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Wind Energy Fundamental Science Issues Requiring HPC

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Presentation Outline

1. **Wind Technology Evolution and Deployment**
2. **Wind Resource and Potential Contribution to the US Energy Demand**
3. **Future Technology Challenges in Achieving High Penetration**
4. **HPC Needs and Opportunities in Wind Energy**

Technology Evolution

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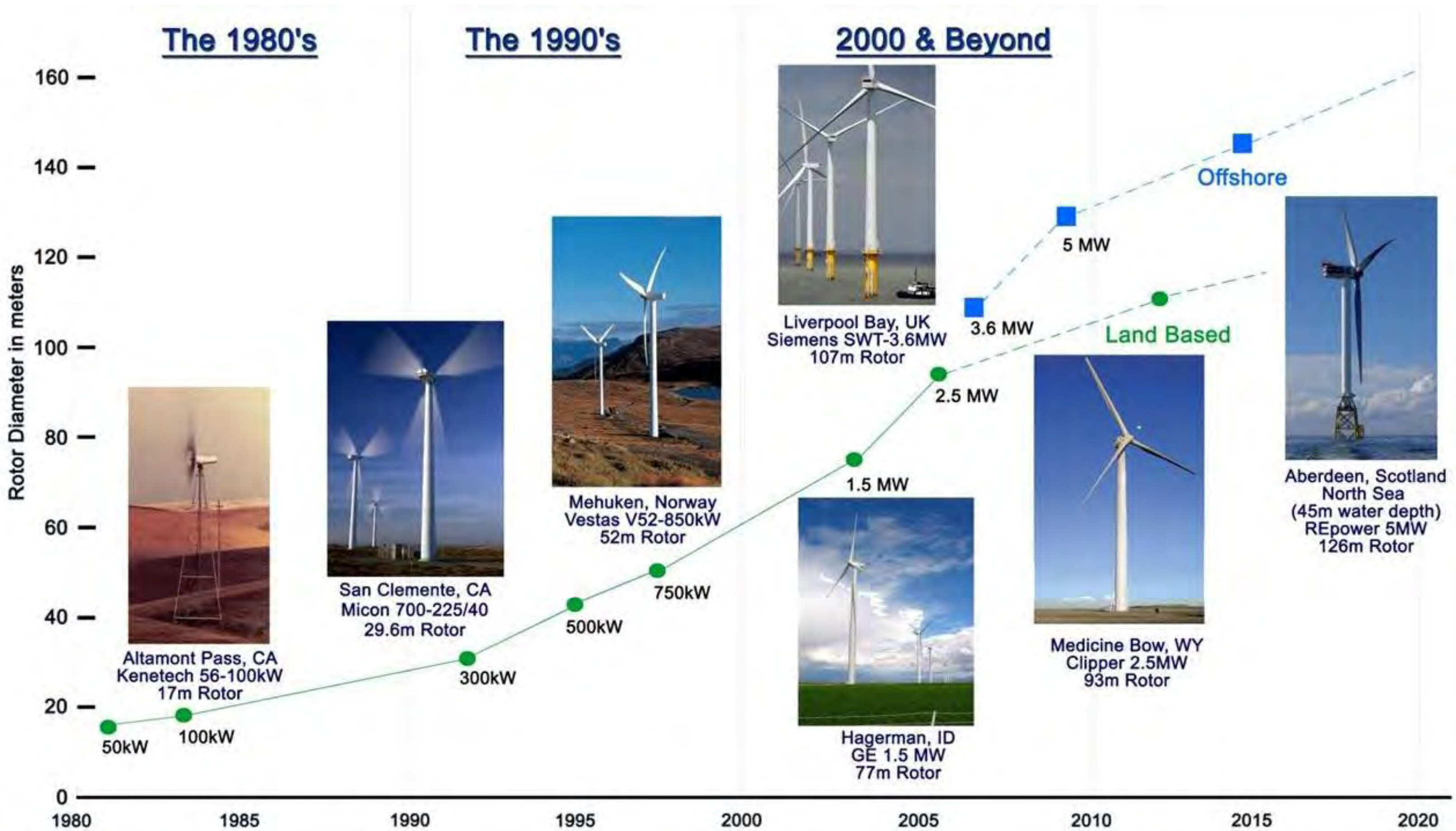
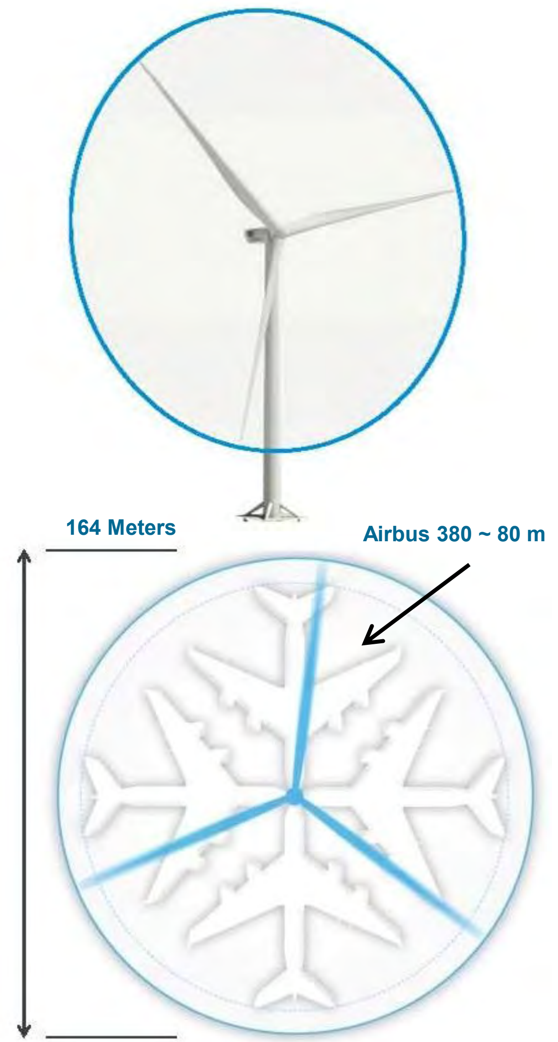


- **Land Based Technology > 2 MW; Turbine 50% Total Installation Cost**
- **Offshore Technology > 5 MW; Turbine 25% Total Installation Cost**
- **Land Based Turbine Size Constrained by Highway Transport**
- **Turbine Stiffness & Dynamic Coupling Driving Design Innovation**

Technology Future

- **Commercial Technology:**
  - ➢ **2.5 MW - Typical Commercial Turbine Installation**
  - ➢ **Offshore 5.0 MW Prototypes Being Installed for Testing in Europe**
  - ➢ **Most Manufacturers Have a 10-15 MW Offshore Machine in Design**
- **Large Turbine Development Programs Targeting Offshore Markets**
- **US Deployment Characterized by Large Multi-Array Wind Farms Containing Broad Spectrum Inflow Load Drivers**
- **Turbine Dynamic Stability and Non-Linear Behavior are Becoming a Major Design Factor Requiring High Fidelity Coupled Models**



