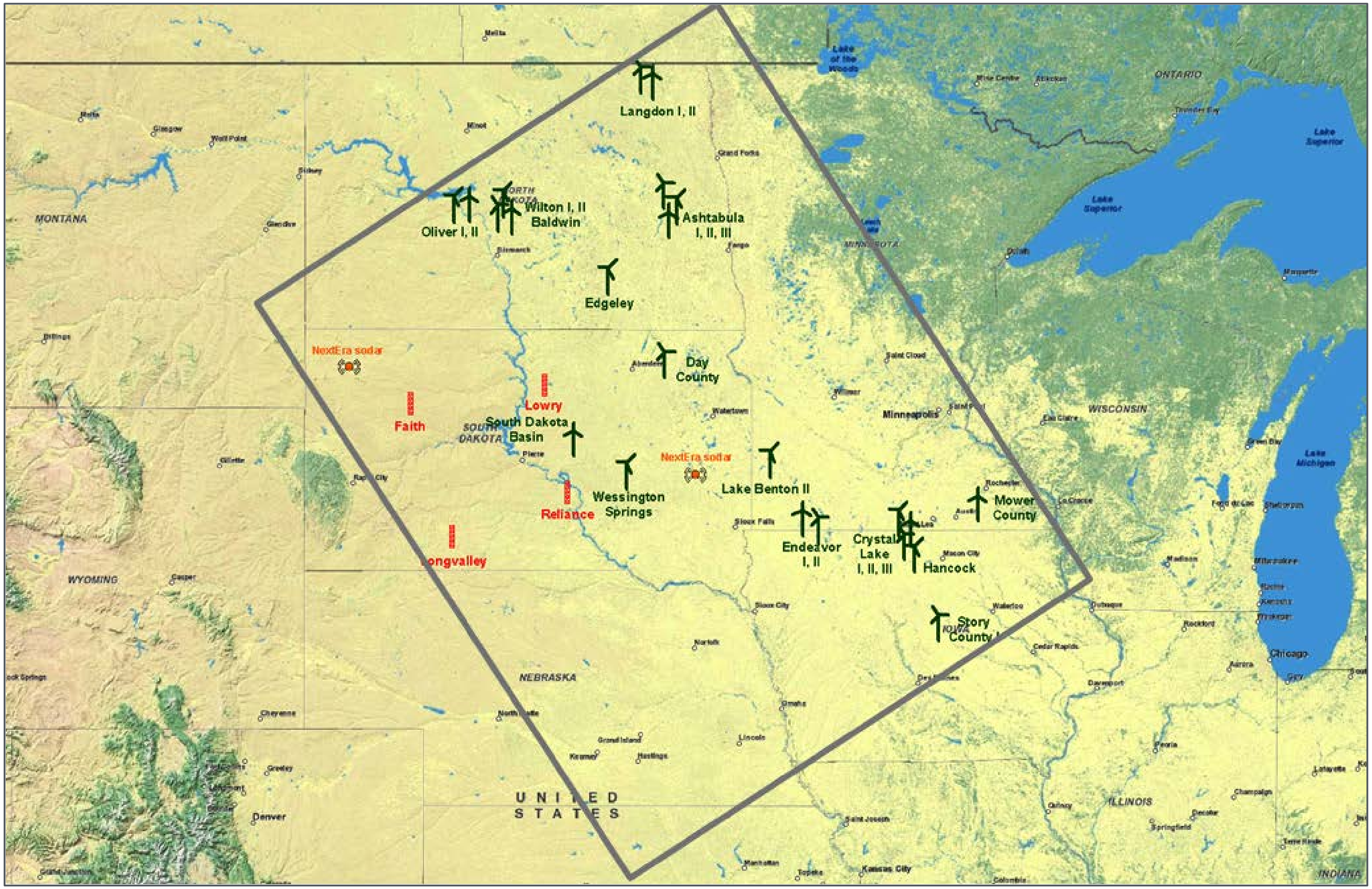
- Optimize Wind Plant Performance
- Mitigate Market Barriers
- Advance Grid Integration

Main Objectives

- Deploy/provide additional meteorological observations over a large area in the Northern Plains.
- Assimilate additional observations into NOAA weather forecast models with the aim of improving short-term wind (energy) forecasts.
- Evaluate the impacts of the enhanced weather forecast models on short-term wind power forecasts.
- Quantify the economic benefits of forecast improvements on power system operations in MISO operating area and power system operations in general. (Additional economic analysis will be funded in a separate project and results published in a separate report.)

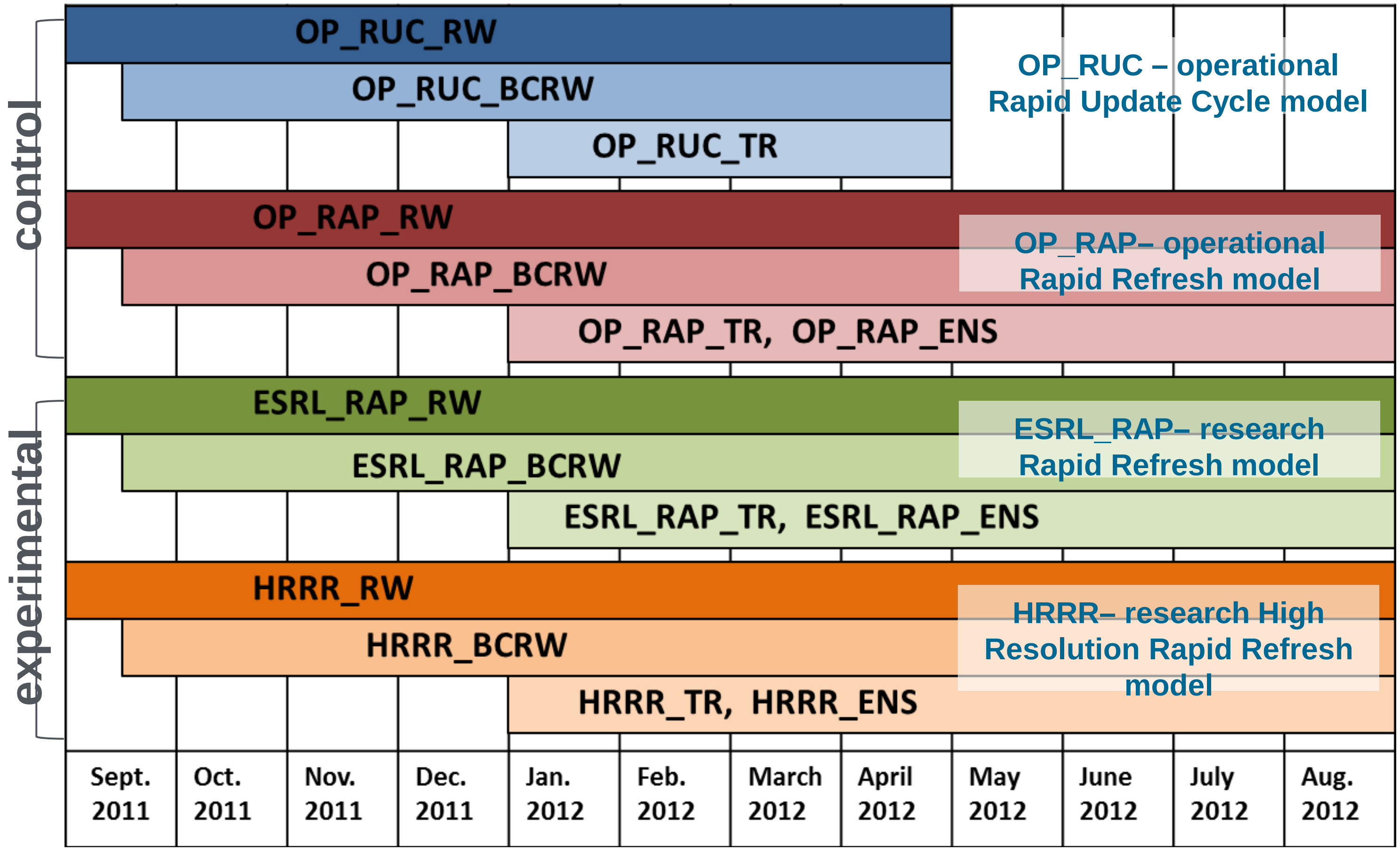
Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Location of NextEra wind plants in the Northern Study Area (turbines), SDSU tall towers (red bars) and WindLogics sodars (red dots).

Technical Approach



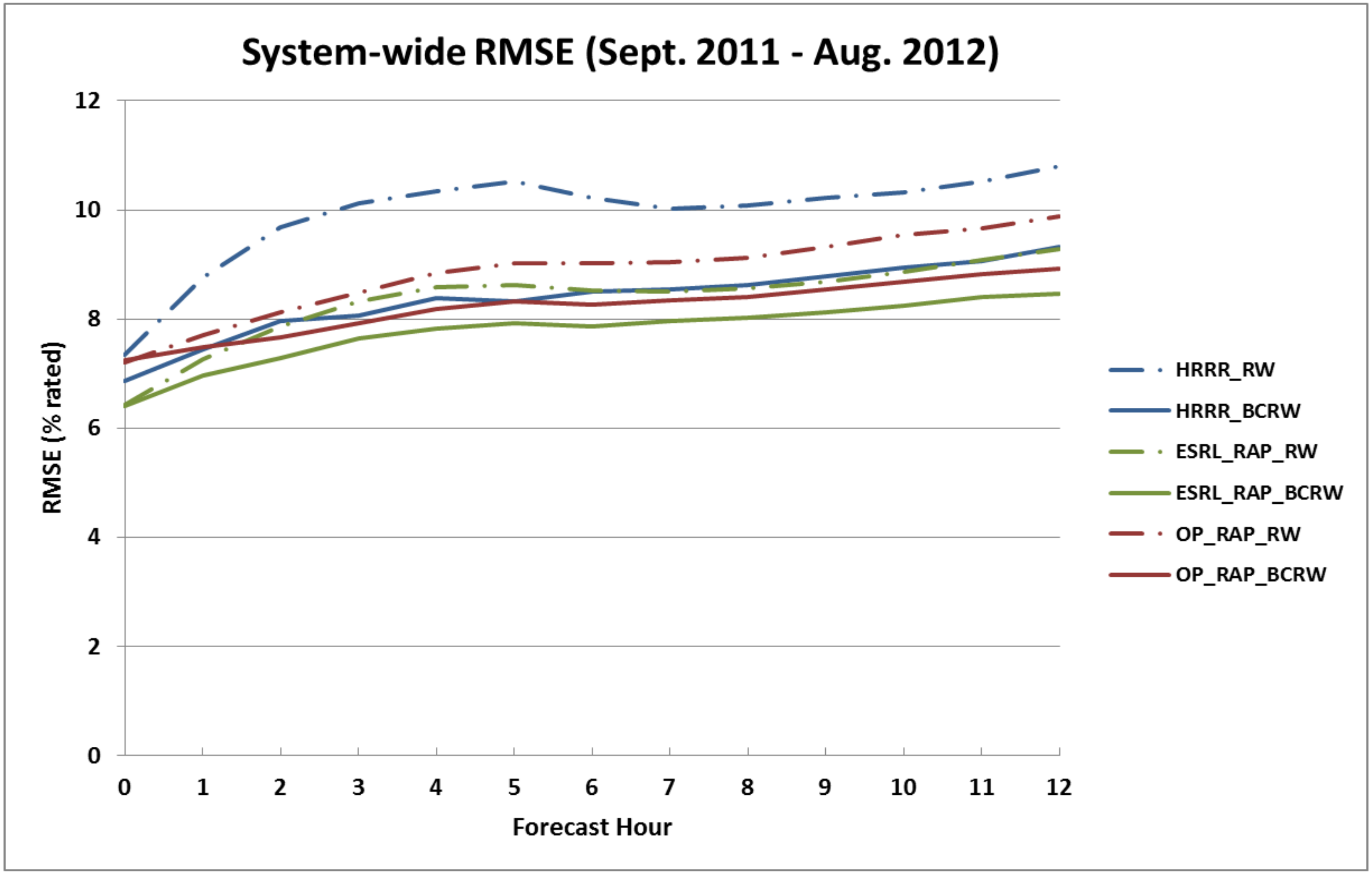
'Raw' fx (RW): model hub-ht. wind speed → plant power curve

