



Wind Energy Aerodynamics – Rotor, Wake, and Wind Plant



**Stanford Seminar for
Faculty and Students
Stanford, CA**

October 12, 2010

Scott Schreck, PhD

**NREL's National Wind
Technology Center**

NREL/PR-5000-49705

National Wind Technology Center

- Turbine technology since 1977 (SERI)
- Development of design and analysis codes
- Pioneers in component and field testing
- Unique test facilities
 - Blade Testing
 - Dynamometer
 - CART turbines
- Modern utility-scale turbines
- Approx. 160 staff on-site
- Budget approx. \$35M
- Many CRADAs with industry
- Leadership roles for international standards



PIX #15847

Critical Elements for 20% Scenario

300 GW by 2030

- 80% Land 20% Offshore
- Improved Performance
 - 10% reduction in capital cost
 - 15% increase in capacity factor
 - Address Wind Farm underperformance
- Mitigate Risk
 - Reduce O&M costs by 35%
 - Foster the confidence to support continued 20% per year growth in installation rates from now until 2018
- Enhanced Transmission System (AEP)
 - \$60 billion cost estimate over 20 yrs
 - 19,000 mi of line
 - Supports 200-400 GW addition
- Policy, Communication & Outreach
- Infrastructure Development

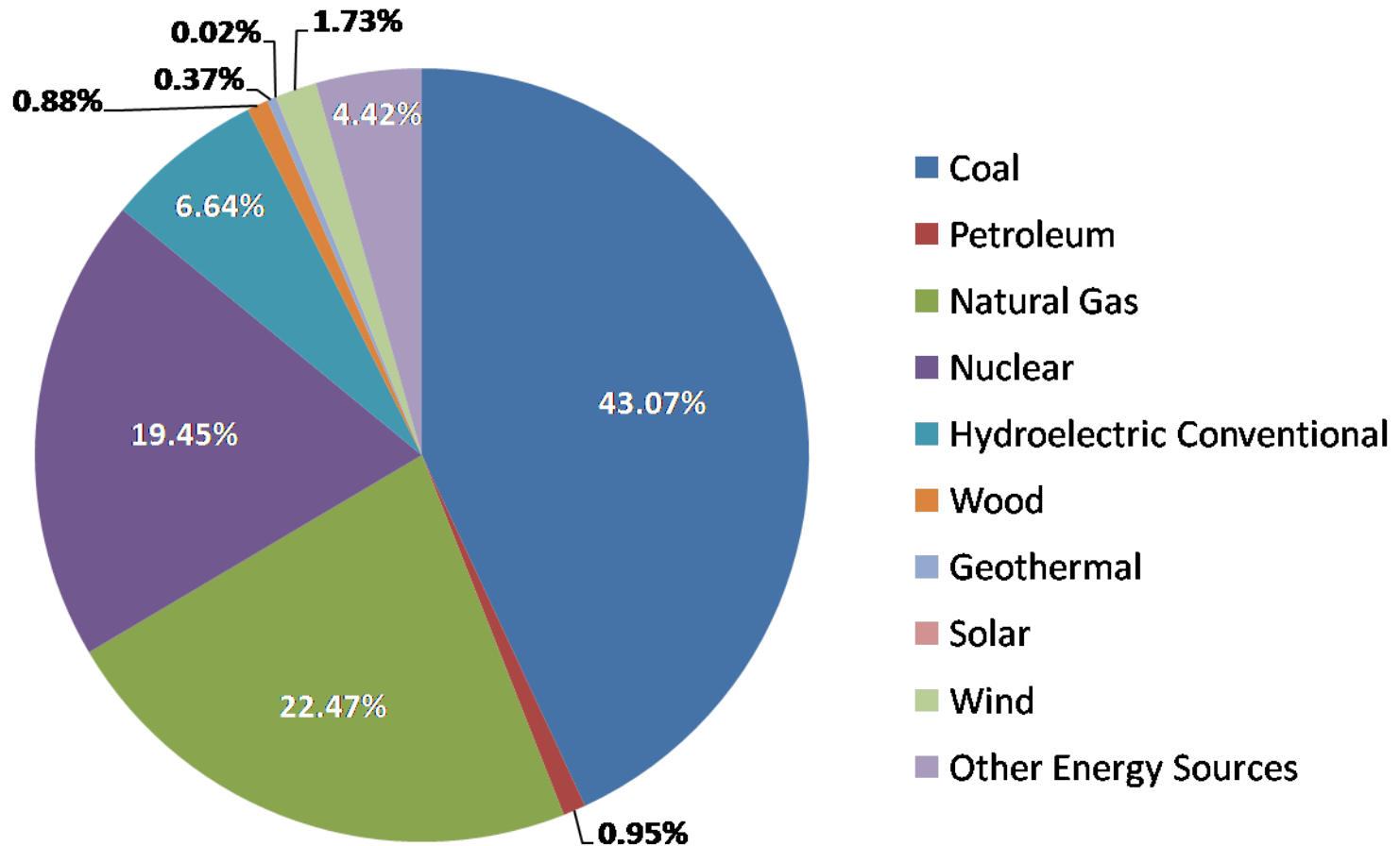
U.S. Department of Energy
Energy Efficiency
and Renewable Energy
Enriching your prosperous future where energy
is clean, abundant, reliable, and affordable

