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

WIND PROGRAM

Complex Flow

Workshop Report

January 17–18, 2012

University of Colorado, Boulder

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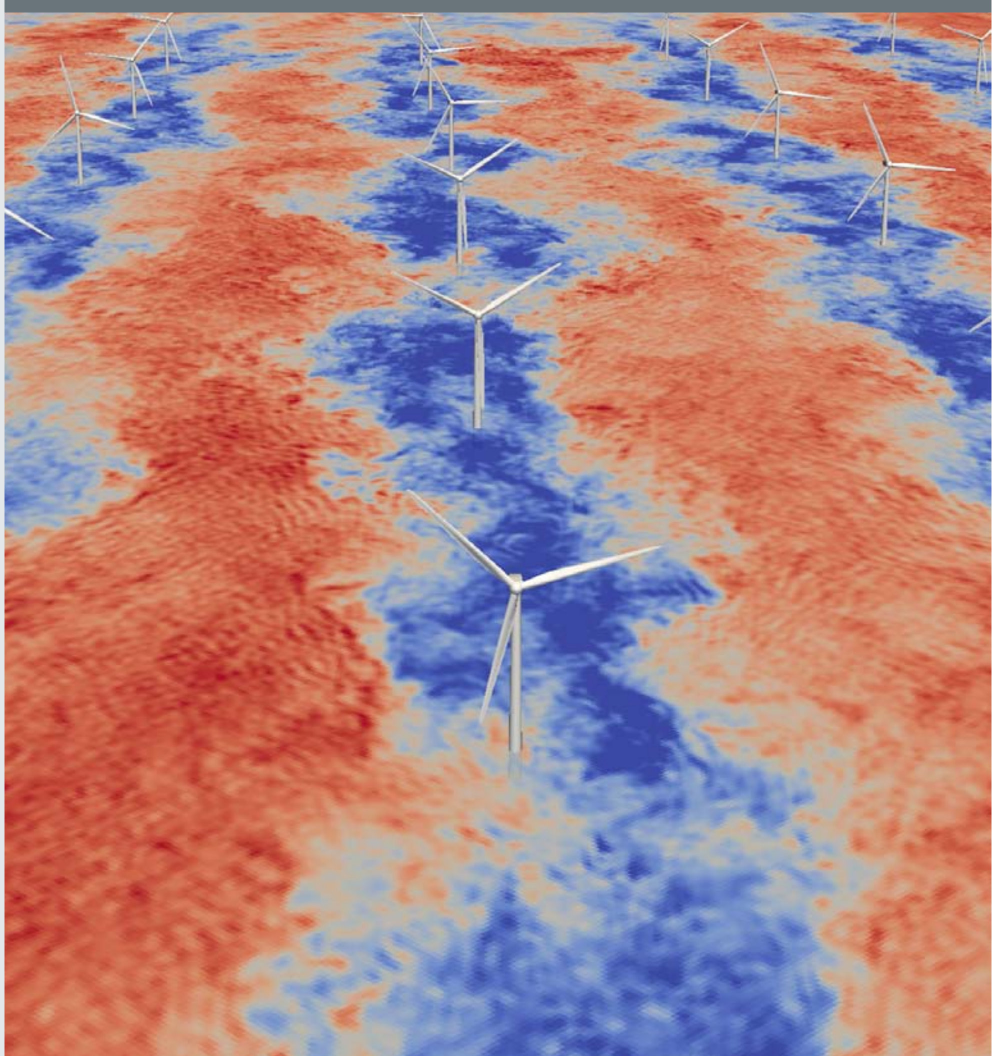


DOE Complex Flow Workshop Report

January 17-18th, 2012 at the University of Colorado, Boulder

Executive Summary

The significance of complex flow R&D

Wind power plants are already cost effective compared to fossil fuels in some U.S. regions, and they are poised to become the leading form of low cost renewable energy in the coming decade. However, significant innovation is still required to achieve parity with natural gas and gain widespread adoption. Understanding the complex multi-scale aerodynamics involved with modern wind farm systems is a significant technical challenge for future innovation, and it represents one of the largest potential sources of cost reduction for wind energy. Large wind plants comprised of multi-megawatt turbines arranged in multiple arrays are the preferred installation paradigm with the lowest capital cost, and the resulting deployments, often in complex terrain, have produced unique opportunities to reduce the levelized cost of energy (LCOE). Consider (see Appendix F for References):

- *Power losses can be as high as 20-30% in operating wind farms, due solely to complex wake interactions occurring in wind farm arrays. [1,2,3]*
- *Forecasting accuracy improvements of as little as 10-20% could result in hundreds of millions of dollars (est. ~$140-260M) in annual operating cost savings for the U.S. wind industry. [4]*
- *Drivetrain components such as gearboxes and generators are failing significantly earlier than their twenty-year design life. These failures are caused in large part by uncertainty in aerodynamic loading conditions. [5,6]*

Furthermore, forecasting used in conjunction with active control at the wind plant and grid system level can be used to optimize production and further decrease LCOE.

In light of these significant opportunities to reduce the cost of wind energy, the Department of Energy's (DOE's) Wind and Water Power Program (WWPP) organized a two-day workshop to identify research needs and challenges. Specifically, the workshop was designed to examine complex wind flow into and out of the wind turbine environment, as well as the resulting impacts on the mechanical workings of individual wind turbines. An improved understanding of these processes will subsequently drive down the risk involved for wind energy developers, financiers, and owner/operators, and thus drive down the cost of energy for the valuable wind resource.

Workshop Focus and Construct

The Complex Flow Workshop was held on January 17-18th in Boulder, CO. The workshop was located on the campus of the University of Colorado, Boulder, and was comprised of plenary sessions, Breakout Groups (BOGs), and sub-topic breakout groups. The BOGs were organized around the following four topics (see Figure 1):

- **BOG 1: Mesoscale Control Volume**
  - *The mesoscale group focused on regional scale modeling challenges, which include the impacts of turbulence, shear across scales, global scale physics, flow forcing, coupling kilometer-scale models to sub-kilometer models, and the resources required to improve such models. Inter-wind farm impacts were also considered.*
- **BOG 2: Plant Scale Control Volume**
  - *The plant scale group focused on inflows and outflows at the wind plant scale, which encompasses several individual wind turbines. Topics of discussion included complex terrain, wake creation, wake interaction, wake meandering, wake-turbine interaction, and the necessary observations for model validation. Specific meteorological attention was in the area of scaling from the regional foundational forecast models to the geographically specific wind plant location models and smaller scale. Attention was also given to power losses resulting from down-wind turbines and the implications for rotor loading.*
- **BOG 3: Turbine Scale Control Volume**
  - *The turbine scale group focused on the impacts of inflow on an operating wind turbine, as well as the creation of a wake during outflow. Specific technical topics included coupling meter-scale aerodynamic data with sub-meter rotor and drivetrain loads models, experimental requirements for collecting aeroelastic measurements, and the impact of small- and large-scale turbulence on the wind turbine rotor. Specific meteorological topics included air-sea interactions, observations that fit all required temporal and spatial scales, and interoperability of larger scale forecast models to turbine scale.*
- **BOG 4: Experimental Data and Validation**
  - *The experimental data and validation group examined challenges and opportunities for future experiments at multiple scales. While it was necessary to touch on some modeling requirements, in general, this group focused on methods for obtaining experimental data that will be needed to validate existing and advanced new models, as well as identifying requisite instrumentation and test beds on the appropriate scales. Interaction between public research and private industry was also considered.*

Each BOG was tasked with providing the following deliverables, aligned around specific sub-topics that each group identified as important:

1. Define the current state of the art for each sub-topic
2. Identify and prioritize gaps and obstacles
3. Specify desirable outcomes for a concerted R&D effort
4. Outline potential paths forward for R&D activities

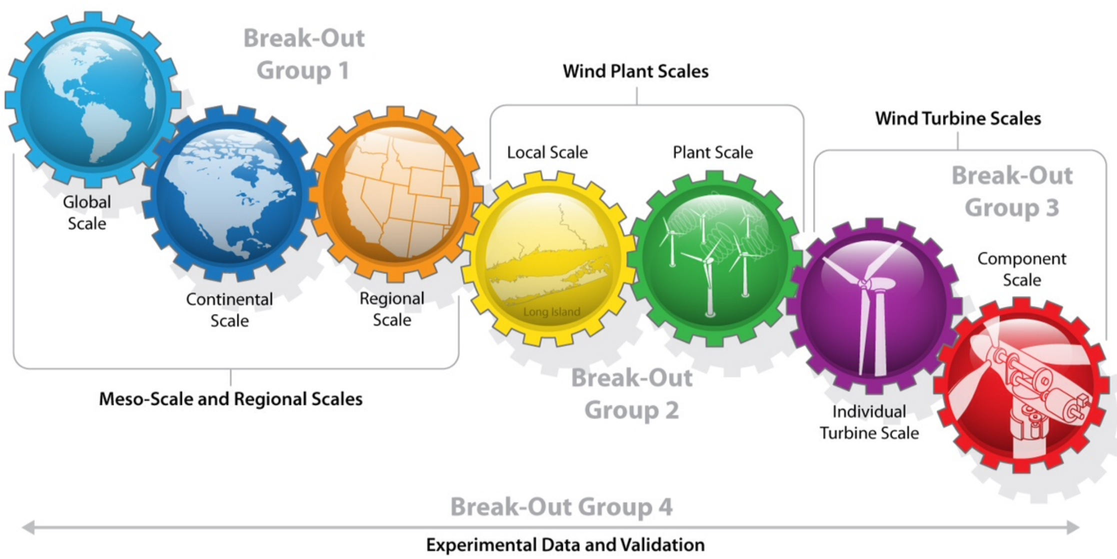


Figure 1: Breakout Group (BOG) coverage of relevant complex flow spatial scales. Coupling diverse, interdependent models and simulations across all of these scales represents a significant challenge.

Overview of Key Findings

General observations

While the detailed findings from each BOG were distinct in terms of scale and scope, there was considerable overlap at a high-level. Several common needs and gaps were identified, as well as common types of activities that would be required to address those needs. Taken as a whole, these commonalities provide an insightful set of key findings to be taken from the workshop.

There was a general consensus that future complex flow R&D will need to improve meteorological and engineering models and measurements that cross-spatial and temporal scales simultaneously. Each spatial and temporal scale has its own set of priorities for model physics and observational measurements, which provides a challenge when coupling different models. For example, global-scale foundational forecast models will need to interface seamlessly with kilometer-scale mesoscale models, which will need to interface seamlessly with sub-kilometer wind plant scale models, which in turn will need to interface seamlessly with sub-meter turbine blade scale models. Furthermore, the validation data that is collected must span these scales as well.

There was also a general consensus around the types of R&D activities that might be required to address the outlined needs. Further planning exercises with specific industry, government, and university stakeholders was a common refrain, as was engaging industry to access validation data.

Common need: models that operate across multiple scales and complexities

While many models and measurements exist today, future complex flow research will require even more emphasis on bridging the multitude of scales inherent to this problem. Four distinct spatial scales, along with associated time scales, must be addressed in future R&D efforts:

- Regional Inflow
- Wind Plant Inflow
- Wind Turbine Inflow
- Turbine Response

Common need: improved model physics and accuracy

Future complex flow models will need improved treatment of atmospheric stability, turbulence, and atmospheric dynamics across all spatial and temporal scales. Self-consistent physics parameterizations will also be a must. High performance computing (HPC) will be an important asset in improving the understanding of the underlying physics in these models, but it was pointed out that the use of HPC should not be a goal itself. There is differing opinion regarding industry's ultimate adoption of high performance computing. Some in the international research community see HPC as a means towards less computationally intense design tools for industry, while others see turbine manufacturers moving towards the use of in-house petascale computing. Either way, it is clear there will be increasing opportunities for the use of HPC within the complex flow research community, with impacts that ultimately contribute to reductions in LCOE. For example, manufacturers may be requested to run dozens of site evaluation models in a single day – this would be impossible with resource heavy computing requirements. Clearly, there is a desire on the part of industry to transition improved laboratory simulations into industry ready design tools.

Common need: field validation of models

While some of the details may have varied, each BOG identified a need for the following types of field tests:

- Single or dual turbine testing in real (i.e., operational) conditions (not necessarily in an operating wind farm)
- Multiple turbine test beds within an operating wind farm
- Detailed inflow and outflow measurements for single or multiple turbines
- Turbine loads data (e.g. drivetrain loads)
- Supervisory control and data acquisition (SCADA) data that can be linked to other data sources
- Meteorological data collection for better prediction of atmospheric phenomena such as turbulence, stability, Low Level Jet, etc.

Common need: wind tunnel testing

Because of the ability to control testing parameters (e.g. inflow conditions), wind tunnel testing provides a highly useful test bed for modelers. The size of modern multi megawatt wind turbines, and the resulting size requirement for any wind tunnel facility, poses a challenge to the research community. Specific needs of future wind tunnel tests include:

- Single and/or multiple turbines in a single wind tunnel
- Open-source and/or very-well defined turbines
- Full aerodynamic, drive train and control systems designs

The latter two requirements provide the modeler with a complete set of data with which to validate their codes. Non-proprietary or older model wind turbines would most likely be needed to provide this capability without running into intellectual property (IP) barriers. While it would be desirable to have such fully defined systems for field tests in operating wind farms, IP barriers may be more challenging at multi-megawatt scale.

Common need: well defined data requirements

Each BOG identified the following requirements for the data resulting from future validation experiments:

- Must be driven by user needs, which may not be universally aligned
- Need two- and three-dimensional fields
- Must push bounds of knowledge (i.e., must be novel data, non-trivial)

Common need: improved instrumentation at the needed scales

Future experimental validation efforts will require new and novel instrumentation. The design and use of instrumentation should be data driven – researchers should figure out what type and scale of data they need for the appropriate application, then identify and/or design the instrumentation. At current, this process can be somewhat backward. Future instrumentation should not be limited to existing technology, but should push the limits of accuracy, ease of use, and affordability.

Furthermore, it will be necessary to increase the length of time that equipment is able to remain in the field – for example wind developers need to know what the wind resource will be at a wind plant location for the lifetime of the equipment (~20 years), yet met towers are left in place to collect data for one year or two years at the most. To extrapolate one year of data out to 20 years leads to a great deal of uncertainty in the forecast that could be eliminated with not only *more* data, but *longer term* data as well.

Required activity: ramp-up planning exercises

Workshop attendees suggested that the level of detail required for specific next steps or specific future R&D activities are beyond the scope of any one event, and will require input from industry as well as the research community. Details oriented planning activities may be the best way to define specific modeling and testing requirements, as might requests for information from industry. Some specific ideas generated by the attendees regarding the use of detailed planning exercises include:

- Subject matter experts should be heavily involved
- Needs must be well defined
- Leverage existing modeling and experimental capabilities
- Determine future modeling and experimental capabilities (e.g. model coupling & hand-off, uncertainty, etc.)
- Ensure widely useful data and results

Required activity: incentivize data owners & users

One of the largest obstacles to obtaining useful validation data for public use has been the inability of the research community to convince industry players to share their data. While this is entirely understandable given the competitive nature of the wind industry, future public R&D efforts must rely on such data. As such, it will be highly important to find ways to incentivize data owners and users to share their data and/or provide access to their assets for testing purposes. The idea is not to simply expect that these data should and would be provided, but rather that public research institutions need to find ways to bring value to the industry participants in exchange for their openness. Some common thoughts regarding these incentives include:

- Data collection, sharing and collaboration must be improved

- Must identify data quality and relevance to existing and future models before spending resources attempting to access new data sets
- It is not enough to ask "what data are useful?" Must ask "what can we do to get access to this data?"
- Must determine how best to engage owner/operators
    - E.g. what types of test beds are best? What is accessible?
    - E.g. how many test beds would be required to validate public models?
- Data sharing through Non-Disclosure Agreements is an option

Required activity: archive data and make it accessible

The need for improved data archiving was brought up by several individuals and across all the BOGs. There are current efforts to collect available meteorological and engineering data and classify existing wind plant models, but it was the consensus of the group that a larger, broader data archiving effort must be undertaken. Specific considerations for a data archiving effort include:

- Requires large amounts of metadata
- Must be open to as many people as possible
- Must be useful for several, if not all, stakeholder groups
- Must be on the appropriate spatial and temporal scales
- Resources will be required to provide the necessary level of effort

Required activity: improve standards and practices

Ultimately, all the gains in model improvements and model validation must work themselves into the wind plant design process. This is accomplished by incorporating these innovations into standards and practices. For example, as industry's understanding of the impact of turbulence improves, future rotor load cases must be adapted within existing standards. Otherwise, new information will not find its way into new turbine or plant designs. Beyond design standards, it will be important to incorporate new learning into industry best practices as well.

Regarding meteorological standards, none currently exist to govern the type of equipment each project/developer should use to measure the wind resource or at what level the measurements should be taken. Therefore the data may or may not be comparable directly from project to project and may or may not make the foundational forecast models better. Industry standards would be a major step. Currently, the closest thing to "standards" seem to be determined by the banking and insurance industry who might not finance a project unless they install a met tower that is 50 m tall and leave it for a period no less than 18 months. The research community may be more appropriate to determine future standards.

Standards and best practices must also be applied to the use of existing and future models, as well as to data collection methods and quality assurance processes. It is not enough to focus only on design space standards.

Significant Observations

Overall, the Workshop was very well received. Several members from industry commented that they found the meeting useful, and in-line with what their organizations perceived to be the issues at hand. That being said, they all said that they learned something, and it was helpful to see such a diverse community of researchers all focused on such an important problem. While several commented that complex flow R&D is a high priority area for their respective companies, they also noted that the resources and access to data required are difficult to come by for a single company in the competitive wind industry. There seems to be a strong desire on the part of turbine manufacturer R&D groups to work together and share data, however, the management of these companies will still require convincing.

It is clear that a significant effort will be required to achieve the performance and cost benefits that are possible from a concerted complex flow R&D campaign to improve wind plant performance, forecasting accuracy, and operational efficiency. This effort will require advanced modeling capabilities, data sharing and archiving, high performance computing, large-scale test beds, field and wind tunnel testing, and a high level of coordination. The level of effort required is most likely beyond the scope of any single industry stakeholder.

Introduction

DOE's Wind and Water Power Program (WWPP) will occasionally hold expert workshops to help identify promising new areas of research and development. WWPP has recently identified complex flow R&D as a potentially large source of future levelized cost of energy (LCOE) reductions, and as such, decided to hold a workshop to further explore this promising field of study.

Wind Power Plants are poised to become a cost effective energy alternative to fossil fuels in the coming decade. Increasing the wind industry's understanding of the complex aerodynamics involved in harvesting wind energy represents the largest potential impact towards reducing LCOE. As noted in the Executive Summary, there exist some very real, very large opportunities for cost reduction (see Appendix F for References):

- *Power losses can be as high as 20-30% in operating wind farms, due solely to complex wake interactions occurring in wind farm arrays. [1,2,3]*
- *Forecasting accuracy improvements of as little as 10-20% could result in hundreds of millions of dollars (est. ~$140-260M) in annual operating cost savings for the U.S. wind industry. [4]*
- *Drivetrain components such as gearboxes and generators are failing significantly earlier than their twenty-year design life. These failures are caused in large part by uncertainty in aerodynamic loading conditions. [5,6]*

In order for DOE to obtain input on existing gaps and future opportunities in regards to complex flow modeling and experimental validation, the WWPP held a workshop on January 17-18th in Boulder, CO. The meeting was an opportunity for participants to provide, based on individual experience, information and facts regarding this topic. It was not the object of this session to obtain any group position or consensus. Rather, the Department was seeking as many recommendations as possible from all individuals at this meeting.

The public meeting consisted of an initial plenary session in which invited speakers surveyed available information and needs for various applications related to complex flow modeling and validation testing (see Appendix C for introductory presentations). For the remainder of the meeting, Breakout groups (BOGs) provided participants an opportunity to present to DOE information on specific areas regarding computational products and existing gaps in observations (i.e., models and data needs). Each BOG was assigned two primary speakers, whose role was to facilitate the discussion where necessary, aggregate the group's comments and opinions, and then present this information back to the plenary session. Groups were organized around the following topics:

I. **Mesoscale Modeling and Validation.** Participants examined the meteorological effects at the regional, multi-wind plant scale. This exploration of atmospheric science topics included model nesting, long-term data collection requirements, and down-wind effects of wind plants.

II. **Wind Plant Scale Modeling and Validation.** Participants examined complex aerodynamic phenomena in, around, and through wind plants, including turbine-wake interaction, wake-wake interaction, complex terrain, and turbulence effects. Several temporal and spatial scales were considered.

III. **Wind Turbine Scale Modeling and Validation.** Participants examined inflow and outflow characteristics in the vicinity of a single wind turbine, as well as the implications for aerodynamic loading of the rotor and overall structure. Several temporal and spatial scales were considered.

IV. **Experimental Data and Validation Requirements**. Participants examined the requirements for, as well as the feasibility and efficacy of, existing and future experimental techniques for cost effective, high fidelity data collection. Both field and laboratory experiments were explored.

As discussed in the Executive Summary, each BOG was tasked with providing the following deliverables, aligned around specific sub-topics that each group identified as important:

a. Define the current state of the art for each sub-topic
b. Identify and prioritize gaps and obstacles
c. Specify desirable outcomes for a concerted R&D effort
d. Outline potential paths forward for R&D activities

The meeting was designed to be a public forum for experts involved in research, manufacturing, planning, deployment, operation, and regulation of wind power related projects and activities.

The following four chapters provide a detailed account of what was discussed during the workshop. Each details a single breakout group (BOG), with sub-chapters dedicated to individual sub-topics. For each sub-topic, technical details and ideas based on workshop discussion are provided for each of the above-mentioned deliverables. During the course of the workshop, each BOG, consisting of approximately 12-20 people, broke into smaller groups to discuss each sub-topic. These discussions were captured and subsequently discussed with the larger group. As a result, there was variance from group to group and sub-topic to sub-topic in terms of how much information was recorded and conveyed, however, in the end a very complete set of expert opinion has been compiled. Each BOG was assigned two primary speakers, whose role was to facilitate the discussion where necessary, aggregate the group's comments and opinions, and then present this information back to the plenary session.

1 Mesoscale Control Volume Group

Group overview

The mesoscale control volume group (BOG1) examined atmospheric science and meteorological effects at the regional and multi-wind plant scale. This included discussion around model nesting, model coupling, model physics, inter wind farm impacts, long- and short-term measurements and measurement technology. The spatial scales of interest range from hundreds of kilometers down to tens of meters. BOG1 was divided up into six separate sub-topics:

a. Influence of global scale motions on the mesoscale
b. Impact of forcing on the flow (terrain, land/sea contrast, etc.)
c. Impact of physics on the flow (radiation, moisture, etc.)
d. Turbulence modeling across scales (terra incognita, etc.)
e. Modeling shear at the mesoscale (stability, low level jets, etc.)
f. Integrating mesoscale models with plant-scale models

For each sub-topic, the expert attendees defined the current situation (state-of-the-art), complicating factors and obstacles, desired outcomes of a concerted R&D effort, and the necessary considerations for any path forward. Upon completing work in each breakout group, the sub-topic teams reconvened in the larger breakout group to discuss their sub-topic. As a group, each BOG was able to distill the sub-topic information into common benefits and findings related to their particular topic. This information was finally presented to the larger plenary session. For the mesoscale control volume group, the following individuals acted in the role of group speaker (Speaker presentations are available in Appendix D):

- Bruce Baily, AWS Truepower
- Sue Ellen Haupt, UCAR/NCAR

Benefits of improved mesoscale modeling

The mesoscale control volume group identified the following benefits that may arise from improvements in mesoscale models:

- **Improved wind plant performance**: More accurate, higher resolution mesoscale models will enable improved wind turbine and wind plant designs that more efficiently convert wind energy into electricity. These future wind plant designs will be optimized for their specific complex terrain, controlled in real-time, and utilize significantly more accurate pre- and post-construction wind forecasts. The aggregate performance of separate, regionally proximal wind plants may also be optimized. Improved forecasts will enable better financing terms due to better project performance, as well as reduce grid interconnect costs and grid operator imposed fines for missed wind power forecasts.

- **Reduced operations and maintenance (O&M) costs**: Improved wind plant control and a better understanding of flow physics and the implications for rotor loading will allow wind turbine designers to build more reliable wind turbines. These improvements will also allow wind plant operators to optimize operations on existing wind turbines.

- **Reduced plant impact on the environment**: As the penetration of wind power increases, there may be as-of-yet unknown impacts on the environment. An increased understanding of inter-wind farm interactions, as well as the potential impacts on mesoscale flows will lead to a better understanding of the problems that may arise in the future, as well as their potential severity.

Knowledge Gaps

While each sub-topic team identified several specific knowledge gaps (see the detailed sub-topic tables that follow each BOG summary), some common themes emerged upon reconvening back into the larger BOG. These common, or generalized, knowledge gaps were summarized as follows:

- Communication across grid interfaces is lacking
    - This encompasses adapting models, meshes, etc.
    - Spans global to mesoscale, mesoscale to wind farm scale, and wind farm scale to wind turbine scale (via mesoscale)
    - Similar with problems coupling wind farm models to rotor models
- Do not have a full understanding of flow physics
    - Not able to accurately model the detailed flow structure
    - Do not fully understand the impact of stability on the flow
    - Do not fully understand the impact of different weather regimes
    - Parameterizations and appropriate numerical schemes for transition from mesoscale to Large Eddy Simulation (LES) and Computational Fluid Dynamics (CFD) - this is also known as “terra incognita”
    - Wake turbulence and interactions with the ambient flow
    - Regional variability of wind power generation
- Unable to fully characterize flow in heterogeneous conditions
    - Complex terrain, detailed land use cases, air/sea interaction, vegetation
    - Intermittent mixing processes (Low Level Jet (LLJ), breaking waves, etc.)
- Unable to accurately model the impact of precipitation
    - Impact on boundary conditions
    - Impacts of ice accretion on turbine loads, design, and efficiency
- Do not understand the impact of wind farms on the local or regional environment
- Do not have sufficient data for validation or verification
    - Unknown impact of assimilating new, non-traditional datasets

  - There are existing issues with user centric verification, for example, a lack of user-centric verification metrics or scoring rules
- Uncertainty quantification is immature

Expected outcomes of a concerted R&D effort

Common themes also arose regarding the expected outcomes of an R&D effort. These outcomes would be expected to tie to the overall benefits from improved mesoscale modeling identified above. Furthermore, while it would be expected that any R&D effort would address the knowledge gaps listed above, the BOG identified the following as specific, important outcomes:

- Improved models
  - Improved handling of boundary conditions (BCs)
    - Hand-off of BCs to "local" models
  - Quantified variability and uncertainty
  - Improved understanding of flow physics
    - Wind plant interaction with downstream
    - Wind plant effect on local weather/climate
  - "Weather Research & Forecast (WRF) for Wind Energy" (or similar)
    - Optimized WRF model for wind energy (is it possible?)
- Successful data collection, model validation, and model verification activities
  - Standard observation sets
  - Case studies of "extreme" wind character events
  - Data for meso, LES, and CFD scale explicit and parameterized physics
- Improved industry communication
  - Improved methods for leveraging existing research programs
  - Multi-disciplinary dialogue
  - Information exchange for field projects, including agencies and groups such as NSF, DOE, NOAA, Europe, etc.
- Established sets of design standards and best practices
  - Applies to modeling, data collection, validation, and verification
  - Standards for design constraints based on improved modeling capabilities

Considerations for a path forward

Once knowledge gaps and desired outcomes were identified, each BOG discussed the challenges and steps that may arise attempting to overcome the gaps and achieve the outcomes. This hypothetical "path forward" identifies several practical steps that an R&D effort may need to address. The mesoscale group identified the following components of a path forward:

- Coordinate parallel teams that test different modeling approaches
  - Span industry, academia, national laboratories, etc.

    - Utilize public-private partnerships
    - Research coordination frameworks to facilitate success
- Develop multi-scale modeling approaches and inter-comparisons
    - Idealized simulations for verification and inter-comparison (data archive)
    - Validation on common datasets
    - Multi-scale integration
- Develop multi-scale test beds
    - Represent diverse wind resource regions and a range of weather phenomena including: stability, LLJ, Land/Sea Breeze, Outflow Boundaries and climatological conditions
        - Flat terrain, complex terrain, offshore, etc.
    - Integrate the test beds over a region
        - Several wind farms and undisturbed flow
- Establish data repositories with open access
    - Based in US and/or internationally
- Seek interagency collaborations
    - DOE Office of Science, NSF, NOAA, DoD, etc.
    - Develop cost benefit analysis to illuminate benefits of improved modeling

Taken together, the common BOG benefits, knowledge gaps, outcomes, and paths forward represent the key "take-aways" for each group. In following sections, the information provided for each sub-topic is given in detail, arranged around the four deliverables each group was expected to address: the current situation, complicating factors and obstacles, desired outcomes, and aspects of a path forward.