'Bias-Corrected Raw' fx (BCRW): bias-correct hub-ht. wind speed → plant power curve

'Trained' fx (TR): single model data + onsite power data → computational learning system

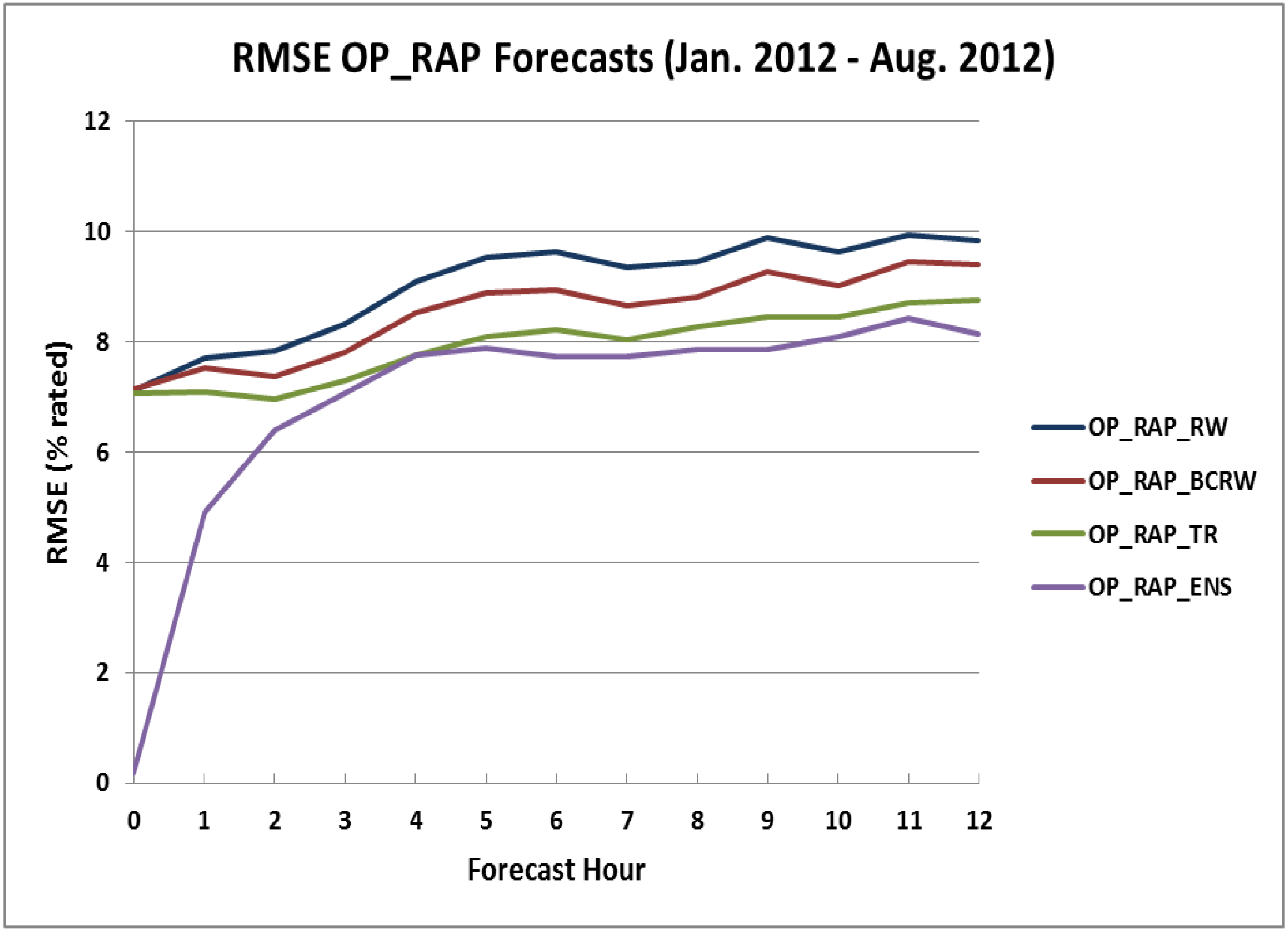
'Trained Ensemble' fx (ENS): short-range model + NAM + onsite data → computational learning system

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Wind Energy Ramps and Metrics

Ramp definition:

– power change of X% (rated capacity) over a Y hour period (or less) [suite of X,Y chosen based on observed distributions]

$$\boldsymbol{Frequncy\ Bias = \frac{\#\ forecasted\ events}{\#\ observered\ events}}$$

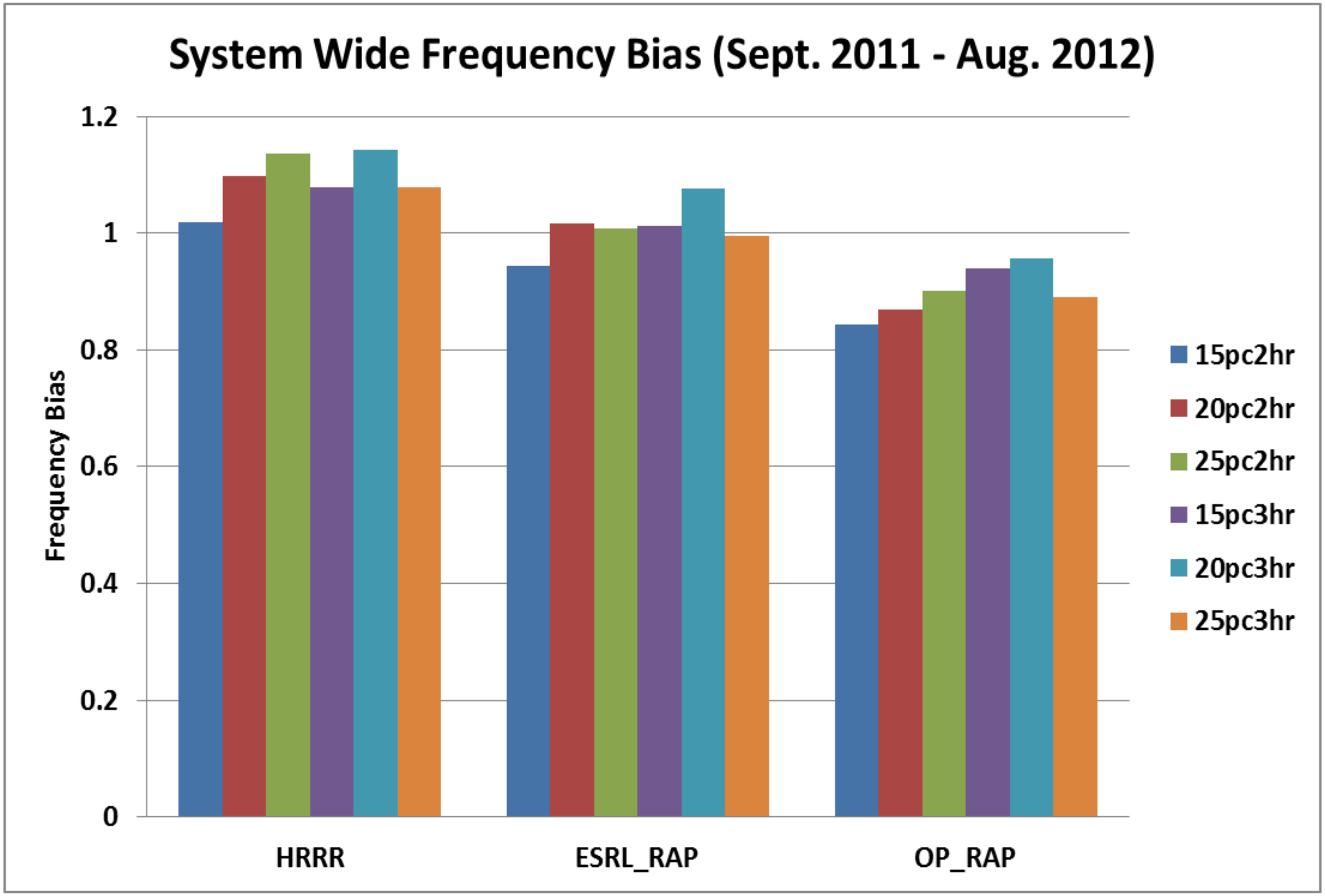
=1 for perfect forecast

$$\boldsymbol{Recall = \frac{\#\ hits}{\#\ observed\ events}}$$

=1 for perfect forecast

In addition to the above, also calculated average and absolute timing errors, magnitude errors, ramp rate errors, false alarm rates, others.