**ADVANCED
ENERGY INITIATIVE**

20% Wind Energy by 2030
Increasing Wind Energy's Contribution to
U.S. Electricity Supply

July 2008

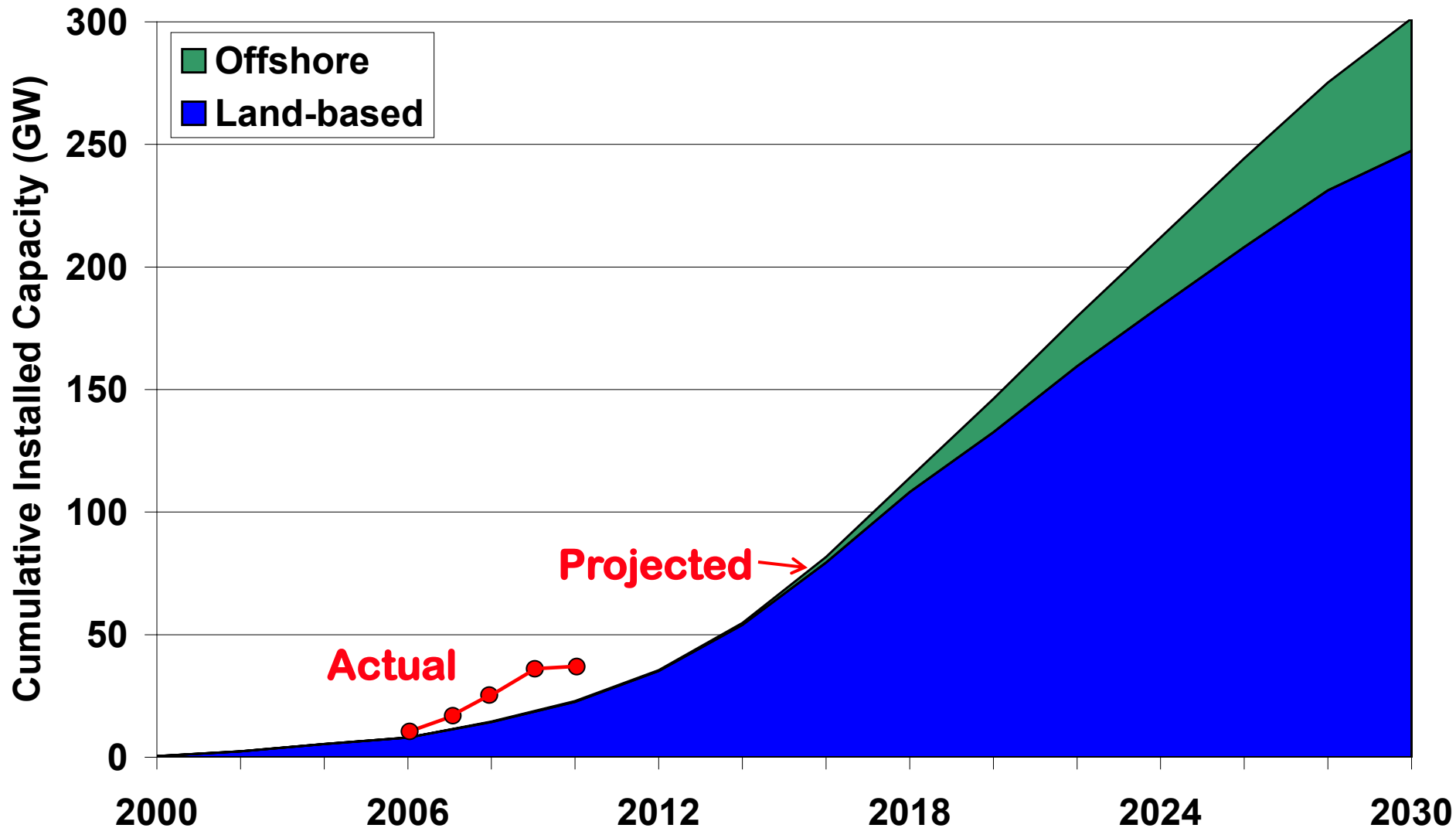
Electrical Power Generation by Source