Vestas V164
7 MW Offshore Wind Turbine Design

Wind Resource Assessment

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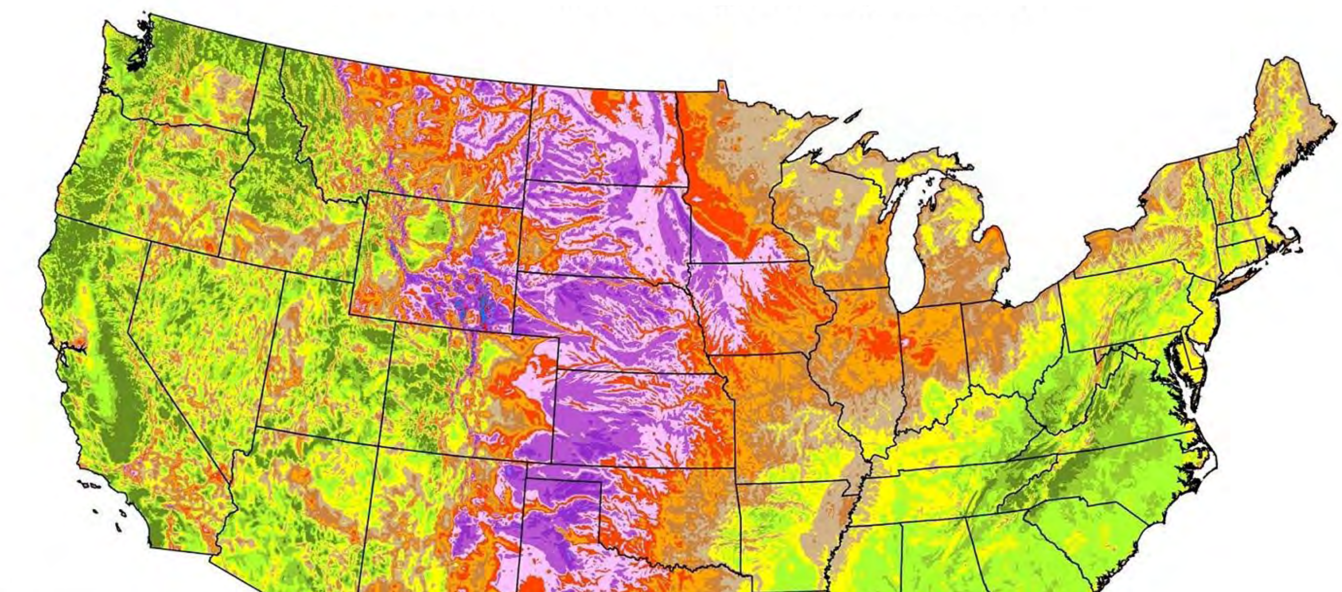
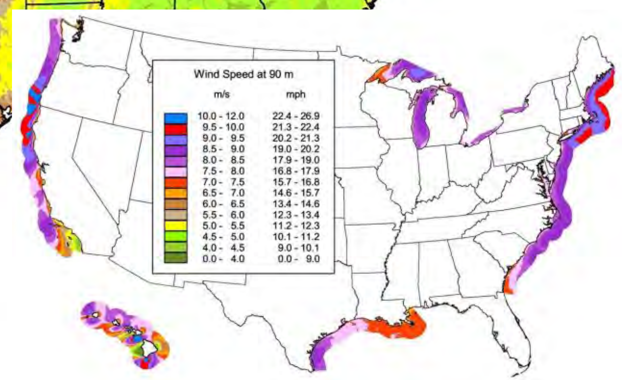
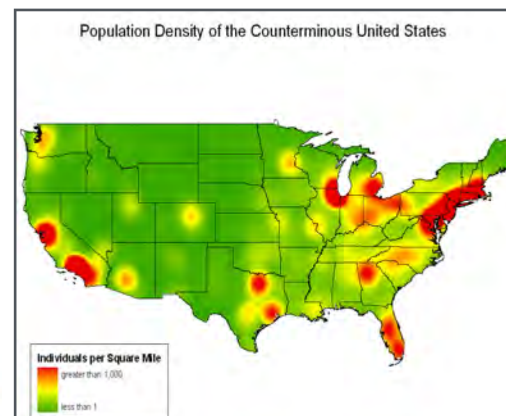
Annual Wind Speed at 80 Meters



Source: Wind resource estimates developed by AWS Truewind, LLC for windNavigator®. Web: http://navigator.awstruewind.com | www.awstruewind.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.



- 80% Domestic Load Within 150 Miles of the Coast and Great Lakes
- Resource Assessment Derived from Validated Mesoscale Modeling
- Future Resource Assessments Require Spatial & Temporal Comparison With Load Flow
- 11 Midwest States Can Provide 3x US Electrical Load
- HPC has a Key Role in Future Transmission & Generation Planning



Total Wind Resource Potential

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		Land Based Wind			Offshore Shallow Water (< 30 meters)			Offshore Deep Water (> 30 meters)		
Wind Class (@ 80 meters)	Velocity Range (m/s)	Resource Potential (GW)	Capacity Factor (Weibull)	Quads (Quadrillion BTUs)	Resource Potential (GW)	Capacity Factor (Weibull)	Quads (Quadrillion BTUs)	Resource Potential (GW)	Capacity Factor (Weibull)	Quads (Quadrillion BTUs)
III	6.4 - 7.0	4186	30%	37.5						
IV	7.0 - 7.5	3544	35%	37.0	249	35%	2.6	292	35%	3.1
V	7.5 - 8.0	1109	40%	13.2	365	40%	4.4	505	40%	6.0
VI	8.0 - 8.8	64	42%	0.8	294	42%	3.7	712	42%	8.9
VII	8.8 - 11.9	16	45%	0.2	164	45%	2.2	1569	45%	21.1
Total :		**8919**		**88.8**	**1072**		**12.8**	**3078**		**39.1**

- **Total Wind Energy Potential ≈ 141 Quads**
- **Total Domestic Energy Use ≈ 98 Quads**
- **Total Electrical Energy Use ≈ 13 Quads**
- **20% by 2030 Goal (300 GW) ≈ 3 Quads**
- **Current Contribution (40 GW) ≈ 0.4 Quads**

Significant Resource Potential to Support High Wind Penetration Scenarios !!!

Future Technology Challenges to Achieving High Penetration

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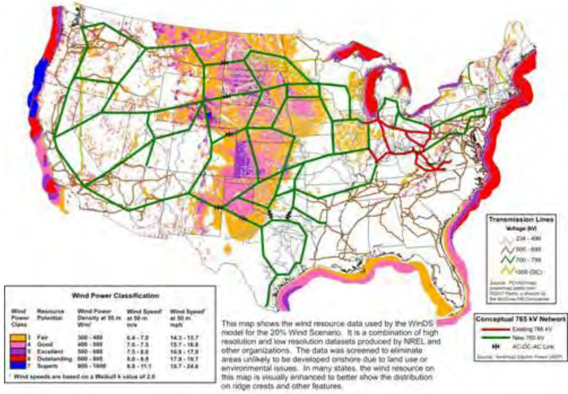
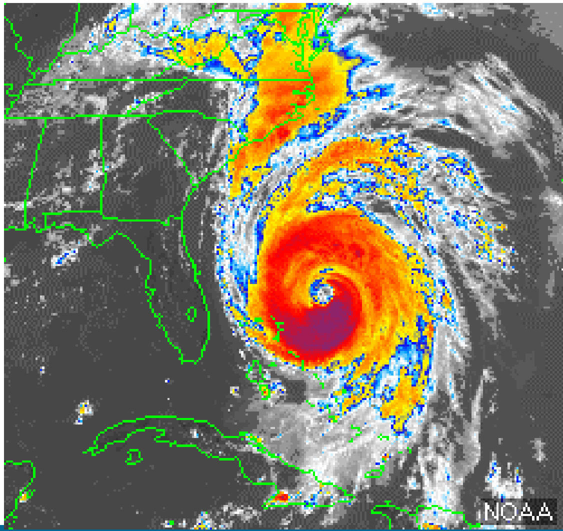
High Penetration Levels (>30%) Will Require Federal R&D and Operational Oversight to Insure Power Availability, Reliability, and Stability