1a Sub-topic: Influence of global scale motions on the mesoscale

Current Situation	Complicating Factors and Obstacles
Global and mesoscale models – Diverse user base (industry, national labs, etc.) – Wide range of skill and experience using models – Incomplete physics and limited accuracy **Model coupling** – Mismatches at boundaries between global and mesoscale models – Have not fully resolved physics parameterizations, spin-up, phase errors, and turbulence length scales **Uncertainty Quantification** – Ensemble techniques still need development	**Domestic and International R&D Coordination** – Lack of coordinated effort to improve all aspects of model development. – To date, there has been a reluctance to move forward internationally with improvements in the global observation network (e.g. WMO initiative, Global Earth Observing System of Systems, etc.) – There is a lack of common advocacy across agencies **Scarcity of HPC for global scale modeling** – There is a lack of HPC capability at NOAA, which impacts U.S. weather forecast capability. • *For example, the NOAA Global Forecast System (GFS) model is not as accurate as the European Center for Medium-range Weather Forecast (ECMWF) model*

Desired Outcomes	Path Forward
Improved global & mesoscale model physics – Improved assimilation of in-situ & remote datasets – Improved physics parameterizations **Model coupling** – Improved methods and techniques for seamlessly coupling models where the discontinuities (grid spacing and physics) at the seams are resolved **Uncertainty Quantification (UQ)** – Improved ensemble techniques **Enhanced options for modeling community** – New version of WRF ("WRF – Wind") that is tuned for the lower ABL skill level – may be closer to WRF-LES to ensure physics consistent with resolution – Best Practices for model configuration & tuning **Improved R&D Coordination** – Government consortia of agencies focused on common goals (NOAA, DOE, NSF, DOD, DHS, DOI, etc.)	**Establish a stakeholder group** – Define unmet needs – Establish specific research agendas for specific research topics **Execute field data collection campaigns** – Need long-term and well-funded field campaign for onshore and offshore wind installations – Resources could be shared across agencies **Develop & communicate new modeling options** – Establish a database repository for shared (public domain) datasets and models. – Create tutorials and workshops for end users **Address NOAA's computational shortfalls** – Develop a roadmap to improving global scale models through advanced computational capability **Schedule coordination meetings** – Include multiple agencies – Discuss common research needs – Identify leveraging opportunities – Create an international 'agreement' to develop and share research efforts (field tests and data sharing)

1b Impact of forcing on the flow (complex terrain, land/sea contrast, etc.)

Current Situation	Complicating Factors and Obstacles
WRF model – Current state of the art – Employs nesting – Includes smoothed terrain simplification – Land-use datasets likely from USGS (out of date) or satellite (MODIS, more up-to-date but still does not contain recent land-use changes such as urbanization, deforestation, etc.) – Sub-grid scale variability in terrain and wave height not accounted for routinely – "Standard" boundary-layer turbulence closure – Need to improve initial state definition – Need to quantify uncertainties and understand sensitivity of industry to uncertainties – Need to improve model coupling methods and techniques – Need to develop user-oriented verification methods and metrics **Model Validation** – Operational and field campaign data used to evaluate model performance. This includes: surface meteorology, radiosondes, radiometers, sodars, radar wind profilers & satellite (clouds & precip) – More extensive data to resolve spatial variability is made less frequently, but very valuable – Past evaluation studies to evaluate models may be too idealized (flat terrain, simple land use) – Need to get away from idealized cases into real cases, not well-behaved systems – There have been campaigns in complex terrain and with land/sea contrasts, but not for wind industry objectives **Uncertainty Quantification** – Still conducted in a "haphazard" way	**Physics Variability** – Underlying physics is typically tuned to different specific sites of interest via sensitivity studies – Current physics is not universally applicable – Still greatly over simplifying boundary layer physics **Wind Speed Biases and Fluctuations** – Model performance decreases with large variations in surface characteristics (e.g. complex terrain) – Nesting to smaller scales can produce noise in areas of complex terrain – Unknown potential future impacts from climate and land use changes **Turbulence Modeling** – Not as easy as simply increasing grid resolution – Turbulence Theory was developed over flat terrain, making it less applicable over complex terrain – Not parameterized between 100m and 1km **Atmospheric Stability** – Stable atmospheric conditions (e.g. nocturnal boundary layer) are particularly difficult due to intermittent turbulence, slope flows, etc. – Surface fluxes difficult to simulate accurately **Grid Spacing/Resolution** – Typical vertical grid spacing may not be sufficient – Unclear if increased vertical resolution will improve simulations **Model Validation Obstacles** – Data are lacking at spatial and temporal scales appropriate for terrain and land-use variability – Existing historical data sets not consolidated **Computational Resources** – Must be sufficient to tackle issues of complex terrain and land-use variations for wind industry needs (real-time forecasting, resource assessment) – Computational resources are lacking for coupling land and water surface models across scales

Desired Outcomes	Path Forward
Improved mesoscale models – Improved boundary layer parameterization • *Utilize extensive data collected in complex terrain in the vicinity of one or more wind farms* • *Data would also shed light on variability of winds and wakes in these regions* – Improved physics for mesoscale & global models • *Complex boundary layer flows* • *Improved mesoscale circulations for boundary conditions allowing higher resolutions (long term)* • *Improved treatment of turbulent mixing at scales valid from 10m to 10km (long term)* • *Improved understanding of weather phenomena affecting forecasts of wind leading to better modeling of the physics of the phenomena* – Improved handling of model coupling • *Atmosphere & land surface model coupling* • *Two-way nesting techniques* • *Ocean behavior coupling* – Determine whether non-uniform adaptive grids (like those typically used for CFD) are superior to traditional nested mesoscale models – Improved model of mean & turbulent wind fields affected by complex terrain & land-use variations – Ability to test new verification metrics **Improved uncertainty quantification** – Quantify uncertainty with current parameterizations under a variety of conditions in a systematic way. **Access to real world data and test beds** – Need real world datasets for modelers and industry – Test bed of new data relevant to wind farms • *Area(s) of complex terrain* • *Area(s) with land use issues/constraints* • *Area(s) that include bodies of water* – Need better definition of current land, e.g.: • *High-Resolution Land Data Assimilation system*	**Establish a model improvement roadmap** – Set-up model inter-comparison study • *Include industry and greater research community* • *Modelers systematically test parameterizations* • *Use the test bed data to show improved predictions across scales (regional, wind plant, & turbine)* • *Compare current techniques with new ones* – Assess impact of improved simulations/forecasts on predicted power output and wind turbine loadings • *What's financial benefit of new understanding?* – Is there an opportunity to "mine" existing data? – Establish metric of success • *Identify improved statistical values in areas of complex terrain and land-use variations* – Develop probabilistic methods • *Must better understand existing use within industry* **Improve Data Sharing and Archiving** – Facilitate data becoming widely available • *Allows improved understanding of processes* • *Can be used for building new parameterizations* **Engage the atmospheric science community** – Opportunity to expand pool of resources • *Include oceanographic experts, since currents, ocean surface fluxes, and wave dynamics are important for offshore sites* **Execute field data collection campaigns** – Identify suitable complex terrain "test bed" location – Instrument the site with standard sensor package • *Measure mean and turbulent winds* • *Other meteorological quantities, i.e. weather phenomena responsible for producing complex flow* • *Measure at surface and aloft*

1c Impact of physics on the flow (radiation, moisture, etc.)

Current Situation	Complicating Factors and Obstacles
Radiation models – Radiative transfer models within mesoscale models • *Generally two- or multi- stream parameterizations* • *Radiative transfer is 3-D* • *Still under development within research community* – Perform reasonably well for most applications • *Especially in clear-air conditions* – Some important sources of inaccuracy • *Clouds, dust, and aerosols impact parameterizations* **Cloud Parameterization** – Convective parameterizations • *Large source of regional/global scale uncertainties* – Current formulations are parametric representations of observations – Some first principle models use LES parameters • *Currently under development* • *Implemented in some models* – Cloud resolving models becoming more common • *Operate at very high resolution* • *Expensive to implement* – Mesoscale implementations show some success • *Only under specified conditions* **Cloud Microphysics** – Mesoscale models have moved from bulk parameterizations of microphysics to describing microphysics using detailed size distributions – Representation of the complete water cycle within clouds is slowly making its way into the models • *The most accurate cloud physics parameterizations are generally too expensive to implement* **Turbulence** – Turbulence is parameterized primarily using 2 or 2.5 level closure for the Reynolds stress terms – In general, parameterizations have problems under stable conditions – There are numerous schemes available • *Need an optimal scheme for the lower 300 m* **Land-atmosphere coupling** – Need to couple: • *Vegetation, tree canopies, wind farms* • *Air-sea interactions and wave breaking* • *Gravity wave parameterizations* • *Surface fluxes/soil moisture, spatial variability* – Land-atmosphere coupling is generally treated as a physical process in mesoscale models – The representation of vegetation and flow inside tree canopies and above are highly parameterized and untested for wind applications	**Radiation** – Priority for increased emphasis on radiation codes to produce near surface stability and surface temperature correctly for producing the diurnal pattern driven by the incoming radiation – Parameterization of radiative transfer through clouds is needed for more accurate representation of PBL energy budgets • *Need more data on in-cloud radiative transfer* **Cloud Parameterization** – Primary obstacle: • *Observations of cloud convection with simultaneous radiation measurements* **Cloud Microphysics** – The representation of precipitation in the form of ice, snow and rain is highly uncertain in most mesoscale and global models – In general, all precipitation is described as rain and equivalent amount of precipitable water – For wind energy applications the precipitation type will need to be modeled with greater realism **Turbulence** – Need improvements of RANS parameterizations to spatial scales of 1,000 meters and greater – High-resolution LES methods can be used to guide RANS parameterizations • *Current computational limitations make this difficult* **Land-atmosphere coupling** – Vegetation data sets at high resolution are not generally available – Canopy flow requires better turbulence schemes • *E.g. LES methods* – There is limited understanding of the energy transfer through soil-atmosphere and water-atmosphere interfaces • *Need to know this to develop better parameterizations*

Desired Outcomes	Path Forward
Improved representation of wind power variability under a variety of meteorological conditions – Improved wind plant performance & design criteria – Accurate LLJ simulations • *LLJ's strongly affect wind speed variability at turbine hub height, yet are often not accurately simulated in mesoscale models* – Improved handling of icing and snow collection • *Requires accurate predictions of temperature at blade height, which depends on getting the radiative transfer and energy budgets right and representing mixing within the PBL better* • *Measurements of the icing phenomena on turbine blades will be needed for validating the parameterization of these events in a model* – Better understanding of wind farm impact on local environment • *How do wind farm impacts feed back up to the mesoscale?* – Better understanding surface waves • *To what degree to they affect the low level wind profile and turbulence?* **Prioritized meteorological phenomena** – Low level jets and associated increased wind shear • *Parameterizations: turbulence, radiation* – Conditions that lead to icing and snow • *Parameterizations: cloud physics, radiation* – Turbine feedback on the mesoscale • *Parameterizations: turbulence/PBL; radiation; surface fluxes; canopies; vegetation;* – Air-sea interaction, wave effects on atmospheric wind profile and turbulence • *Parameterizations: wave-atmosphere coupling; radiation* **Completion of a successful field testing program** – Need to validate model	**Plan and execute a field testing program** – Develop test beds • *Make observations inside of and near to an operational wind farm* • *Need to be long-term (multi-year) to capture a variety of weather regimes and allow for refinements to the sensing systems, data collection processes, and experimental designs* – Tie observations to model development • *Begin validation effort starting with a base code that can be performance benchmarked over time* **Identify & prioritize specific data sets of interest** – Explore resource pooling • *Include the larger atmospheric community* • *Leverage existing field programs if possible* – Engage the larger wind community to identify data needs. Data considerations may include: • *Complex terrain and land-use variations* • *3-D turbulence fields inside and in the outflow of a wind farm* • *Blade level condensation properties of the atmosphere and tendencies for icing* • *Radiation and energy balance in the lower 300 meters of the atmosphere at a high spatial resolution* • *Latent heat and sensible heat fluxes near turbines and wind farms* – Utilize standard data practices for quality control – Measurements should be long-term • *Facilitates development and testing of new parameterizations* • *Facilitates validation of the new physics* – Dense observation network is needed • *Must resolve turbulent scales and velocity variability within the wind farm and around* – Offshore will need a dedicated test bed **Develop a new code base** – Advanced mesoscale models • *Operate at very high spatial resolutions with LES/RANS based turbulence* • *Requires running efficiently on new HPC platforms* – Establish metrics of success • *Improved performance of the codes in predicting the variability and uncertainty of hub height wind fields, temperature, icing and turbulence* – Cost Implications • *Improved models will lead to optimized installations and grid operations* • *Reduced installation costs* • *Improved use of land resources*

1d Turbulence modeling across scales (terra incognita, etc.)

Current Situation	Complicating Factors and Obstacles
Parameterization schemes – Designed to account for all the effects of their associated turbulent processes – Overall, approach to these parameterization schemes is rather discrete/modular • *That is, the parameterizations are simply on or off for each grid nest and aren't designed to transition gradually from coarse to fine spatial resolution* – Cheng, Canuto, and Howard (2002) in the Journal of the Atmospheric Sciences may be the only attempt at a parameterization that transitions across scales smoothly **Specific turbulence handling** – There is a very large suite of turbulence models that have been developed but not extensively evaluated for wind energy applications • *Evaluations have used 2 m and 10 m data, which is shallower than what is needed for wind energy* – Large eddy simulation (LES) is capable of solving a lot of turbulence issues for idealized cases • *Has not been used extensively in general terrain (on its own)* • *Has a somewhat difficult time spinning up turbulence from boundary conditions* – Surface layer schemes are developed assuming flat terrain • *In reality, inhomogeneity, terrain slope, vegetation, and large roughness elements affect turbulence scales in the sub-grid and terra incognita ranges* – PBL schemes such as QNSE or Total Eddy Mass Flux (Angevine) can account for effects of water surface waves • *Also have a terra incognita type problem*	**Modeling obstacles** – There is some, but not enough, communication between the mesoscale, LES, and convection communities – Lacking sufficient HPC capabilities for many researchers and laboratories – Lacking validation data to test models across scales • *Need observations to evaluate parameterization/model improvements* – Sub-critical funding for existing efforts, such as • *Immersed boundary method* • *Canuto, Arakawa type approaches for getting them broadly distributed and rigorously tested in the large community (WRF, for example)* **Gaps** – Models do not transition smoothly across scales • *Happens discretely* • *For example, PBL schemes and shallow cumulus type parameterizations work from the 4 km range down to 500 meters.* – There is no coherent and organized effort to test a variety of schemes – Lacking measurements at heights between 10 m and 500 m AGL. – A problem exists regarding coupling between schemes • *Overlap w/ physical parameterizations*

Desired Outcomes	Path Forward
Unified, validated modeling scheme (longer term) – Includes high resolution numerical simulations – Includes dense observational network – Naturally transitions from mesoscale to LES scale • *Turbulence-resolving LES* – Naturally transitions back up in scale **Theoretical, unified, validated model (short term)** – Transitions smoothly up/down spatial scales – Need to define the mathematics • *Must understand how to handle scale transitions from knowledge of the 3D turbulence spectrum* – Must test the theoretical turbulence scheme • *Compare coarse resolution simulations against high-resolution numerical simulations* **Successful, completed field campaigns** – Need one or more field campaigns – Collect data to test the unified modeling framework **Improved understanding of plant level models** – Handoff of boundary conditions between grids – Upstream wind plant impacts on downstream **Open, multidisciplinary dialogue** – Among meteorological & engineering disciplines	**Invest in unified modeling approaches** – Offer funding specific to these approaches – Increase HPC capacity and availability – Fund different groups early on then have comparison exercises to focus on candidate approaches most likely to succeed. **Coordinate model improvements** – MPAS (modeling for prediction across scales) **Plan and execute measurement campaigns** – Need high resolution datasets • *Basic Data: wind, temperature, & moisture profiles* • *Enviro Data: soil moisture, leaf area index, etc.* • *Height: measure near surface (2-10m) up to 500m* • *All measurements time synchronized* – Instrumentation requirements • *High horizontal measurement density appropriate for testing large eddy simulations* • *Can include scanning LIDAR* • *High density horizontal, vertical, and temporal measurements are required* **Cost Implications** – Measurement costs are large – Ideal to spread costs across several stakeholders – Must identify groups with similar validation goals

1e Modeling shear at the mesoscale (stability, low level jets, etc.)

Current Situation	Complicating Factors and Obstacles
Current Models – The current models do a decent job of predicting mean shear under non-stable conditions and in areas of simple terrain – The current sets of models are most challenged by accurately simulating stable conditions **Shear simulation depends on several factors** – Accurately knowing the thermal stability of the atmosphere – Accurate representation of the surface properties (e.g. land cover, surface roughness, soil moisture) – Vertical and horizontal resolution of the model.	**Measurement issues** – Lack of meteorological data necessary to accurately initialize and validate mesoscale models • *Especially for boundary layer stability & wind shear* • *Shear data should be time and height varying.* – Lack of necessary data about surface properties **Modeling issues** – Industry simplifies shear as a single unit parameter – Land use not subsampled below grid resolution – Lack of ability to capture effects of upwind projects – Veer not incorporated into discussions of shear

Desired Outcomes	Path Forward
Improved Simulations – Ability to simulate shear structure and its temporal variability more accurately – Ability to predict low-level jet phenomena at the correct frequency, intensity and vertical structure – Run mesoscale models at higher resolutions to take advantage of available high-resolution input data **New code bases** – Improve modeling methodologies for addressing stable conditions and subsampling surface condition **New policies** – Better account for shear and veer across the rotor blade in standard setting processes **Specific data sets** – Shear data (structure and temporal), stability observations, roughness and soil characteristics **Improved Plant Power Prediction** – Plant power output predictions (short term) • *Need more accurate predictions* • *Need more accurate treatment of power variability* • *Improvements based on better sheer and veer info* **Diverse Turbine Design Standards (long term)** – Standards should be site and technology specific • *Aid in turbine selection (e.g. geared vs. direct drive)* • *Describe blade lengths for particular region* **Better integration of sheer & veer into standards** – Need to educate standards organizations – Need to make this part of the standards process	**Invest in unified modeling approaches** – Develop community consensus of issues and steps forward and collaboration – Increase HPC capacity and availability **Model improvements** – Conduct case studies of model improvements and validations that use more or better data inputs – Develop regional climatology of shear characteristics and low-level jets **Measurements** – Assemble & share wind project measurements – Specific measurements needed • *Atmospheric profilers, tall towers & radiometers* **Cost Implications** – Given mesoscale model calibration test description: • *Tens of tall met towers in a given region* • *Shear data – temporal and height* • *Temperature data – temporal and height* – Probably costs several million dollars

1g Integrating the mesoscale with the plant scale models

Current Situation	Complicating Factors and Obstacles
Current models – One-way coupling approach only: meso is used as inflow BC for wind plant – Do not fully understand all of the underlying physics • *Plant to plant interactions* • *Impact of many wind plants on local/regional weather* • *Impacts on regional power production* – Forecast models not accurate enough • *Lack of measurement density/fidelity*	**Measurement obstacles** – Need quality upstream & downstream data for wind plant inflow + outflow to verify correct coupling – Insufficient resolution of land-use data **Modeling obstacles** – Inner/outer computational model are different • *Reynolds Averaged Navier-Stokes (RANS) vs Large Eddy Simulation (LES)* • *Leads to BC/data sharing challenges* • *Could make progress on this with focused R&D* • *Cut out inner domain from outer domain?* • *Use interior points of outer domain as internal forcing function for inner domain or just subdivide meshes?* • *What is the best interpolation Function process?* – Two-way coupling is challenging • *Incompressible (wind plant) to compressible (WRF)* • *LES to RANS* • *Don't know best BCs for model coupling* • *E.g. moisture content is in mesoscale models, but not wind plant models – how to do 2-way coupling?* • *Interpolation between meshes not optimized* • *Discontinuity in numerical dissipation* • *Uncertainty: no data to test coupled model* – Chaotic behavior from extreme Initial Condition (IC)/Boundary Condition (BC) sensitivity • *What are the best BCs for each model to work best with the companion model: will vary with the boundary* – Meso & LES models have different time steps – Mesoscale model does not properly seed LES in wind plant model – Unknown exit characteristics • *What happens to the outflow turbulence structure from an upstream wind plant when it exits the LES and enters the mesoscale?* • *How can you capture the effect of those exit characteristics on the downstream wind plant?*

Desired Outcomes	Path Forward
Measurement & model obstacles are overcome – See list of complicating factors and obstacles for what must be overcome – Impact of many wind plants on local/regional weather – Must understand plant-to-plant interaction – Quantify effect on regional power production **Improved Coupling** – Want to prove that coupling works correctly – Establish coupling best practices • *Must lead to successful calculations* • *Verify + validate* – Develop 2-way coupling • *Need 2-way coupling to achieve some key outcomes* • *E.g. wind plant to wind plant coupling* **Improved forecasts** – Observational targeting – Denser measurements	**Establish a series of test cases** – Identify idealized problems to work on • *Must verify correct coupling* • *How to handle meso ice predictions* – Verify that numerics are working correctly • *Perhaps cases with escalating complexity* – Include the wider wind community • *Several teams trying different techniques* – Validate models with experimental data • *Ensure measurements are made at large enough geometrical scale to satisfy validation needs* – Establish criteria for success (metrics) • *Conservation, numerical stability, grid invariance etc.* **Coordinate R&D Community** – Hold workshops to compare results – Share problems and solutions etc. – Use websites, regular teleconference, open-source – Educate NSF about importance of problem • *Explore joint projects* **Plan Demonstration Cases** – Demonstrate success with impactful demo cases (longer term) – Measure required variables on the same spatial and temporal scale as the phenomena that determine complex flow forecasts

2 Wind Plant Control Volume Group

Group Overview

The plant scale control volume group (BOG2) examined inflows and outflows at the wind plant scale. This included discussion around complex terrain, wake creation, wake interaction, wake meandering, wake-turbine interaction, wake induced power losses, implications for rotor loading, and the necessary observations for model validations. Specific meteorological attention was given to scaling from the regional foundational forecast models to geographically specific wind plant location models and even smaller scale models. The spatial scales of interest range from multiple kilometers down to meters. BOG2 was divided up into four separate sub-topics:

a. Air/sea interface and near surface flow modeling
b. Complex terrain and aggregated inflow/surface/wake modeling
c. Computational approach (turbulence, interfaces, & boundary conditions)
d. Wind plant control implementation

For each sub-topic, the expert attendees defined the current situation (state-of-the-art), complicating factors and obstacles, desired outcomes of a concerted R&D effort, and the necessary considerations for any path forward. Upon completing work in each breakout group, the sub-topic teams reconvened in the larger breakout group to discuss their sub-topic. As a group, each BOG was able to distill the sub-topic information into common benefits and findings related to their particular topic. This information was finally presented to the larger plenary session. For the wind plant control volume group, the following individuals acted in the role of group speaker (Speaker presentations are available in Appendix D):

- Branko Kosovic, UCAR/NCAR
- Rebecca Barthelmie, Indiana University (IU)

Benefits of improved wind plant-scale modeling

The wind plant control volume group identified the following benefits that may arise from improvements in wind plant scale models:

- **Improved wind plant performance**: More accurate, higher resolution wind plant-scale models will enable improved wind turbine and wind plant designs that more efficiently convert wind energy into electricity. These future wind plant designs will be optimized for their specific complex terrain, controlled in real-time, and account for turbine-wake and wake-wake interactions. The aggregate performance of wind turbines oriented in complex arrays will be optimized. Better understanding of intra-plant flows will also improve wind turbine control systems, leading to enhanced energy capture – these controls improvements will extend to the entire wind plant.

- **Reduced operations and maintenance (O&M) costs**: Improved wind plant control and a better understanding of flow physics and the implications for rotor loading will allow wind turbine designers to build more reliable wind turbines. In particular, improved understanding of wind plant scale complex flow will allow wind turbine designers and operators to account for the effects of complex terrain and turbine wakes on wind turbine inflow (e.g. wake ingestion, etc.). These improvements will also allow wind plant operators to optimize operations on existing wind turbines.

Knowledge Gaps

While each sub-topic team identified several specific knowledge gaps (see the detailed sub-topic tables that follow each BOG summary), some common themes emerged upon reconvening back into the larger BOG. These common, or generalized, knowledge gaps were summarized as follows:

- Do not have sufficient data for validation or verification
  - Lack of validation for prediction tools
  - Lack of data for performing validation or input to prediction tools
  - "One-off" measurement campaigns are not sufficient
- Do not have a full understanding of the costs for big experiments
  - Current cost models are inadequate
- Controls improvements are reliant on improved model physics and validation

Expected outcomes of a concerted R&D effort

Common themes also arose regarding the expected outcomes of an R&D effort. These outcomes would be expected to tie to the overall benefits from improved plant-scale modeling identified above. Furthermore, while it would be expected that any R&D effort would address the knowledge gaps listed above, the BOG identified the following as specific, important outcomes:

- More accurate models
  - Improved physics and parameterizations
- Successful characterization communication of measurement campaign benefits
  - Future deployment costs are very large compared to experiments
  - Experiments could yield knowledge that cuts overall deployment cost by 1%-2%, which is still large compared to experiment costs
- Successful and large scale experimental campaign
  - No one measurement campaign will answer all questions
- Improved controls systems
  - Both turbine and plant-level controls

Considerations for a path forward

Once knowledge gaps and desired outcomes were identified, each BOG discussed the challenges and steps that may arise attempting to overcome the gaps and achieve the outcomes. This hypothetical "path forward" identifies several practical steps that an R&D effort may need to address. The wind plant-scale group identified the following components of a path forward:

- Plan and execute large scale experimental campaigns
    - Plan high-resolution temporal and spatial scaled data campaigns on multiple test beds to measure the phenomena responsible for complex flow
        - Conduct multi-objective measurement campaigns
    - Consider both modeling and measurement requirements
        - Identify model sensitivities
        - Identify entire model input requirements set
        - Understand uncertainties
        - Augment existing wind farm experiments with expanded data sets
    - Utilize inter-governmental/academia/industry expertise and resources
- Plan and execute experiment cost/benefit modeling
    - Tie to overall cost justification for conducting large-scale experiments
- Coordinate with controls development programs

Taken together, the common BOG benefits, knowledge gaps, outcomes, and paths forward represent the key "take-aways" for each group. In following sections, the information provided for each sub-topic is given in detail, arranged around the four deliverables each group was expected to address: the current situation, complicating factors and obstacles, desired outcomes, and aspects of a path forward.

2a Air/sea interface and near surface flow modeling

Current Situation	Complicating Factors and Obstacles
Current Models – Air-sea models currently exist in mesoscale models and hurricane models • *Lack of coupling at the fine scale relevant for turbine inflow and intra-wind farm environment* – Able to model momentum transfer from wind to waves as drag/roughness. • *Assumes transfer from atmosphere to water and wind & water traveling in same direction (water traveling slower than wind)* – Wave resolving large-eddy simulation (LES) • *E.g. Sullivan* **Organizations Working on This Problem**	**Model Issues** – Lack downscaling capability • *From mesoscale to wind and waves at turbine scale* – Lack coupled model for impacts of wave field on intra-wind farm atmospheric flow field under varying stability conditions • *Need to include swell (non-local waves)* • *FINO-like data sets are not sufficient (FINO is a German off-shore research platform)* • *Need an instrumentation tower facility/ test bed* – Lack ability to evolve the wave field from wind • *Needed for 2-way coupling (momentum exchange)* – Lack ability to model radiative and fluid mechanical

– Includes national labs and industry, e.g.: • *NOAA/NCAR* • *SUNY, Indiana U.* • *Office of Naval Research (not yet for wind)*	effects of aerosols – Lack ability to model extreme events **Models lacking validation data** – Lack of measured wave spectra – Lack data to validate extreme conditions – Lack good understanding of what the air-sea interface actually looks like in extreme wind/wave/spray conditions

Desired Outcomes (D)	Path Forward (D)
Improve ability to model the influence of waves – Must understanding the wind farm environment under the influence of waves • *Allows better characterization and prediction of wind resource* **Successful U.S. offshore measurement campaign** – Establishment of U.S. based test beds – Geographic diversity • *E.g., mid-Atlantic, Gulf of Mexico, great lakes, etc.*	**Model, measure, & develop parameterizations** – Utilize and improve existing models • *Include better parameterization of wind-wave interactions* – Improve coupling and boundary layer handling • *Wind from land to water (East coast, Great Lakes)* **Improve instrumentation & measurement systems** – Develop new U.S. test beds • *FINO-like towers/measurement platforms* • *E.g. tall tower on platform off Virginia* – Utilize existing, potentially opportune, test beds • *E.g. Navy ASIT tower off Martha's Vineyard* – Enhance capability for measuring extreme events • *Can NOAA tailor existing observations (e.g. drop-sounds) for better vertical resolution at the lowest 100 meters in hurricanes?* **Conduct a cost analysis study** – What are the different sources of cost? • *Measurement costs (high)* • *Computer time* • *Human time* • *Others*

2b Complex terrain and aggregated inflow/surface/wake modeling

Current Situation	Complicating Factors and Obstacles
Current Models – Linearized Navier-Stokes (NS) • *WASP* • *Very fast tool* • *Range of applicability limited* • *Can't do much in terms of stability correction* • *Turbulence modeling is very simple* – Reynolds-Averaged Navier-Stokes (RANS) • *Relative spatial changes and turbulence* • *Difficult to rely on absolute numbers* • *Can predict separation, but not always well* • *Large number of inputs leads to more mistakes than linearized NS* • *Stability correction underutilized* – LES/DES and Coupling LES with Mesoscale Models • *Currently not used much in industry* **Wake Models** – Dynamic Wake Meandering (DWM) • *Cutting edge reduced-order model* • *Questionable load prediction with above tools* – Neutral stability typically assumed by industry • *Becoming accepted as a deficiency* • *Assuming neutral stability is not engineering-conservative for loads predictions* **Organizations Working on This Problem** – Includes national labs and industry, e.g.: • *Non-dynamic wake modeling: NCAR, LLNL, LANL, Vestas* • *Dynamic wake modeling: Risoe, Vestas, NREL, CU, Univ. of Mass.*	**Modeling deficiencies** – Lack of code validation – Stability and turbulence not well handled – Wind direction typically assumed uni-directional – Spatial fields used as input rather than point measurements **Not enough experimental data validation** – Codes are not well benchmarked – Lack of data on all timescales • *Extends from the longest (climate) through the shortest (turbulence)* • *Spatial and temporal scales* – Prediction tools not being validated • *Lack of data for use as input to prediction tools*

Desired Outcomes	Path Forward
Successful large scale experimental campaign – Should include several groups: • *Inter-governmental organizations* • *Academia and consultants* • *Industry (OEMs, developers, owners, operators)* **Validated models with improved physics**	**Plan & execute large scale validation campaign** – Include government/academia/industry – Utilize multiple locations • *Great Plains may be important because of the potential for a large number of high quality sites* • *Consider offshore test beds* – Include power and loads data collection • *Moves toward integrated optimization modeling* – Investigate role of project certification for offshore **Develop roadmap to improve simulations** – Do model ensembles have a role in helping to define uncertainty?