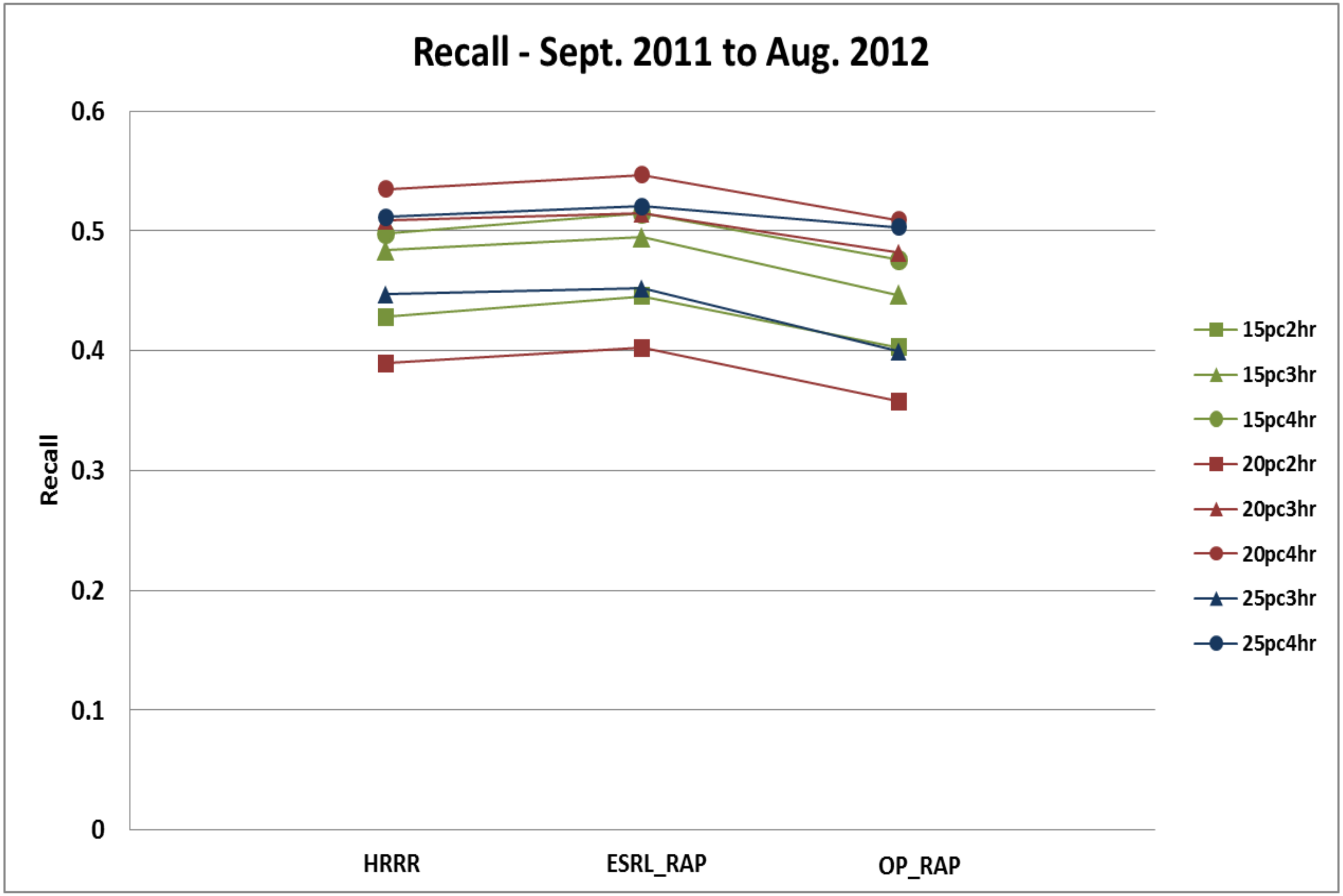
Results: System-Wide Aggregate Wind Energy Ramps



Bias-corrected raw power forecasts. Results are shown for 8 different ramp definitions (ex: 15pc2hr is a 15% (of rated) change over 2 hrs).

Accomplishments and Progress

Results: System-Wide Aggregate Wind Energy Ramps

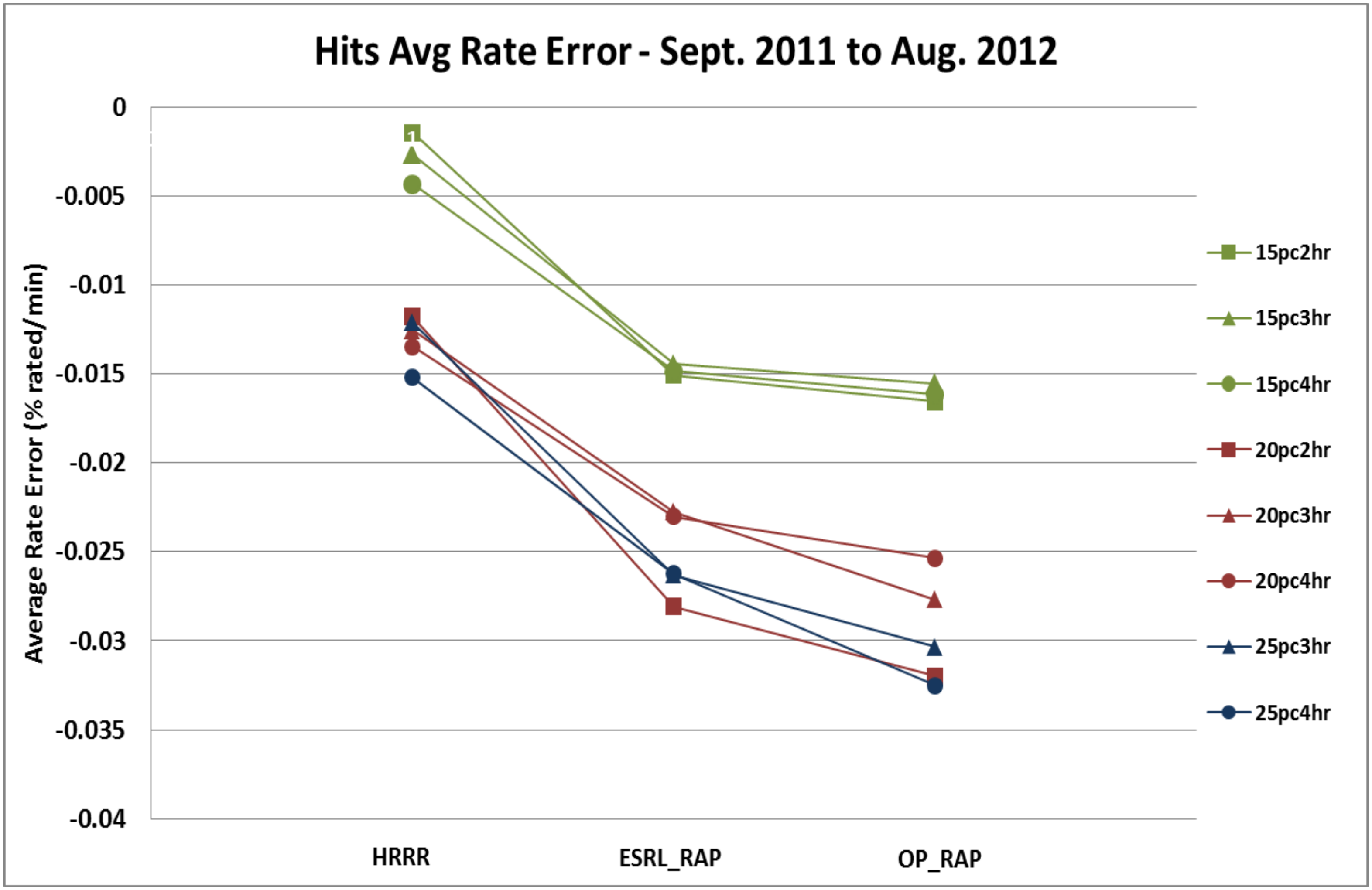


Bias-corrected raw power forecasts. Results are shown for 8 different ramp definitions (ex: 15pc2hr is a 15% (of rated) change over 2 hrs).

Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Results: System-Wide Aggregate Wind Energy Ramps



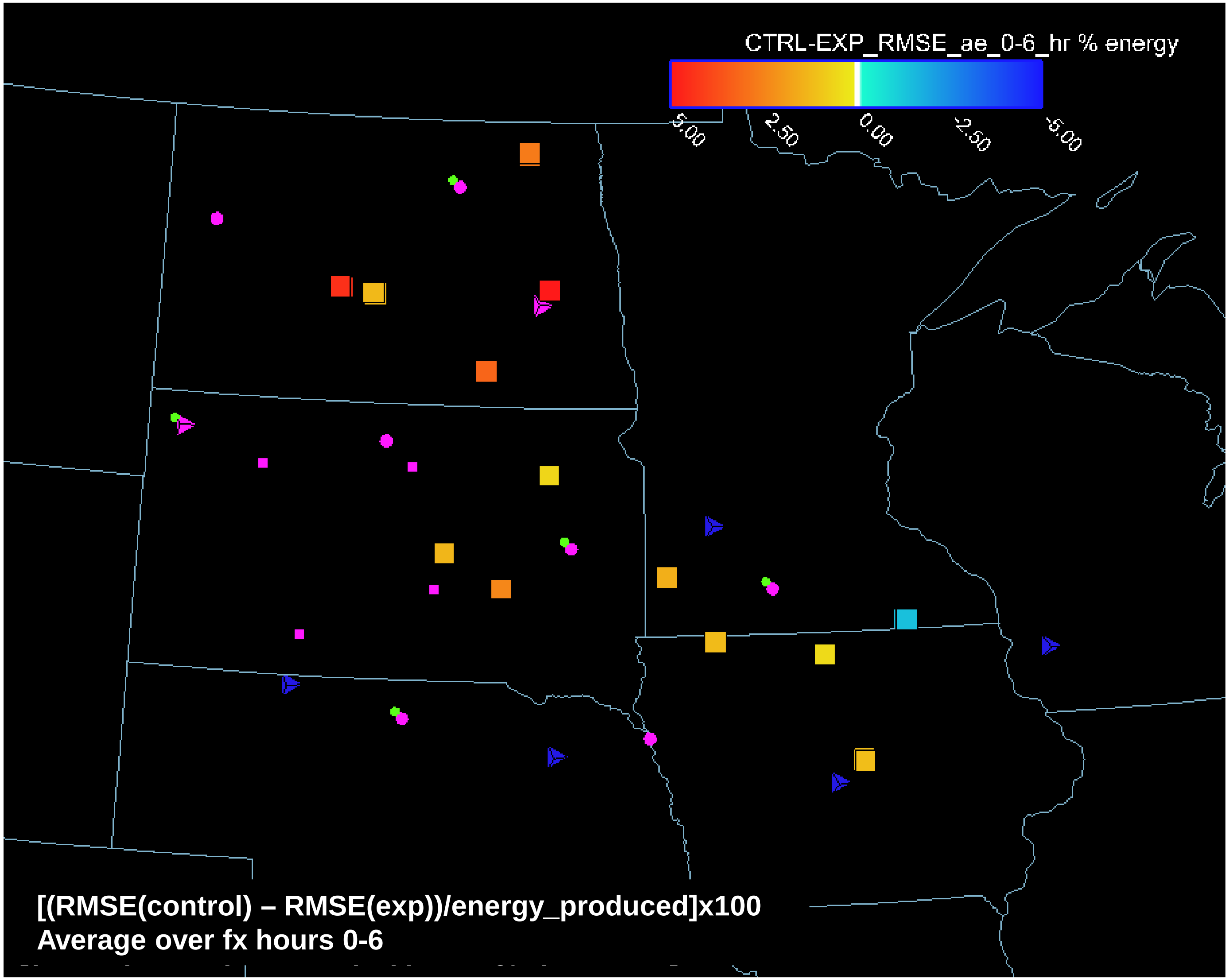
Bias-corrected raw power forecasts. Results are shown for 8 different ramp definitions (ex: 15pc2hr is a 15% (of rated) change over 2 hrs).