- **Engagement and Participation by Multiple Government Agencies; e.g. DOE, DOC, DOI, DOD, NASA, NSF …….**
  - Evolution and operation of an integrated national transmission grid providing generation, access, collection, dispatch balance and distribution of renewable power resources
  - Advanced wind (and solar) forecast modeling tools that range from global circulation to mesoscale and at resolutions supporting wind plant power production
  - Strategic and operational wind forecast and power predictions at the temporal and spatial scales required for the operation of a national grid system driven by weather related phenomena
  - National grid modeling and control network coupling wind resource weather and power flow monitoring, load and power generation to actively administrate operation, distribution and dispatch strategies required for grid stability
  - Climate change models capable of predicting long term wind resource variability to mitigate venture capital risks, resource availability and performance concerns
  - Characterizing the wind resource as a strategic national energy reserve including availability, spatial and temporal behavior, effects of topography, etc., on land and offshore to the same fidelity as fossil and nuclear resources
  - Defining the Operational Wind Plant Environment Driving Future Technology Development & Innovation

Classic Coupled Multi-Scale & Multi Physics Problems





Computational Modeling Scales

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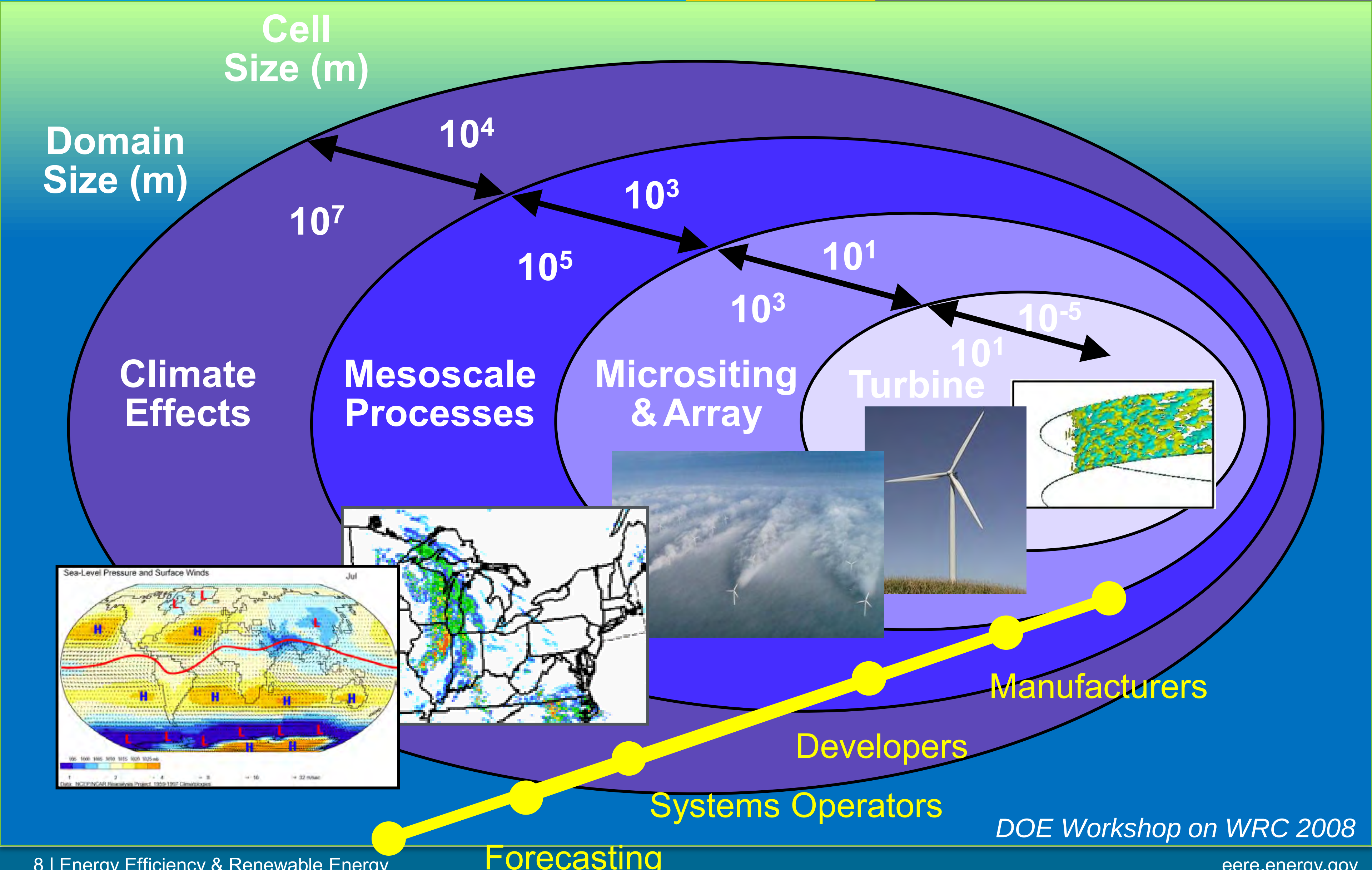

DOE Workshop on WRC 2008

Turbine Modeling Challenges

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- **State-of-the-Art Tools Have Difficulty Predicting Turbine Rotor Aerodynamics**
  - ➢ **Linear Aerodynamics used extensively in integrated system design**
  - ➢ **Aeroelastic coupling with complex 3-D flow field is critical to performance estimate and cost-effective design**
  - ➢ **Advanced Computational Aero-Acoustics Prediction (CAA)**
  - ➢ **Required physics include separation, dynamic stall, blade loading, and acoustic emissions; sub-chord dimensional scale**
- **Advanced Structural Rotor Modeling**
  - ➢ **Simple reduced-order models, e.g., 3-DOF linear modal blade models are extensively used by industry**
  - ➢ **Geometrically nonlinear shell and reduced-order beam models for highly flexible blades needed for aeroelastic tailoring**
  - ➢ **Must include material-failure models, nonlinear buckling, uncertainty quantification, fully coupled fluid-structure interaction**
- **Integrated System Dynamics Simulation Modeling for both Load & Performance Prediction**
  - ➢ **Fully coupled FEM models capturing rotor, tower, platform and mooring dynamic behavior including non-linear response**
  - ➢ **Supporting Deep Water Offshore Platform Design**

Fully Coupled Multi Array Simulations with Fidelity and Scales from Atmospheric Inflow to Blade Boundary Layer