2c Computational approach: turbulence, interfaces, & boundary conditions

Current Situation	Complicating Factors and Obstacles
Computational Approach and Turbulence Models • *Fit power/log law wind profile to one-point velocity at a height, and then use turbine power curve to compute performance* • *Linearized Navier-Stokes (NS)* • *Common implementations: Wasp, Ainslee, Park* • *Mass conserving* • *Ambient turbulence intensity is input* • *Wakes modeled in time-averaged sense* • *Computationally fast* • *Predict annual energy production quickly* • *Simple eddy-viscosity wake turbulence model* • *Reynolds-averaged Navier-Stokes (RANS)* • *Time-averaged solution* • *Resolve geometry* • *All turbulence modeled* • *Runs several cases fairly quickly with modest computational resources* • *Variety of turbulence models, but it seems like k-epsilon and SST model most commonly used in wind* • *Detached-eddy simulation (DES)* • *Blend of RANS and LES* • *Used in some cases with aggressive terrain* • *Turbulence model: Spalart-Allmaras/Smagorinsky blend or SST/Smagorinsky blend* • *Large-eddy simulation (LES)* • *Currently mostly a research tool* • *Computationally-expensive* • *Resolves larger turbulent scales* • *Used to understand fundamental physics* • *Uses a variety of sub-grid scale (SGS) turbulence models ranging from Smagorinsky to Lagrangian-averaged scale-similarity dynamic Smagorinsky or non-linear models* **Model interfaces and boundary conditions** • *Loosely coupled approach* • *Variables passed through at time step* • *Mesoscale nesting* • *Usually top-down from mesoscale to local scales* • *Models "stove-piped" based on discipline* • *Separate parameterization of models* • *E.g. WRF is RANS, wind plant is LES* • *More downscale than upscale is implied* • *Incomplete description of surface roughness* • *Should include heating, sometimes vegetation* • *Inappropriate models often used* • *Time averaged at walls (e.g. law of the wall)* • *MO, sponge layer at ABL top* • *Data quality available for validation is poor* • *Data assimilation at mesoscale not at wind plant scale*	**Modeling deficiencies** – Linearized-NS models • *Do not account for stability, atmospheric turbulence structures, wake meandering (dynamic-wake meandering model)* – RANS • *Need turbulence modeling specifically designed for atmospheric boundary layer and turbines* – LES • *Many Subgrid-Scale (SGS) models are designed for atmospheric boundary layer, but we don't know how they predict wakes. Need to understand this.* – There are too many available turbulence models • *None is perfect.* • *Users must be well informed to choose proper model* – Models break down or work differently with: • *Buoyancy effects* • *Flow separation* • *Simultaneous capture of atmospheric & turbine wake* – Lack of turbine data (IP issues) – Resolution requirements not fully understood – Need data assimilation at plant scale – Models need to better inform each other, e.g.: • *Need to use LES findings to improve linearized NS* • *Need to look at the deficiencies of certain models to guide the research use of other models* – Significant uncertainty in boundary conditions • *Turbulence models and surface boundary conditions at model and scale interfaces* – Model best practice documents are not very useful – Engineering quickly running tools calibrated using data and higher order models – Improved aggregated turbine parameterizations – Mesoscale does poor job of terrain modeling due to terrain following coordinates **Model interfaces inaccurate** – Simultaneous up-scaling and downscaling across scales and interfaces – How do you validate at interfaces? What are uncertainties due to interfaces? – What variables are required at the interface? • *E.g. does humidity matter?* – Do not have unified physics at interfaces – Need observations at interface boundary • *What is really happening between mesoscale and wind plant scale?* – Better wall models – varying in time – used in

• *Some physics are not continuous across boundaries* • *E.g. clouds* **Organizations Working on This Problem** – Includes national labs and industry, e.g.: • *NCAR, LANL, others* • *Industry, consultants*	complex terrain **Turbulence handling insufficient** – How is turbulence generated when downscaling? – Adequate turbulence resolution needed for models **Need validation data** – Data assimilation helps drive simulations

Desired Outcomes	Path Forward
New code base specifically-designed for wind energy (longer term) – Improve multi-scale simulations: • *New modular software framework/infrastructure to facilitate code inter-communication* • *New unified, multi-physics model* • *Series of consistent models of differing complexity (consistent in terms of software, physics models, and turbulence models)* • *Different physics models should communicate well* **Improved model performance** – New heterogeneous terrain-appropriate surface boundary condition – Incorporate stability/atmospheric turbulence effects into linearized N-S models – Mesoscale models coupled to URANS or DES • *Industry can learn & use more complex flow models* **Detailed best practices document** – Guidelines for various computational approaches, turbulence models, and boundary conditions **New large-scale data sets for validation** – Flow over terrain representative of wind plants – Include marine flows **Metrics of success** – Model agreement with validation data – Cost-to-benefit ratio of improved models • *Reduce uncertainty in spatial wind speed variation* • *Potentially reduce number of meteorological masts*	**Plan & execute parallel modeling efforts** – Address multi-physics, unified model in long term • *Fundamental turbulence model research* • *Software framework research* • *Solver, gridding/dynamics research* • *Wind turbine-specific modules/components: wake models, turbine aero-structural models, farm models for mesoscale* – Create/refine specialized wind-specific models and model couplings for short term to bridge time gap – Requires a multi-disciplinary, multi-institute, set of coordinated tasks **Conduct data assimilation at wind plant scale** – Diverse measurements needed • *Appropriate spatial and temporal scales* • *Coastal Sites, plain sites, marine sites* • *Wakes under different stability conditions* – Large-scale experiment • *Within an operating wind farm* • *Well-instrumented turbines* • *Inflow characterization* • *Multiple wake measurements* • *Detailed turbine description, including blade geometry and operational information* • *Turbine details need to be totally available to participants*

2d Wind plant control implementation

Current Situation	Complicating Factors and Obstacles
Current control paradigm – Individual turbine control – Wind farm simulations done from one direction – Multiple directions not typically considered – Rotor pitch control – Collective pitch control currently used by industry – Individual pitch control under study – Power management is the main objective – Coordination with utilities is not yet efficient – Utilities demand curtailment based on ramp events **Validation data are held in various locations** – OEM data repositories – Owner/operator data repositories – Sandia National Lab CREW database **Organizations Working on This Problem** – Includes national labs and industry, e.g.: • *National Renewable Energy Laboratory (NREL)* • *Sandia National Laboratories (SNL)* • *Turbine manufacturers such as Vestas* • *Europeans – Aeolus project, EERA-DTOC*	**Control models do not account for realistic flow** – Stability effects not integrated into controller **Lack of validated simulations & validation data** – Access to operational wind farm data is difficult • *Available data are sparse (SCADA data)* – Testing facilities are sparse • *Energy research Centre of the Netherlands (ECN), NREL, Sandia National Lab* • *Need a range of test facility sizes* **Difficult to tie controls benefits to financial benefit** – Industry hesitant to accept plant level controls • *Financial case has not been made* – Accurate real world cost models difficult to obtain • *Need these as a basis for plant control cost models* • *Operations & maintenance cost info is unavailable* – Cost trade-offs of advanced control hardware have not been studied in depth • *LIDAR, advanced actuators, etc.* **Manufacturers protective of control system details** – Unknown hardware & component limitations

Desired Outcomes	Path Forward
Wide acceptance of plant level control systems – Industry must view control as a plant-level problem **Advanced, low cost plant control systems** – Advanced controls must be cost effective • *Fast in response* • *Minimal impact on wind plant cost construct* – More accurate wake modeling, cost modeling – Optimize power production & reduce fatigue loads – Reduce turbine noise and reduce bird strikes – Best practices for using advanced wake models **Active data sharing framework** – Shared data from operational farms • *Take lessons from aerospace industry* • *Incorporate sharing into PTC* **Test site for wind plant control** **Established goals for future R&D** – What type of goal? Some examples: • *Minimize the cost of energy* • *Increase energy capture* • *Reduce maintenance (O&M) costs* – Establish metrics • *Cost of energy reduction targets* • *Siting optimization metrics* • *Wind plant wholesale rates* • *Number of wind farms using plant level control*	**Plan & Execute control system testing campaign** – Utilize simulation tools • *Model control system performance and costs* • *Consider optimized plant layouts* – Continue support of existing test centers – International wind plant scale experiment and simulation exercise in control • *Cost shared across countries and industry* – Proof of concept within smaller scale test sites • *Could be wind tunnels* • *National laboratories, universities* – Long term monitoring of control performance • *Perhaps necessitates adaptive control* **Develop new instrumentation & test beds** – Augment existing test centers and instrumentation – SCADA data and root bending moment needed to check validity of control system (near term) • *Need O&M records within existing wind farms,* • *If now electronic, transfer from paper records* – Expand sensor suite within wind farm (long term) • *Include long term O&M records* • *Highly dependent on sensors required (e.g. LIDAR)* – Long term simulations required (~20 years) • *Fast simulation tools will be needed* **Develop partnership with industry** – Cost prohibitive for any single entity to undertake full scale wind plant testing • *Engage manufacturers, owners, utilities* **Establish the financial benefits of plant controls** – What's the potential for owner/operators to recoup research costs? Need to establish this. • *Recoup costs in one year? Five years?* • *If industry benefit can be shown to be substantial, the economic case can be made to industry* • *Frame costs in terms time to recoup R&D costs*

3 Wind Turbine Control Volume

Group Overview

The turbine-scale control volume group (BOG3) examined the impacts of inflow on an operating wind turbine, as well as wake creation during outflow. This included discussion around coupling meter-scale aerodynamics models with sub-meter rotor and drivetrain loads models, experimental requirements for collecting aeroelastic measurements, and the impact of small- and large- scale turbulence on the wind turbine rotor. Specific meteorological topics included air-sea interactions, observations that fit all required temporal and spatial scales, and interoperability of larger scale forecast models to turbine scale. The spatial scales of interest range from kilometers down to millimeters. BOG3 was divided up into five separate sub-topics:

a. Coupled near surface, air/sea, aeroelastic, turbine- & hydro-dynamic models
b. Design standards and site assessment
c. Wind turbine control implementation
d. Modular frameworks for code development
e. Rotor wake modeling, interfaces, and computational domain approach

For each sub-topic, the expert attendees defined the current situation (state-of-the-art), complicating factors and obstacles, desired outcomes of a concerted R&D effort, and the necessary considerations for any path forward. Upon completing work in each breakout group, the sub-topic teams reconvened in the larger breakout group to discuss their sub-topic. As a group, each BOG was able to distill the sub-topic information into common benefits and findings related to their particular topic. This information was finally presented to the larger plenary session. For the wind turbine control volume group, the following individuals acted in the role of group speaker (Speaker presentations are available in Appendix D):

- Bob Banta, NOAA/OAR/ESRL
- Niels Troldborg, DTU Wind Energy

Benefits of improved wind turbine-scale modeling

The wind turbine control volume group identified the following benefits that may arise from improvements in wind turbine scale models:

- **Improved wind plant performance**: More accurate, higher resolution turbine-scale models will enable improved wind turbine and wind plant designs that more efficiently convert wind energy into electricity. With an increased understanding of complex inflow conditions, turbine designers will be able to reduce losses arising from wind shear, wakes, turbulence, etc. Furthermore, a better understanding of rotor loading will allow for design enhancements that reduce the overall loading, which will allow manufacturers to increase blade length, further increasing energy capture. Turbine control systems will also be improved, further improving overall energy capture.

- **Reduced operations and maintenance (O&M) costs**: A better understanding of flow physics and the implications for rotor loading will allow wind turbine designers to build more reliable wind turbines. Currently, wind turbine designers must use a simplified representation of the flow field seen by the rotor – as a result, the designs do not fully account for the complex loading, which can lead to part failures and increased O&M costs. Fully understood inflow conditions will allow these costs to be reduced significantly. This applies to existing as well as future wind turbine designs.

Knowledge Gaps

While each sub-topic team identified several specific knowledge gaps (see the detailed sub-topic tables that follow each BOG summary), some common themes emerged upon reconvening back into the larger BOG. These common, or generalized, knowledge gaps were summarized as follows:

- Critical need for multivariable space-time synced experimental field data
- Current design standards do not sufficiently address state-of-art models
    - Interactions between complex airflow and rotor/turbine
- Insufficient collaboration between industry/designers and researchers
    - There are obstacles to collaboration
- HPC simulation capabilities are underutilized
    - Unclear how best to utilize these resources

Expected outcomes of a concerted R&D effort

Common themes also arose regarding the expected outcomes of an R&D effort. These outcomes would be expected to tie to the overall benefits from improved turbine-scale modeling identified above. Furthermore, while it would be expected that any R&D effort would address the knowledge gaps listed above, the BOG identified the following as specific, important outcomes:

- Extensive multivariable space-time synced experimental field data
    - Provide required inputs and validation data for numerical models
        - Engineering design tools
        - High-fidelity simulations
- Development of new experimental techniques
    - Expanded capability to gather the required validation data for next generation high-fidelity techniques
- Transition of research simulation tool learning to engineering design tools
    - Improved design standards
- HPC simulation capabilities that represent real wind turbines operating in the real atmospheric environment

Considerations for a path forward

Once knowledge gaps and desired outcomes were identified, each BOG discussed the challenges and steps that may arise attempting to overcome the gaps and achieve the outcomes. This hypothetical "path forward" identifies several practical steps that an R&D effort may need to address. The wind turbine-scale group identified the following components of a path forward:

- Plan and execute expansive wind-plant and wind-turbine scale experiments
    - Develop field and computational experiments
    - Develop the required measurement techniques
    - Utilize the current generation of experimental techniques
    - Explore the potential for a standardized public experimental facility
        - Study the performance of "open-source" turbines
- Develop and validate a multi-scale computational framework
    - Develop a reference tool set that provides standard validated calculations for pre-defined test cases
        - Include an Application Programming Interface (API)/code framework
    - Establish joint framework between researchers and industry
    - Utilize high performance computing
- Develop an "open-source" turbine
    - Could be manufactured at different scales
    - Describe how airflow-turbine interactions scale
- Coordinate between wind stakeholders to improve design standards
    - Utilize current understanding of complex airflow-turbine interaction
    - Develop and provide lower-order models
- Form a collaborative to address gaps in experimental techniques
    - Instrumentation sharing collaborative
    - Standard instrumentation packages and test procedures

Taken together, the common BOG benefits, knowledge gaps, outcomes, and paths forward represent the key "take-aways" for each group. In following sections, the information provided for each sub-topic is given in detail, arranged around the four deliverables each group was expected to address: the current situation, complicating factors and obstacles, desired outcomes, and aspects of a path forward.

3a Coupled near surface, air/sea, aeroelastic, turbine- & hydro-dynamic models

Current Situation	Complicating Factors and Obstacles
Computationally inexpensive design codes – Used for rapid analysis of concept designs – Used for design optimization – Typically use simplified system descriptions: • *Aerodynamics* • *Hydrodynamics* • *Turbine structural response* – Examples of these tools include: • *FAST (NREL), HAWC2 (Risoe), Bladed (Garrad Hassan), and others* **High-fidelity computational simulations tools** – Require high performance computing (HPC) – Used to study complex system details • *Address problems that are difficult to predict using "design codes" alone* • *Computationally expensive* • *E.g. Wind turbine & wind turbine array performance* – Example 1: Reynolds-Averaged Navier Stokes (RANS) Computational Fluid Dynamics (CFD) • *Simulations of fully resolved turbine blades/rotors* • *Velocity and turbulence are typically included* • *Simplified inflow fluid structure interactions between the rotor and the surrounding air* – Example 2: Large Eddy Simulations (LES) and Hybrid RANS-LES simulations • *Turbine blades may be resolved by the computational grid using traditional or immersed boundary techniques* • *Alternatively, the blades can be represented using actuator line, or actuator disk models.* • *Aeroelastic effects may be modeled using modal representations of the blades* • *Inflow conditions that closely represent "real" atmospheric turbulence can be used* **State of the art measurements techniques** – LIDAR measurements • *Characterize inflow, wakes, and turbulence* – Meteorological towers upstream of turbines • *Characterize inflow and the boundary layer* – Instrumentation (e.g. pressure taps, strain gauges) • *Sensor the blades, tower, and drivetrain* • *Measure flow aerodynamics, structural response, and performance of the turbine*	**Limited high-quality experimental data** – Few comprehensive data sets that can be used to validate numerical models – Need aerodynamic, structural, & acoustic data – Need time-synced data – Need multivariable space-time synced data • *Must provide required inputs for numerical models* • *Must provide validation data for numerical models* • *Applies to both design tools and high-fidelity models* **Poor understanding of the air/water interface** – How does this interface affect the atmospheric boundary layer at rotor disk elevation? **Coupling aero and structural codes is difficult** – No common interface exists **Poor understanding current model accuracy** – Applies to existing simplified physical models – E.g. actuator line and actuator disk rotor models **Wake/array effects not accurate in current models** – Applies to design codes and high-fidelity models – Turbine loads are not well predicted – Discreet turbulent structures not well understood **Design standards don't capture wake/array effects** – Turbine fatigue loads are highly complex in arrays **Aero-elastic and aero-acoustic codes lacking** – Need further development and validation

Desired Outcomes	Path Forward
Improved design standards – Requires verified/validated high-fidelity models – Requires significant experimental data **Improved design codes and tools** – Includes existing and future design codes – Must tie-in with design certification standards **Successful full-scale wind turbine experiments** – Address important outstanding questions • *Aero-elastic dynamics* • *Complex 3D inboard blade flows* • *Near wake dynamics* • *Effects of complex inflow* **Improved understanding of aero-acoustic effects** – Thorough experimental databases – Advanced computational modeling tools **Improve wind stakeholder interaction** – Better coordination among owner/operators, OEMS, developers, national labs, and academia – Transition technology from research simulation tools to engineering design tools **Development of a baseline "open-source" turbine** – Compete design & performance characteristics • *Must be state-of-the-art wind turbine* • *Full aerodynamic and structural details* – Must be beneficial to all wind stakeholders • *Should be freely available to research community* • *OEMs can use it to validate their design codes* • *Useful for model-to-model comparisons* • *Should be endorsed by several industry partners* **Improved understanding of turbulent structures** – Requires research into simplified inflow cases – Examine interplay between rotor & surrounding air **Advanced instruments & experimental techniques** – Must enable future high-fidelity data requirements **Development of advanced HPC tools** – Must accurately represent the performance of "real turbines" in "real conditions" • *E.g. fully resolved turbine blades, turbine rotors, full turbines, and turbine arrays.*	**Plan and execute large-scale experiments** – Integrate modeling and experimental efforts – Utilize existing experimental techniques – Identify model accuracy improvement opportunities • *Develop coupling tools for aero-elastic simulations* • *Develop high-fidelity acoustic models* • *Characterize inflow with complex terrain* – Address mesoscale parameterizations, E.g.: • *Develop turbulence mixing parameterizations* • *Develop complex terrain parameterizations* – Utilize high-fidelity HPC simulations • *Define "best practices" for high-fidelity simulations* • *Consider grid generation and near wake resolution* • *Define appropriate inputs and boundary conditions* • *Predict wind turbine loads and performance with high spatiotemporal accuracy* • *Consider complex terrain* – High-fidelity full-scale experiments • *Plan for both field and wind tunnel experiments* • *Characterize wind turbine loads and performance with high spatiotemporal accuracy* • *Measure complex terrain effects at large scales* **Develop multi-year plan to improve testing capabilities and instrumentation** – Consider testing standards for existing technology – Need advanced field measurement capabilities • *Time synchronized field data* – Need advanced instrumentation • *Develop noise measurement package* – An international instrumentation sharing collaborative can facilitate uniform data quality **Plan development of the "Open Source" turbine** – Gas turbine industry provides a successful example • *Gas turbine test bed was developed & used by several companies*

3b Design standards and site assessment

Current Situation	Complicating Factors and Obstacles
Design standard structure – A set of load cases separated by classes • *Deterministic* • *Contain normal and extreme cases* • *Parameterized by wind speed & turbulence intensity* – Simulate flow over the terrain **Design standard development** – Defined by International Electrotechnical Commission (IEC)/Det Norske Veritas (DNV)/Germanischer Lloyd (GL), etc. – Take local measurements for 6 months • *Validated models already exist at several locations*	**Research results chasing standards generation** – R&D and early implementations results should be leading standard generation **Incomplete physics treatment in standards** – Atmospheric flows not realistic in standards, e.g.: • *Wake modeling & complex terrain* • *Offshore conditions & air/sea interface* • *Specific non-neutral flow conditions* – Load estimation not ideal – Load cases not well understood at the margins • *Currently simply pass/fail* **Incomplete model validation data** – Wake simulations are missing validation data for several locations and terrain types – Site measurements lacking detail • *Often too coarse* • *Do not capture significant site variation*

Desired Outcomes	Path Forward
Improved link between research and standards – Simplified R&D results that can benefit standards • *Not enough to simply understand the flow* • *Must be applicable to standards* • *Research areas should target phenomena impacting complex flow forecasts, including storms, stratified atmosphere, wake effects, low level jets, etc.* – Risoe meandering wake study is a good example • *Include list of atmospheric conditions in standards* • *Generate load cases for each condition* – Standards more in line with existing models **Inclusion of cost reduction as a factor in standards** – Not enough to simply eliminate failures **Vastly expanded pool of validation data** – Need a lot more and varied data • *Large scale wind farms* • *Variety of terrains and atmospheric conditions* **New types of standards** – Site assessment standards may be useful **Improve load estimation** – Need a more complete set of atmospheric inputs – Need the ability to simulate these inputs **Improved site optimization** – Applies to both turbine layout and site selection	**Launch major experimental Initiative** – Expansive field tests at large wind plants • *Multiple measurement instruments* • *Multiple locations* • *Onshore test beds first* • *Offshore test beds to follow* • *Long term studies (5+ years)* **Link experimental results to design standards** – Need to include the entire wind community • *Invite to submit own results against test cases* – Create simplified descriptions • *Varied atmospheric conditions* • *Wake models (near and far wake)* • *Load cases*

3c Control implementation

Current Situation	Complicating Factors and Obstacles
Controls implementation – Currently turbine-level control – Simple instrumentation **Controls linked to design process** – Controls effects calculated in detail within aeroelastic design tools	**Control not yet done at the farm level** – Turbines don't share information with each other – Complex aerodynamics vary significantly intra-plant **Controls not fully considered in design standards** – Sizing of wind farms incomplete without considering controls implementation **Controls currently implemented post-design** – Need to be incorporated earlier in design process

Desired Outcomes	Path Forward
Farm-level control implementations – Move beyond simple turbine-level control **Improved control performance** – Better uncertainty estimates of load & sensor data – Better real-time control • *Requires simplified atmospheric and aeroelastic models (like those in the design standards)* **Improved instrumentation and sensors** – Full suite of sensors that operate within expected sensor bandwidth **Incorporation of control design into turbine design process** – Need specific models of control designs	**Launch controls improvement initiative** – Include greater wind community – Consider plant level controls – Compare design standard results with field results – Utilize simple design standard criteria when prioritizing controls implementations

3d Modular frameworks for code development

Current Situation	Complicating Factors and Obstacles
Not standard practice – Still in the discussion/planning stage	**No central organization to coordinate efforts** **Existing legacy code with lots of inertia** – No incentive in place to refactor code to connect with new interfaces

Desired Outcomes	Path Forward
Functional, widely accepted modular frameworks – Improve the modules found to have weaknesses – Combined atmospheric-aero-elastic capability with a standardized interface – Code comparisons with a set of benchmark datasets derived from a large collection of field data	**Establish consortium to define common interface** – Require participants to exchange modules – Conduct a code comparison study with field data **Conduct a round of model improvements** – Identify and improve model deficiencies

3e Rotor wake modeling, interfaces, and computational domain approach

Current Situation	Complicating Factors and Obstacles
Industry models for turbine & wind farm design – Sten Frandsen Model • *Increased ambient turbulence intensity (TI)* • *Applies to wakes for single turbine loads* • *Can be extended to turbine clusters & wind farms* – Jensen Wake Model • *Wind farm performance estimation* – Dynamic Finite State Wake Model • *Single turbines only (induction)* – WaSP-like comprehensive wind farm models • *Collection of methods & variants used for siting* **Researcher models for turbine & wind farm R&D** – Simplified Navier-Stokes (NS) • *Wake deficit and performance of clusters and parks* – Dynamic wake meandering • *State of the art using desktop computers* • *Small clusters and full wind farms* • *Performance and loads* – Lagrangian flow methods • *Single turbines and turbine clusters* – Actuator techniques (lines, disks, surfaces) • *Current state of the art for wake modeling* • *Single turbines, small clusters, & full wind farms* – Steady RANS techniques – Unsteady RANS, LES, hybrid CFD methods • *Full rotor (steady, unsteady, adaptive, hybrid)* • *Single turbine performance, loads, induction* • *Small turbine clusters (<9)*	**Industry models for turbine & wind farm design** – Currently extrapolating from small time scales to 20 years lifetime – Unclear how simplified wake models and wind fields can handle stability – CFD/research codes not fast enough – Unclear if CFD/research results are being incorporated into turbine and wind farm design – Wake design standards not fully formulated **Researcher models for turbine & wind farm R&D** – Difficult to address all scales at once • *How do we couple scales in simulations?* • *Includes weather down to microscale* • *May include microscale to blade scale* – Model interfaces not yet developed • *E.g. between LES and wake models* – Turbulence simulations not yet accurate in CFD • *From plane to volumetric* – Few measurements/benchmarks for validation • *What are scaling params for wake measurements?* – Standards not sufficient • *E.g. standard definition for cut-off between the near wake and far wake* • *Not standards for doing wake measurements or wind farm measurements for wakes* – Lacking procedures for reproducing field tests in simulations • *Need 3D data* • *Need better spatial-temporal data resolution* • *Airflow data should be syncrinized with structural and/or power measurements on the turbine*

Desired Outcomes	Path Forward
Improved models for turbine & wind farm design – Mid-fidelity models will still be important in the future, because they run relatively fast and offer a good deal more insight than existing, simplified design tools – Scalable CFD & Lagrangian codes for CFD wakes • *Access to source prefereable* – API for Coupling with structural and ABL solvers • *Generalized case* **Better trained workforce for model usage** – Improved use of tools with validation cases – Improved transfer of students to industry – Updated design standards **Improved models for turbine & wind farm R&D** – Improved model resolution and accuracy • *Computational parallelization* • *High performance computing (HPC) algorithms* • *Complex terrain handling* • *Non-neutral atmospheric conditions* • *Improved uncertainity & error quantificaiton* – Multi-scale validation from rich wake data sets • *Temporally synched inflow/wake/outflow data* • *Non-uniform inflow (yaw, shear, etc)* – Better instrumentation & experimental techniques • *New & cheaper measurement techniques* • *Sub-scale test sites and wind tunnel facilities* • *Scaling laws for doing subscale wake experiments* • *Improved wake measurements* – Quantification of wake progression • *Applies to all wind conditions* • *Stability, terrain, sea, turbulence, yaw, shear, etc.* • *Incorporation of these resutls in lower order models* – Improved uncertainty quantification • *Sources and magnitudes for different applications* **Improved standards for multi-scale wake testing** – Diverse set of standards • *Operating turbines, instrumentation, resolution and wind field generation in wind tunnels* • *Recreation of test data in simulations, including volumetric turbulence generation*	**Create roadmap for wake model improvement** – Establish starting point for R&D • *Conduct standard literature review* • *Determine the scales that need to be captured* • *Define required experimental resolutions* – Include entire wind stakeholder community to identify roadmap goals and objectives **Plan & execute wake model validation campaign** – Define required experimental measurements • *Wind Tunnel: simple 1-3 turbine interactions* • *Sub Scale: 10-30 m turbines* • *Full Scale: multi MW turbines, multi turbines* • *Simulation scaling studies for design of experiments* – Define instrumentation requirements • *Develop new high resolution field instrumentation* • *Establish reference subscale test sites (wind tunnel)* – Conduct uncertainty quantification • *Establish success criteria* – Optimize computational environment • *Scale wake codes to 100-10,000 cores for CFD and Lagrangian wakes* • *Develop scalable algorithms that can be easily adapted to evolving hardware technologies, such as multi-core CPSs and GPUs* **Development new, fully coupled software** – Fully coupled, multi-scale interactional code – Clear APIs to couple structural solvers, ABL solvers, rotor solvers, and wake solvers – Coupled multi scale/physics high-fidelity code – Modular frame work that facilitates the coupling of various simulation tools **Coordinate industry & research communities** – Compare new wake models to industry data • *Basic turbine performance and loads in wakes* • *Basic farm performance and loads* – Draft new design standards – Establish goals for industry workforce training

4 Experimental Data and Validation

Group Overview

The experimental data and validation group (BOG4) examined challenges and opportunities for future experiments at multiple scales. This included discussion around methods for obtaining the experimental data needed to validate existing and advanced new models, as well as identifying requisite instrumentation and test beds on the appropriate scales. There was some discussion of model requirements, as these will drive the data collection requirements. Interaction between public research and private industry was also considered. The spatial scales of interest range from hundreds of kilometers down to millimeters. BOG4 was divided up into four separate sub-topics:

a. Rotor wake modeling, interfaces, and computational domain approach
b. Wind tunnel experiments
c. Wind farm measurement campaigns
d. Scaling, fidelity, and instrumentation requirements

For each sub-topic, the expert attendees defined the current situation (state-of-the-art), complicating factors and obstacles, desired outcomes of a concerted R&D effort, and the necessary considerations for any path forward. Upon completing work in each breakout group, the sub-topic teams reconvened in the larger breakout group to discuss their sub-topic. As a group, each BOG was able to distill the sub-topic information into common benefits and findings related to their particular topic. This information was finally presented to the larger plenary session. For the experimental data and validation group, the following individuals acted in the role of group speaker (Speaker presentations are available in Appendix D):

- Melinda Marquis, NOAA/OAR/ESRL
- Gordon Randall, DNV

Benefits of improved experimental data and validation

The experimental data and validation requirements group identified the following benefits that may arise from improvements in experimental data and validation:

- **Improved wind plant performance and reduced operational costs**: More accurate, higher resolution models at scales require high fidelity data for validation and to improve the modeling communities' understanding of the underlying physics. Because model improvements are so reliant on this data, expanded data collection will invariably lead to better forecasts, improved characterization of complex aerodynamics (e.g. turbulence, wake interaction, etc.), a more complete understanding of rotor loading conditions, and overall better project economics.