3700 TWh Annually
(0.42 TW Continuous energy use)

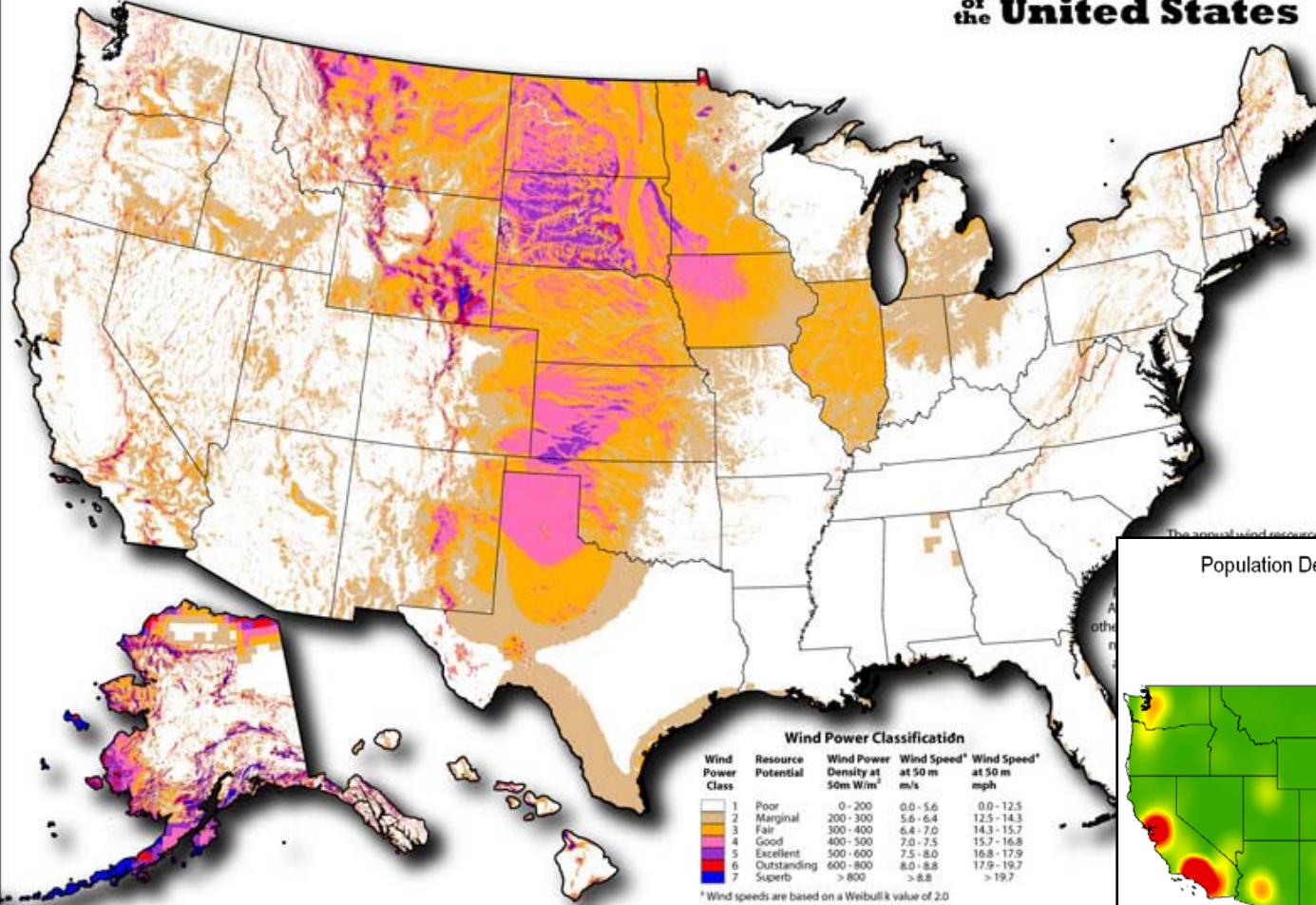
Source: *Electric Power Monthly*, March 15, 2010
http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html