Deep Water Modeling Requirements

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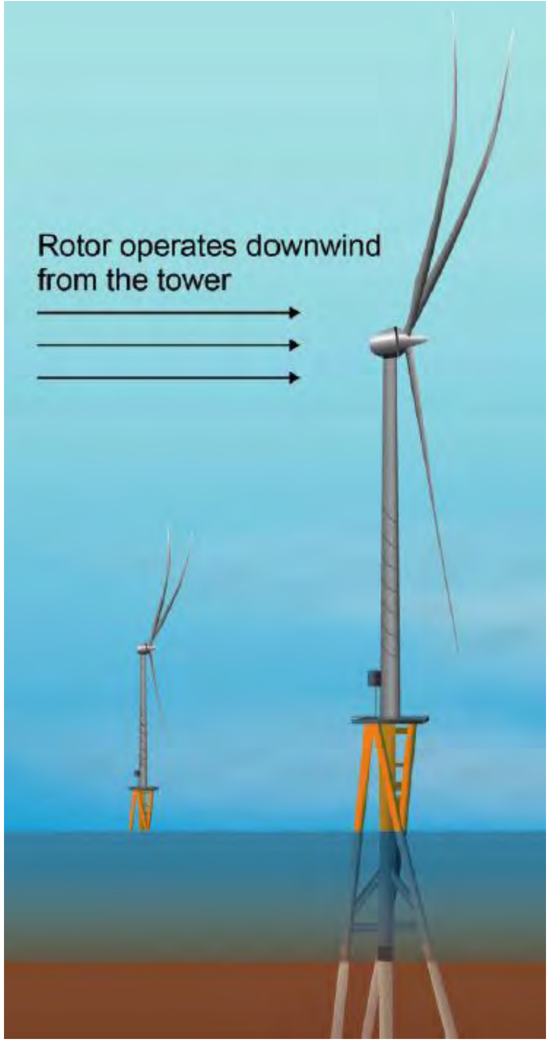

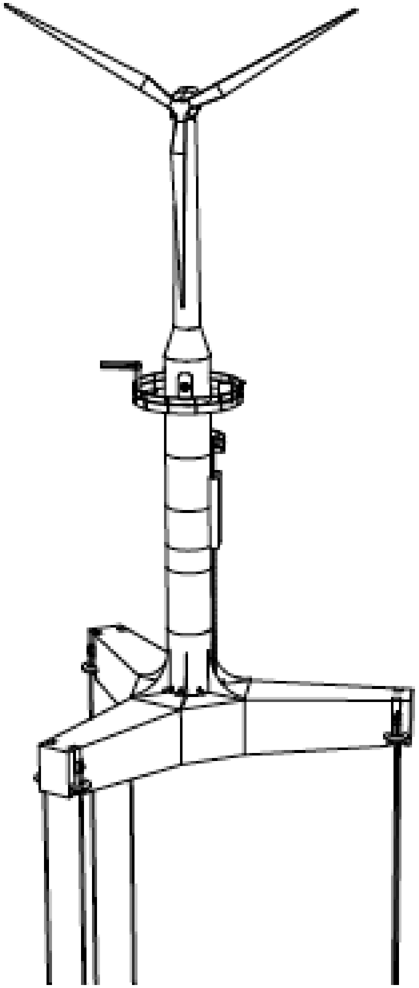

Fully coupled aero-hydro-servo-elastic interaction

- **Wind / Wave Interaction:**
  - discrete event prediction
  - turbulence effects
  - wave spectra
  - surface roughness
- **Aerodynamics:**
  - induction
  - rotational augmentation
  - skewed wake
  - dynamic stall
- **Hydrodynamics:**
  - scattering
  - radiation
  - hydrostatics
- **Structural dynamics:**
  - gravity / inertia
  - elasticity
  - foundations / moorings
- **Control system:**
  - yaw, torque, pitch

Offshore Floating Wind Turbine

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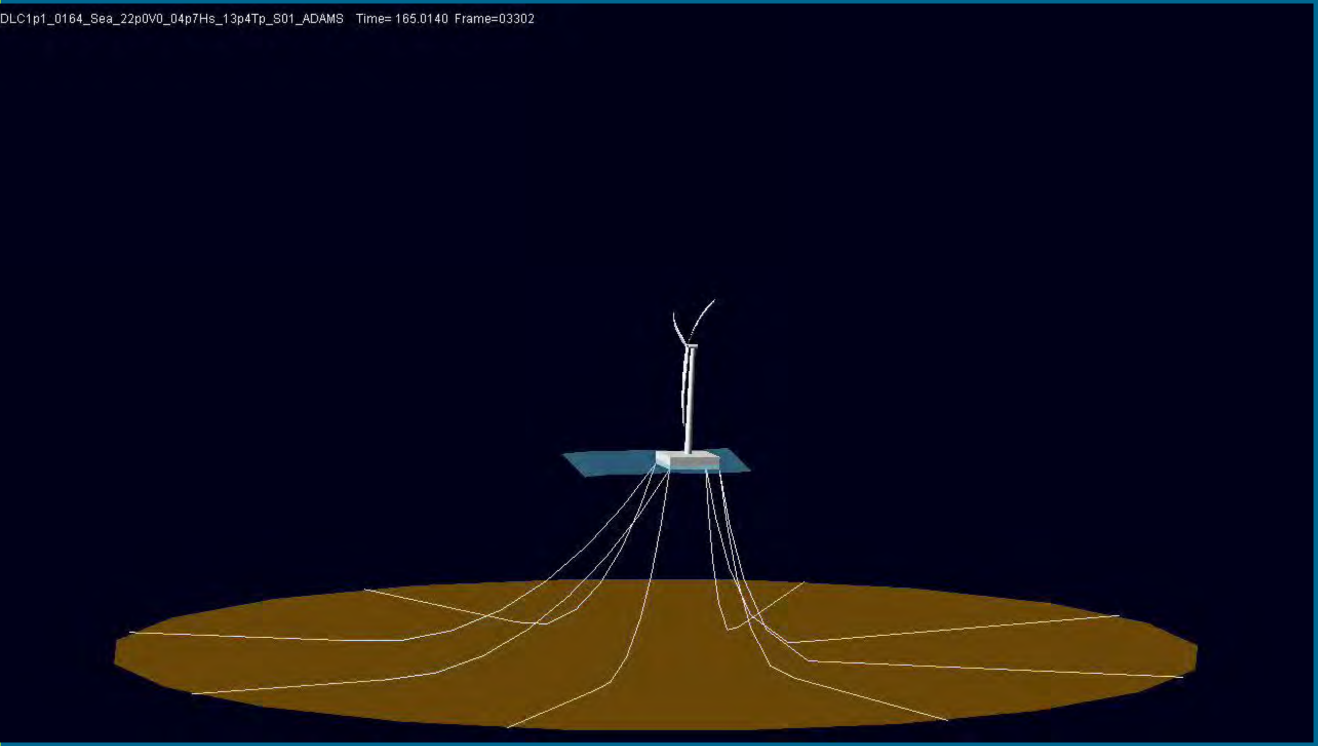
Advanced Coupled Aero-elastic Hydrodynamics Model of an Offshore Floating Wind Turbine