- **More profitable wind industry**: Validation data can be used across several stakeholder groups, including government, academia, and industry. The more data that becomes widely available, the better everyone's codes will become – this applies to high-performance simulations, design tools, and everything in between. As the rate of deployments increase, and as wind power represents a greater percentage of the national generation portfolio, even small improvements in performance will have tremendous financial implications for the entire wind industry.

Knowledge Gaps

While each sub-topic team identified several specific knowledge gaps (see the detailed sub-topic tables that follow each BOG summary), some common themes emerged upon reconvening back into the larger BOG. These common, or generalized, knowledge gaps were summarized as follows:

- Lacking data of sufficient temporal and spatial resolution to validate models and/or include as initial conditions within models
  - Need quality assurance
- Uncertainty is not fully understood or quantified
  - No agreed-upon uncertainty to use as starting point
- Not enough existing test beds to collect validation data
- Data sharing and archiving is inadequate and faces significant challenges
  - No clear incentives for industry to share data
  - Intellectual Property (IP) issues

Expected outcomes of a concerted R&D effort

Common themes also arose regarding the expected outcomes of an R&D effort. These outcomes would be expected to tie to the overall benefits from improved experimentation and validation identified above. Furthermore, while it would be expected that any R&D effort would address the knowledge gaps listed above, the BOG identified the following as specific, important outcomes:

- Extensive high-fidelity data made widely available for use in model validation and model improvement
  - Existing and new models
- Multiple, open test beds for experimental data campaigns
  - Small scale tests (e.g. universities)
  - Medium scale field tests (e.g. 500-1,000 kw turbines)
  - Large scale field tests
  - Wind tunnel tests
- Improved data sharing and archival
  - Data sharing/archiving effort needs funding/resources

Considerations for a path forward

Once knowledge gaps and desired outcomes were identified, each BOG discussed the challenges and steps that may arise attempting to overcome the gaps and achieve the outcomes. This hypothetical "path forward" identifies several practical steps that an R&D effort may need to address. The experimental data and validation group identified the following components of a path forward:

- Conduct planning exercises that lead to a testing and validation roadmap
    - Establish needs based on greater wind stakeholder community
        - Establish required range of scales (e.g. 20 Hz to decadal)
        - What kinds of data might be useful or needed?
    - Evaluate past experiments and identify future experiments
        - Identify needed measurement technologies
        - Establish existing datasets
    - Identify best practices for validation
    - Identify technology development requirements
        - Identify needed instrumentation based on desired data
        - Create R&D plan to develop new instruments
- Plan and execute the deployment of multiple test beds
    - Establish turbine design criteria for optimal validation
        - System dataset must be very well defined
        - E.g. full blade geometry, drivetrain architecture, etc.
    - Leverage existing instrumentation when possible
    - Assure sufficient data quality and completeness
- Expand data sharing and archiving
    - Come up with what an "adequate description" of a data clearinghouse
        - Consider metadata requirements
        - Location (e.g. housed at a neutral party)
    - Include datasets that go across all necessary temporal and spatial scales
    - Establish data sharing requirements and IP issues
    - To what extent can we leverage/improve existing efforts?

Taken together, the common BOG benefits, knowledge gaps, outcomes, and paths forward represent the key "take-aways" for each group. In following sections, the information provided for each sub-topic is given in detail, arranged around the four deliverables each group was expected to address: the current situation, complicating factors and obstacles, desired outcomes, and aspects of a path forward.

4a Rotor wake modeling, interfaces, and computational domain approach

Current Situation	Complicating Factors and Obstacles
Existing Data Sets – Widely used field data: Sexberium (1992), Horns Rev (2008), and Egmond aan Zee (2001) – Widely used wind tunnel data: NREL's Phase VI (2001) and MEXICO (2001-2006) – ECN wake propagation data set **Instrumentation and Testing Capabilities** – LIDAR and RADAR studies are starting to become widely available – Can measure wake effects up to 5 km	**Instrumentation and testing challenges** – Need both subscale and full-scale measurements – Smaller turbines could be adequate for some purposes, but not all – Larger turbines are needed to measure long distance wake propagation and LLJ effects – Full-scale tests are long term, and expensive. • *Maybe ~ $3-4 Million / test bed* • *May need 4-8 onshore test beds.* • *Offshore test beds would cost significantly more* **Industry IP Sensitivities** – Field tests require a two-way flow of information – Data users may be required to share simulation results with other users – Some data may become publically available

Desired Outcomes	Path Forward
Enhanced validation for model coupling – Coupled inflow-wake measurement – Coupled inflow-power measurement – Coupled wake-load measurement – Improved coupling/crossover at differing scales (e.g. near wake vs. far wake) **Improved instrumentation and testing capabilities** – Deliberate, large-scale data sets and test cases – High resolution data collection – Multiple spatial and temporal scales – Load sensors, pressure taps, stream gauges, etc. – Data collection from MW-scale turbines – Include non-power data (e.g. wind speed) to correlate measurements to turbine models – Better across and above rotor measurement of behavior or evolution of velocity deficit – Increased scale wind tunnel testing – Improved/standardized uncertainty quantification **Isolated wind turbine data** – Wake impacts on loading conditions – Upstream wind measurements correlated to loads **Multiple turbine array data** – Wake turbine interaction data in complex terrain – Turbine-turbine interaction – Wind farm to wind farm interaction – Near-wake measurements (~10D downstream) – Far-wake measurements (>1km downstream) – Velocity deficits at different stabilities (up to 5 km) – Multiple, synchronous wind farm field tests	**Develop a validation requirements roadmap** – Evaluate past experiments and identify future experiments and data requirements – Consider existing and future model needs – Identify unique complex terrain where development may occur • *E.g. upstate NY, Pacific North West, Ridgelines, Canyons, etc.* – Address the following types of tests: • *Multi-scale wake measurements* • *Isolated wind turbines* • *Multiple turbine arrays* • *Wind farm to wind farm interaction* **Establish instrumentation requirements** – Identify needed measurement technologies, including existing and future – Leverage existing capabilities & equipment where possible (e.g. anemometers, facilities, etc.) – Quantify uncertainty **Plan and execute series of validation campaigns** – Be opportunistic when approaching owners – Consider approaching developers, owners, and operators before and after construction – Utilize a standard testing process, for example: • *Identify multiple test beds in unique sites* • *Start with simple flat terrain, then proceed to more complex inflow environments* • *Stakeholders bring instrumentation to test sites* • *Conduct tests for 6-12 months*

Established testing standards and best practices – Uniform testing processes and equipment **Improved data sharing, archiving, & accessibility** – Increased stakeholder participation – Better access to data sets & experiment results – Applies to both existing and future data sets – All/most project data, not just sub-sets	**Facilitate data sharing and model improvement** – Share data with modeling community to improve and validate existing and new models – Inform model simplification efforts. For example, downscale/simplify RANS/LES to desktop models, such as eddy viscosity or Park wake models – Proposed metric for data sharing: • *Frequency with which a data set is used for validation purposes*

4b Wind tunnel experiments

Current Situation

Existing Data Sets
- Individual turbines: NREL's Phase VI (2001) and MEXICO (2001-2006)
- ABL tunnel with mini turbines, sometimes with terrain effects added
- SAFL, PSU, Johns Hopkins, Iowa

Instrumentation and Testing Capabilities
- NASA AMES wind tunnel
  - *Largest potential facility for wind tunnel tests*
  - *Widely available for use*

Complicating Factors and Obstacles

Wind Tunnel Test Deficiencies
- Turbines in a wind tunnel are inherently smaller scale because of size constraints
  - *Can't easily fit a multi-MW turbine in a wind tunnel*
- No wind tunnel tests currently exist for a modern, well documented multi-MW scale turbine
  - *Limits to applicability of wind tunnel tests*
  - *E.g. wake interaction tests may need large turbines*

Overly Idealized Inflow Conditions
- Inflow and boundary condition are idealized/clean
- Idealized inflow does not represent the real world
  - *E.g. impact of blade degradation and deformation on performance is unknown, but could be important*
- Unable to generate complex inflow conditions
  - *E.g. inclined flow, varied stability, complex terrain, KHI, swirl, etc.*

Scaling issues
- Unclear how to scale many real world variables
  - *Scale gap exists due to Reynolds dependency*
  - *E.g. thermal stability and/or surface heat fluxes*
  - *E.g. turbine-wake interaction & wake meandering*

Desired Outcomes

Full utilization of existing wind tunnel capabilities
- Small scale testing at universities
  - *Examine complex terrain, stability, farm layout, etc.*
- Mid-scale testing at the NASA Ames 80x120 tunnel
  - *Modern architecture wind turbines*
- Quantify turbine-turbine interactions
  - *Attempt two turbines with varied spacing*
- Explore energy production impacts
  - *E.g. blade degradation and deformation*

Improved instrumentation and testing capabilities
- Turbine level, high-fidelity measurements
- Improved capabilities to measure flow complexity
  - *Enable incremental increase of flow complexity*
  - *Increased turbulence, shear, & stability*
- Improved energy production testing capabilities
  - *Incremental impacts of flow changes*
  - *Incremental impacts of controller changes*

"Open Source" Turbine
- Fully characterized test components
  - *No "hidden data"*

Path Forward

Develop a validation requirements roadmap
- Data requirements and accessibility
- Solicit input from the greater wind community
  - *Industry, national labs, and academia*
  - *Identify requirements and expectations for tests*

Identify and prioritize wind tunnel resources
- Survey wind tunnels for availability & capabilities
  - *Dimensions, wind speeds, climatic control, etc.*

Instrumentation requirements
- Identify promising existing and future technologies

Plan & Execute series of wind tunnel campaigns
- Engage a diverse group of stakeholders
- Prioritize using requirements for model validation
- Leverage existing facilities and capabilities
- Utilize novel experimental methods, e.g.:
  - *Optical fiber strain gages & pressure taps*
  - *Particle Image Velocimetry (PIV), Laser Doppler Anemometer (LDA), & Pressure Sensitive Paint (PSP)*
  - *Advanced control strategies*
  - *Requirements for model validation*

– Complete aero-structural information, including: • *Detailed blade geometry and rotor design* • *Detailed drivetrain design (w/gearbox & generator)* • *Full structural details* • *Fully defined control system* – Complete description of inflow and outflow **Improved Data sharing and archiving** – Better access to data sets & experiment results – Mechanism and/or methods to transfer knowledge to real-world operations & existing models	– Quantify uncertainty **Facilitate data sharing and model improvement** – Share data with modeling community • *Should apply to model improvement and validation*

4c Wind farm measurement campaigns

Current Situation	Complicating Factors and Obstacles
Existing Data Sets – Widely used field data: Sexberium (1992), Horns Rev (2008), and Egmond aan Zee (2001) **Instrumentation and Testing Capabilities** – Coupled, multi-sensor measurement campaigns • *E.g. Turbine Wake and Inflow Characterization Study (TWICS), Crop Wind Energy Experiment (CWEX), DOE/SNL Scaled Wind Farm Technology Facility (SWIFT), NREL large turbine studies* – Pre-construction sensing • *60-m met towers (1-3 km max between towers)* • *SODAR* • *Isolated cases of remote sensing* – Post-construction Sensing • *Nacelle anemometers* • *On-site met towers (not common)* • *Isolated cases of remote sensing* **Forecast Model Capabilities** – Coupled, time-resolved models • *Mesoscale Numerical Weather Prediction (NWP)* • *Micro-scale models* • *Air-sea interaction*	**Instrumentation and Data Limitations** – Pre-construction measurements are limited • *Often only include wind speed* • *Fail to capture information about forcing conditions* – Few measurements within the wind farm • *Wake impact typically not measured directly* • *Measurements treated as relative not absolute* – SCADA data are not sufficient • *Doesn't include "research grade" wind data* – Met tower heights (60 m) are not sufficient • *60-m height is the effective limit to site met towers* • *Limit driven by large planning requirement/cost* • *Measurements don't cover the entire rotor plane* – Measurement packages are not easily deployed • *Difficult to capture atmospheric and turbine data* **Economic Benefits Not Widely Accepted** – Financial rewards of technically rigorous measurements have not been tied conclusively to increases in performance and/or productivity • *Getting high quality data is costly (and rare)* • *Inexpensive, easily accessible data is not sufficient* • *Potential benefits, therefore, are hidden or unclear* – Industry frequently assumes mechanical issues • *Underproduction not attributed to the resource* **Standards are not universal** – De-facto standards are set by financiers or investors and are not always technically advanced

Desired Outcomes	Path Forward
Expanded Data Sets – High resolution data at multiple temporal and spatial scales – Long-term power production data sets – Coupled inflow and wake data sets – Incremental complexity and/or difficulty, e.g.: • *Added turbulence, shear, stability, unsteady and non-uniform inflow* – Multiple, diverse regions, e.g.: • *Mountains, plains, coastal, offshore* **Improved instrumentation and testing capabilities** – Inflow conditions at every turbine location • *Upwind leading-edge turbine* • *Turbine deep within an array* – Easily deployable field equipment package • *Inflow, wake, and turbine response (blade loads, deflection, pitch, torque, SCADA signals, etc.)* • *Remote sensing or non-invasive methods* – SCADA data interpretation and reduction tools • *Identifying problems, failure modes, availability* – Fully defined turbines or components **Improved coordination amongst stakeholders** – Data must be useful for all stakeholders – Identify high value field tests; do not simply go after the cheapest possible tests **Highly skilled industry testing/analysis staff** – Establish standards and best practices **Validated Models** – More accurate turbine performance models • *Beyond simply wind speed versus power curves* • *Include turbulence intensity, shear, wind speed, etc.* – Uncertainty quantification **Improved Data sharing and archiving** – Meet needs of entire community • *Shared by site owners/operators* • *Informs requirements for new technologies* • *Transfer research knowledge to industry* – Improved access to experimental data and results	**Detailed planning exercise** – Request For Information (RFI) process to generate ideas for measurement • *Examine the cost/benefit to owner/operators* • *Compare pre- and post- construction* • *Campaigns over time scales from days to years* • *Identify and overcome existing obstacles* – Solicit input from the entire wind community • *Modelers, observers, and experimentalists* • *OEMs, resource assessors, and consultants* • *Developers, owners, and operators* – Create a modeling or process framework • *Simulate from pre-construction to decommissioning* • *Identify validation gaps to inform R&D priorities* **Plan and execute series of validation campaigns** – Prioritize list of potential climates and terrains – Establish standard instrumentation requirements • *Define common information/data needs* – Target operational sites to optimize production • *Validation results can be fed into new designs* – Finalize specific data requirements. For example: • *3-D wind components, 20 Hz, 2D upstream* • *3-D wind components at blade tip & ½ blade length* • *Temp profile w/ 20m resolution & 0.1°C accuracy* • *Velocity: In/out-flow, up/down-stream, 1-5km* • *SCADA data, power output, diagnostic info, etc.* – Derive/estimate local atmosphere • *Shear, stability, turbulence, etc.* **Facilitate data sharing and model improvement** – Reach out to industry to identify incentives for data sharing and shared R&D projects • *Identify legal mechanism for safeguarding data* • *Identify data that does not limit competitive market place but still carries common benefit* – Create data standards • *Ensure useful, comparable, consistent data* • *Create best practices for data sharing* – Incentivize industry collaboration & data sharing • *Align research community and owners/operators* • *Statutory data sharing is an option (e.g. via PTC)* • *Voluntary collaboration & data sharing is preferred*

4d Scaling, fidelity, and instrumentation requirements

Current Situation	Complicating Factors and Obstacles
Existing Data Sets – Widely used field data: Sexberium (1992), Horns Rev (2008), and Egmond aan Zee (2001) **Instrumentation and Testing Capabilities** – Wind tunnel studies and field measurements – Flow scale ranges from ~10 microns to many km – Wind Forecast Improvement Project (WFIP) • *Upper Midwest and Texas* • *Standard LIDAR & RADAR* • *Heavily instrumented* – Wind Farm Test Capabilities • *3D scanning LIDAR* • *Multiple vertical profiling LIDAR* • *Multiple SODAR (expensive)* – Rotor scale testing • *Upwind / downwind towers* • *Large-field Particle Image Velocimetry (PIV)* • *Dual Doppler LIDAR* • *Smart rotor (not necessarily rolled out to farms)*	**Existing Data Gaps** – Limited historical and climatological data – Not much aero-coupled mechanical loads data – Missing long term data at high resolution • *Scales comparable to LIDAR campaigns* • *Limited inter-annual, seasonal, & diurnal variability* **Instrumentation and Testing Capabilities** – Fine-scale observations are lacking – Limited turbulent scale remote sensing capability – Limited access to wind tunnels – Limited access to operating wind farms – Lab techniques like Pressure Sensitive Paint (PSP) not widely deployed **Data Sharing and Accessibility** – IP issues between industry & government/academia – No universal standards and best practices

Desired Outcomes	Path Forward
Better Parameterizations – Need to develop parameterizations that can handle non-linearity on file scale – Need to validate these as well with horizontal and vertical data – Need to validate these at multiple sites **Higher Resolution Data** – Air flow around blades • *Spatial scale: ~1-10m to 10 m* • *Temporal scale: kHz to seconds* – Atmospheric forcing • *Spatial scale: ~10 μm to >100 m* • *Temporal scale: 20 Hz to seasonal/inter-annual* **Improved Understanding of Climate Variability** – Not data intensive to identify different flows – Data need not be collected simultaneously – Experiments required at several different scales **Improved Instrumentation and Test Beds** – Need better means of measuring turbulence • *E.g. Arrayed sonic anemometers (higher-res)* – Need more "top-down" inflow data • *Measured above the turbine* • *Can cause sever turbine damage*	**Develop a set of test cases** – Identify R&D priorities to describe complex flow atmospheric phenomena. For example: • *Oklahoma Atmospheric Radiation Measurement (ARM) data, including LLJ & upwind data* • *Coastal area, looking at sea breeze effects* • *Complex terrain area including hills and ridges* • *Columbia river gorge, OR/WA (high complexity)* • *Nighttime stable BL flows, including intermittent turbulence and breaking gravity waves* – Focus on what is not well understood – Identify "model breaking" cases – Prioritize well-instrumented locations – Include several different length scales • *From rotor to regional (observational data sets)* • *Include simple and complex flows* – Use data to inform uncertainty quantification • *For parameterizations and model fields* **Expand access to cost effective instrumentation** – Deploy existing sensing technologies • *E.g. Strain gauges, pressure taps, etc.* • *Leverage remote sensing technologies* – Develop new, cost-effective instruments, e.g.: • *High-resolution turbulence measurement*

Improved Archiving and Data Sharing – Include quality control, metadata, & calibration data – Open access to how and where data was collected – Must be easily accessible & high quality – Maintenance requirements will require resources	• *Vertical temperature profiles (for stability)* **Develop and Launch a Data Clearing House** – Several approaches, examples include: • *"Wiki" style website* • *ARM raw data repository* • *NASA distributed active archive centers (e.g. NSIDC)* **Develop a standard for data sharing** – Include metadata in the standard – Improve financier/investor acceptance – Improve owner/operator acceptance

Question and Answer Session

Once each breakout group (BOG) concluded its discussion, the designated group speakers consolidated the key findings into a brief summary to be presented to the plenary session. The summaries are included in Appendix D. After each summary was presented, the audience was given an opportunity to ask questions to the BOG speakers or to other members of the audience. What follows in this section is a summary of the Q&A proceedings.

Mesocale/Regional Control Volume (BOG 1)

Group speakers

Sue Haupt and Bruce Bailey

Scale interaction

Q: How do you account for the interaction between the PBL and surface layer, where transfer of rotor-scale turbulence into the surface layer can be important?

A: This is implicit in the question of how we cross scale boundaries and transfer data from model to model.

How do we capture all of the forcing?

Q: How do we include 500 mBar forcing that may be important to the surface layer?

A: Not a variable of interest – currently using wind speed as the primary predictive variable of turbine performance.

How do better models lead to better turbines?

Comment: Impacts of better mesoscale models are similar to better understanding the atmosphere, and maybe it's the process of better understanding that leads to better designs.

A: Better models are often assumed to result in better understanding, but maybe that's not always the case!

A: Need open source frameworks to couple models, e.g. WRF-WIND.

Comment: Parameterizations that work in one place don't work in another. There are many choices that should be explored.

Comment: Need to follow multiple paths to avoid the risk of taking the wrong path.

Q: What about dynamical downscaling?

Comment: No clear answer. It's not clear that it provides the extra accuracy that we hope.

What kind of data do we need?

Q: There have not been many comments about the measurement resolution or precision that's needed. How do we decide what precision, resolution and coverage is needed?

Comment: NWS has standards, so they can compare measurements at different sites. Is there a standard in the wind industry, or can we make one?

A: There are no international standards for wind resource standards, but there is one in power performance. There is however industry consensus based on 3rd party, due-diligence reviews of energy predictions. This may be in advance of other industries due to the scale of the economic decisions that are made based on the data.

A: See the discussion from Group IV to create a roadmap to look at what measurements need to be made, at what precision and with what resolution.

Q: Can we get each different group to look at their scaling requirements?

A: Need to get regional-scale measurements. Could we use UAVs? See ETHZ and U. Indiana groups.

Q/A: Can we get everything we need from remote sensing (SODAR, LIDAR, radiometers) and RADAR, rather than having to resort to tall towers? This would be it's own conference!

What parameterization should be used?

Q: Is there something that sets out what the best parameterizations are for mesoscale modeling?

A: Unfortunately not, and people are running different Atmospheric Boundary Layer (ABL) schemes as part of ensembles. There is no simple answer.

Q: Can we carry out a comparison exercise?

A: We could leverage existing comparisons for this, rather than doing it directly.

Does finer scale modeling help?

Q: Finer scales don't always lead to better models, and often require new parameterization.

A: Many industry folks are aware of this.

Comment: Finer scale models are often penalized for various reasons that are not strictly related to accuracy. This needs to be recognized.

Comment: Need to look at improved metrics.

Wind Plant Control Volume (BOG 2)

Group speakers

Branko Kosovic and Rebecca Barthelmie

Specific test cases

Comment: Need to capture several different test cases that are focused on particular questions rather than scatter shot.

A: Yes, need to build on many existing facilities and studies, and can do some nice work when we have a good strategy.

A: During the breakout session, we did discuss looking at geographically and atmospherically diverse conditions.

Data needs

Comment: There is data out there, but frequently not well synchronized or described. TWICS is a good example of focused, simultaneous measurements. If we don't get good data, we don't advance the state of the art.

Comment: Funding for measurement projects may encourage this in the short term – perhaps bring instruments but don't ask for other money.

Transferring data between models and experiments

Comment: Models and experiments need to inform each other, rather than just go in one direction.

Comment: Test beds should be iterative and include models and observations, with model output and errors informing the choice of observations until models and observations agree.

Industry computational resources and approaches

Q: How does industry use HPC now and expect to use it in the future?

Comment from industry #1: Can afford this on the design stage but not on controls or optimization (using PLCs rather than HPC). Need very, very simplified models for turbine operational models. Want to get lifetime. Not necessarily going to use modeling data, more likely to react to real world situations / data modeled at the turbine level.

Comment from industry #1: CFD or HPC is used in the design stage, or for site suitability. DES or OpenFoam used but not at later stages. Need to figure out how to make more useful simulations with faster turnaround.

Comment: Can we create a middle-fidelity model that is almost good enough, with turnarounds of hours, to understand some of the questions that we face? Do we need the leading edge models?

A: Research tools from 10-20 years are used operationally

Comment: Need a variety of models at different levels of fidelity. How do we bridge the middle ground or bring in more easily accessible models that are somewhere between LES and Blade Element Momentum theory?

Wind Turbine Control Volume (BOG 3)

Group speakers

Bob Banta and Niels Troldborg

The role of High Performance Computing (HPC)

Comment: HPC will be important for understanding the underlying physics involved in complex flows, but it is vital to keep in mind there is an equally important need for mid-fidelity models that do not require HPC resources (i.e., the previous generation of HPC codes that no longer require HPC resources to run.).

Comment: Most researchers will agree with the previous comment. There is a need for mid-level physics-based models that are relatively fast. Such models offer more insight than the current simplified design tools used by industry, while not ultimately being as accurate as HPC-based tools. The point is, these mid-level tools will still be quite important to the industry going forward and in the future. This tends to be overlooked in conversations about HPC.

Design standards

Comment: Models need to inform standards.

Comment: There is increasing recognition that shear and turbulence need to be included more frequently within standards.

Open Source Wind Turbine

Comment: There's a need for information from industry to mesh or interface with information coming out of the research community. A physical, open source wind turbine bypasses this limitation. The open source turbine becomes the test case allowing more direct comparison of industry and research codes and methods and facilitates the transfer of experience and methods.

Comment from Industry: Might not need to develop a new turbine, but could take an existing chassis or older model.

Comment: Need to have full knowledge of the turbine aerodynamics, gearbox, and control system to make it worthwhile.

Comment: Don't forget that you need to go multi-MW to get scale effects. What about going to NDAs?

Comment: NDAs and proprietary data can be very challenging. Why not follow the lead of reference models, e.g. NREL 5MW. Very widely used. See also the Sandia research blades that are extensively used in smaller studies.

Comment: New open design allows us to move into the future. Could one be installed in a real wind farm environment, with wakes and a real atmosphere?

Comment: Look at the common technology platform shared between Rolls Royce, GE and Pratt & Whitney that allowed each company to step forward. Not always one right approach.

Comment: Also, internal combustion engines as an example are very important.

Comment: Needs to be data driven – do we need a new turbine to answer the question we want to ask?

Comment: Might need an array of open-source turbines…can't we get data for aero-elastic simulations? Should be able to get airfoil cross sections, stiffness – mass distributions, DLLs, etc.

Comment: Very much dependent on the manufacturer and country.

Scales in meteorology and engineering

Comment: Interesting cultural gap between meteorologists and engineers. Meteorology and engineering turbulence are very different scales.

Experimental Data and Validation (BOG 4)

Group speakers

Melinda Marquis and Gordon Randall

How do we get industry to engage?

Comment: How much can you do validation with something less than industry partnerships? You can generate collaboration by better leveraging existing data – what's it *good enough* for?

Comment/Q: If industry thinks it's already doing well enough, then there'll be no incentive to go further. The real issue is what questions does industry need answered?

Comment from Industry: Don't always care about performance, more concerned about condition monitoring so they can see that a gearbox is about to fail.

Comment: Each O&M manufacturer will have a different take.

Comment: Doesn't help reduce LCOE.

Comment: Need to give industry ammunition to look more deeply at the issues. If we can tell industry that we see *x*, and this is the impact on your lifetime, then maybe that's the message. Think big, but be aware of the pragmatic issues that prevent data sharing.

Comment from Industry: Not very proactive about this type of research, tends to be short-term thinking until lessons are learned the hard way. Sooner or later industry will need to do larger scale R&D in this area. Gas turbine industry OEMs tend to have a large turbine test bed, while there aren't many in the wind industry. Data sharing has to improve but we have to start somewhere. Roadmap would be helpful.

Comment from Industry: Some developers are not thinking about 20 years. Some choose to run above rated power to take advantage of high spot prices. Need to capture this in models. Will manufacturers sell entire power plants?

Planning

Comment: Need to figure out roadmaps for all of the topics covered at this workshop. In commenter's experience this has been very beneficial for other industries.

Inflow and statistical description

Comment: Don't often see good statistical descriptions of spectra or spatial covariance in descriptions of measurements or experiments. These are often used to define the inflow models. Need to tie observations back to design descriptors.

Comment: Trying to match manufacturer's information requirements for things like shear - frequently similar to a black box or single value.

Uncertainty and resolution

Comment: Uncertainty quantification turns up in every discussion. Impacts LCOE and should be embedded in processes and measurements.

Comment: On top of uncertainty, also need to think about precision.

Comment: Precision needs to match resolution and validation requirements.

Crossing boundaries between situations and scales

Comment: How do we account for the scales in the ABL that are not included or modeled in wind tunnels? Do we have a good way to do this?

Comment: This kind of thing is also important for the choice of measurement systems. Some systems cannot resolve the features we are interested in because of the limits on the systems. Vendor specs do not always agree with reality. Need to look at availability over time and with height as well, to make sure we get what we want.

Comment: Need to be led by the data that's needed, not simply the available instruments. Require realistic assessment of instrument capabilities.

Comment from Industry: Don't know how to generate synthetic turbulence in CFD so that different model runs are using the same inflow conditions. Some folks in industry are investing in this research area.

General Q&A

Group speakers

N/A - audience driven Q&A.

Role of HPC

Comment: High Performance Computing (HPC) efforts might now need to be application oriented, or community-focused. Might not be as broadly applicable as previous HPC research. Wind includes very complex issues, such as multiple scales.

Comment: Multi-scale experiments using HPC will inform field research more and more in the future.

Comment: Industry needs something that works. Would suggest that using HPC should not be a goal in itself.

Industry handover

Comments from Industry: Training workshops are very helpful for knowledge transfer. It would be nice to include a workshop as part of the outcome. Be aware of wind tunnel testing in Europe, e.g. BMW and Italy.