20% Requires 300 GW - Land & Offshore



Wind Resource Distribution

Wind Resource (50m) of the United States



Wind Power Classification

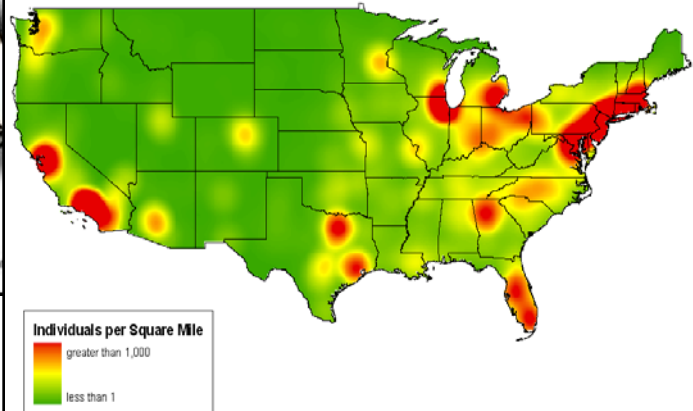
Wind Power Class	Resource Potential	Wind Power Density at 50m W/m ²	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
1	Poor	0 - 200	0.0 - 5.6	0.0 - 12.5
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

* Wind speeds are based on a Weibull k value of 2.0