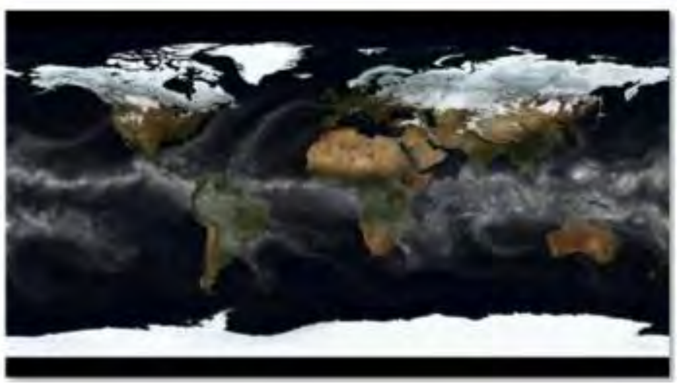


Jason Jonkman; 2007

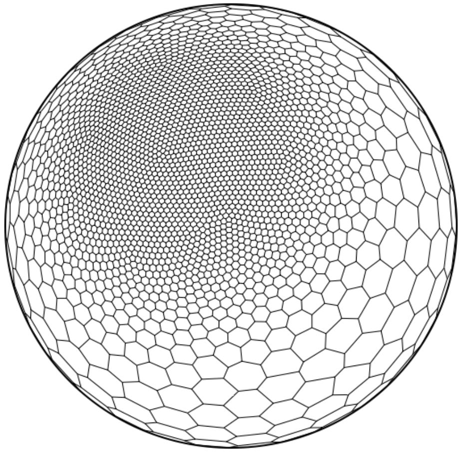
- NREL 5 MW Turbine Used as Baseline
  - Adopted as an international standard for comparison
- Concatenation of Reduced-Order Models:
  - Linear modal blade & tower
  - Linear wave dynamics
  - Homogeneous turbulence
  - Linear aerodynamics (BEM)
  - Platform treated as rigid body
  - Quasi-static mooring
  - Integrated state space and PID control modeling
- Existing Capability
  - Lacks Fully Coupled Inflow, Wake and Wind/Wave Physics for Multi-Array Modeling
  - Not Well Suited for Highly Flexible Blades, Examination of Failure Modes, Non-Linear Coupled Response

Improved Physics For Wind Prediction

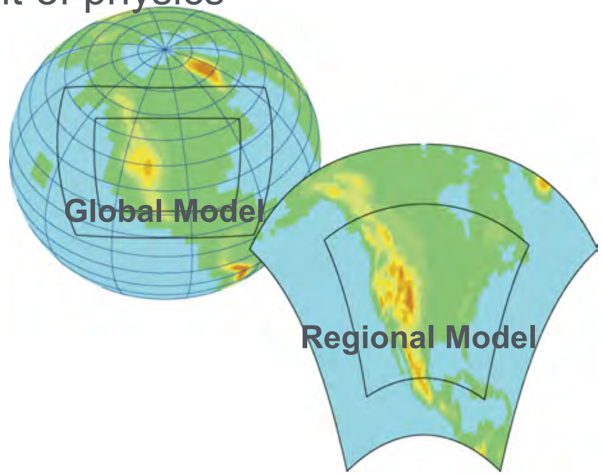
- Accurately modeling wind resources requires high spatial resolution
  - To represent surface heterogeneity
  - To simulate the multi-scale processes that influence surface winds
- With high performance computing, three approaches are feasible to simulate wind climates at regional scales
  - Global high-resolution model
  - Global variable-resolution model
  - Nested regional climate model
- As spatial resolution increases, conventional subgrid-scale parameterizations become questionable, necessitating advances in treatment of physics



Global high resolution model



Global variable resolution model



Nested regional climate model

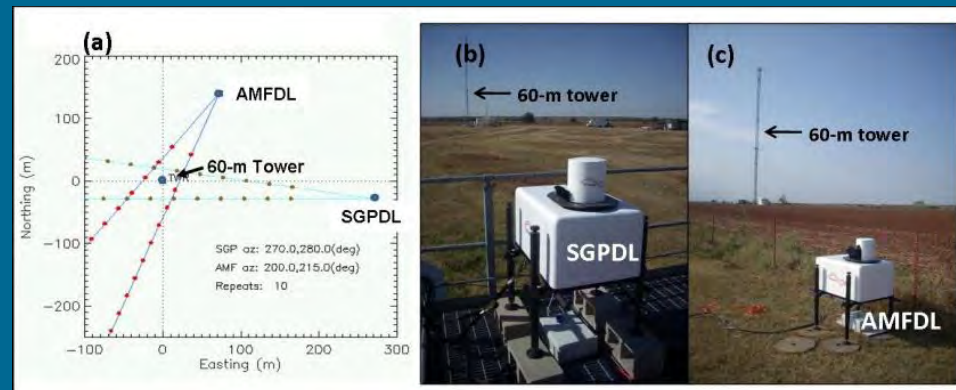
Atmospheric Measurement and HPC Code Validation

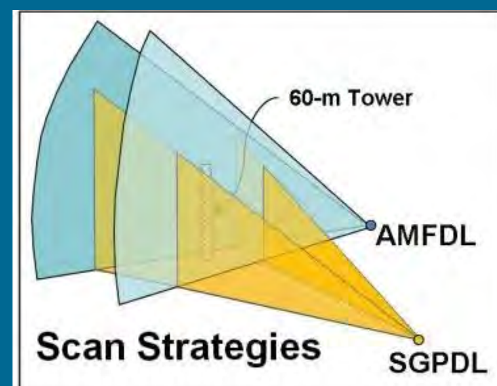
New Measurement Technologies

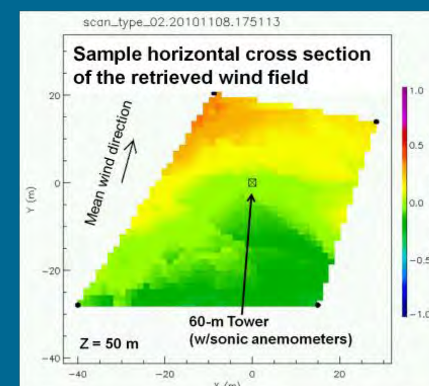
- Doppler volumetric scanning remote sensing
- Computer-controlled coordinated scanning
- Computational and storage capacity to support sophisticated wind field retrieval algorithms

New Data for Validating Modeled Fields

- Three-dimensional wind fields
  - ➢ Spatially detailed
  - ➢ Short times
  - ➢ Previously unavailable
- Data collected in real atmosphere
  - ➢ Allows more rigorous testing of models







Detailed wind field retrieval using volumetric scanning from coordinated Doppler lidars

[data from DOE's Atmospheric Radiation Measurement (ARM) site in the Southern Great Plains; algorithm development by Rob Newsom, PNNL]

Complexity of Multi-Array Wakes

Deployment:

- Large Multi-Array Wind Farms Most Cost Effective Approach
- 50-80% Penetration Scenarios Under Development
- Growing Deployment Concerns by Regulators & Investors
  - Resource Valuation With Multiple Wind Plants
  - Environmental, Micro- & Macro- Climatology Impacts
  - Effects of Climate Change on Infrastructure Investment
  - Assurance of Future Resource Availability?

Technology Performance:

- Power Under Production From Large Multi-Arrays ≈ 10 – 40%
  - Inter & Intra Array Effects Not Quantified
  - Power Performance Predictions Unreliable in Complex Terrain
  - International Standards Do Not Adequately Address Large Wind Farm Operating Conditions & Turbine Interactions
- Premature Hardware Failures & Excessive O&M Costs
  - Existing Design Codes & Tools Should Achieve 20 Year Life
  - Premature Failure of Major Components - Gearbox
  - Frequent Operational Faults
  - May Adversely Impact Offshore Installations

What Flow Physics are We Missing?