What impact does additional data provided during study have on wind energy forecast accuracy?

- NOAA ran several data denial experiments in which select periods were 're-forecasted' creating two sets of forecasts:
  - one forecast set initialized only with data which is currently available operationally (control)
  - one forecast set initialized with operational data + WFIP data (experimental)
  - time periods selected from each season (56 days total)
- all forecasts made with ESRL_RAP model
- results shown for RAW forecasts (i.e. no bias corrections or other statistical corrects applied)

Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Percent Improvement at NextEra wind plants

warm colors – experimental forecasts performing better than the control

cool colors – control forecasts performing better than experimental

white – statistical tie

Additional WFIP data (NextEra tall towers not shown):

- **449 MHZ wind prof.**
- **915 MHZ wind prof.**
- **sodars**
- **SDSU tall towers**

Existing 449 MHz wind profilers

Major Conclusions

- **Wind power forecasts based on research models with additional data assimilation and model improvements show improved power forecasts compared to current operational forecasts.**
- **Comparison of research model-based forecasts illustrate importance of using multi-model ensemble for wind energy forecasting.**
- **Clear improvement in forecast accuracy at almost all sites in study area due to the assimilation of the additional meteorological data provided in this study.**

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	
Project Number DE-FOA-0000343	
Agreement Number	

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: : A Public/Private Partnership for Improving Short Term Wind Energy Forecasts and Quantifying the Benefits to Utility Operations												
Provide real-time tower and nacelle data to NOAA												
Model Ingest												
Forecast Development												
Forecast Assessment												
Subcontractor-provided Economic Analysis												
Current work and future research												
Write and complete edits to Final Report												

Comments

- Project initiation date: October 1, 2010
- Original completion date: July 31, 2013 (report due October 31, 2013)
- Completion date: January 31, 2014
- Final Report release date: April 30, 2014

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- NOAA/DOE Labs
- NextEra Energy Resources (NEER)
- National Renewable Energy Laboratory (NREL)
- South Dakota State University (SDSU)
- Midcontinent Independent System Operator (MISO)

Communications and Technology Transfer:

- Utility Variable Generation Integration Group Forecasting Workshop: 2011, 2012, 2013, 2014
- American Meteorological Society Annual Meeting: 2012, 2013, 2014
- Paper to be submitted to the Bulletin of the American Meteorological Society.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research: Project complete pending submission of final report and other final documents. (Additional economic analysis will be funded and published in a separate project.)

Proposed future research: Data collected during the project could be used to validate and improve boundary layer representations in weather forecast models, which is critical to improving hub-height wind forecasts.

Quantify the impact of the industry-provided tall tower and nacelle data on forecast accuracy. This will help provide motivation for the industry to share data with NOAA.

Wind Forecasting Improvement Project: Southern Study Area

Jeffrey M. Freedman

AWS Truepower, LLC

jfreedman@albany.edu | 518-437-8737

25 March 2014

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.452M

Total Cost-Share[1]:$1.174M

Problem Statement: How do we improve the performance of short-term (0 – 6 hour) wind forecasting and how do we accurately measure the improvement?

Impact of Project: shows the value of model enhancements and additional atmospheric observations on wind power forecasts at turbine height, and how this will help reduce the levelized cost of energy.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

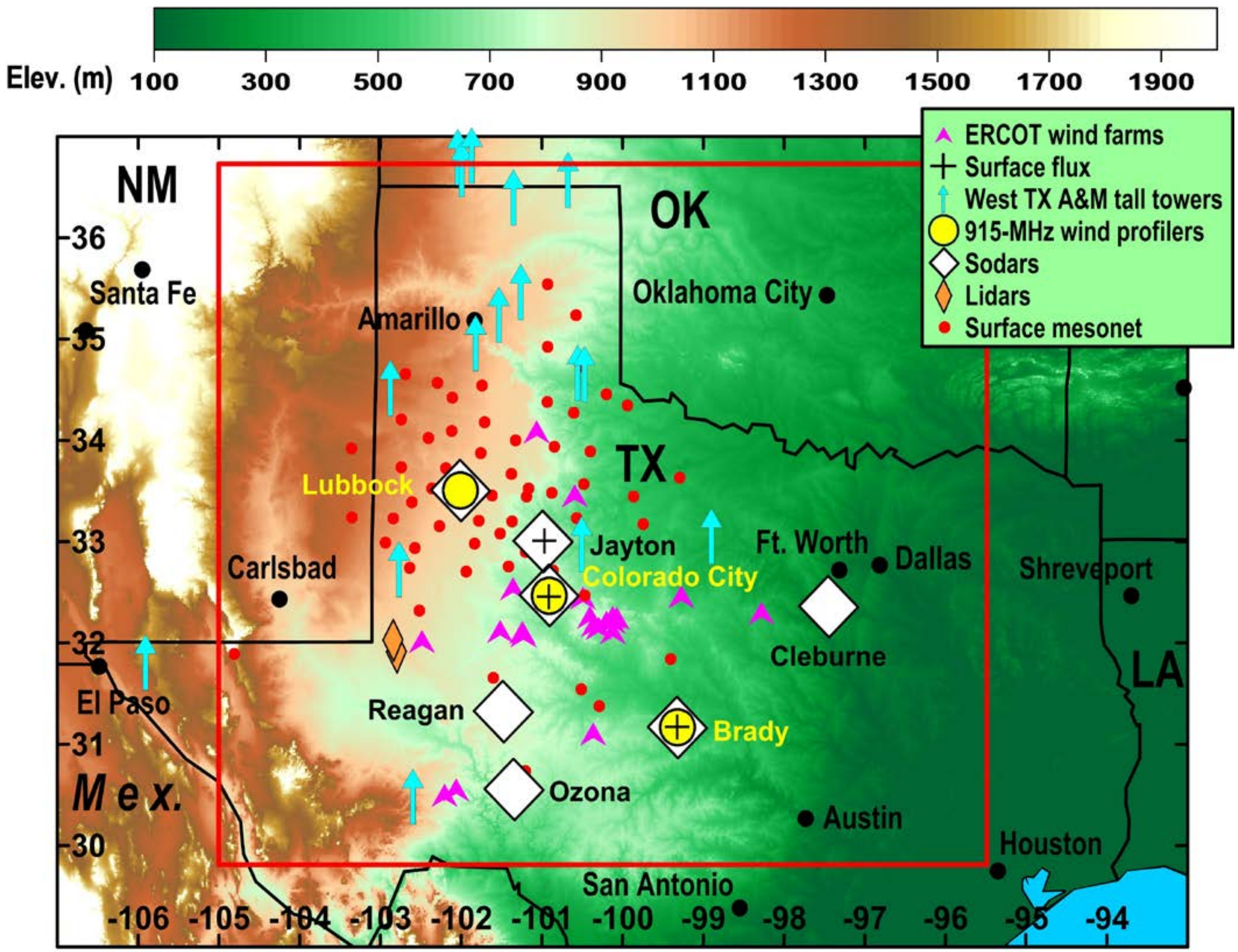
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

1. Determine what instruments placed in what locations are most valuable in facilitating better short-term forecasts;
2. Develop model configurations best suited to produce more accurate short-term forecasts of wind power production and better capture the amplitude and timing of ramp events*;
3. Establish the economic value of the improved short-term wind power production and ramp forecasts

*large excursions of power production in short time periods—defined for WFIP as per ERCOT system requirements

Technical Approach: Field Deployment in the Southern Study Area (SSA)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Additional Instrumentation