Summary

The Complex Flow Workshop was held by the Department of Energy's (DOE's) Wind and Water Power Program (WWPP) on January 17-18th in Boulder, CO. The workshop was located on the campus of the University of Colorado, Boulder, and was comprised of plenary sessions, Breakout Groups (BOGs), and sub-topic breakout groups. The BOGs were organized around the following topics:

I. Wind Turbine Scale Modeling and Validation Requirements

II. Wind Plant Scale Modeling and Validation Requirements

III. Regional Scale Modeling and Validation Requirements

IV. Experimental Data Validation Techniques.

Each BOG was tasked with providing the following deliverables, aligned around specific sub-topics that each group identified as important:

1. Define the current state of the art for each sub-topic
2. Identify and prioritize gaps and obstacles
3. Specify desirable outcomes for a concerted R&D effort
4. Outline potential paths forward for R&D activities

While the detailed findings from each BOG were distinct in terms of scale and scope, there was considerable overlap at a high-level. Several common needs and gaps were identified, as well as common types of activities that would be required to address those needs. There was a general consensus that future complex flow R&D will need to develop models and measurements that cross-spatial and temporal scales simultaneously.

Identified common needs include:

- Models that operate across multiple temporal and spatial scales
- Improved model physics and accuracy at all scales
- Well defined data requirements
- Field and wind tunnel validation of models
- Improved instrumentation at various temporal and spatial scales
- Improved data sharing throughout the wind industry

Identified required R&D activities include:

- Ramp-up planning exercises across stakeholder groups

- Incentivize data owners and users to share data and collaborate
- Archive data and improve accessibility and sharing
- Improve standards and practices

Wind power plants are poised to become a cost effective energy alternative to fossil fuels in the coming decade. Increasing the wind industry's understanding of the complex aerodynamics involved in harvesting wind energy represents the largest potential impact towards reducing the levelized cost of energy (LCOE) and increasing the deployment of wind power plants. Furthermore, it is clear that a significant effort will be required to achieve the performance and cost benefits that are possible from a concerted complex flow R&D campaign. This effort will require advanced modeling capabilities, data sharing and archiving, high performance computing, field and wind tunnel testing, and a high level of coordination. The level of effort required is most likely beyond the scope of any single industry stakeholder, but given the gains to be had, it is an important challenge to address.

Appendix A: Workshop Agenda

Workshop Agenda

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

	Day 1	Day 2
0730	---- Registration ----	
0800	Plenary: Welcome and High-Level Introduction (DOE)	Plenary: Day 1 Progress Report (M. Robinson)
0830	Plenary: Break-Out Group (BOG) Introductions • *SPEAKERS: Bill Mahoney (NCAR) & Torben Juul Larsen (RISOE)*	BOG: Sub-Topic Discussion with full BOG group • Identify organizations already working on each sub-topic • Prioritize the sub-Topics – What's most important?
0930	BOG: Form Sub-Topic Teams	BOG: Prepare for Plenary (sub-topic priorities, etc.)
1000	---- 20 Minute Break ----	
1020	BOG: Meet in Sub-Topic Teams • Define current state of the sub-topic • Identify and prioritize gaps and obstacles	Plenary: Break-Out Group Overviews • 20 mins for each BOG Speaker • <u>*Submit Questions*</u> for Afternoon Session
1200	---- 1 Hour Lunch Break ----	
1300	BOG: Meet in Sub-Topic Team • Outline expected outcomes of a concerted R&D Program • Define a path forward with sample activities & timeframe	Plenary: Open Discussion and Q&A • Are the identified priorities useful? • Are the identified Paths Forward realistic?
1500	---- 20 Minute Break ----	
1520	BOG: Sub-Topic Discussion with full BOG group • Teams quickly debrief full BOG group on each sub-topic • Discuss merits of each sub-topic	Plenary: Summary and Take-Away (DOE) • 20-25 mins per BOG
1700	---- Adjourn ----	

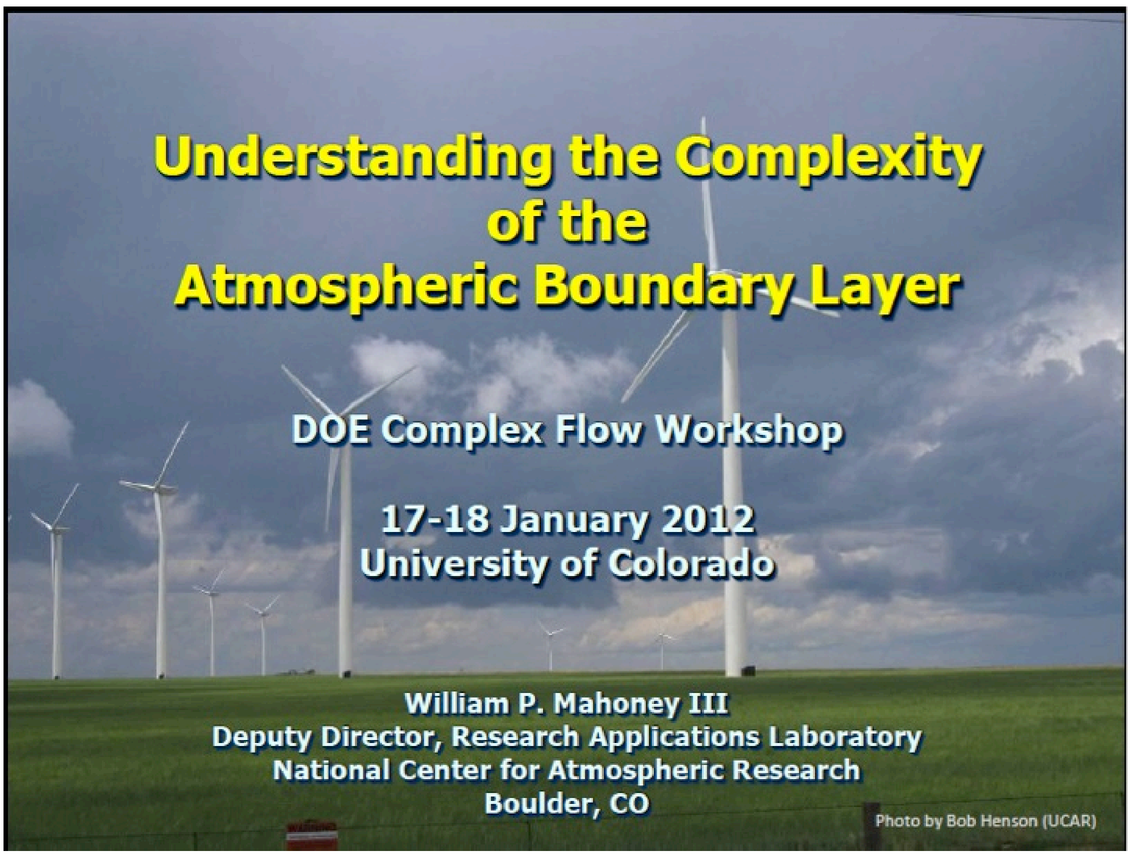
1 | Energy Efficiency & Renewable Energy   eere.energy.gov

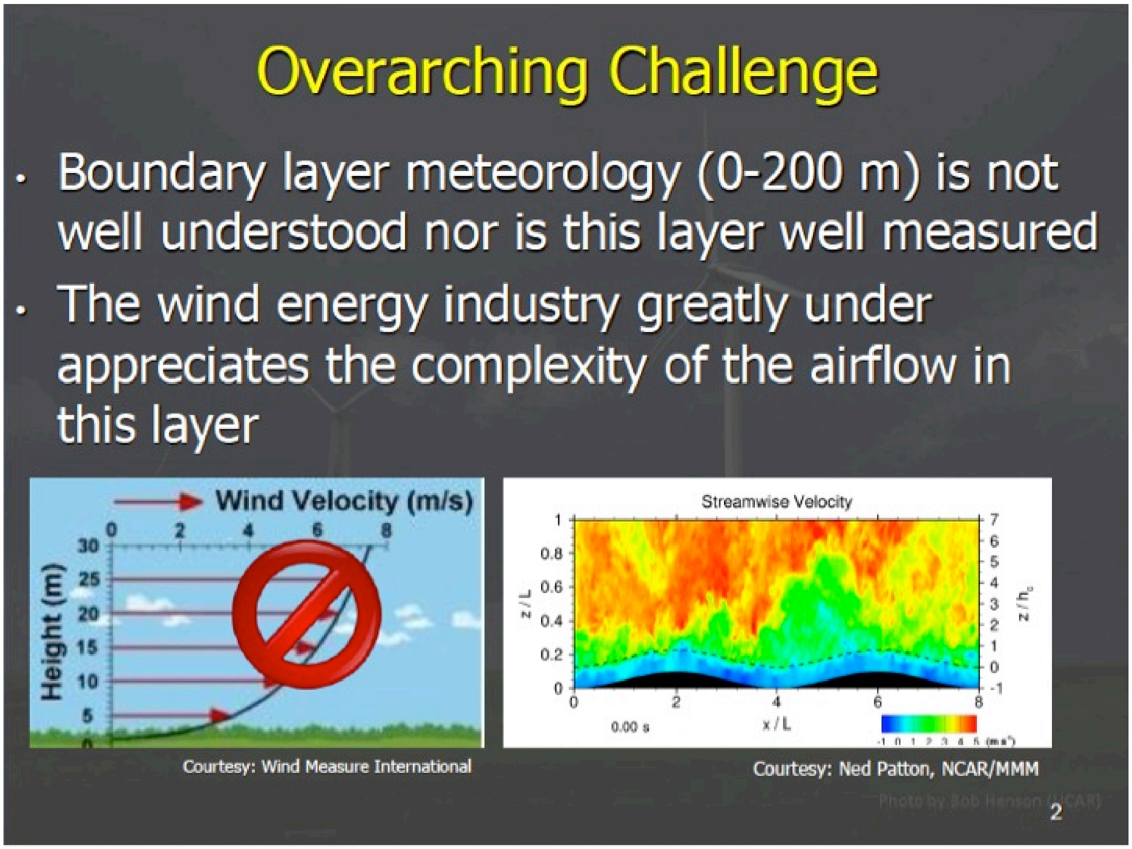
Appendix B: Workshop Attendees

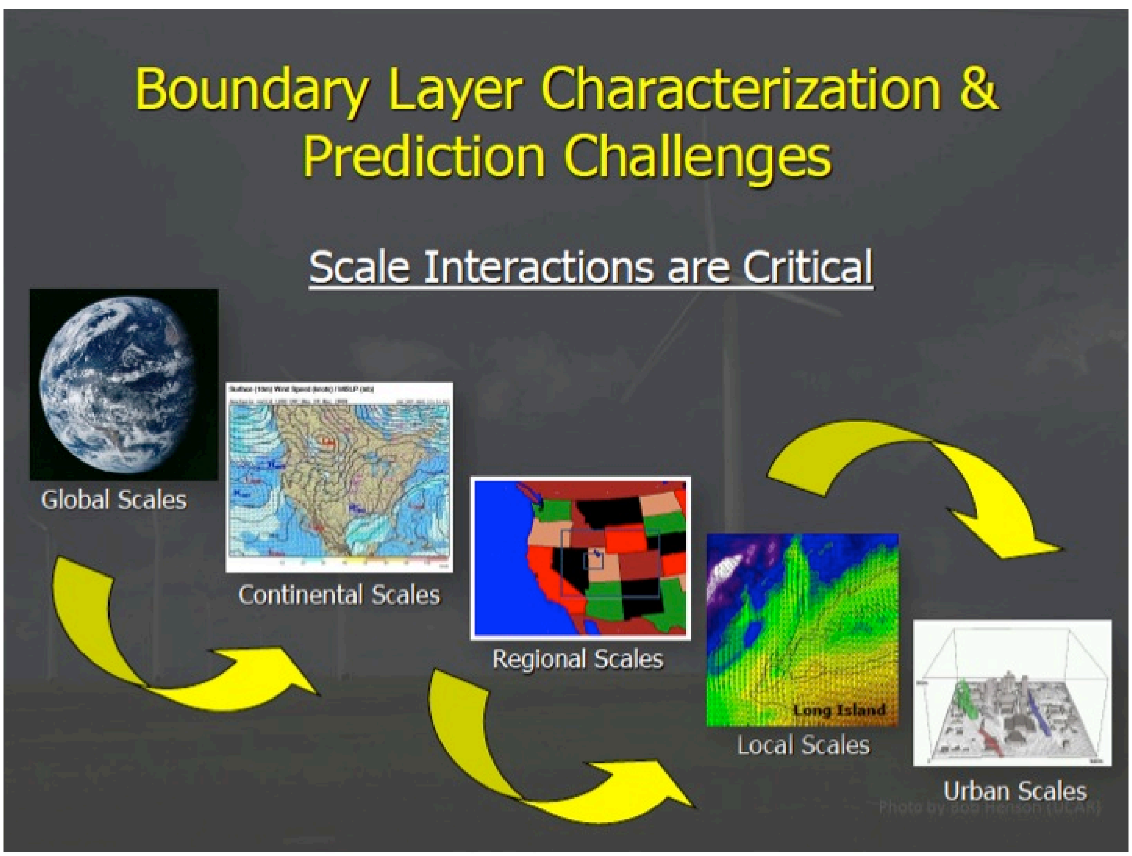
Hubert Ley	ANL	Bob Banta	NOAA
Rao Kotamarthi	ANL	Joseph Olson	NOAA/ESRL
Yulia Peet	ANL	Jim Wilczak	NOAA/ESRL
Bruce Bailey	AWS Truepower	Melinda Marquis	NOAA/ESRL
Philippe Beaucage	AWS Truepower	Stan Benjamin	NOAA/ESRL
Sandy Butterfield	Boulder Wind Power	John Michalakes	NREL
Glen R. Whitehouse	Continuum Dynamics	Pat Moriarty	NREL
Julie Lundquist	CU, Boulder	Paul Veers	NREL
Gordon Randall	DNV	Steve Hammond	NREL
Robert Poore	DNV	Sang Lee	NREL
Brian Naughton	New West Technologies	Matt Churchfield	NREL
Joel Cline	DOE	Simeon Ning	NREL
John Meissner	New West Technologies	Michael Lawson	NREL
Jose Zayas	DOE	Andrew Clifton	NREL
Mark Higgins	DOE	John A. Turner	ORNL
Mike Derby	DOE	James "Jim" Brasseur	Penn State
Mike Robinson	DOE	Jerome Fast	PNNL
Stan Calvert	DOE	Rob Newsom	PNNL
Bernard Boulder	ECN	Will Shaw	PNNL
Avinash Taware	Gamesa	Matt Smith	RES Americas
Daran Rife	Garrad Hassan	Niels Troldborg	RISø
James Bleeg	Garrad Hassan	Torben Juul Larsen	RISø
Rebecca Barthelmie	Indiana University	Pamela Crane	Shell Wind Energy
Christopher Anderson	Iowa State University	Sara Jean Tyler	Shell Wind Energy
Curtt Ammerman	LANL	John Shroeder	SNL
Kevin Farinholt	LANL	Jonathan White	SNL
Rodd Linn	LANL	Matt Barone	SNL
Jeff Mirocha	LLNL	Henry Shiu	UC Davis
Wayne Miller	LLNL	Fotis Sotiropolous	Univ of Minnesota
Sonia Wharton	LLNL	Jonathan Naughton	Univ of Wyoming
Andy Stern	National Weather Service	Lance Manuel	UT Austin
Sukanta Basu	NC State	Greg Poulos	VBAR
Bill Mahoney	NCAR	Anurag Gupta	Vestas
Branko Kosovic	NCAR	Bradley Johnson	Vestas
Ned Patton	NCAR	Greg Oxley	Vestas
Sue Ellen Haupt	NCAR	Bob Conzemius	Windlogic

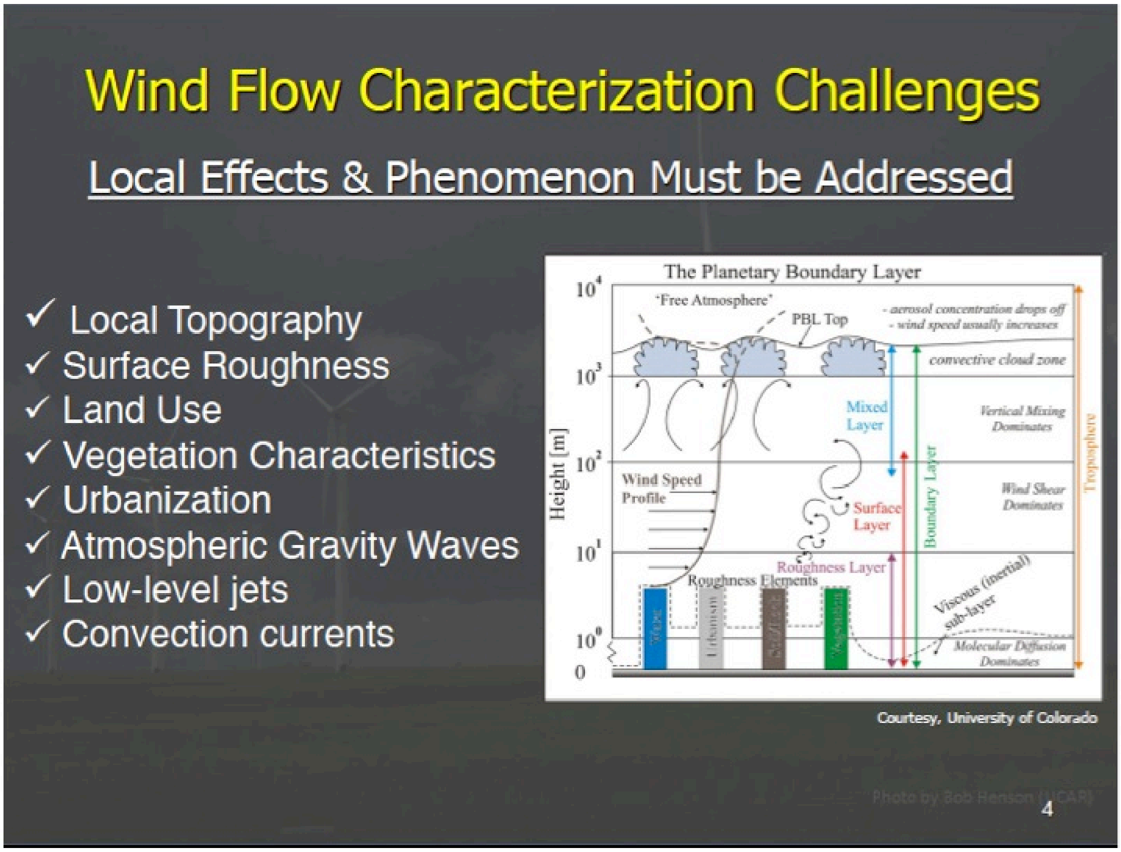
Appendix C: Plenary Presentations

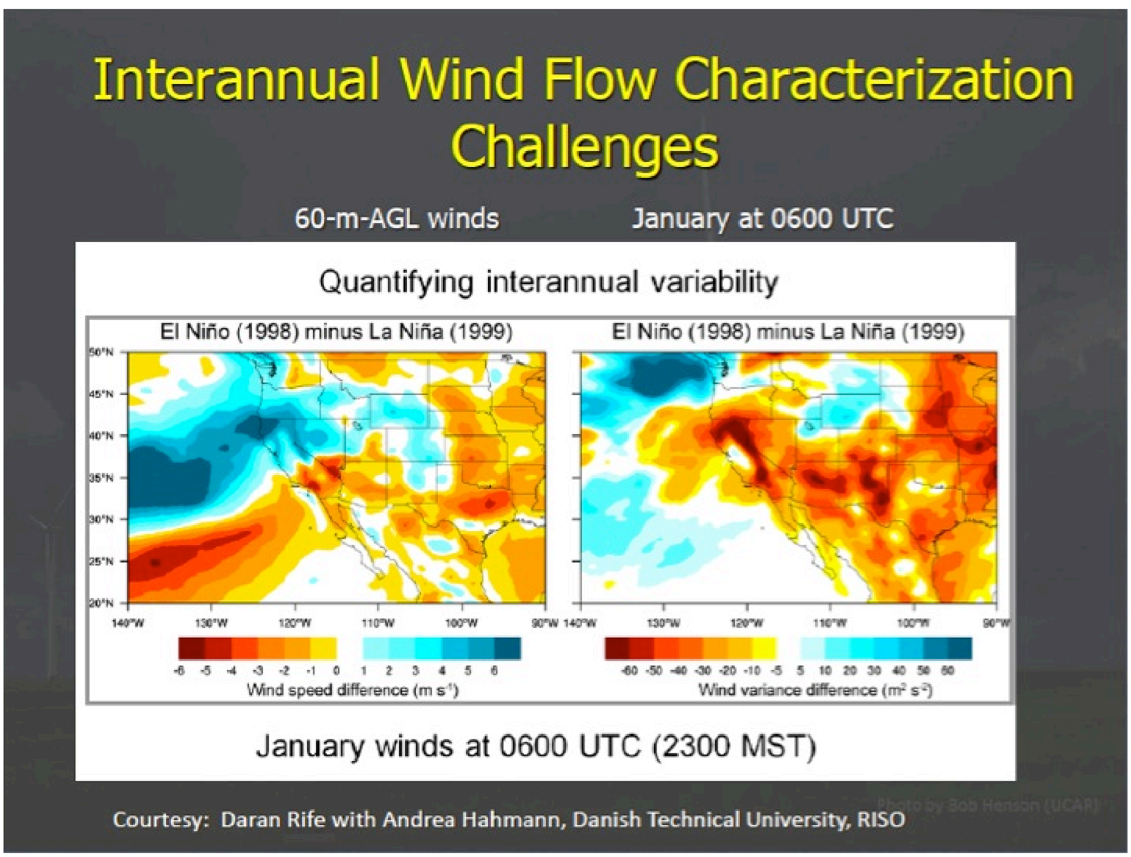
At the start of the Workshop, the following slide decks were presented to the plenary session as an overview of complex flow phenomena and issues, as well as to help provide context for the scope of the issue at hand. The first presentation was given by Bill Mahoney of the National Center for Atmospheric Research (NCAR), and the second was given by Torben Larsen and Niels Troldborg, both from DTU Wind Energy, Campus Risø. The first presentation (Mahoney) is below:




Overarching Challenge
Boundary layer meteorology (0-200 m) is not well understood nor is this layer well measured
The wind energy industry greatly under appreciates the complexity of the airflow in this layer
Wind Velocity (m/s)
Height (m)
Streamwise Velocity
z / L
x / L
z / h
0.00 s
Courtesy: Wind Measure International
Courtesy: Ned Patton, NCAR/MMM
Photo by Bob Henson (UCAR)
2

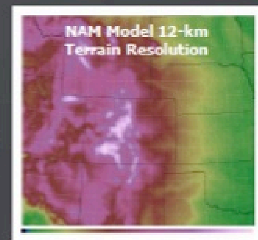

Boundary Layer Characterization & Prediction Challenges
Scale Interactions are Critical
Global Scales
Continental Scales
Regional Scales
Local Scales
Long Island
Urban Scales
Photo by Bob Henson (UCAR)


Wind Flow Characterization Challenges
Local Effects & Phenomenon Must be Addressed
✓ Local Topography
✓ Surface Roughness
✓ Land Use
✓ Vegetation Characteristics
✓ Urbanization
✓ Atmospheric Gravity Waves
✓ Low-level jets
✓ Convection currents
The Planetary Boundary Layer
'Free Atmosphere'
PBL Top
- aerosol concentration drops off
- wind speed usually increases
convective cloud zone
Mixed Layer
Vertical Mixing Dominates
Wind Speed Profile
Surface Layer
Wind Shear Dominates
Boundary Layer
Troposphere
Roughness Layer
Roughness Elements
Viscous (inertial) sub-layer
Molecular Diffusion Dominates
Height [m]
Courtesy, University of Colorado
Photo by Bob Henson (UCAR)
4


Interannual Wind Flow Characterization Challenges
60-m-AGL winds
January at 0600 UTC
Quantifying interannual variability
El Niño (1998) minus La Niña (1999)
El Niño (1998) minus La Niña (1999)
Wind speed difference (m s⁻¹)
Wind variance difference (m² s⁻²)
January winds at 0600 UTC (2300 MST)
Courtesy: Daran Rife with Andrea Hahmann, Danish Technical University, RISO
Photo by Bob Henson (UCAR)

Wind Flow Prediction Challenges

Prediction Limitations



Smoothed Rocky Mountains

Weather analyses and predictions are inherently non-precise due to uncertainties in:

- ✓ analyzing the initial state of the atmosphere
- ✓ model resolution
- ✓ model physics/parameterizations (“terra incognita”)
- ✓ course treatment of surface characteristics
- ✓ inaccuracies in model coupling (oceans, surface, etc.)
- ✓ many other simplifications

Photo by Bob Henson (UCAR)

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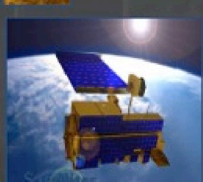
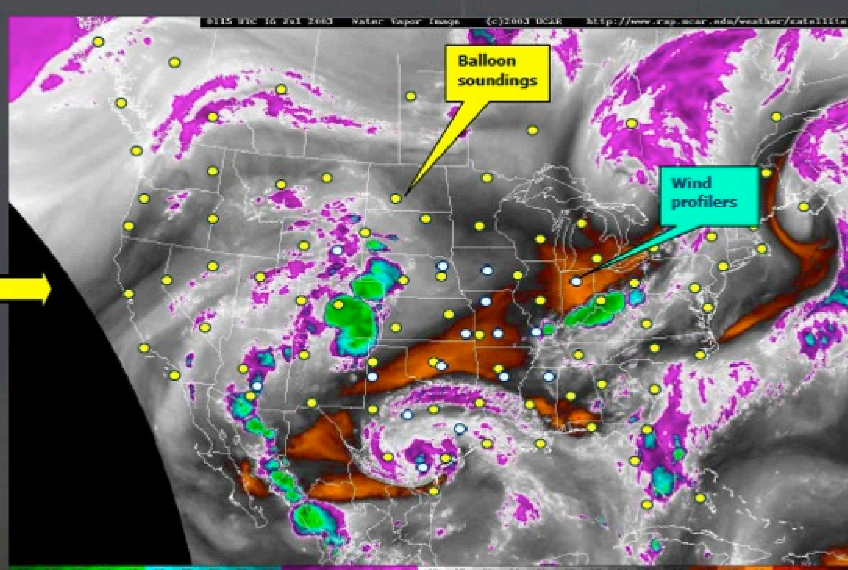
Wind Prediction Challenges

Complex Atmospheric Flows

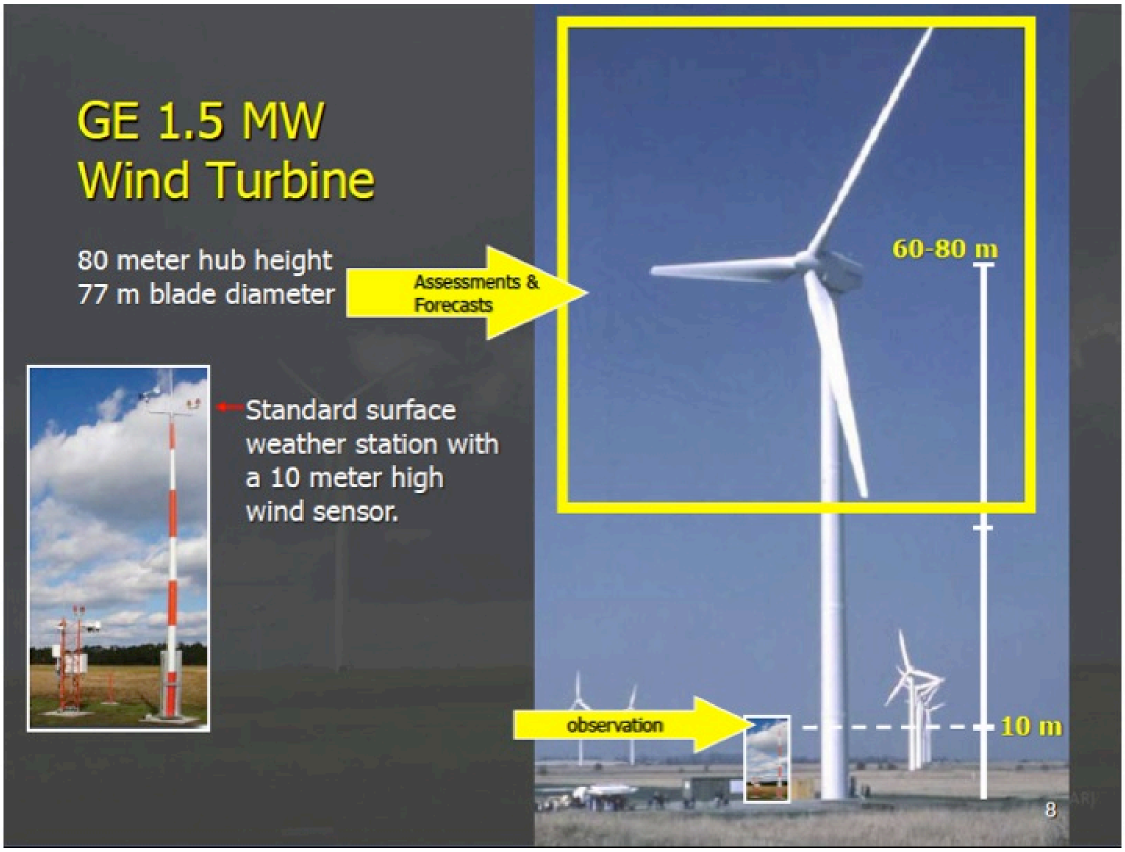


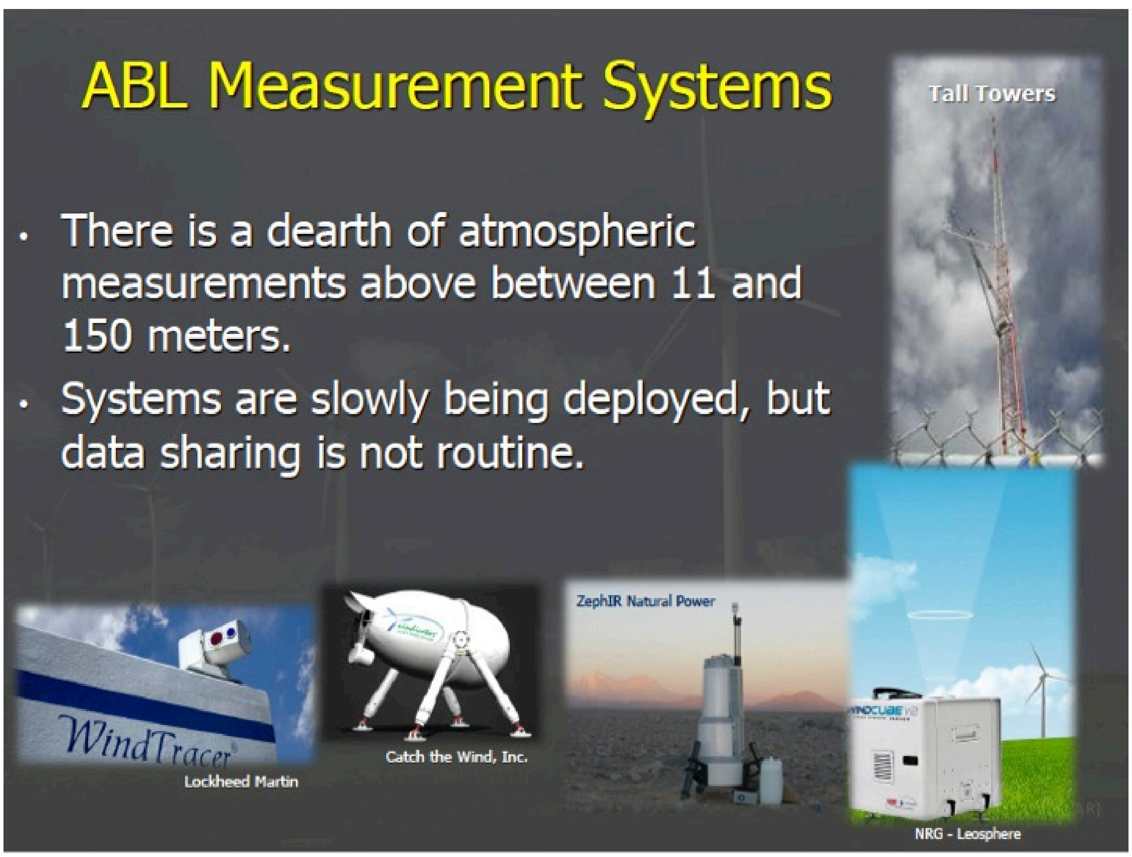



A lot of critical details are missed between observations!