Complexity of Multi-Array Wakes

Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness.

Multi-Array Wakes Assessment

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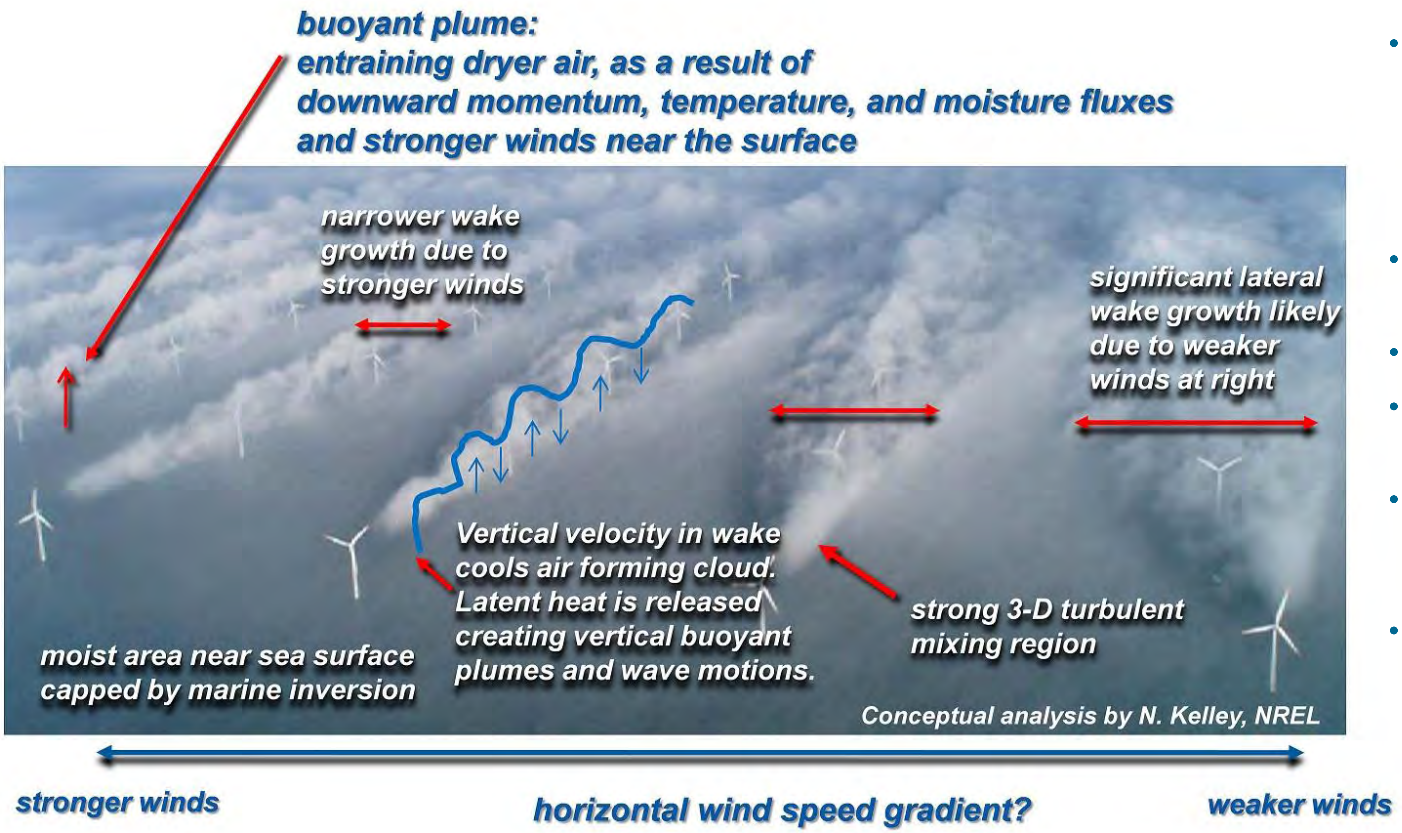

- **Characteristic Dimensional Scales equivalent PBL**
  - **300 Meters Height**
  - **Multiple Kilometers Length & Width**
- **Wake Interaction Drives Turbine Performance**
- **Strong 3-D Inflow Turbulence**
- **Full Quantification of Inflow-Wake interaction Required**
- **Plant Performance Affected by Vorticity Coherence Driven by PBL Stability**
- **Requires Coupled Modeling with Control at the Individual Turbine Level to Assess Causal Relationships**

Stability	Array Efficiency	% occurrence (2005)
Unstable	74%	44.2%
Neutral	71%	30.4%
Stable	66%	25.4%

[1] L. E. Jensen. Array Efficiency at Horns Rev and the Effect of Atmospheric Stability, Dong Energy Presentation, 2007.
[2] R. Barthelmie, D. Cabezon, E. Politis. UpWind Wp8, Deliverable D8.1, Wake Measurements Used in the Model Evaluation, 2008.

Wind Farm Simulation Capability

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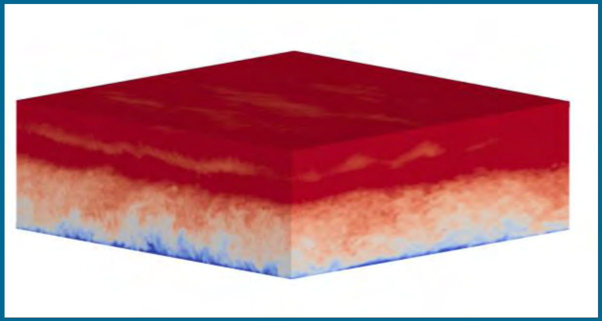
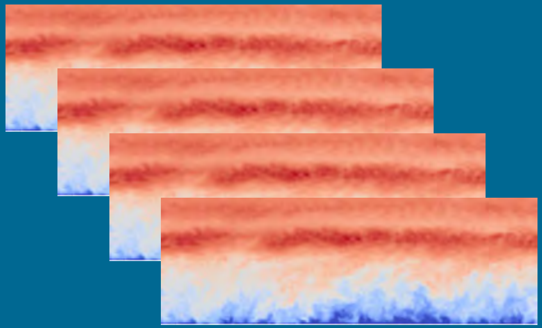
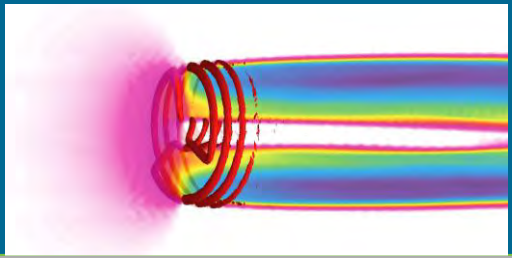
Precursor ABL Simulation Using LES