3 profilers w/RASS

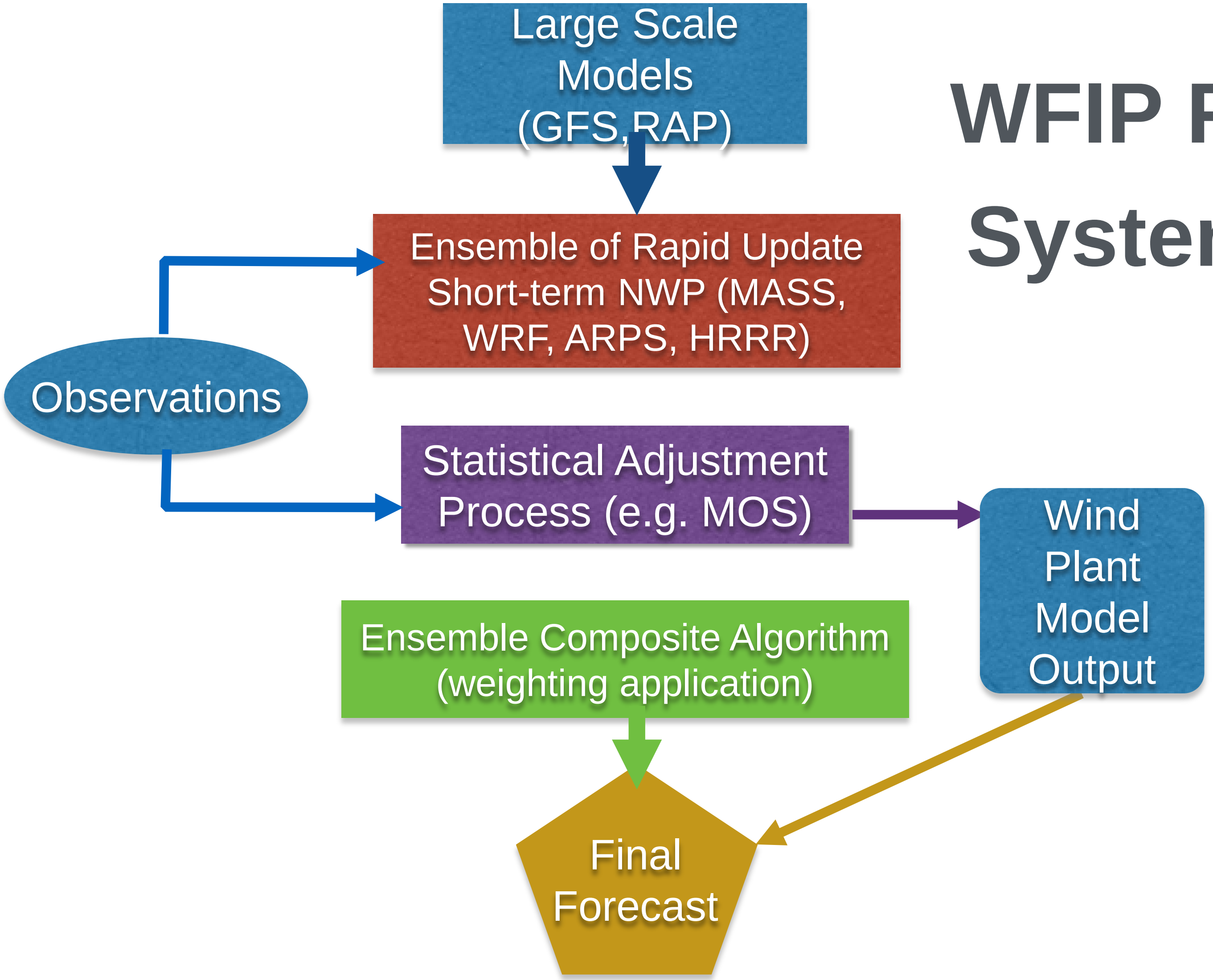
7 sodars

6 surface met and flux stations

200-m TTU tower and 15 - 35 Tall Towers (wind farms; 50 total)

Technical Approach: WFIP Forecast System (SSA)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



WFIP Forecast System (SSA)

Phenomena

1. **Synoptic scale** (fronts, dry lines) ➠ big ramps; easier to predict

2. **Low-level jets (LLJs)** ➠ common (Freedman et al. 2008); periodic but large variability in small Δz presents forecast difficulty

3. **Mesoscale** (convection, outflow boundaries) ➠ tougher to predict given temporal and spatial scales

Accomplishments and Progress—Field Campaign

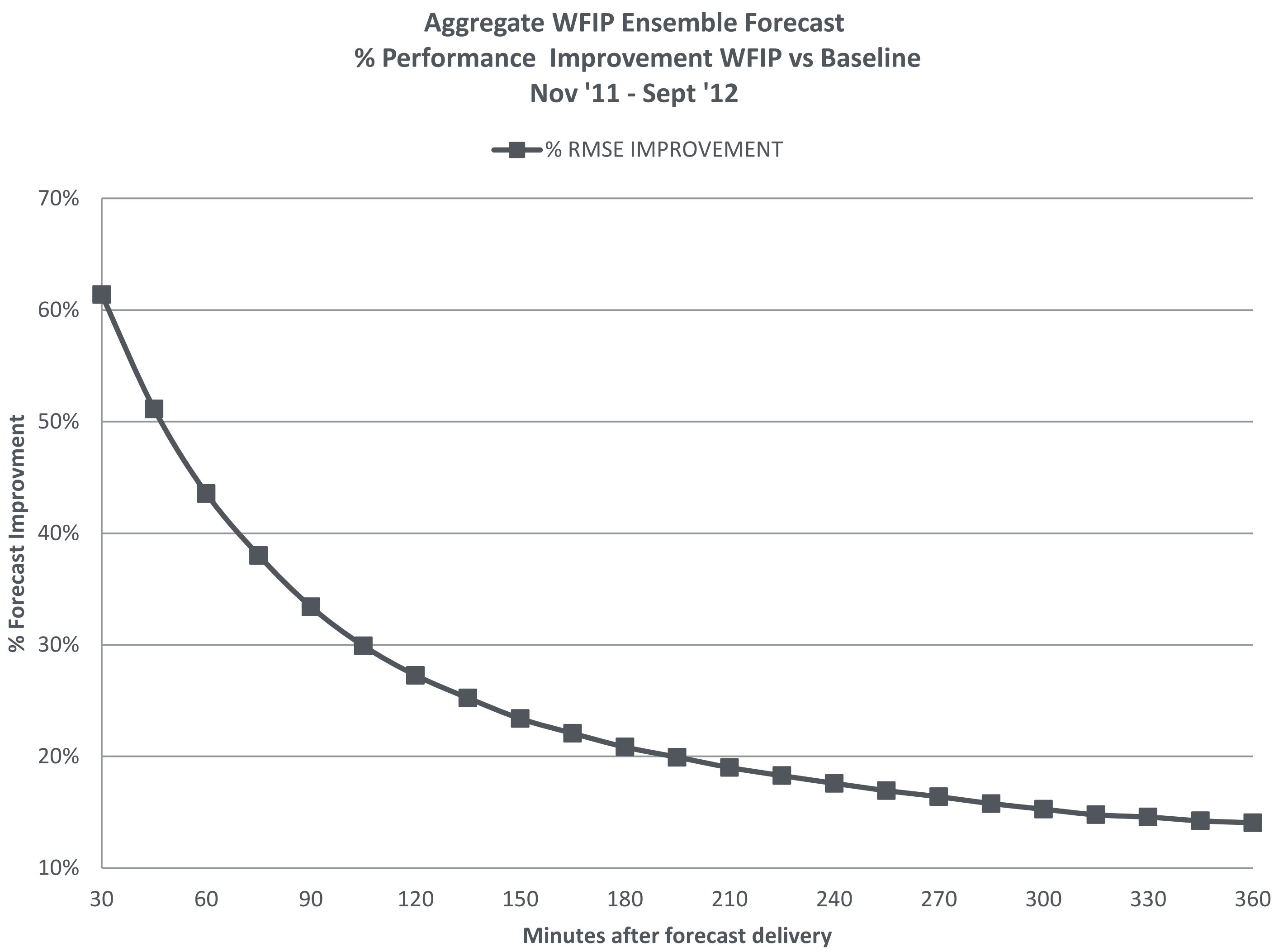
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Successfully deployed full suite of instrumentation *as originally set forth* in Task 1 of the SOPO (and subsequently modified by DOE/NOAA) for 1 year (17 July 2011 – 13 September 2012) with > 90% data recovery (most instruments > 95%).
- All remote sensing (and most surface) data from enhanced observations assimilated into WFIP modeling systems.
  - Additional deployment (August – October 2012) of two LiDARs at participating wind farm—data recovery poor, however
- Identified, categorized, and analyzed phenomena predominantly responsible for ramp events in the SSA

Accomplishments and Progress—WFIP Forecast System

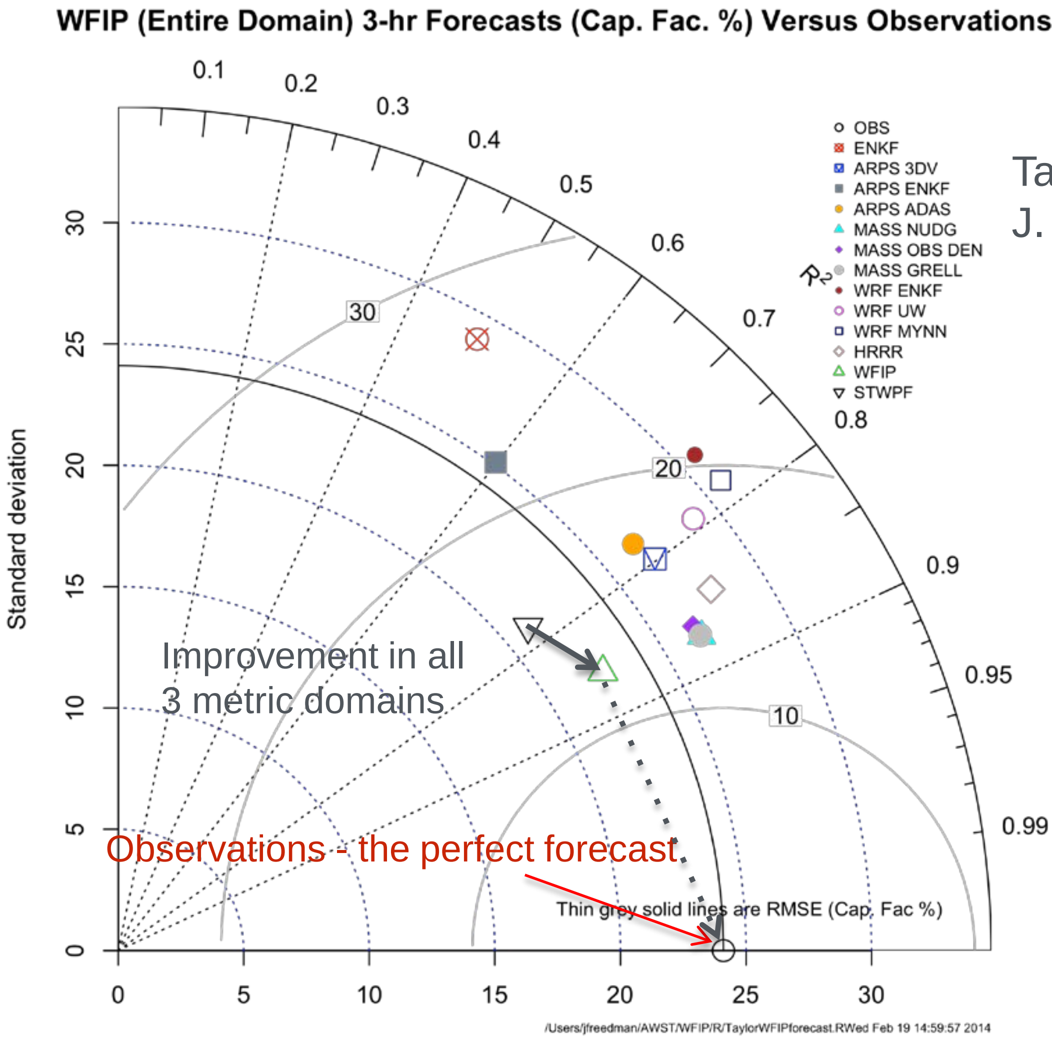
- WFIP forecast and baseline systems (AWS Truepower/MESO) in real-time operation for field/modeling deployment period (26 August 2011 – 13 September 2012) and SOPO objectives met.
- OU CAPS ARPS forecast system operational for entire deployment period and sensitivity studies completed.
- TTU successfully carried out data assimilation sensitivity studies.
- Collaborated with NOAA on data denial experiments.
- Overall 10 – 20% improvement in forecast accuracy
- Data denial experiments show less but still significant improvement in forecast performance using enhanced observations