Author: Billy Roberts - December 12, 2008

This map was produced by the National Renewable Energy Laboratory

Population Density of the Conterminous United States

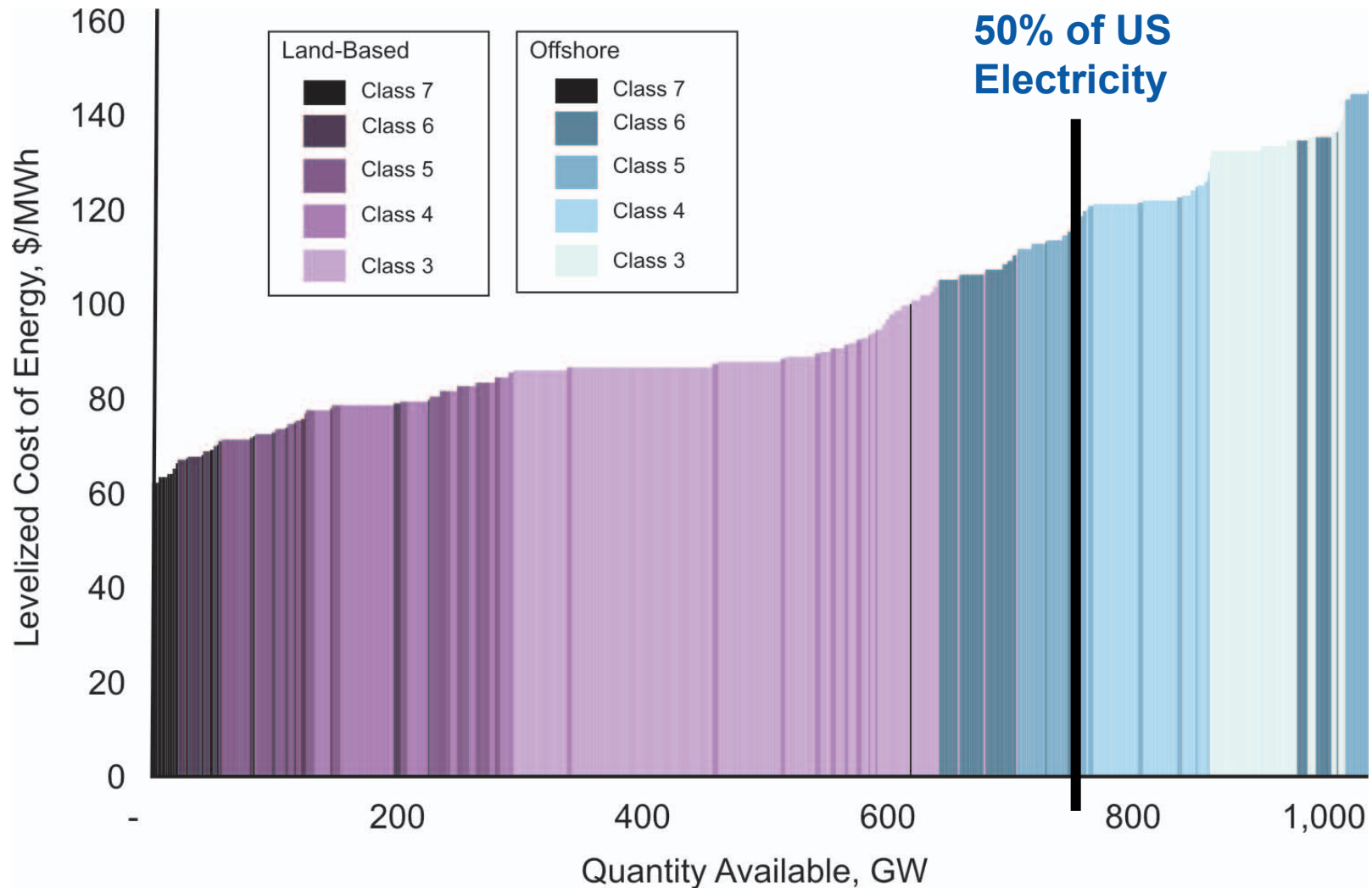


Individuals per Square Mile

greater than 1,000

less than 1

How Much Wind is Available ... Really?

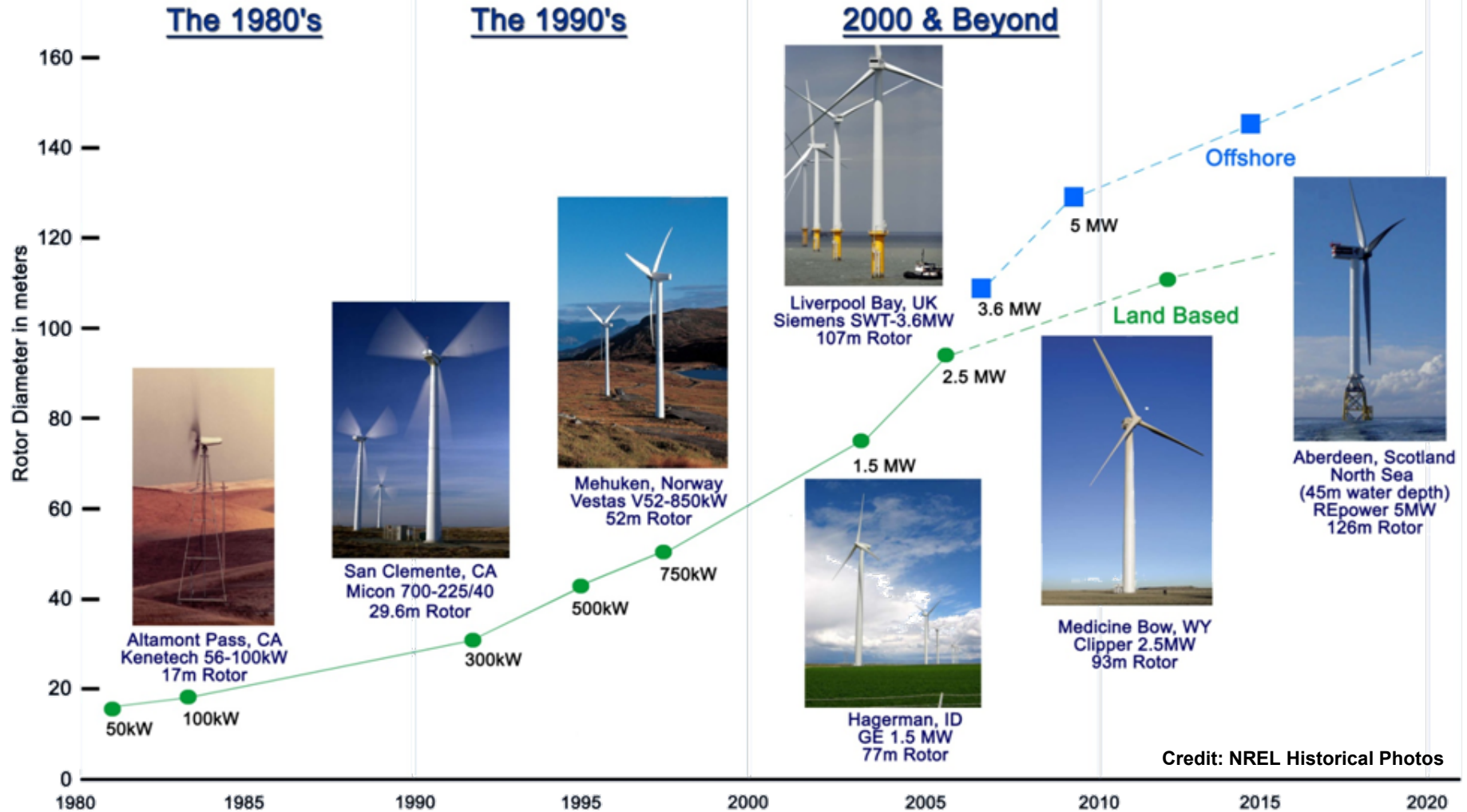


Excludes PTC, includes transmission costs to access 10% existing electric transmission capacity within 500 miles of wind resource.