Photo by Bob Henson (UCAR)

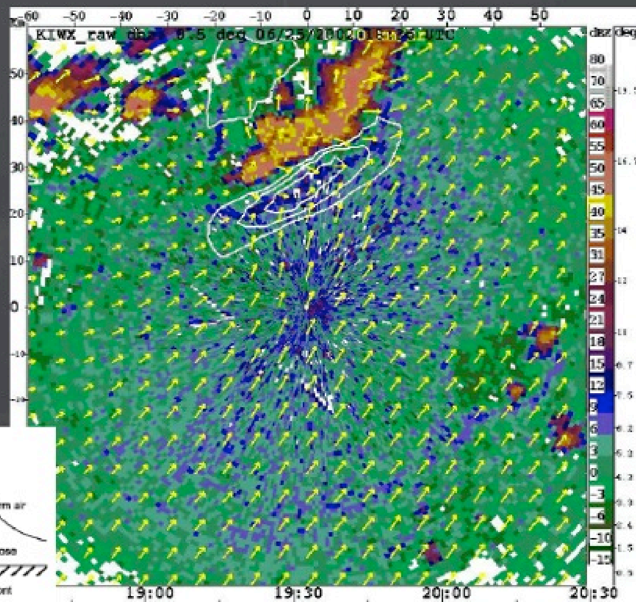
7


GE 1.5 MW
Wind Turbine
80 meter hub height
77 m blade diameter
Assessments &
Forecasts
Standard surface
weather station with
a 10 meter high
wind sensor.
60-80 m
observation
10 m
8


ABL Measurement Systems
• There is a dearth of atmospheric measurements above between 11 and 150 meters.
• Systems are slowly being deployed, but data sharing is not routine.
Tall Towers
WindTracer
Lockheed Martin
Catch the Wind, Inc.
ZephIR Natural Power
NRG - Leosphere

Complex Flows

Thunderstorm gust fronts



Gust front analyzed with the Variational Doppler Radar Assimilation System (VDRAS) - NCAR

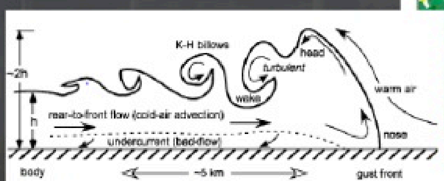
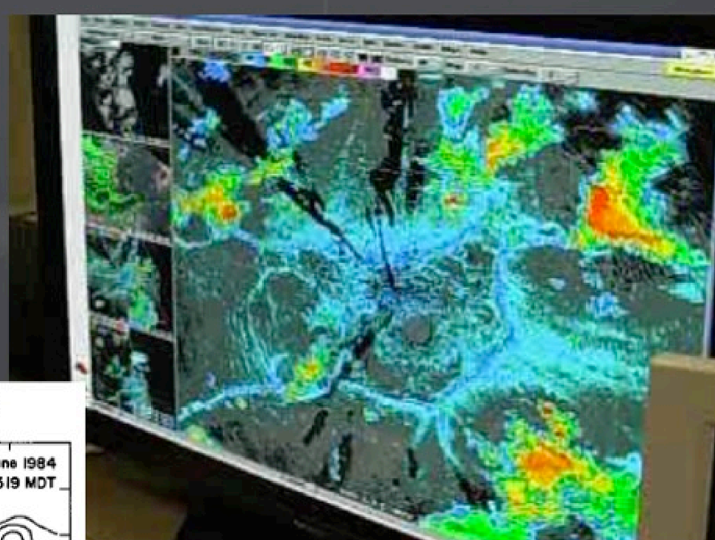


FIG. 1. Schematic view of a density or gravity current (adapted from several sources including Simpson 1969; Charba 1974; Droegemeier and Wilhelmson 1987; and Mueller and Carbone 1987).

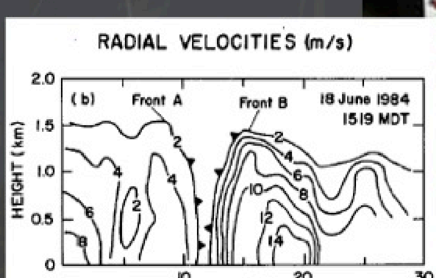
10

Interacting Boundaries

Colliding thunderstorm gust fronts in Texas



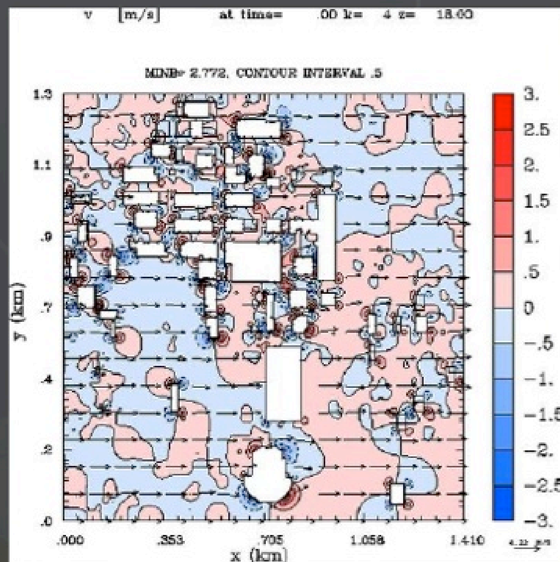
Interacting thunderstorm gust fronts - NCAR



Mahoney 1988

11

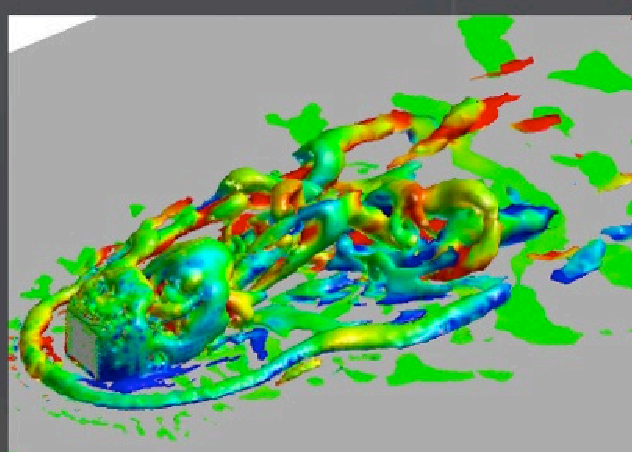
Urban Scale Complexities



V component – Contours 0.5 ms^{-1}

Courtesy, Paul Bieringer, NCAR

Building Scale Complexities



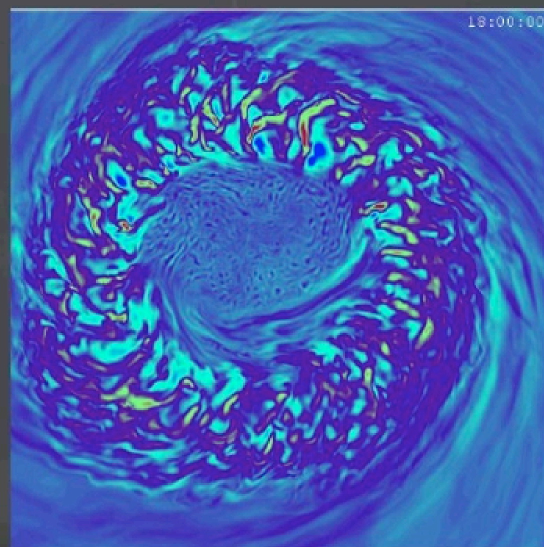
Flow around a 6 m cube

Penn State Applied Research Laboratory: Sue Haupt, Frank Zajaczkowski, Joel Peltier, 2010: J.Fluid Eng

Miso to Mesoscale Complexities

WRF Hurricane Simulation
Large-Eddy Simulation
62 m Resolution

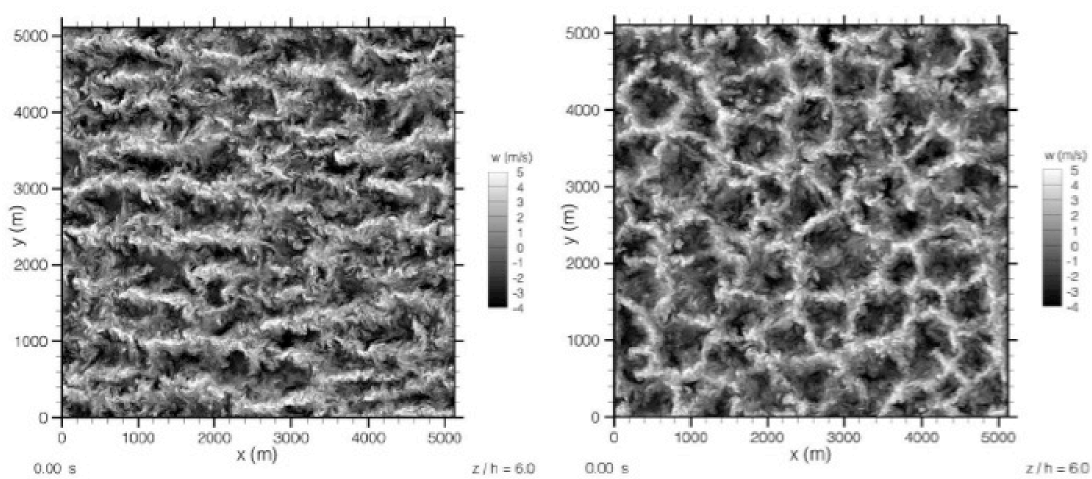
Resolving Turbulence Scales



(Rich Rotunno NCAR 2009

Influence of stability on PBL-scale

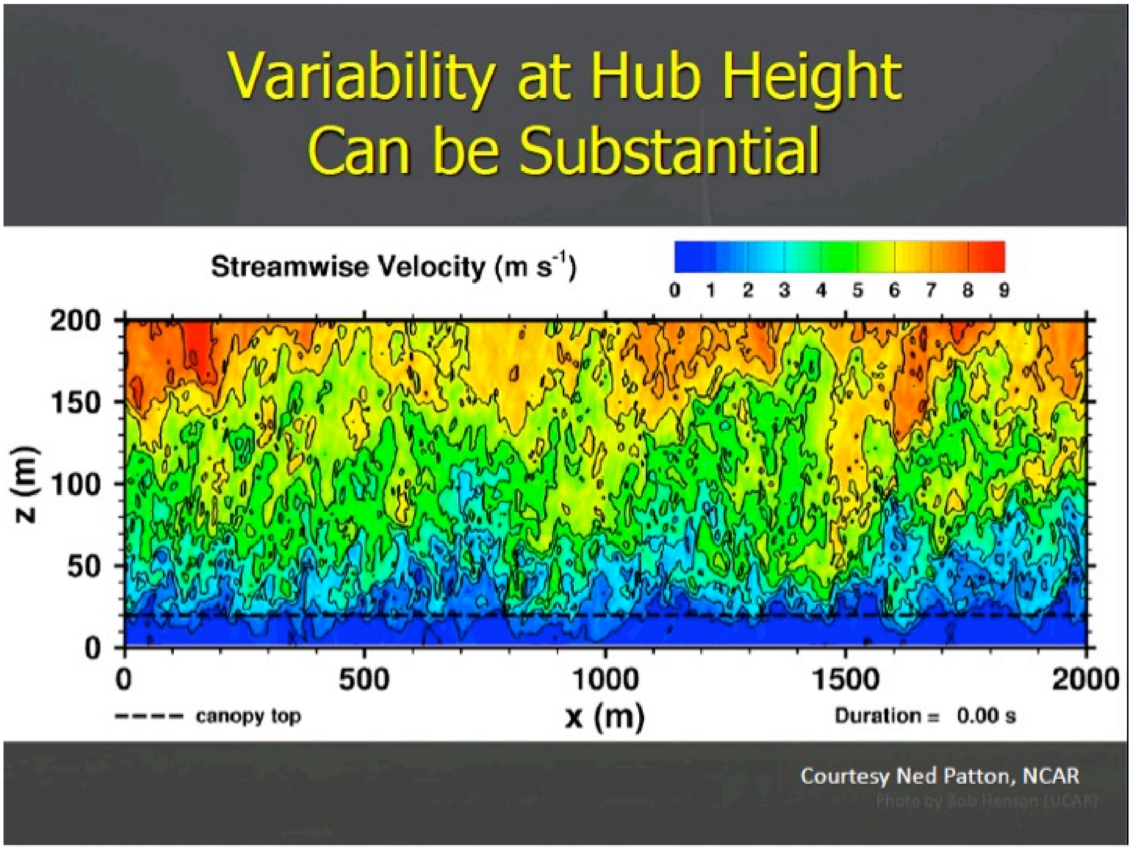
Horizontal slices of vertical velocity at 120 m

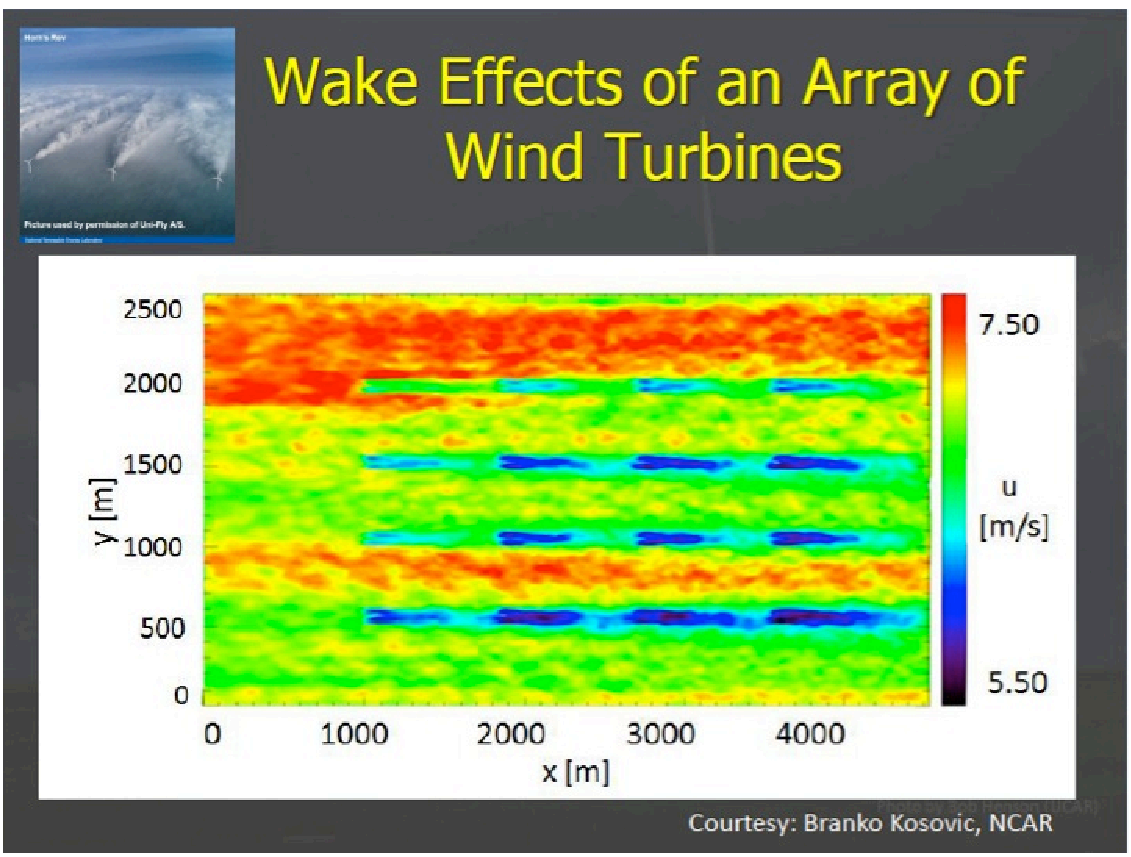


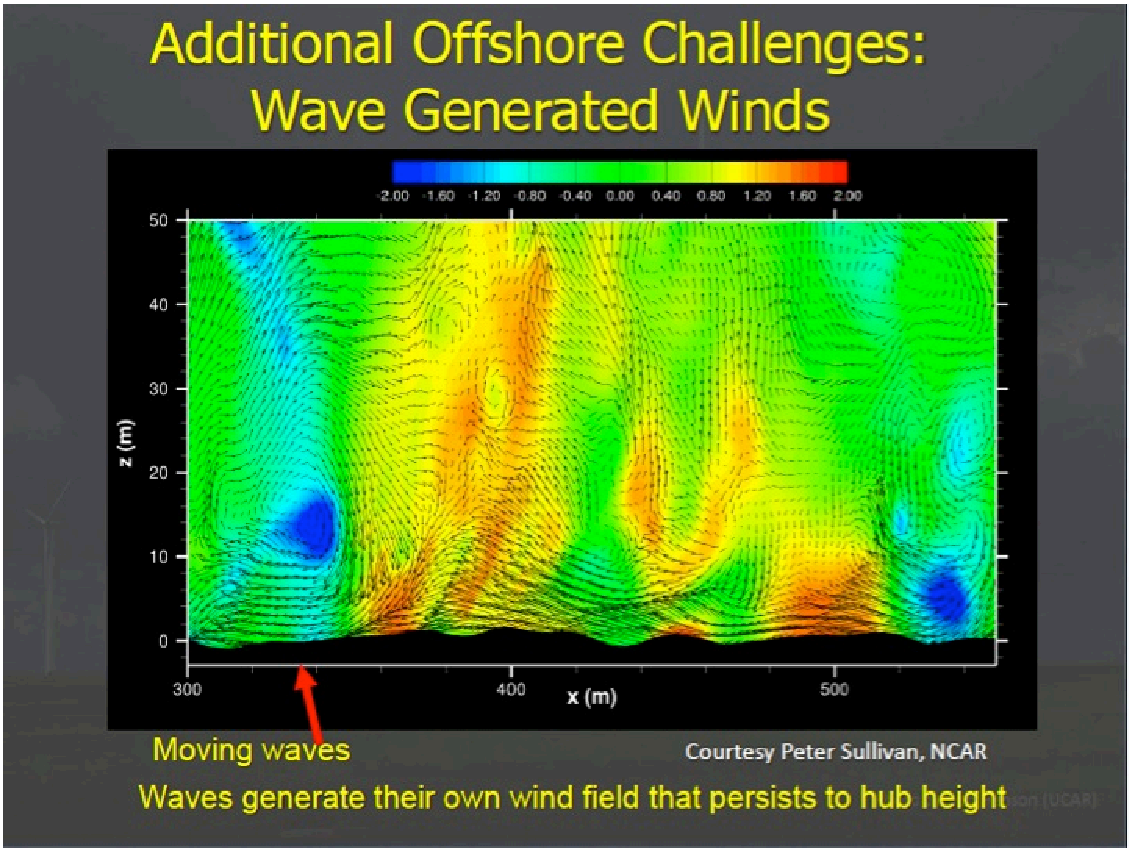
Near neutral

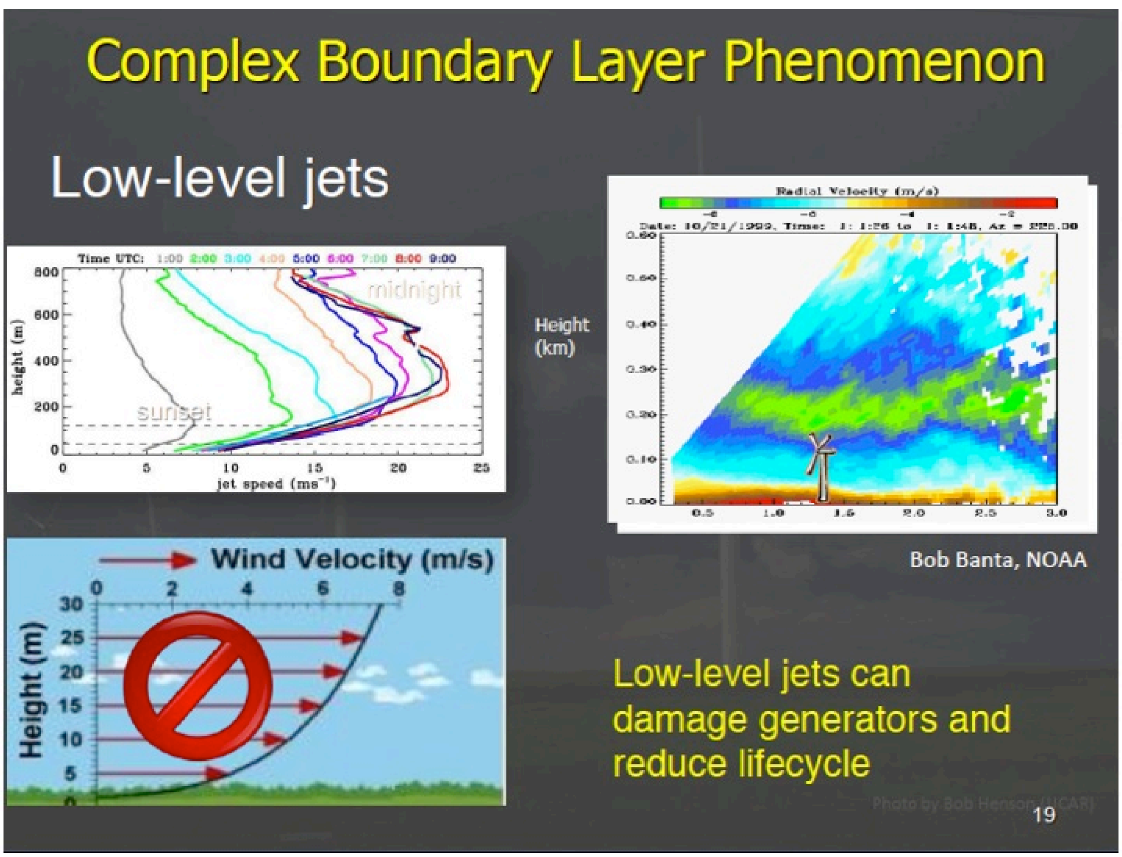
Strongly unstable

Courtesy Ned Patton, NCAR


Variability at Hub Height Can be Substantial
Streamwise Velocity (m s-1)
0 1 2 3 4 5 6 7 8 9
200
150
100
50
0
z (m)
0
500
1000
1500
2000
x (m)
---- canopy top
Duration = 0.00 s
Courtesy Ned Patton, NCAR


Picture used by permission of Uni-Fly A/S.
Wake Effects of an Array of Wind Turbines
2500
2000
1500
1000
500
0
y [m]
0
1000
2000
3000
4000
x [m]
7.50
u [m/s]
5.50
Courtesy: Branko Kosovic, NCAR


Additional Offshore Challenges:
Wave Generated Winds
-2.00 -1.60 -1.20 -0.80 -0.40 0.00 0.40 0.80 1.20 1.60 2.00
z (m)
x (m)
Moving waves
Courtesy Peter Sullivan, NCAR
Waves generate their own wind field that persists to hub height


Complex Boundary Layer Phenomenon
Low-level jets
Time UTC: 1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00
midnight
sunset
height (m)
jet speed (ms⁻¹)
Radial Velocity (m/s)
Height (km)
Bob Banta, NOAA
Wind Velocity (m/s)
Height (m)
Low-level jets can damage generators and reduce lifecycle
19

Summary

- Boundary layer flows are complex and not well understood
- Wind energy concerns may provide an additional impetus to make progress in this area
- Research, development, and stakeholder involvement are required (field experiments and modeling efforts)

Photo by Bob Henson (UCAR)

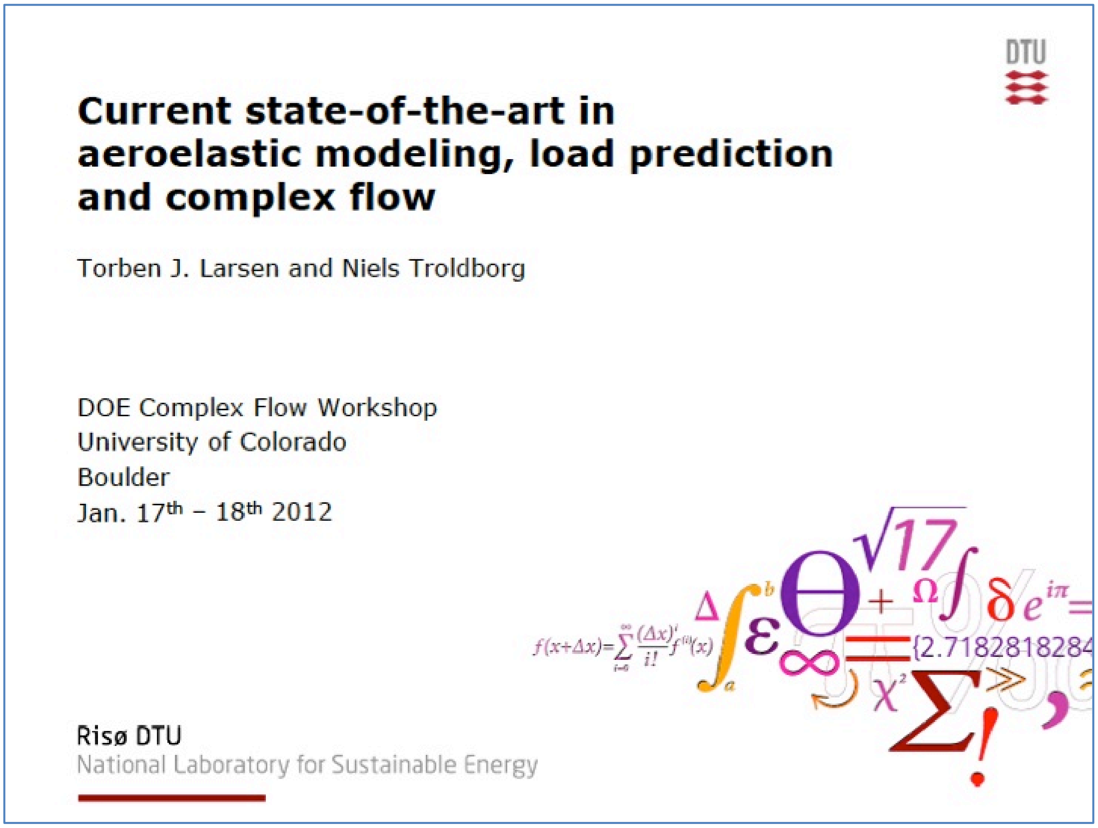
Summary (cont.)