Accomplishments and Progress—Results: overall WFIP model performance



Accomplishments and Progress—Results: overall WFIP model performance

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Taylor diagram
J. Geophys. Res., 106(D7), 7183–7192 (2001)

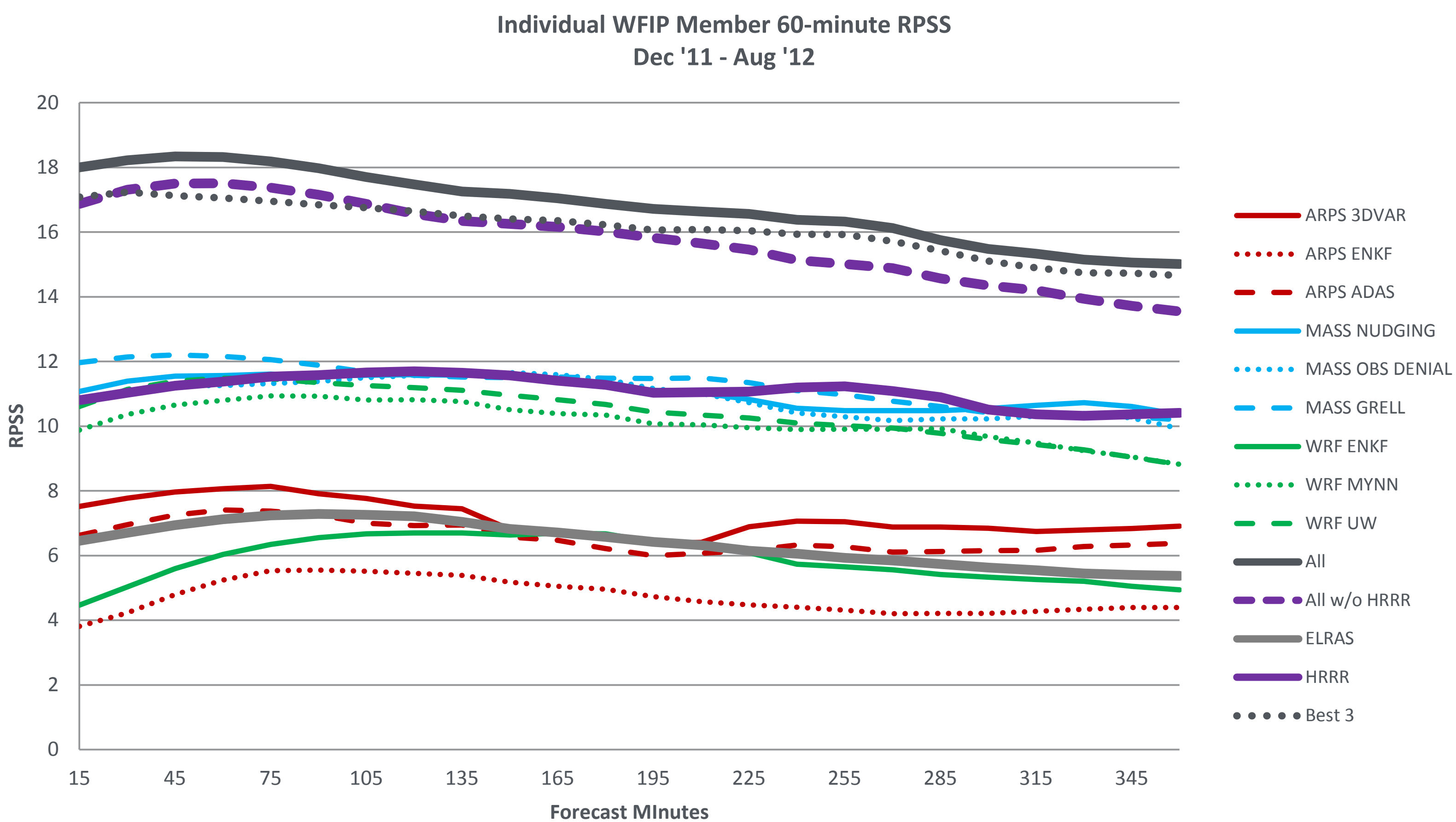
3 metrics (R^2, RMSE, and SD) on 2D space

Here, overall significant improvement in model performance but still room for more

Accomplishments and Progress—WFIP model performance: ramps

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Ranked Probability Skill Score (RPSS): improvement of the ramp probability forecast over climatological ramp probabilities (> 0 → skill over climatology)



Accomplishments and Progress—Economic Analysis

- ICF International, in collaboration with DOE NREL, completed a comprehensive economic evaluation of the benefits attributable to the improved forecasts from the enhanced WFIP modeling system.
- DOE has decided to undertake additional studies to explore the complex interactions between wind forecasting and power system operations prior to publication of these results. The initial work performed by the WFIP teams provided important insight into the benefits and shortcomings of various power system assumptions, market designs, and modeling tools in identifying costs and savings. The desire to explore these important issues in more detail is the impetus for the new analysis. Over the next year, DOE plans to engage with industry experts, grid operators and economic modelers to accurately define methodologies that provide quantification of total financial savings and other ancillary benefits of improved short-term wind power production forecasts.

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary	
WBS Number or Agreement Number	10EE0004420
Project Number	DE-EE000420
Agreement Number	DE-EE000420

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Forecasting and field campaigns continue												
Q4 Milestone: Forecasting and field campaigns end/decommissioning (including LiDAR deployments)												
Q2 Milestone: Forecasting performance, data analysis and economic analysis continue												
Q2 Milestone: Second User Group Meeting												
Q4 Milestone: Forecasting performance, data analysis and economic analysis continue												
Q4 Milestone: Forecasting performance, data analysis and economic analysis completed												
Q2 Milestone: Draft Technical Report												
Current work and future research												

Comments

Project original initiation date: 1 October 2010

Project planned completion date: 31 January 2014

Explanation for slipped milestones and slips in schedule: delay in contract execution; NOAA data assimilation issues; economic analyses—questions regarding methods, consistency between Northern and Southern Area findings, limitations regarding economic tools, exploratory discussions regarding further work.

Partners, Subcontractors, and Collaborators: The Electric Reliability Council of Texas (ERCOT), MESO, Inc.,Texas Tech University (TTU), North Carolina State University (NCSU),The University of Oklahoma (OU) Center for Analysis and Prediction of Storms (CAPS), ICF International (ICF), and the National Renewable Energy Laboratory (NREL)

Communications and Technology Transfer: Two project User Group (composed of utilities, ISOs, and other interested stakeholders) meetings were held in Tucson AZ on 7 February 2012 and Salt Lake City on 27 February 2013. Presentations were given on project progress and preliminary results. Preliminary results and findings were also presented at other conferences and workshops, including:

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Communications and Technology Transfer: the Utility Wind Integration Group (UVIG) meeting in Maui, Hawaii (October 2011); American Meteorological Society's (AMS) Annual meeting, New Orleans LA, January 2012; UVIG Forecasting Workshop, Tucson AZ, February 2012; Western Electric Coordinating Council, March 2012; American Wind Energy Association (AWEA), Wind Power 2012, 3 – 6 June 2012 Atlanta, GA; AMS 20th Symposium on Boundary Layer and Turbulence, Boston MA 9 – 13 July 2012; 11th International Workshop on Large Scale Integration of Wind Power into Power Systems, 13 – 15 November 2012, Lisbon, Portugal; AMS Annual Meeting, Austin TX 5 – 10 January 2013; UVIG Workshop on Forecasting Applications, Salt Lake City, UT 27 – 28 February 2013; AWEA Wind Power 2013, Chicago IL 6 – 8 May 2013; AMS Annual Meeting, Atlanta GA, 2 – 6 February 2014; UVIG Forecasting Workshop, Tucson AZ, 26 – 27 February 2014.

Publications: Ancell, B., E. Kashawlic, and J. L. Schroeder, 2013: "Evaluation of Wind Forecasts and Observation Impacts from Variational and Ensemble Data Assimilation during the WFIP Project," Monthly Weather Review, submitted.

Wilczak et al., 2014: The Wind Forecast Improvement Project (WFIP): A Public-Private Partnership Addressing Wind Energy Forecast Needs, Bulletin of the American Meteorological Soc., in preparation.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research: Project completed

Proposed future research

Additional post-WFIP work: 1) more comprehensive economic analysis inclusive of all forecasting time scales and indirect cost savings; 2) identification of the ultimate recipients of economic benefits; 3) additional, more extensive analysis of phenomena responsible for ramp events/outliers (leverage one-year's worth of continuous remote sensing/surface observation field data

General: embrace efforts by DOE and NOAA to use information learned from this project to expand existing network capabilities or deploy new sensor networks in regions already populated by or undergoing an expansion of wind farms, or those areas set to deploy such facilities. Apply lessons learned from modeling sensitivity studies to further enhance forecasting efforts and reduce power production forecast errors (and increase cost savings) on a variety of temporal and spatial scales.

Enhancing Short Term Wind Forecasting for Improved Wind Utility Operations

Larry Berg

Pacific Northwest National Laboratory

509.375.3916, larry.berg@pnnl.gov

3/25/14

Budget, Purpose, & Objectives

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Total DOE Budget[1]: $0.120M

Total Cost-Share[1]: $0.000M

Problem Statement: Additional wind data is needed to improve short-term forecasts of hub height wind speeds, which is the primary goal of the Wind Forecast Improvement Project (WFIP)

Impact of Project: This project provided data used as part of the WFIP study, and demonstrated the need for improved parameterizations for predicting hub-height winds, wind shear, and ramp events.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach: Field Deployment

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objective: Provide data for assimilation into NOAA High Resolution Rapid Refresh (HRRR) and other models