Source: Black & Veatch/NREL

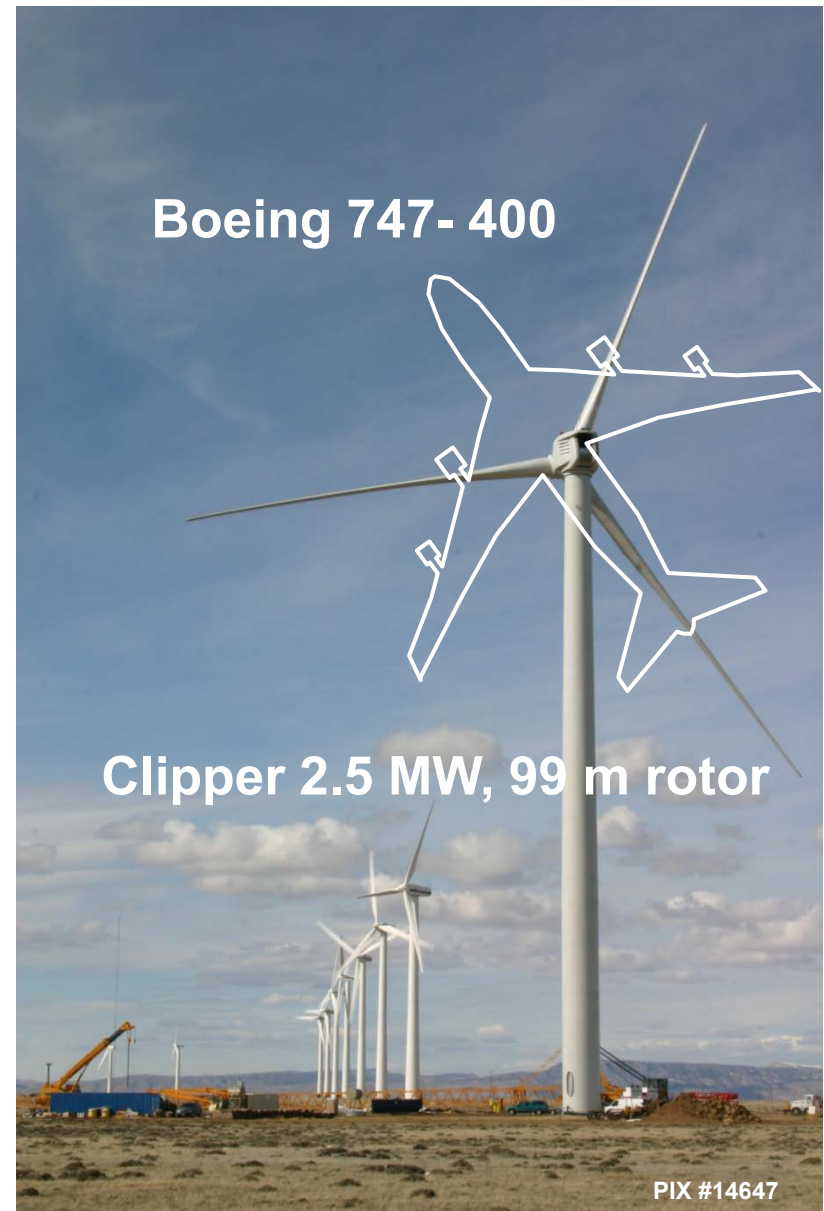
Technology Evolution

Evolution of Commercial Wind Technology



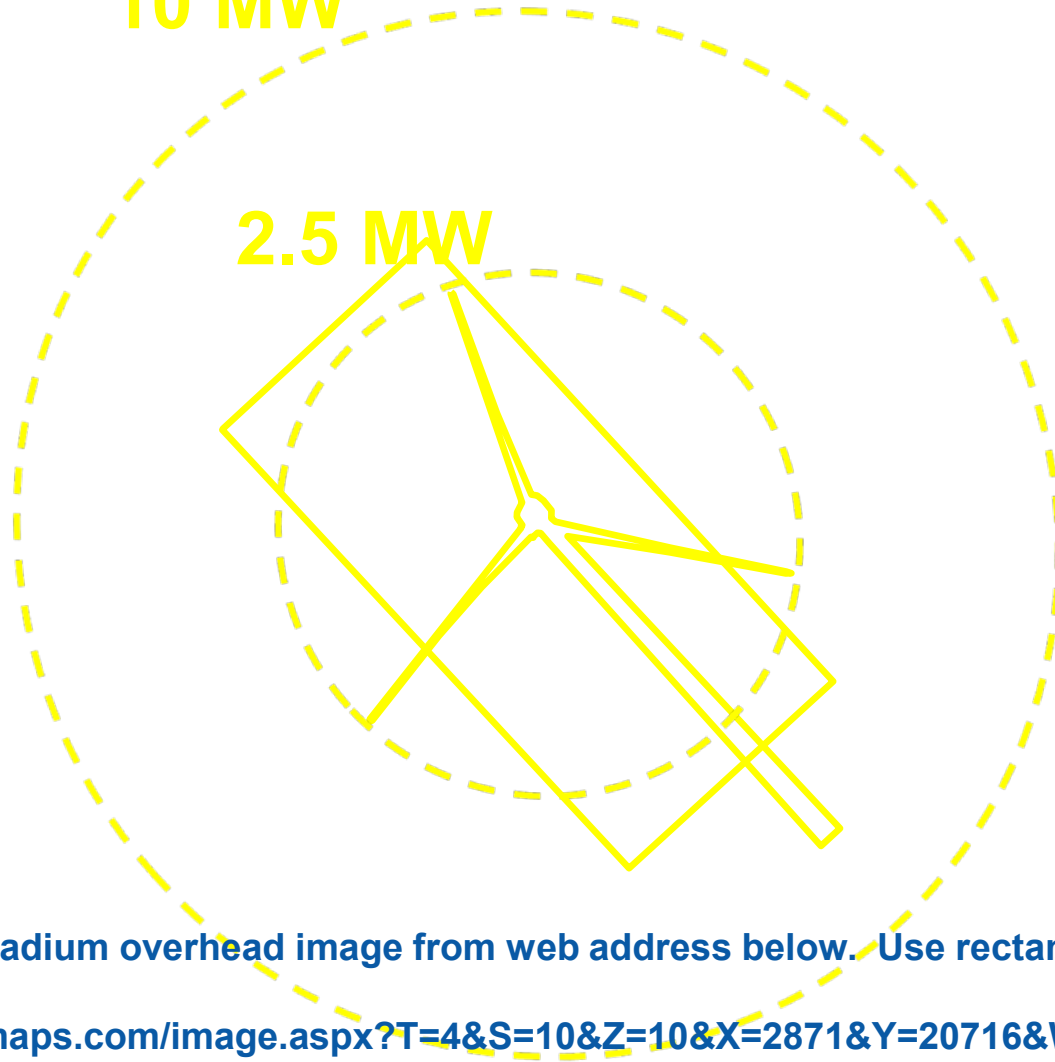
Wind Turbine Scale – Present and Future

- **2.5 MW - typical commercial turbine Installation**
- **5.0 MW prototypes being installed for testing in Europe**
- **Clipper Wind Power developing an 8.5 MW turbine**
- **Most manufacturers have a 10 MW machine in design**
- **Large turbine development programs targeting offshore markets**
- **Development Outpacing Test & Validation Capability**