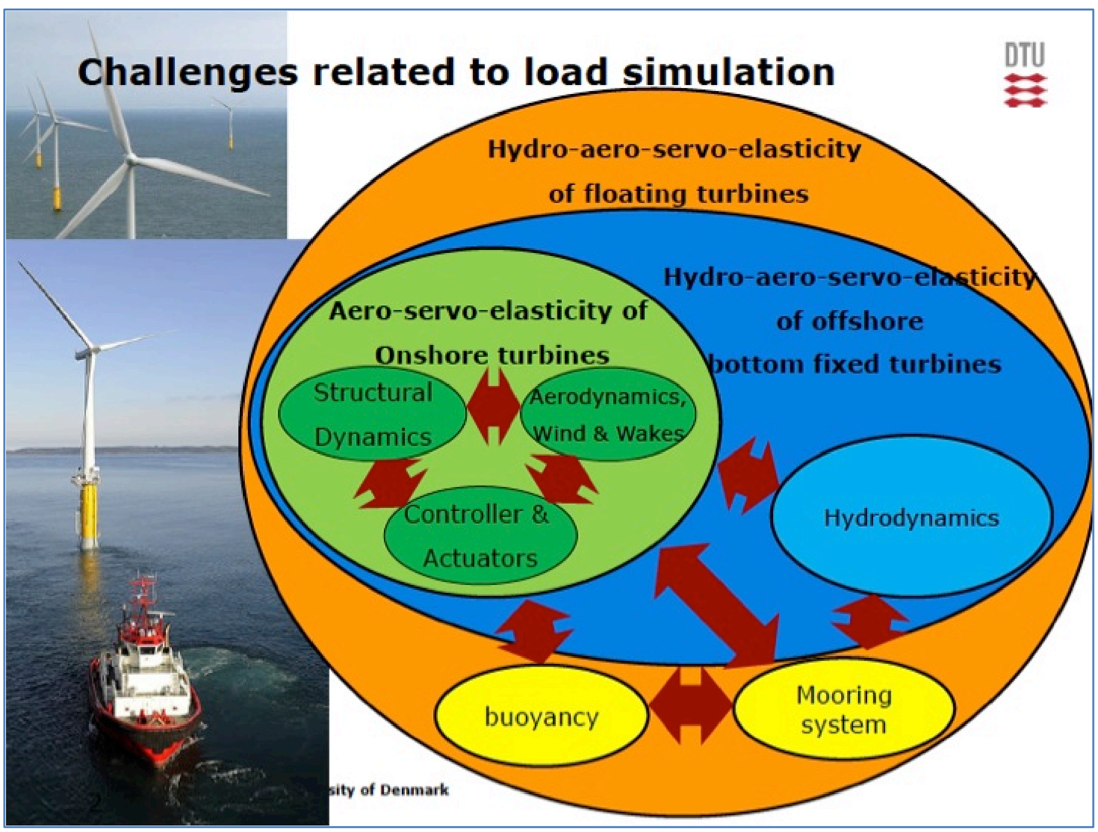
- Need to capture and also model real 'extreme' wind datasets for turbine design & testing
  - Gust fronts & interacting boundaries
  - Low-level jets
  - Sea breezes & ocean wave effects
  - Kelvin-Helmholz wave events
  - Hydraulic jumps
  - Mechanical turbulence due to complex terrain
  - Weather regime impacts on turbine wakes
- Need to improve model coupling to capture complex flow across scales

Photo by Bob Henson (UCAR)


THANK YOU
22

The second plenary presentation (Larsen & Troldborg) follows:





Wake effects:
The basic idea of the Dynamic Wake Meander model (DWM)

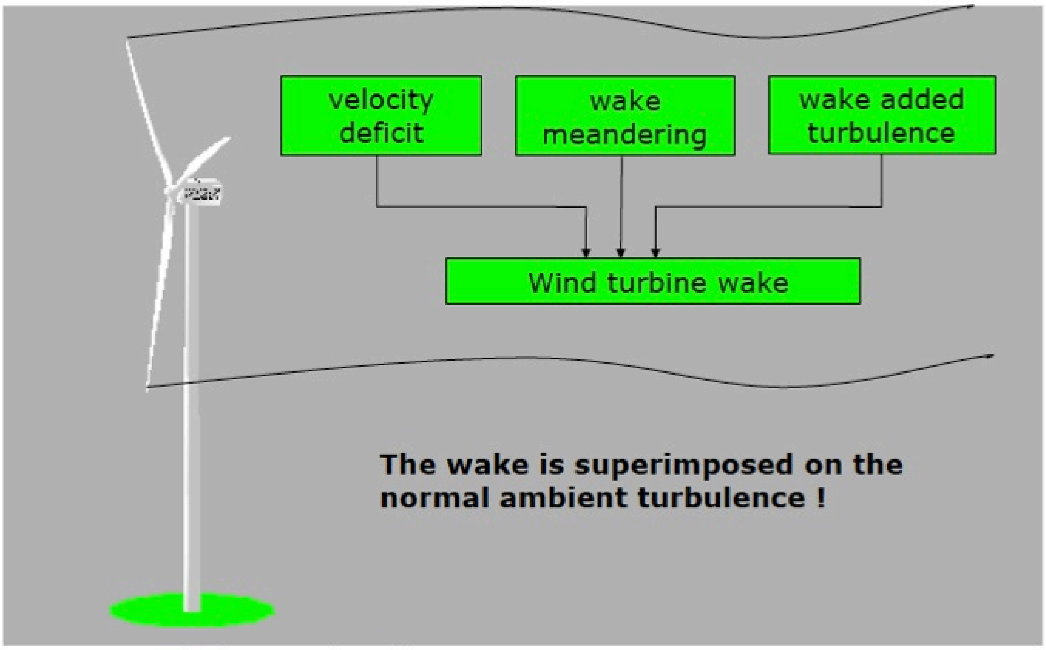
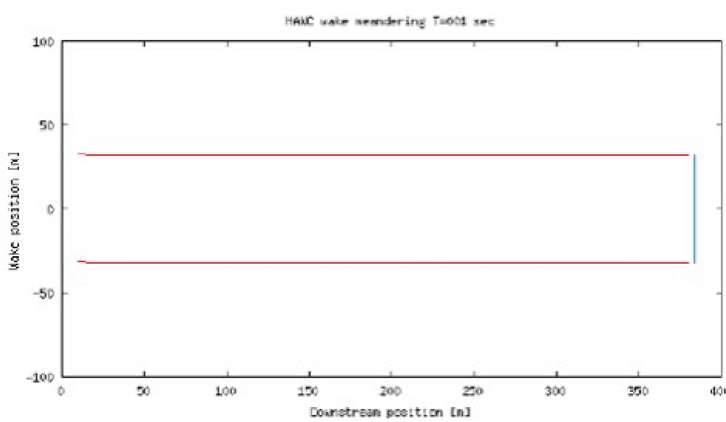
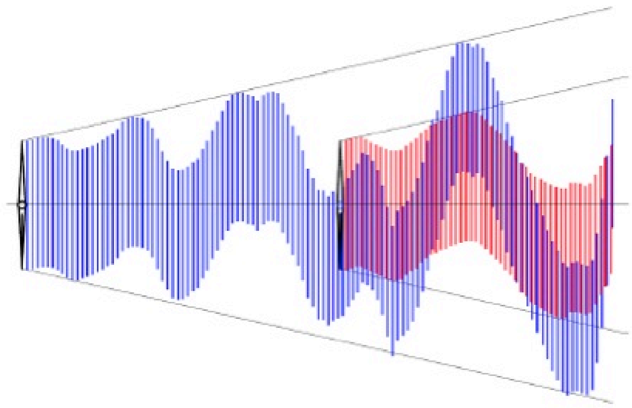


Illustration of wake deficit meandering



Meander path from multiple turbines - straight forward extension of DWM

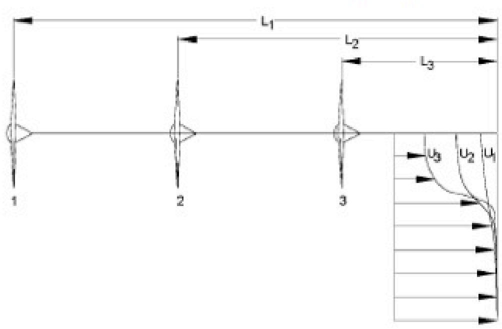


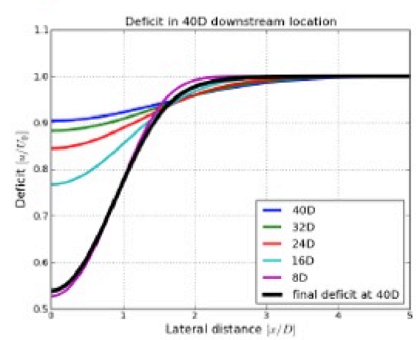
The wakes from two turbines (or more) only rarely coincide. Even in full wake direction, the path's will be different.

It would be convinient if the total wake velocity (when they collide) could be modeled based on individual wake deficits.

Wakes from multiple turbines

Ambient turbulence is low (1%), meandering is ignored



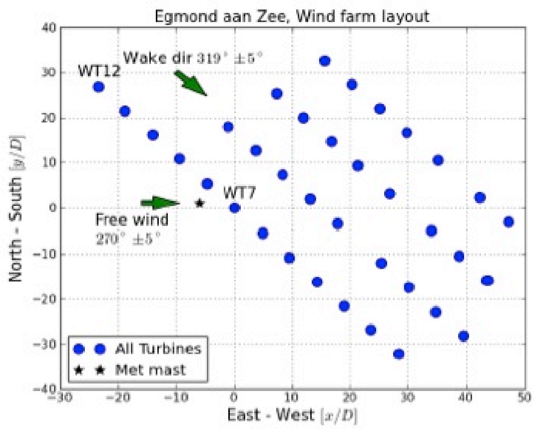


Deficits from individual turbines are compared with a more accurate solution including the wake of the upstream turbines.

The final deficit seem to be very well aproximated with the deficit of the nearest turbine (where free wsp was assumed)

A good and practical approximation: $u_{def,final}(r) = \text{MIN}(u_{def,i..N}(r))$

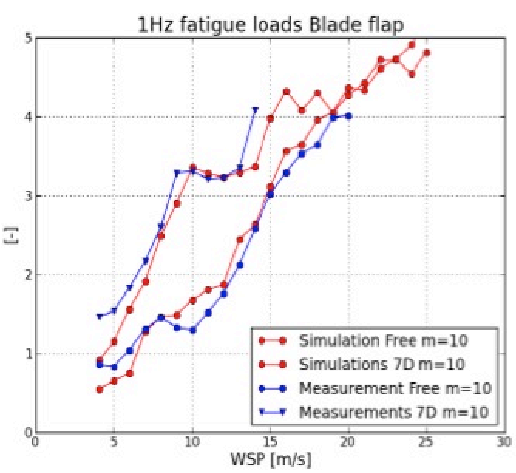
Comparison of loads for the Egmond aan Zee windfarm

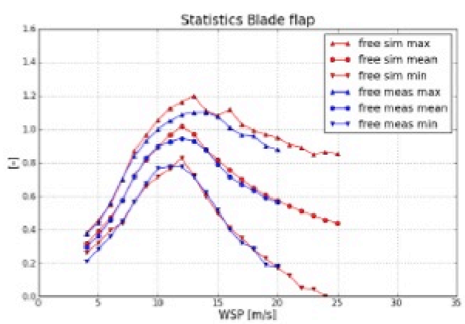


7 Risø DTU, Technical University of Denmark

Comparison of loads

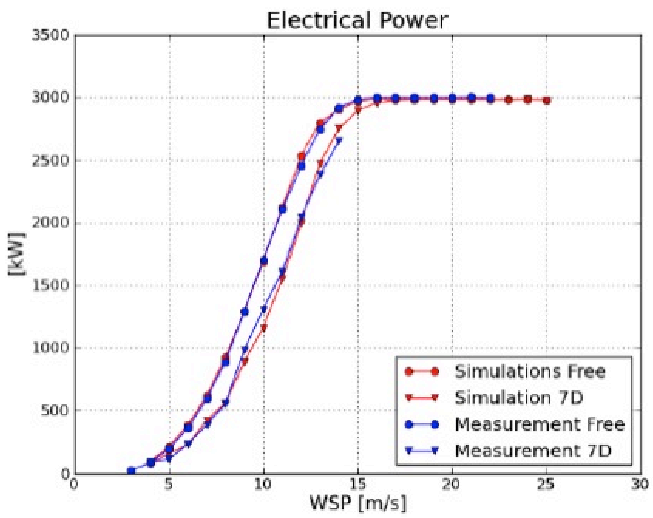
- Fatigue and mean loads



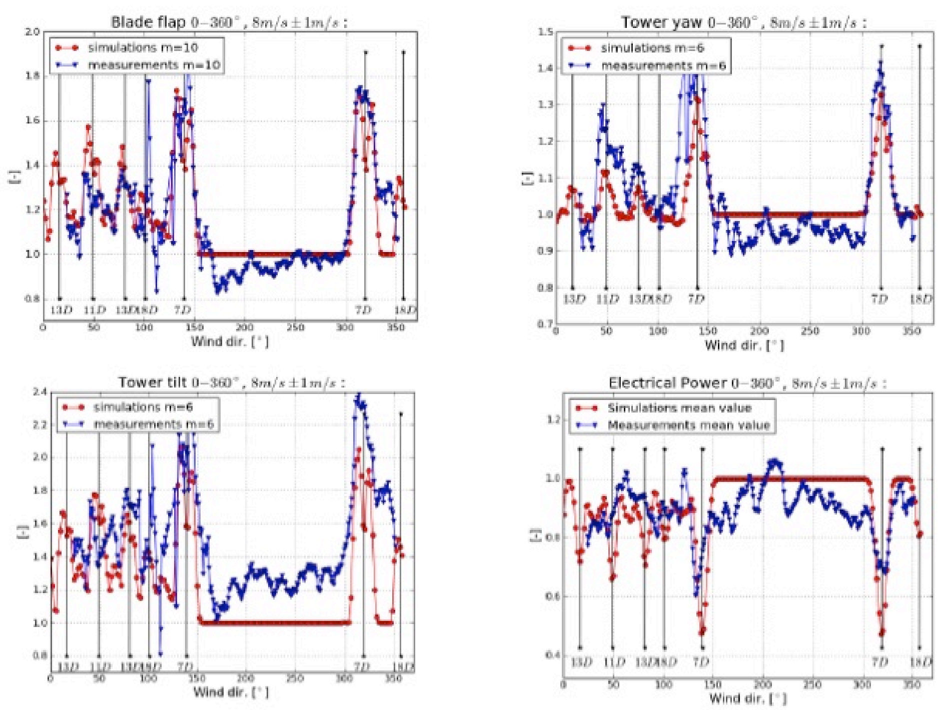


8 Risø DTU, Technical University of Denmark

Comparison of power production

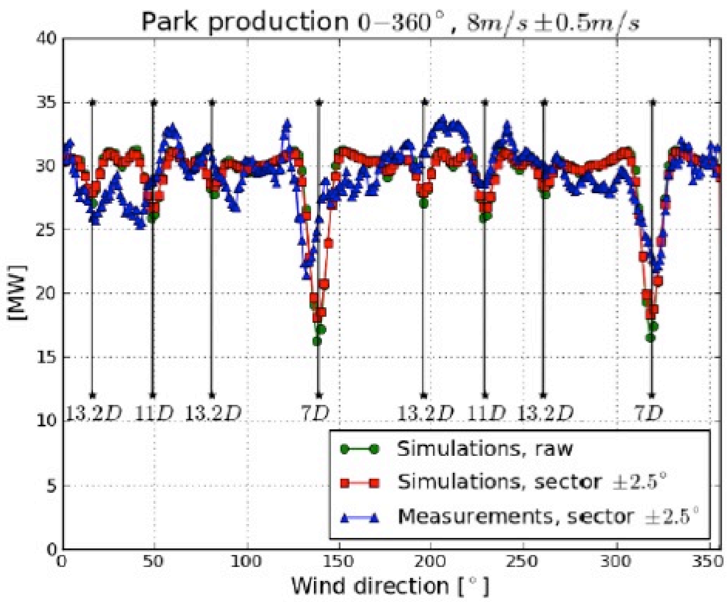


Loads for 0-360°, 8m/s



DTU

Park power production for 0-360°, 8m/s

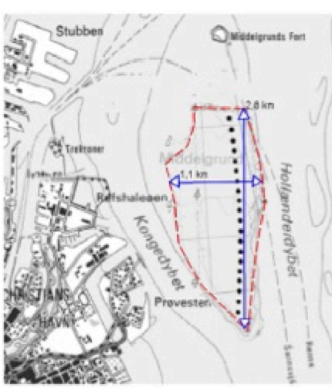


DTU

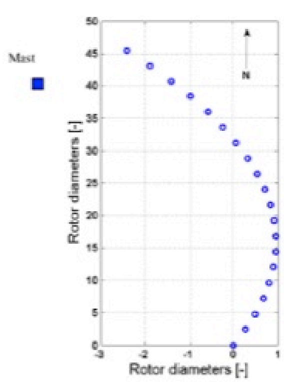
TOPFARM – Topologi optimization of wind farms

Middelgrunden - A row of turbines located just outside of Copenhagen

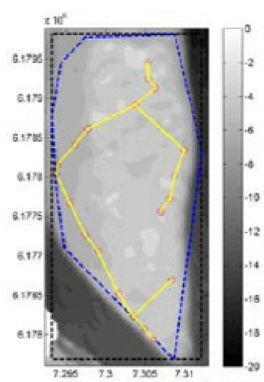
- With the knowledge of today, could we then do better with respect to layout
- More detailed knowledge about energy production and loads give a better basis for cost estimates covering all essential elements of total wind farm costs.



Allowed wind turbine region



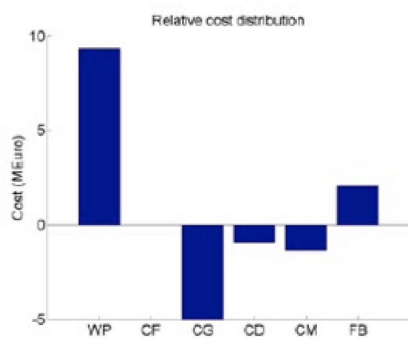
Middelgrunden layout



Optimized alternative

Optimization results

- The optimized solution is fundamentally different from the baseline layout … the resulting layout makes use of the entire feasible domain, and the turbines are not placed in a regular pattern
- The foundation costs have not been increased … because the turbines have been placed at shallow water
- The energy production was increased, but also the grid cost
- A total improvement of the financial balance of 2.1 M€ was achieved compared to the baseline layout



WP - Farm production

CF – Foundation cost

CG – Grid cost

CD – Turbine load degradation

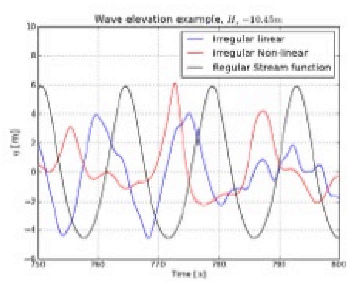
CM – Operation & Maintenance

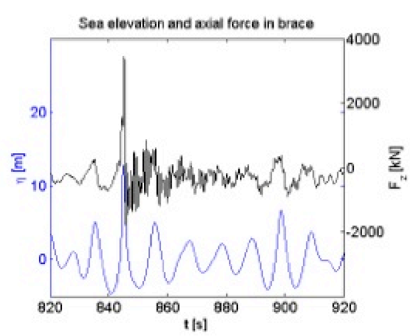
FB – Financial balance

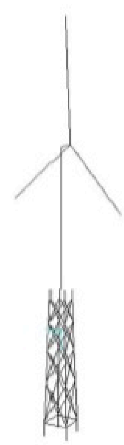
Recent studies on hydrodynamic loading of an offshore turbine using HAWC2

- NREL 5MW ficticious turbine placed on a jacket foundation at 50m MSL.
- Wind turbine at stand still, blades pitched, aerodynamics ignored.
- Irregular linear and non-linear waves applied for selected values of H_s
- Regular stream function waves included – also with the selected H_s

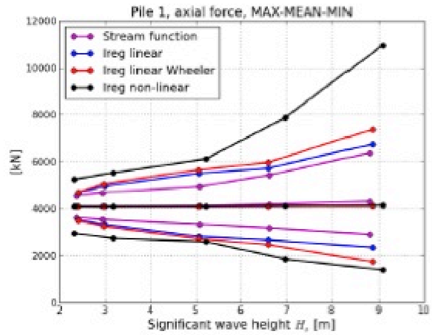
- The difference in dynamic response is observed.

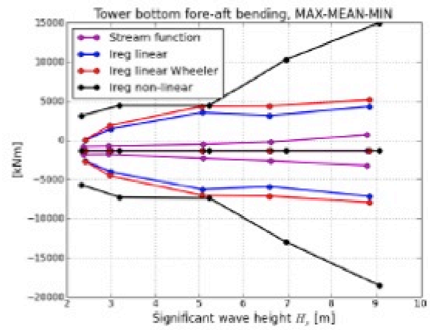






Load results





- The first set of fully non-linear irregular wave kinematics have been applied for a numerical case study of the response of the IEA Annex 30 defined jacket with the 5MW ref. turbine at stand still.
- A significant increase in load levels is observed.
- Further studies needed to verify this.
- Does the jacket, or the very heavy concrete transition piece cause an extra high effect for this particular design or could other substructures be affected too?

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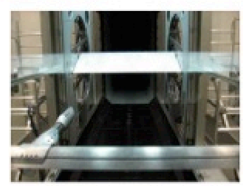
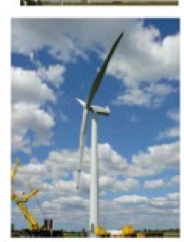
The DAN-AERO MW experiments

Objectives:

- Provide high quality data to improve knowledge of fundamental aerodynamic and aeroelastic issues
  - 2D/3D airfoil data, transition, noise, etc.
- Improve the design basis for MW rotors





Approach:

- Wind tunnel tests of airfoils in three different wind tunnels –- LM, Velux and Delft
- Measurement of inflow characteristics on a MW wind turbine at the Hoevsoere test site – the Siemens 3.6 MW turbine
- Measurement of blade surface pressure and inflow on a MW turbine in the small Tjaereborg wind farm in Jutland – NM80 2MW turbine

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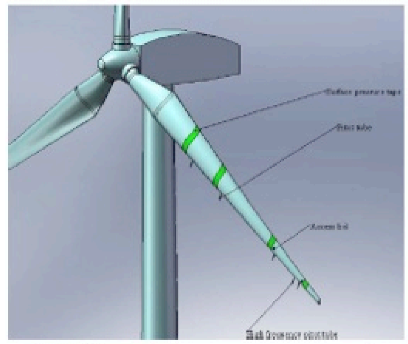
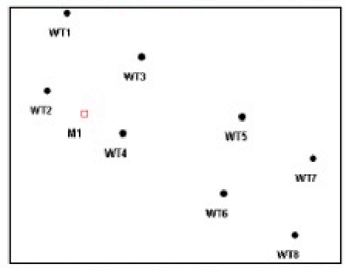
Pressure and inflow measurements on the NM80 turbine in the Tjaereborg wind farm

DTU

- measurements from June to September 2009
- surface pressure and inflow measured at 4 radial stations
- strain gauge measurements of moments at 10 radial stations
- the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements
- high frequency measurements of the inflow

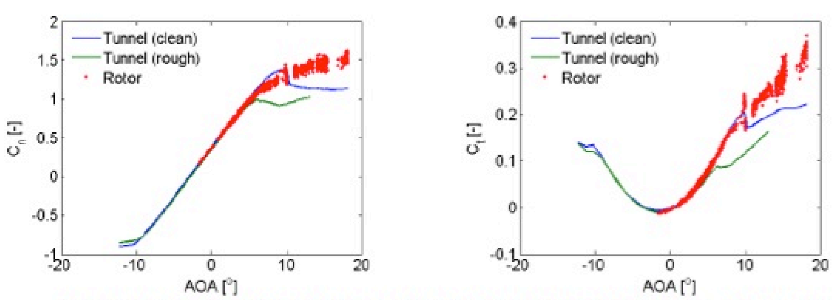




Layout of the Tjæreborg wind farm

Estimation of 3D airfoil data

DTU



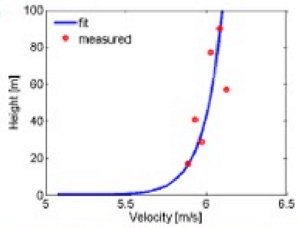
Normal force (left) and tangential force (right) coefficient vs. AOA. Blue curve is tunnel measurements on a clean airfoil, green curve is tunnel measurements on an airfoil with leading edge roughness and red dots are measurements at r=20m on the rotor.

Code validation using DAN-AERO data

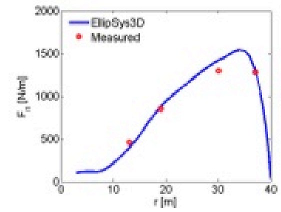
Measured and computed results at nearly uniform inflow condition:

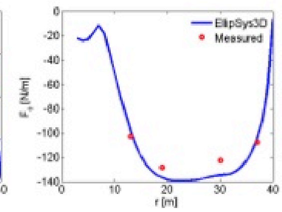
$$V_0(z) = V_\infty \left(\frac{z}{H}\right)^\alpha$$

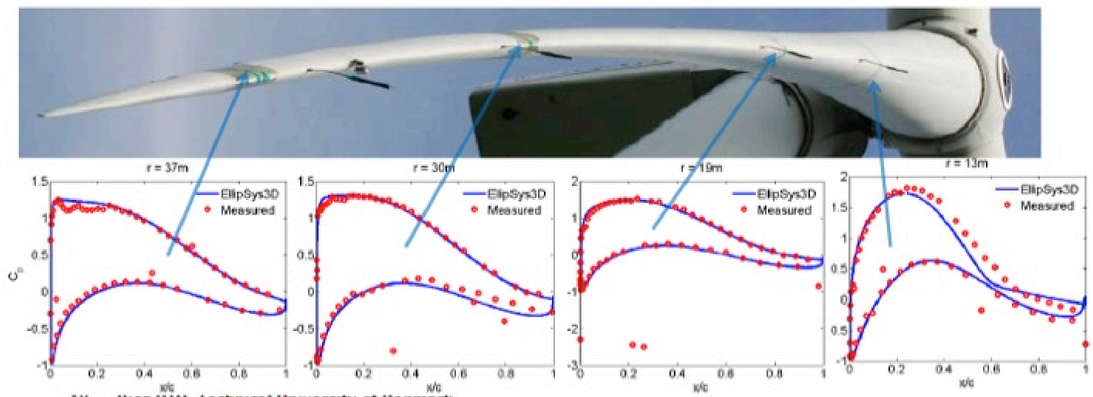
$\alpha = 0.02$
$V_\infty = 6.2 m/s$
$TI \approx 10\%$



Normal and tangential loads along blade:



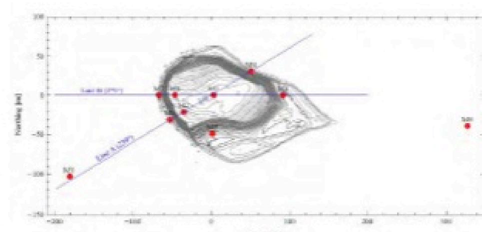


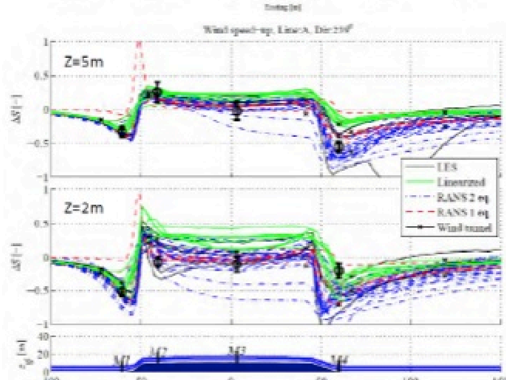


The Bolund experiment

Blind test comparison of flow over the coastal Bolund hill

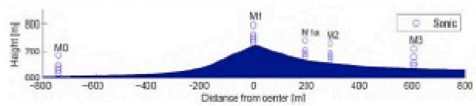
- 80 participants
- Linearized, RANS, LES models
- Rather large scatter in predictions





Other experiments

- Benakalahalli experiment
- Tjæreborg (NM80 with LIDAR mounted on blade)
- LIDAR measurements of double wake at Risoe



Flow center

Objectives:

Develop methods for bridging the multi-scale flow phenomena connected with operating wind turbines in the atmospheric boundary layer

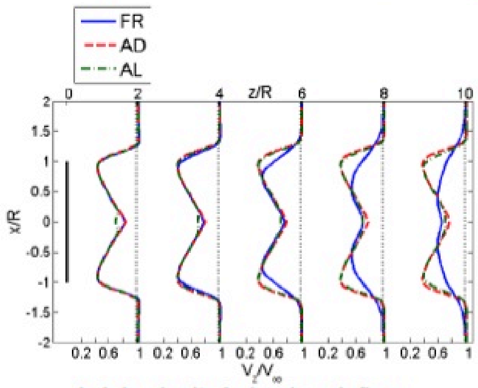
- Rotor/ABL aerodynamics
- Wind turbine wakes and clusters
- Wind farms
- Siting in forrested and complex terrain
- Atmospheric boundary layers

Wind turbine models in CFD

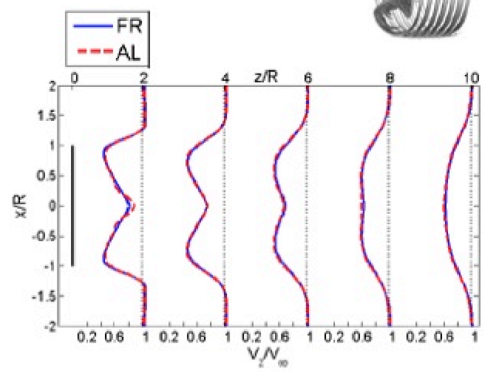
Comparison of wake predicted using CFD and different rotor models

- Fully resolved rotor
- Actuator line
- Actuator disc

Next step: Non-uniform inflow (shear, yaw, wake)



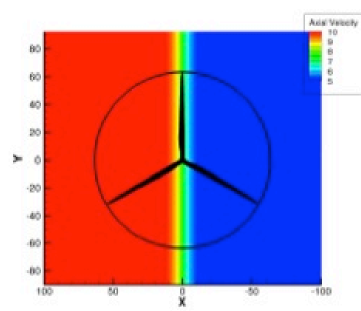
Axial velocity in laminar inflow

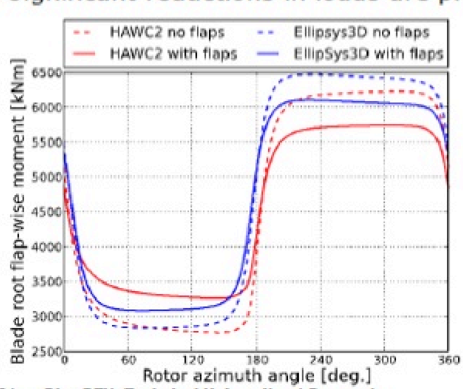


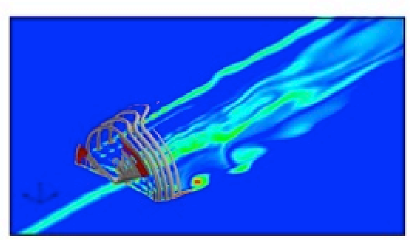
Axial velocity in turbulent inflow

ATEF project

- A series of CFD and HAWC2 simulations were carried out on the NREL 5MW rotor fitted with adaptable trailing edge flaps.
- The figures show results for a simulation with a 'half-wake' inflow with 5 m/s over one half of the rotor disc and 10 m/s over the other half.
- Flaps were actuated to counteract the change in load due to the 'half-wake'.
- Significant reductions in loads are predicted.