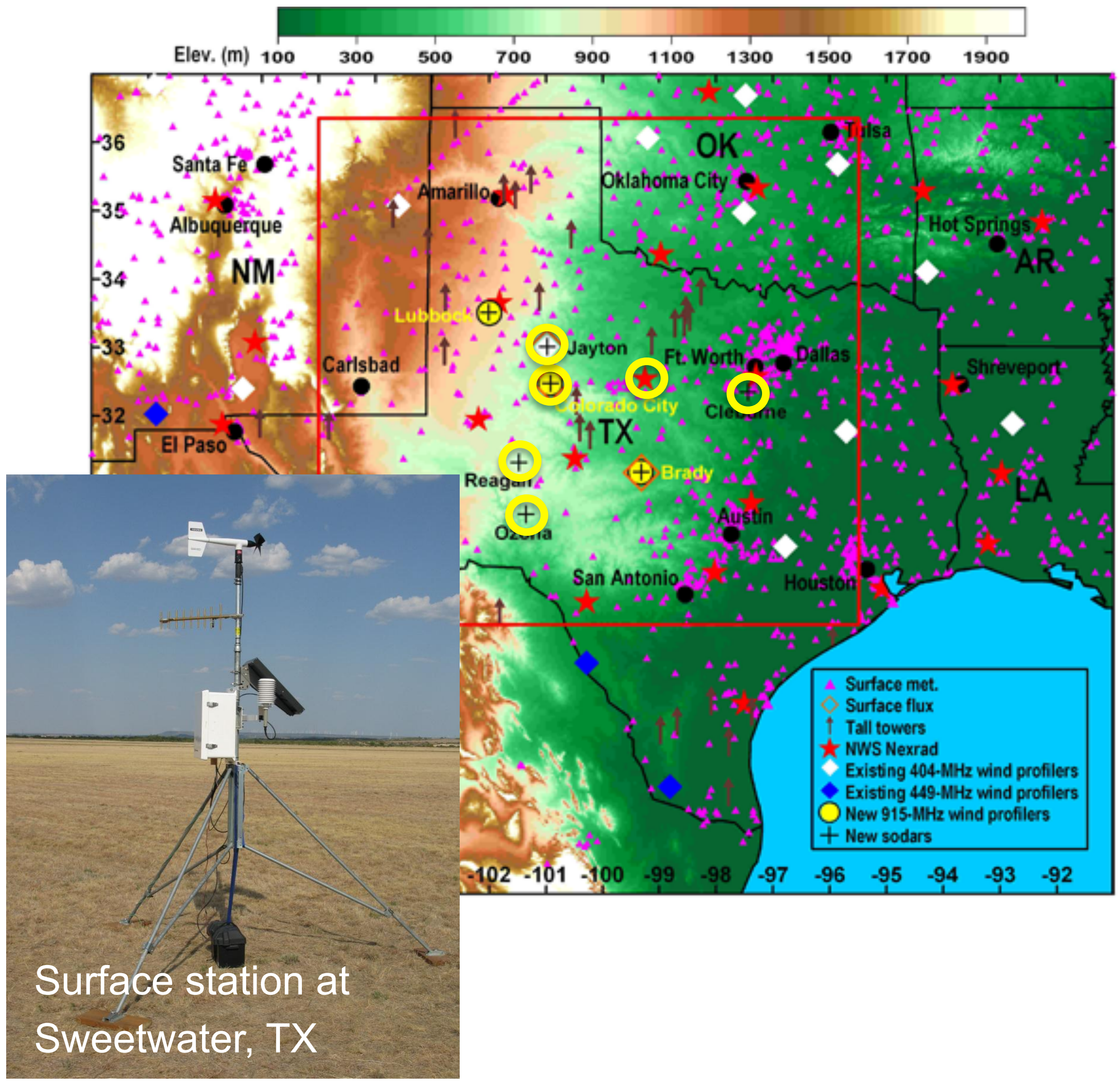
- Configured surface weather stations to augment deployments of radar wind profilers, sodars, and Doppler lidars
- Measurements included:
  - Wind speed and wind direction
  - Temperature
  - Humidity
  - Solar radiation
  - Pressure
- Locations selected in conjunction with AWS Truepower and WindLogics.

Accomplishments and Progress: Field Deployment

- Deployed 6 surface meteorological stations in the southern domain and 1 (Sioux City, IA) in the northern study area
- Data was collected and passed to NOAA in near-real time during the duration of WFIP—data availability greater than 96%

Bottom line:

Data contributed to WFIP, and was a baseline for measurements from remote sensors



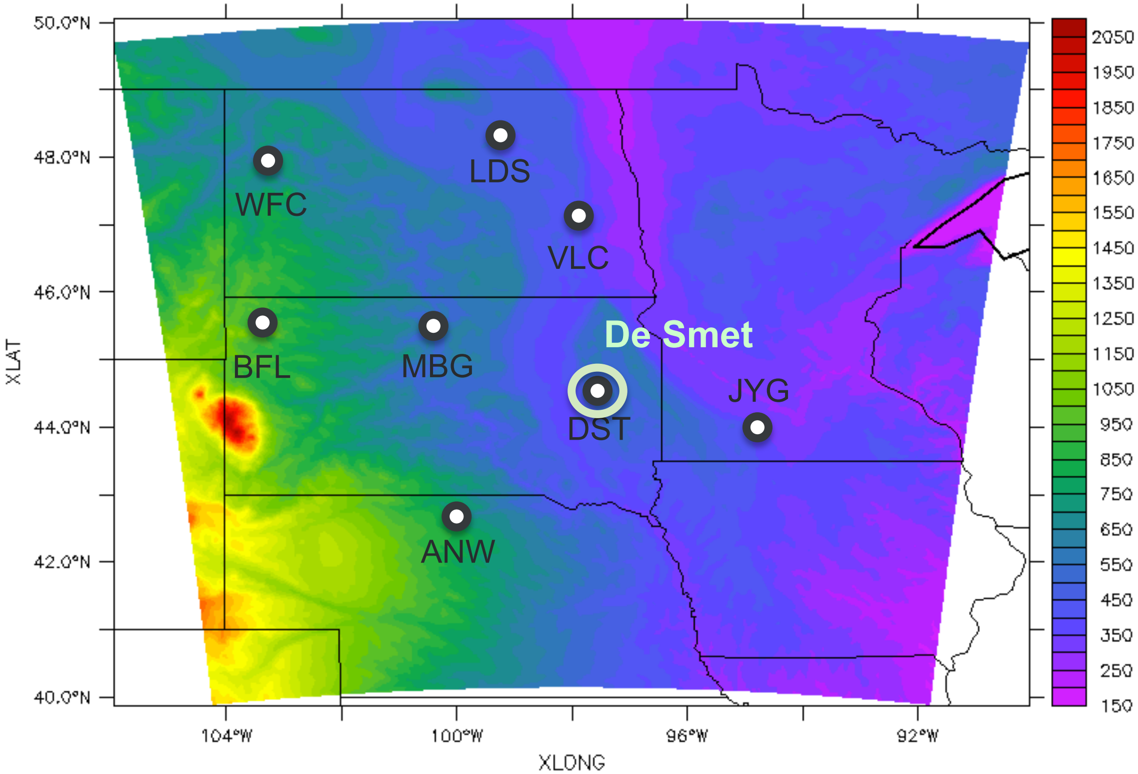
Surface station at Sweetwater, TX

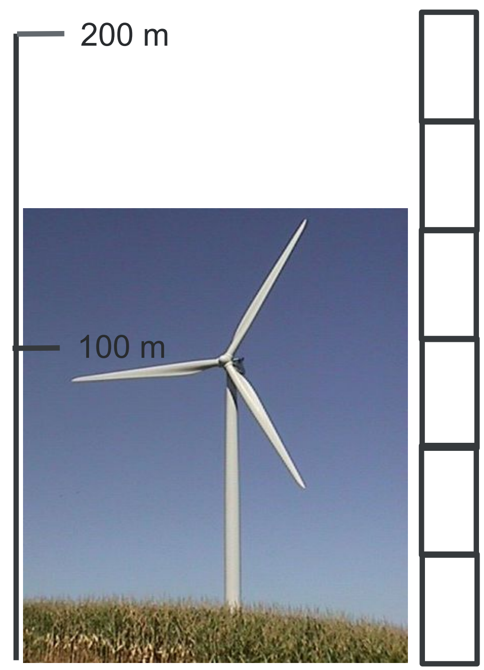
Technical Approach: WRF Simulations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objectives:

- Quantify differences in near-surface wind speeds due to the choice of boundary-layer parameterization and quantify how that affects forecasts of ramp events
- Couple 1) radar wind profiler and 2) high-resolution lidar data to evaluate predicted vertical wind speed gradients within a few hundred meters of the ground



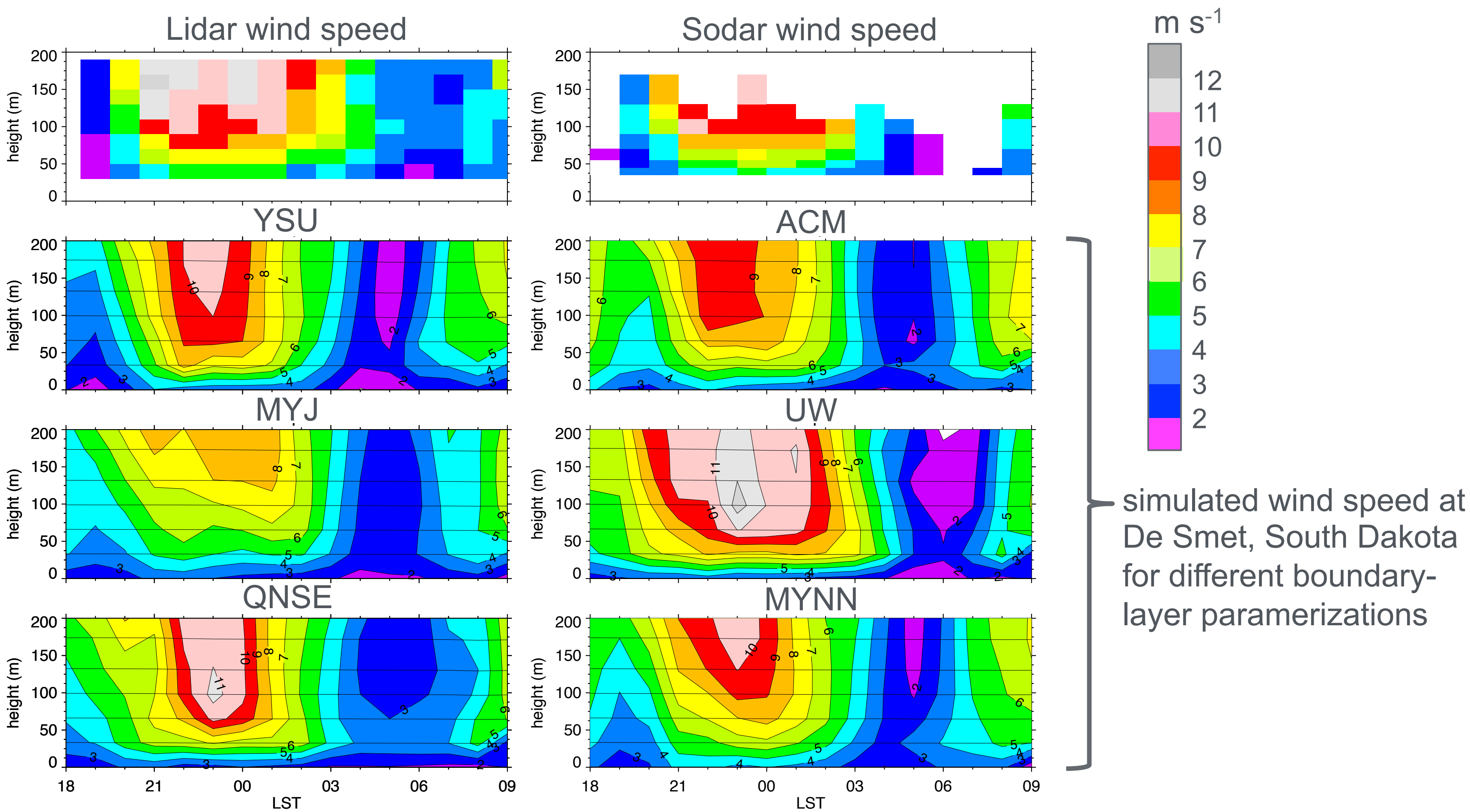


WRF vertical grid cells

- Δx = 3 km, six PBL schemes tested
- Simulation period: September – mid October 2011