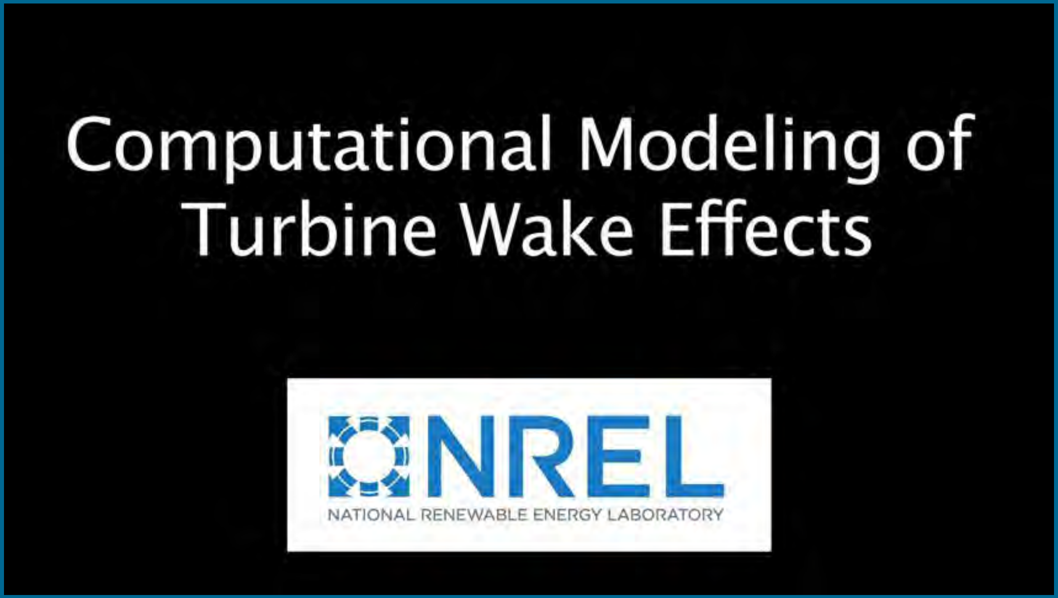


Introduced as Inflow Boundary Condition



Apply an array of actuator line models to wind farm domain



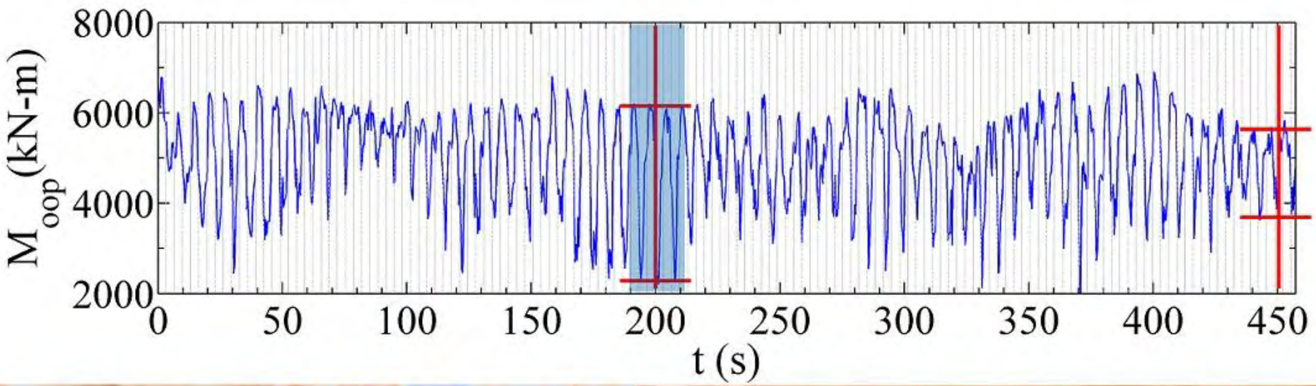


Existing Modeling Capability (Open Foam)

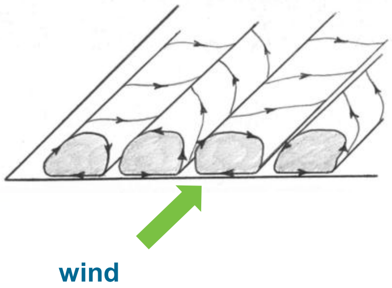
- **NREL 5 MW Turbine Used as Baseline**
  - Rotor Control at Individual Turbine Level
  - 126 meter rotor diameter
  - Cell Size At Blade ≈ 2 meters
- **LES Simulation Characterizing Inflow Boundary Layer**
  - Currently limited to flat terrain
- **Capturing Turbulence / Turbine Interaction on Load and Energy Production**
- **Wind Plant / PBL Interaction Not Captured**
- **SNL Red Mesa Computing Cluster**
  - 512 Processors, 30 Million Cells, 5 day run time, 8 min Simulation
- **Full Model of Horn's Rev Using Simplified Approach Now Possible**

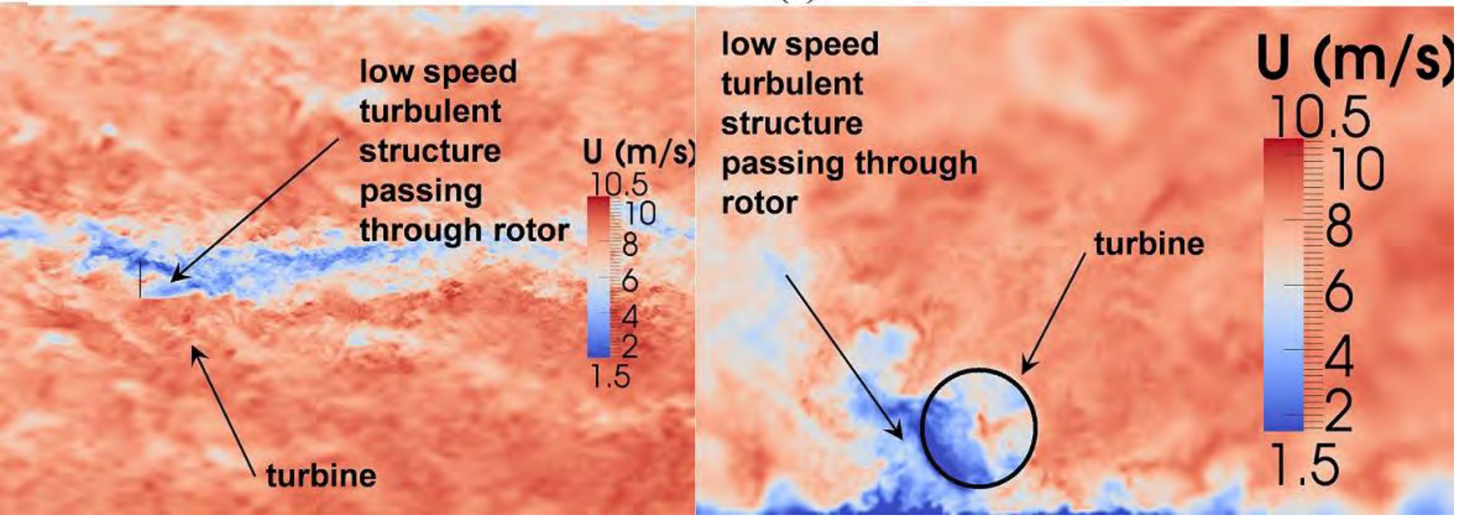
Loads Driven by Turbulence

Root Blade Bending Moment



Moderately unstable condition has updrafts and downdrafts aligned with flow indicative of roll cells