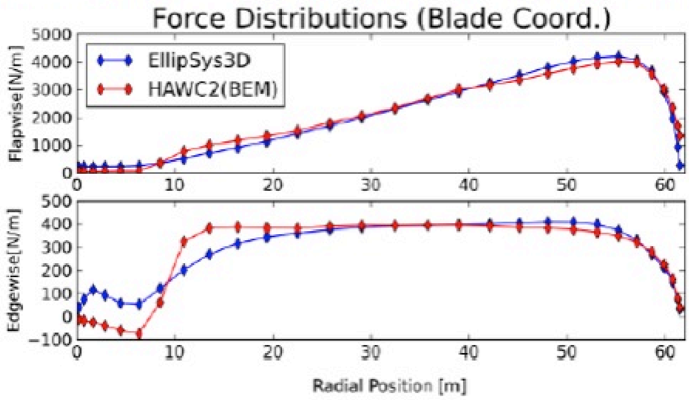


Fluid structure interaction (ATEF)

Coupling of CFD with aero-elastic code to facilitate:

- CFD simulation on flexible structures
- Including control in CFD
- Verify the BEM like methods
- Improve understanding of flow and aero-elastic effects

Simulation of NREL 5MW, Flexible structure, V_∞ = 8 m/s



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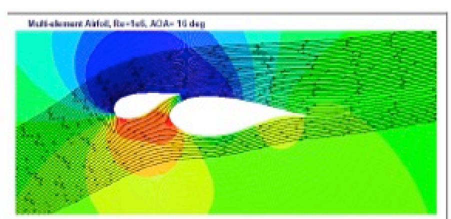
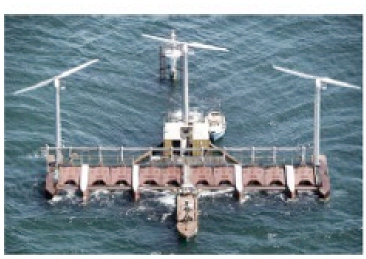
Other topics in focus at DTU WIND ENERGY

- Stability prediction, influence of large deflections
- Controller improvement
- Slats
- Condition monitoring
- Floating turbines
- Wind conditions for very large turbines
- Blade vibration at standstill condition
- Wake turbulence modelling in CFD



- New concepts. E.g. two-bladed design with partial pitch



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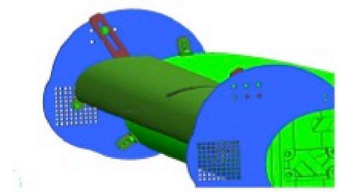
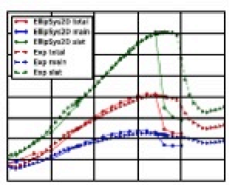
Design and Wind Tunnel Testing of a Thick, Multi-Element High-Lift Airfoil

- A multi-element airfoil was designed and tested in a wind tunnel.
- The slat was designed using an optimization tool coupled with the CFD solver EllipSys2D.
- Thorough comparisons were made between 2D CFD simulations and the experimental data.
- 2D CFD succeeded to a large extent in predicting the correct characteristics.





Appendix D: Breakout Group Speaker Presentations

At the start of the final Plenary Session, each Breakout Group gave a brief presentation describing key findings from their group. The presentations for each group are included in this appendix section, and the speakers for each group are listed again here:

Breakout Group #1 – Mesoscale Control Volume Group:

- Bruce Baily, AWS Truepower
- Sue Ellen Haupt, UCAR/NCAR

Breakout Group #2 – Wind Plant Control Volume Group:

- Branko Kosovic, UCAR/NCAR
- Rebecca Barthelmie, Indiana University (IU)

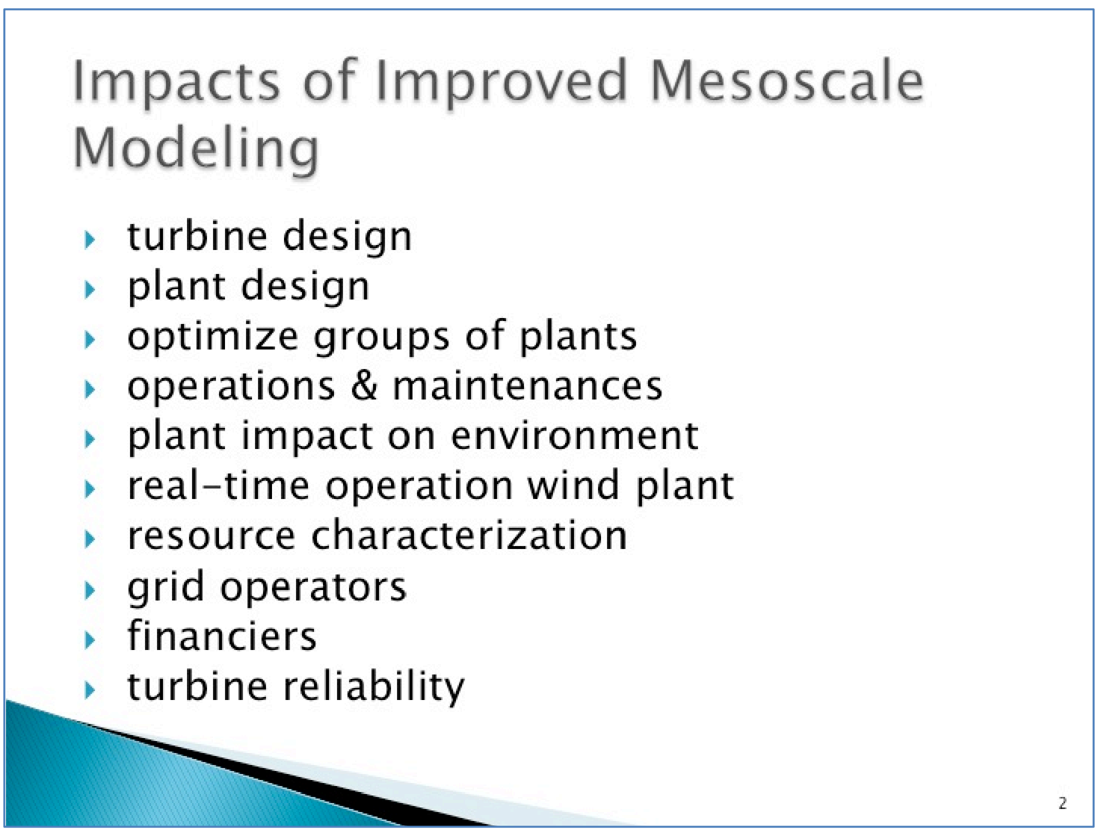
Breakout Group #3 – Wind Turbine Control Volume Group:

- Bob Banta, NOAA/OAR/ESRL
- Niels Troldborg, DTU Wind Energy

Breakout Group #4 – Experimental Data and Validation:

- Melinda Marquis, NOAA/OAR/ESRL
- Gordon Randall, DNV

Breakout Group #1



Expected Outcomes of Improved Mesoscale Modeling

- hand off BCs to local models
- wind plant interaction with that of downstream
- quantify variability and uncertainty
- what observation required for validation
- develop sets of "Best Practices"
- wind plant effect on local weather/climate
- suggestions for leveraging existing programs
- how to continue multi-disciplinary dialogue
- set standards for design constraints

3

Topics – Mesoscale

- Interaction of global scale motions with the mesoscale
- Impact of forcing on the flow – terrain, land/sea contrast, surface roughness, etc.
- Impact of physics on the flow – radiation, moisture processes, land use processes, etc.
- Turbulence modeling across scales – terra incognita issues, etc
- Modeling shear at the mesoscale – stability effects and low level jets, etc
- Integrating the mesoscale with the plant scale models
- (icing – not specific group, embedded)

4

Knowledge Gaps

- Communication across grid interfaces – adapting models, meshes, etc.
  - Global to mesoscale
  - Mesoscale to wind farm
  - Wind farm to wind farm via mesoscale
  - Commonalities with wind farm to turbine, etc.
- Detailed flow structure
- Impact of stability on flow
- Impact of different regimes
- Characterizing flow around complex terrain, land use, air/sea interaction, vegetation
- Impact of precipitation on boundary conditions and ice accretion on turbine loads, design, and efficiency
- Appropriate development of surface models for heterogeneous conditions (vegetation, complex terrain, ...)

5

More Knowledge Gaps

- Impact of wind farms on the local or regional environment
- Physics parameterizations and appropriate numerical schemes for transition from meso-scale to LES and CFD ('terra incognita")
- Data assimilation techniques to optimize use of non-traditional datasets
- Impact of assimilating new, nontraditional data on model accuracy
- Wake turbulence and interactions with the ambient flow
- Intermittent mixing processes (LLJ, breaking waves, ...)
- Regional distribution of wind power generation – how to optimize to reduce variability
- Characterizing uncertainty
- User centric verification issues

6

Path Forward

- Parallel teams testing different modeling approaches – across industry, academia, laboratories (public-private partnerships)
- Development of multi-scale modeling approaches & intercomparisons
  - Idealized simulations for verification and intercomparison – data archive
  - Validation on common datasets
  - Multi-scale integration
- Multi-scale testbeds representing wind resource regions and range of stability and climatological conditions
  - Flat terrain, Complex terrain, Offshore
- Integrated over a region – several wind farms and undisturbed flow
- Data Repositories – US, perhaps international
- Seek interagency collaborations
  - DOE Office of Science, NSF, NOAA, DoD, etc.
- Research coordination framework to move parallel agendas forward

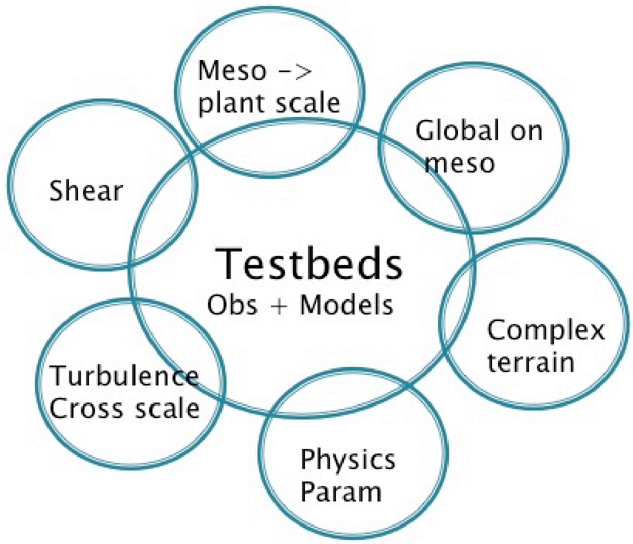
7

Data Needs

- Capture verification datasets for modeling efforts
- Develop case studies of 'extreme' wind character events (need regional test beds)
- Capture data required for meso, LES, and CFD scale explicit and parameterized physics
- Need information exchange for field projects for leveraging opportunities (NSF, DOE, NOAA, Europe, etc.)

8

Integrate across topics



9

Take-aways

- This is worthy of a **Grand Challenge Initiative**
- This is not going to be cheap
- Absolutely critical for high penetration wind
- Will impact prediction for lots of other uses – weather prediction, climate, security, transportation, agriculture, …

10

Breakout Group #2

Group 2: Wind plant control volume

Rebecca Barthelmie
Branko Kosovic

- **More integration**
  - Between partners in industry/academia/government
  - In terms of using models to help frame and validate experiments
  - In terms of optimizing power and loads to improve efficiency
- **Major issues focused on benchmarking/validation/data access**
  - Cost of major new experiments
  - Understanding one experiment can't provide all answers – develop multipronged strategy combined with modeling input
  - Dynamic model development
- **Bridging scales is a major issue**
  - In modeling, main approach is top-down (feedbacks)
  - Lack of 'information' /strategy especially about turbulence in the coupling across scales
  - In measurements, providing input /validation over wind farm spatial scales

1

Sub-topics (1)

Wind plant control

- Control as a plant-level problem, dynamics
- Develop systems, also need test facilities
- Access to data, data insufficient
- Demonstrate cost effects for acceptance
- Partnerships with industry

Air-sea exchange and surface

- Lack of coupling and feedback, impact of different stability
- Issues with downscaling
- Need an instrumentation tower facility/ testbed
- Extreme conditions
- Codes not well-benchmarked

2

Sub-topics (2)

Inflow/surface/wakes

- Role for less comprehensive models, lack of stability/turbulence
- Research in LES/DES – potential
- Wake Models
  - Need for more dynamic models
  - Coupling power and loads for optimization (topology)
  - Issues of wake dissipation/ divergence
- Codes are not well benchmarked
- Lack of data on all timescales
- Need for a large inter-government/ academia/industry experimental campaign
- Research above and downwind of wind farms

Complex terrain

- Lack of surface data
- Canopy, surface roughness, inhomogeneity
- Flow separation & hill wakes
- Use more comprehensive models
- Codes are not well benchmarked

3

Major points (1)

- (Always) Lack of data (probably needs a strategy)
  - Better data sharing/access
  - Some specific funded experiments focused on particular phenomenon (US specific e.g. Gulf, stability Great Plains issues)Using modeling to define measurement strategy. Define measurement types/campaigns needed.
  - Comprehensive campaigns, large to small scales, multi-partner, multi-institution
  - Texas Tech facility (flat), Iowa State wind farm, ONR, Portugal complex terrain, IU DoE funded offshore
  - Engage with developers (?)
  - IEA Wake Benchmarking, similar initiatives?
- Specific issues
  - Complex terrain (resource, spatial issues)
  - Wind-wave (models and measurements)
  - Forest modeling esp. in complex terrain
  - Better surface data, input and validation as spatial fields
  - Flow separation
  - Wake modeling, coupling power and loads, dynamic

4

Major points (2)

- Bridging scales and spatial /dynamic models
  - Increasing data requirements (larger wind farms, shorter time scales, loads).
  - More comprehensive models (RANS already state of the art, DNS, LES for research etc) but less constrained. Probably still need the linear models and RANS while developing more comprehensive approaches
  - Model coupling and coupled models, particularly mesoscale downwards (new models under development) but data requirements not met e.g. more / comprehensive turbulence information
  - Wind plant control
- Turbulence and stability were a common theme
  - Turbulence modeling (improvements but a large task)
  - Synthetic turbulence databases
  - Better/more comprehensive measurements
  - Developing models that include these impacts on resource/loads/wind-waves/ wakes, complex terrain etc.

5

Inflow/surface/wake modeling & complex terrain

Current

- Linearized Navier-Stokes (NS)
  - Fast but applicability limited (complex terrain), lack of stability/turbulence.
- Reynolds-Averaged Navier-Stokes (RANS)
  - Relative spatial changes and turbulence, flow separation, stability
  - A lot more inputs and opportunity to make mistakes than linearized NS
- LES/DES and Coupling LES with Mesoscale
  - Not much in industry yet, long-term potential
- Wake Models
  - Most standard e.g. WAsP, Windfarmer (power)
  - Dynamic Wake Meandering (DWM) is cutting edge reduced-order
  - Questionable how well loads get predicted with above tools
- Industry almost always assumes neutral stability, which is becoming seen as a deficiency (not engineering-conservative for loads prediction)

Gaps

- Codes are not well benchmarked
- Lack of validation of prediction tools
- Both modeling and measurements related to stability and turbulence
- Importance of wind direction
- Spatial fields as input rather than point measurements
- Lack of data on all timescales from the longest (climate) through the shortest (turbulence)

Path Forward

- Need for a large inter-government/academia/ industry experimental campaign
- Multiple locations, but for sure Great Plains
- Include power and loads to move towards integrated modeling for optimization
- Role of project certification for offshore
- Do model ensembles have a role in helping to define uncertainty

6

Air-Sea Interface and Near Surface Flow Modeling

Current

- Air-sea models currently exist in mesoscale models and for hurricane modeling
- Lack of coupling at the fine scale relevant for turbine inflow and intra-wind farm environment
- Able to model momentum transfer from wind to waves as drag/roughness but direction similarity/ local waves
- Wave resolving large-eddy simulation (LES) (e.g. Sullivan).

Gaps

- Downscaling modeling capability from mesoscale to wind and waves at the turbine scale
- Coupled model for on small scales/under varying stability conditions
- Need an instrumentation tower facility/ testbed
- Extreme conditions

Path Forward

- Use existing models but better parameterization of wind-wave interactions
- Measurement systems (testbed, opportunity, partnerships)

Outcomes

- Understanding the wind farm environment under the influence of waves
- Better understanding of wind turbine environment under influence of waves
- Desire for U.S. offshore measurement campaign/ facility -Atlantic, Gulf of Mexico

7

Wind Plant Control

Current

- Not dynamic
- Collective pitch control focused on power management
- Utilities demand curtailment based on ramp events—lack of coordination

Gaps

- Lack of validated simulations
- Does not account for stability effects
- Industry acceptance
- Access to operation wind farm data is difficult, and what is available is sparse (SCADA data)
- Cost modeling is difficult, need to demonstrate cost effects
- Lack of maintenance cost information
- Testing facilities are sparse. Need a range of test facility size
- Introduce other components (e.g. LIDAR, advanced actuators)
- Manufacturers protective of control system information
- What are hardware, turbine component limitations

Path Forward

- Cost plain laid out that includes:
- Developing/Testing wind plant control systems and expanding from existing test centers, develop partnership with industry
- International wind plant scale experiment and proof of concept within smaller scale test
- Long term monitoring of control system performance, additional wind farm sensors
- Topology/optimization

Outcome

- Control as a plant-level problem
- Developing control systems that are fast in response, but have minimal impact on wind plant
- Create a framework for sharing of data from operational farms
- Best practices for using advanced wake models
- Test site for wind plant control
- Metrics
  - Reduce cost of energy by 2%
  - Better siting strategies
  - Increase wind plant wholesale rate
  - Wind plant control strategy in industry

8

Breakout Group #3

Turbine-scale control volume

- Identify gaps
- Examine potential paths forward

1

Gaps

I. There is a critical need for multivariable space-time synced experimental field data. The data must provide the required inputs and validation data for numerical models, both engineering design tools and high-fidelity simulations.

Specific points:

i. Leverage the current generation of experimental techniques

ii. Develop new experimental techniques that are required to gather the required data to validate the next generation of high-fidelity techniques

II. Current design standards do not address/include what we currently understand about the complex airflow-turbine interactions.

2

Gaps

III. Transition of technology of from research simulation tools to engineering design tools.

Specific points:

i. There is insufficient collaboration between industry/designers and researchers

ii. There are existing obstacles to collaboration

IV. Need to develop HPC simulation capabilities that represent real wind turbines operating in the real atmospheric environment.

3

Components of a path forward

I. Develop wind-plant scale and wind-turbine scale "grand experiments" to advance wind turbine technology – this is an iterative process.

Specific points:

i. Develop field and computational experiments

ii. Develop the required measurement techniques

II. Develop and validate a multi-scale computational framework.

Specific points:

i. Develop a reference tool set (codes) that provides standard validated calculations for pre-defined test cases (range of environmental conditions). This should include an API/code framework

ii. Joint framework between researchers and industry

iii. Examples include HPC, high-fidelity, etc.

4

Components of a path forward

III. Develop an "open-source" turbine.

Specific points:

i. Could be manufactured at different scales

ii. Describe how airflow-turbine interactions scale

IV. Distill the current understanding of complex airflow-turbine interactions to provide simplified lower-order models.

Specific points:

i. These lower-order models can be used to improve current design standards

5

Components of a path forward

V. Form a collaborative to address gaps in our experimental data sets and techniques.

Specific points:

i. Instrumentation sharing collaborative could be beneficial

ii. Standard, public experimental facility for studying airflow-turbine interactions

- Study "Open-source" turbine performance over a range of environmental conditions

iii. Standard instrumentation packages and test procedures

6

Breakout Group #4

Group 4: Experimental Data and Validation

A. Wake Assessment
B. Turbine Wake Assessment
C. Wind Farm Measurement Campaigns
D. Wind Tunnel Measurement Campaigns
E. Scaling and Fidelity Requirements
F. Measurement & Instrumentation Campaigns

1

Common Findings across A-F

1. Data of **sufficient temporal and spatial resolution** to validate models, quantify and reduce uncertainty
2. Need multiple **test beds**
3. Increased **data sharing** and **archival**
4. Go through **planning exercise** that leads to **roadmaps** that define **campaigns.**

2

Common Findings

#'s 1&2: Data of sufficient temporal & spatial resolution to validate models, quantify and reduce uncertainty

- What's the validation roadmap for (various needs)
- Assure that dataset creation is complete (know blade geometry, etc.) for optimal validation ***Dataset needs to be very well defined
- More useful for community, have agreed-upon uncertainty
- For existing and new models (note the 3 types of models)
- Justification: downscaling, simplifying. Improvements in models to accomplish....
- **Gather datasets that go across all scales**
- **Come up with an explicit # on the range of scales (From 20 Hz to decadal)**

3

Common Findings

#3: Increased data sharing and archival

- What kinds of data might be useful/needed
- Data sharing requirements
- Come up with what an "**adequate description**" of data would look like if a clearinghouse for data was to be developed (**metadata**), housed at a neutral party *Perhaps an area of DOE leadership
- Need someone doing **quality assurance**, assuring data included is of some sufficient quality
- Data sharing/archiving **needs to be funded**
- To what extent can we leverage/improve existent efforts for this?

4

Common Findings

#4: Conduct a Planning Exercise

- Exercise will build **roadmap** for validation requirements, evaluate past experiments and identify future experiments
  - Identify needed measurement technologies
  - Leverage existing instrumentation when possible
  - What datasets exist?
  - Will indentify new applications of existing technologies

- Long-term: Technological development
  - Analyze all the data from the individual experiments, identify best practices for validation & kinds of instrumentation needed, how to design them

5

Sub-topic Findings

A.) Wake Assessment

B.) Turbine Wake Assessment

- **Data of sufficient temporal and spatial resolution to validate existing models and inform new models**. Focus on 3 models:
  - Isolated turbine models
  - Turbine layouts
  - Farm-farm interaction
- **Near term; provide data required to improve and validate existing and new models and quantify uncertainty, to inform model simplification** (e.g. downscale /simplify RANS / LES to desktop models, such as eddy viscosity or Park wake models), to allow improved micrositing, spatial and temporal resolved observation to understand wake field.

6

Sub-topic Findings

A.) Wake Assessment
B.) Turbine Wake Assessment

- Carry out a **series of validation campaigns** specific to **isolated wake, wake/turbine interactions** and **wind farm wake**.
  - Campaigns must meet purposes of validation and verification requirements;
- **Instrumentation** with improved capabilities
- Better understanding of **velocity deficit under different meteorological** conditions (stability)
- Better **across- and above-rotor measurement** of behavior or evolution of **velocity deficit**

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Sub-topic Findings

A.) Wake Assessment
B.) Turbine Wake Assessment

- Provide as complete as possible data sets / test cases using **deliberately-chosen and specially-instrumented test beds** to allow for validation of models and tools. For example:
  - Coupled inflow-wake measurements
  - Wake and load measurements (upwind turbine wake, downwind turbine load)
  - Coupled inflow-power measurement
- **Horizontal and vertical measurements** at turbine scale (rotor diameter and beyond)
- Full knowledge of **turbine geometry and operation**
- Increased understanding over **previous experiments** (e.g. more highly resolved wake measurements both in time and space)
  - Would include **field** and **wind tunnel** testing

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Sub-topic Findings

C.) Wind Farm and Wind Tunnel
D.) Measurement Campaigns

- **Data archiving and sharing**
- **RFI** for data collection needs
- **Survey existing** wind tunnel experiments, wind field experiments
  - Analyze existing datasets, assure we don't replicate previous efforts
- **Transfer knowledge** from controlled wind tunnel experiments to real world
- How do **we model complex terrain, thermal stability within wind tunnels**? We need to continue studies along this vein.

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Sub-topic Findings

C.) Wind Farm and Wind Tunnel
D.) Measurement Campaigns

Wind Tunnel studies:

- With single/double turbines, not just field of turbines
- With complex terrain (inform research being done in university facilities - ID what needs to be done)
- ***Need mechanism to transfer knowledge obtained in wind tunnel results to real world***
- Increased understanding over previous experiments; ID what would be ueful in practice, e.g., add blade properties to capture aeroelastic effects
- Engage a lot of people in those efforts; not just DoE/NASA…also modeling community & experimental community for proper identification

- **Connect controlled (e.g., wind tunnel, single turbine, turbine-turbine, farm scale, regional) environments to real world**

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Sub-topic Findings

C.) Wind Farm and Wind Tunnel
D.) Measurement Campaigns

<u>Wind farm campaigns...</u>

- Assure that dataset creation is complete (know blade geometry, etc.) for optimal validation ***Dataset needs to be very well defined

Identify common data/information needs, then develop appropriate instrumentation platforms to address... or? ...

Have similar instrumentation, perform similar measurements, at different locations to examine heterogeneous effects (possibly bigger bang for the buck for investment)

-Adjust to particular domain (e.g., wind farm)

-Should be **data-driven** rather than instrumentation driven

Identify technologies necessary to get at data that is not currently available

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Sub-topic Findings

E.) Scaling and Fidelity Requirements
F.) Measurement and Instrumentation Campaigns

<u>Scaling issues</u>:

- Identify atmospheric conditions that are needed for study, and design ***test beds*** to gather observations across **all relevant length scales**, e.g., from rotor to regional.
- **Identify limitations** in current observations and datasets to ensure that scaling up principles have known and validated assumptions (for modeling community)

<u>Data issues:</u>

- Develop an **archival system** for datasets that are well described in terms of experimental design, metadata, the types of measurements available, and to make this data publicly available as appropriate.
- Develop **new applications of current technologies** to meet current gaps in observations needed and to meet gaps in the spatial and temporal scale as needed. These measurements should provide two and three-dimensional ***fields*** of turbulence measurements.
- Understanding the process **for gaining acceptance of new technology or new measurement variables to modelers and industry**.

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Sub-topic Findings

E.) Scaling and Fidelity Requirements
F.) Measurement and Instrumentation Campaigns

- We need to be doing **complex flow studies at the same time as simple flow studies**, else, will never get to complex flows
- Need complete set of data collection campaigns, can identify systematic errors across these.
  - Pin down uncertainties amid and between environments.
- **Need to figure out how best to use remote sensing data across uses/users**

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Summary of Common Points

- Need data of **sufficient temporal and spatial resolution** to validate models, quantify and reduce uncertainty
- Must deploy multiple **test beds**
- Need to increase and improve **data sharing** and **archiving**
- Industry would benefit from a thorough **planning exercise -> roadmaps**

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Appendix E: End of Workshop Summary Presentation

Summary of Plenary Session

Presented during conclusion of workshop

1

General Observations

- Overlap at the edges between Breakout Groups (BOGs)
  - Applies for both technology needs and potential paths forward
  - Actual solutions differed depending on the specific BOG and topic
- BOGs identified several needs for future R&D efforts
  - **The industry needs models and measurements that cross several spatial and temporal scales simultaneously**
- The path forward represents a large opportunity to impact wind plant performance through R&D

2

Common Needs

Distinct but Interlinked Regimes

- Regional Inflow
- Wind Plant Inflow
- Wind Turbine Inflow
- Turbine Response

3

Common Needs

More Accurate Models

- Uncertainty Quantification
- Self-consistent physics parameterizations
- Improved treatment of stability, turbulence & atmospheric dynamics
- HPC may be required to examine the flows/properties of interest
- Transition simulations to design tools
  - Numerically expensive simulation development happens in parallel with design tool development

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Common Needs

Field Validation

- Single or dual turbine testing in real conditions
- Several points in an operating wind farm
- Inflow/Outflow data collection
- Data from SCADA and turbine loads (e.g. drivetrain loads)

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Common Needs

Wind Tunnel Testing

- Single and/or multiple turbines
- Open-source and/or very-well defined turbines
  - Full aerodynamic, drive train and control systems designs

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Common Needs

Well Defined Data Requirements

- Focus on user requirements
- Need two- and three-dimensional fields in data sets
- Must include data sets that push bounds of knowledge

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Common Needs

Improved Instrumentation

- Data Driven
- Multi-scale capabilities
- Not limited to existing technology

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Path Forward

Ramp-up Planning Exercises

- Engage subject matter experts
- Start with well-defined needs
- Leverage existing modeling and experimental capabilities
- Determine future modeling and experimental capabilities (e.g. model coupling & hand-off, uncertainty, etc.)
- Ensure widely useful data and results

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Path Forward

Incentivize Data Owners and Users

- Data sharing and collaboration must be improved
- Beyond simply "what data is useful?"
- Must determine how to engage owner/operators
  - E.g. What type of test beds?
  - E.g. How many test beds?

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Path Forward

Data Archive

- Large amounts of metadata
- Open to as many people as possible
- Useful for several stakeholder groups
- Level of effort requires funding

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Path Forward

Standards & Practices

- Must incorporate findings into industry design standards
- Standardized data collection
  - What to collect and how to collect it
- Inform and guide best practices
  - For models: assumptions, applicability, output, etc.
  - For data: sensor packages, test bed setup, etc.

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Appendix F: References

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