Accomplishments and Progress: WRF Simulations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

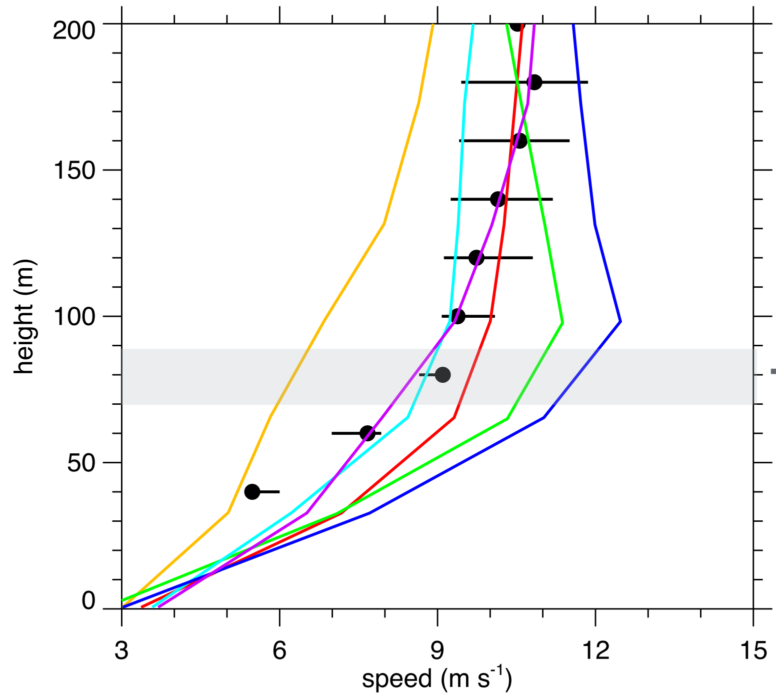


- Lidar and sodar wind speeds are similar, but sodar has more missing data on most days
- Variability in simulated wind speed and vertical wind gradients near hub height associated with choice of boundary-layer parameterization

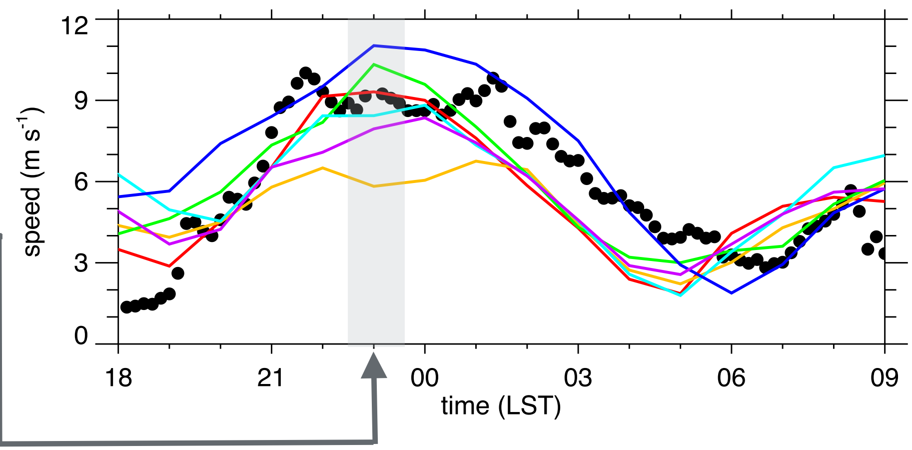
Accomplishments and Progress: WRF Simulations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Wind Speed Profile
23 LST September 18



Time Series at ~ Hub Height
September 18 - 19

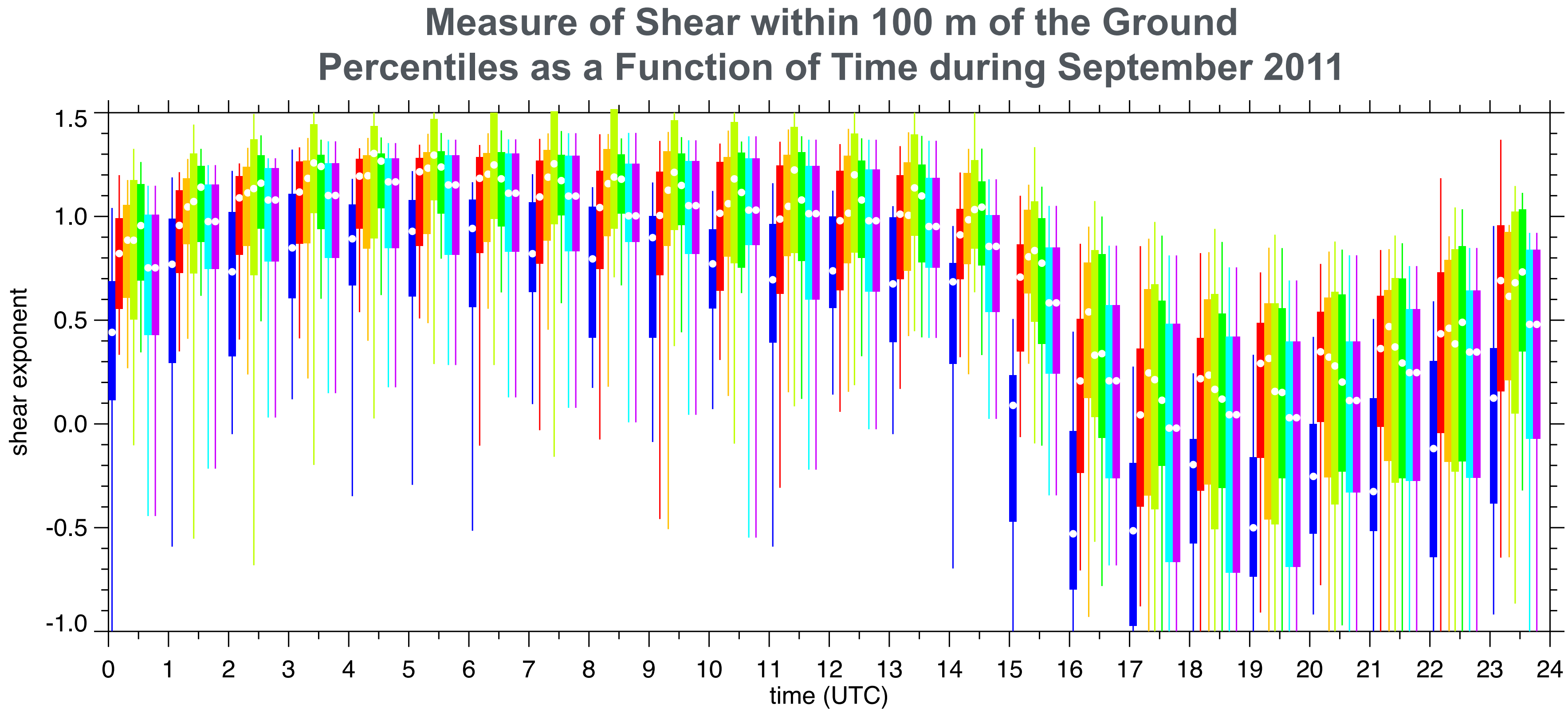


Lidar observations (10-min)
YSU, MYJ, QNSE, ACM, UW, MYNN

- Wind speed gradient across rotor plane varies significantly among boundary-layer parameterizations
- Largest differences among the simulations associated with the peak time of the low-level jet

Accomplishments and Progress: WRF Simulations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Lidar observations

YSU, MYJ, MYNN, QNSE, ACM, UW,

- Model tends to produce near-surface wind shear that is too large, regardless of the boundary-layer parameterization that is used
- Wind shear errors are largest during mid-day

Bottom line: No parameterization was superior—additional improvements needed

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Summary		Legend
WBS Number or Agreement Number		Work completed
Project Number		Active Task
Agreement Number		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)

Task / Event	FY2012				FY2013				FY2014			
	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Complete a set of simulations for the Northern WFIP domain												
Q2 Milestone: Complete a draft manuscript												
Q3 Milestone: Submit a manuscript to a peer-reviewed journal												
Current work and future research												
N/A												
N/A												

Comments

- Initiation Date: February, 2011 Planned Completion Date: 6/30/14
- Project was delayed due to data quality issues and modifications to one of the WRF parameterizations that required re-running simulations.

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- AWS Truepower, WindLogics—WFIP leaders; Southern Study Domain Team: ERCOT, MESO Inc, N.C. State U., NREL,Texas Tech U., & U. of Oklahoma
- NOAA—Data and NWP modeling
- LLNL—Data collection and analysis

Communications and Technology Transfer:

Freedman, J., et al., 2011: Update on DOE/NOAA ERCOT AWST Project. UWIG Workshop on Variable Generation Forecasting Applications to Utility Planning and Operations. Tucson, AZ.

Freedman, J., et al., 2013: The wind forecasting improvement project: Results from the southern study area. American Meteorological Society, 4th Conference on Weather, Climate, and the New Energy Economy.

Mirocha, J.D., et al., 2014: Investigation of lower-atmospheric wind predictions during low-level jet events using the Weather Research and Forecasting model, submitted to *Wind Energy*.

Wilczak, J., et al., 2013: *Data Denial Experiments from the Wind Forecast Improvement Project (WFIP).* American Meteorological Society, 4th Conference on Weather, Climate, and the New Energy Economy.

Next Steps and Future Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research: Current efforts are focused on finishing the project and preparing a manuscript that will be submitted to a peer-reviewed journal to share results with the community.

Proposed future research: Future research efforts include uncertainty quantification to better understand model uncertainty with the goal of guiding field measurements and parameterization development.