- LES Models Capturing Simple BL Physics Including Roll Cell Formation
- Linkages Exist Between BL Stability & Rotor Load
- Clear linkage between Atmospheric conditions and performance
- Ingestion of Coherent Turbulence Fatigue Load Driver
- HPC Would Provide Greater Fidelity, Coupled Turbulence Models, BL Physics & System Response

Wind Energy Fundamental Science Issues Requiring HPC

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HPC Code Development for Predictive, Rational Design and Operation Supporting High Penetration Wind Energy

- **Wind & Solar Resource Assessment as a Strategic National Energy Resource**
  - ➢ Guide the Strategic Development & Deployment of Future Infrastructure – Generation & Transmission
- **Weather Driven Energy Forecast Models - Coupled Wind & Solar**
  - ➢ Integrated Monitoring, Forecast, Generation, Load Flow & Operational Dispatch
- **Quantify Potential Effects of High Penetration Scenarios**
  - ➢ Climate change Sensitivities
  - ➢ Macro & Micro Climatology Impacts
  - ➢ Insure against trading carbon alleviation for unknown consequences
- **Characterize Inflow and Outflow Resource**
  - ➢ Boundary Layer Processes, Stability, Marine & Nocturnal Formation
  - ➢ Atmospheric turbulence
  - ➢ Flow separation in complex terrain
  - ➢ Air/Sea Boundary Conditions & Wave Interaction
  - ➢ Inter & Intra Array Wake Effects
- **Coupled Physics Models Inflow / Wind Plant Interaction / Grid Response**
  - ➢ Energy production optimization and grid integration
  - ➢ Wind Plant Operation & Control Strategy Development
- **Establish the Design Criteria for Future Turbine & Plant Innovation -**
  - ➢ Individual blades and gearboxes, materials.
  - ➢ Multi-turbine arrays.
  - ➢ Mesoscale atmospheric models.
  - ➢ Wind/Wave models.
  - ➢ Inter/intra plant dynamics

Repower 5MW Demonstration at Beatrice Four-pile jacket

Classic Coupled Multi-Scale, Multi-Physics Problems

Wind Plant Scientific Questions Requiring HPC

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Turbine Scale Dynamics:

- Characterize Isolated Turbine Inflow
- Quantify Ingestion of Wake from Upwind Turbines & Atmospheric Turbulence
- Quantify and Predict Extreme Inflow Events
- Aeroelastic & Control Dynamics
- Coupled Non-Linear Response

Wind Plant Performance & Array Effects:

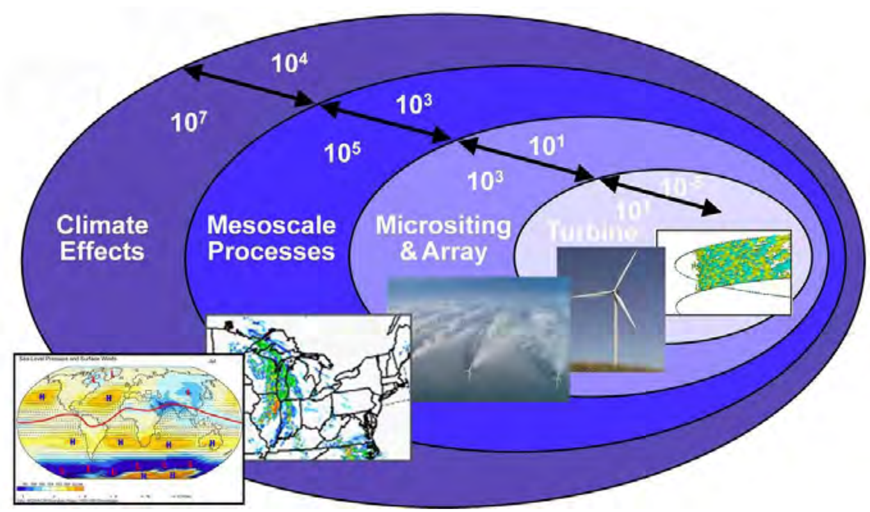
- High Fidelity Turbine Wake Models
- Embedded Turbine Control – Wake Modification
- Quantify Ingestion of Wake from Upwind Turbines & Atmospheric Turbulence
- Quantify and Predict Extreme Inflow Events
- Aeroelastic & Control Dynamics
- PBL Parameterization for Wind Plant Modeling
- Wind Plant Interaction Dynamics with PBL

Mesoscale Processes & Weather Monitoring:

- Mesoscale Models With Accurate Prediction for Wind Prediction
- Incorporation of Relevant Flow Physics & Parameterization
  - Atmospheric Turbulence Structure & Coherence
  - Boundary Layer Development & Complex Terrain
- Forecasting Technology Development for Siting & Grid Operations
- Extreme Events, Ramps, Nocturnal & Marine Jets, Hurricanes
- Develop and deploy new instruments and observational strategies

Regional Impacts:

- Predict changes in future wind resources
- Discern interactions between wind plants affecting macro- and microclimates



Potential Follow-On Collaborations

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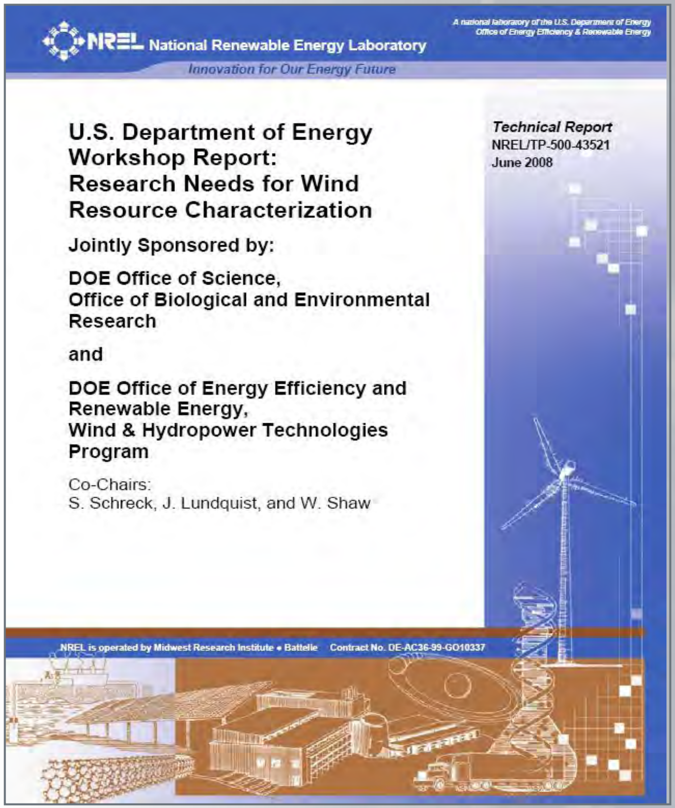
- **Collaborative Workshops**
  - **Defining the "Grand Challenge" for HPC in National High Penetration Scenarios**
  - **Reconvene 2008 workshop to review accomplishments & establish new goals**
  - **Computational development & research requirements to support integrated wind plant performance modeling**
- **Internal Working Groups:**
  - **Identify topic areas of mutual interest and collaboration in HPC**
  - **Review existing DOE/WWP computational capabilities**
  - **Develop long-term plans for HPC application**
- **Future Joint FOA Solicitations:**
  - **Exascale Model Development**
  - **Field Validation Programs**



Questions?

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