10 MW

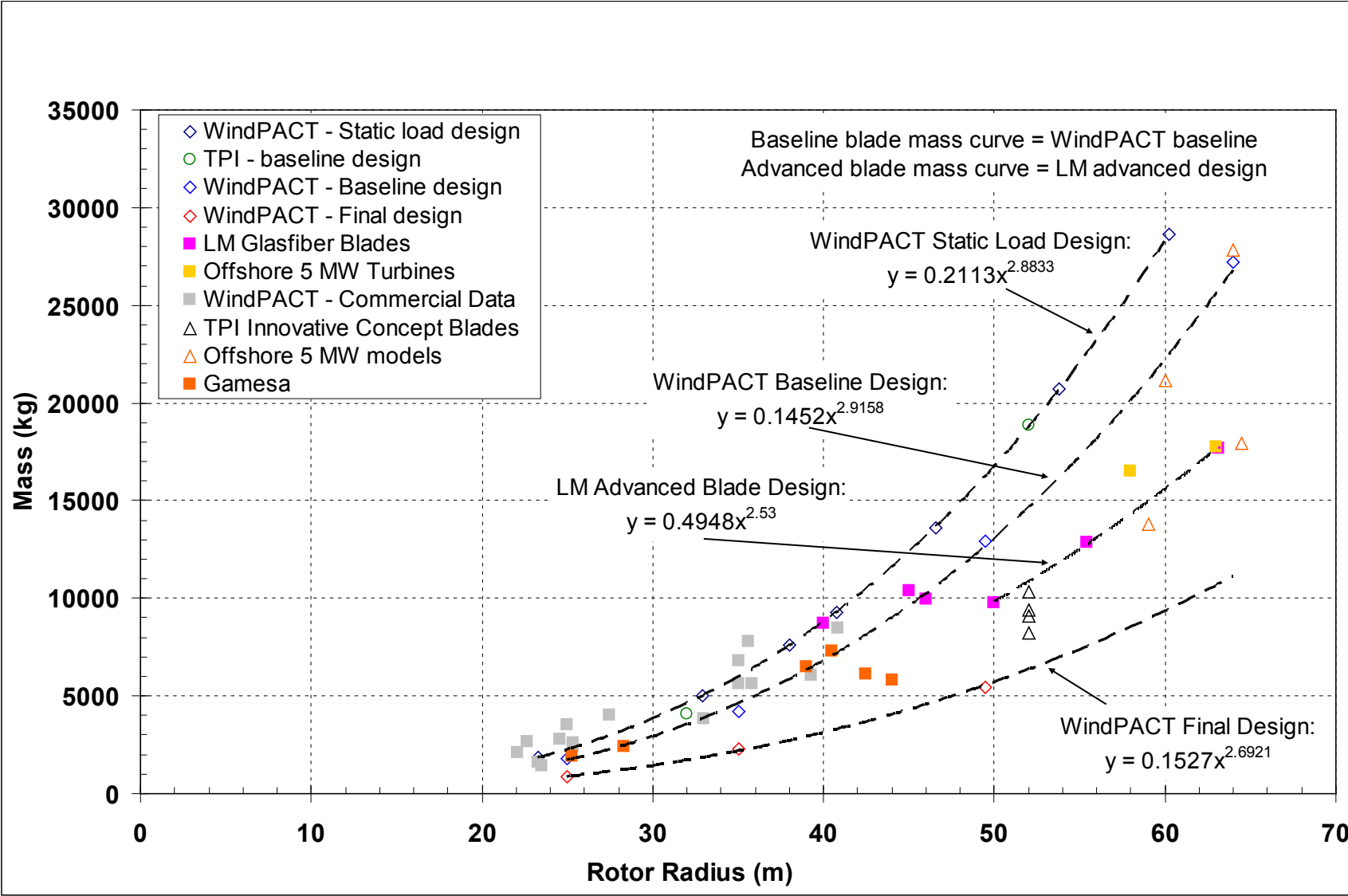
2.5 MW



Stanford stadium overhead image from web address below. Use rectangle above to scale.

<http://msrmaps.com/image.aspx?T=4&S=10&Z=10&X=2871&Y=20716&W=1&qs=Nelson+Road%7cStanford%7cCA&Addr=Nelson+Rd%2c+Stanford%2c+CA+94305&ALon=-122.1601053&ALat=37.4320765>

Structure Size and Weight – Implications



Technology Challenges Remain

Wind plant energy production

– Example

- 200 wind turbines @ 2 MW
- 36% cap factor → 1.26×10^9 kWh/yr
- 5 ¢/kWh, 1% AEP underproduction
- \$630K/year = \$12.6M/plant lifetime

– 1% - 10% underproduction common

Turbine O&M cost prediction

- Blade delamination, cracking
- Gear, bearing failures
- Unanticipated fatigue loading

Wind Turbines vs. Aircraft

- **Overall cost**
 - Aircraft: 600 USD/lb
 - Wind turbine: <6 USD/lb
- **Wing/blade cost**
 - Aircraft: >600 USD/lb
 - Wind turbine: <9 USD/lb
- **Lifetime fatigue cycles**
 - Aircraft: 10^6
 - Wind turbine: 10^8
- **Inspection/maintenance**
 - Aircraft: Daily/weekly
 - Wind turbine: Six months/one year

Fundamental Challenges

Current engineering approach

- Linearized and reduced order
- Partitioned for tractability
- Limited scale range and interaction

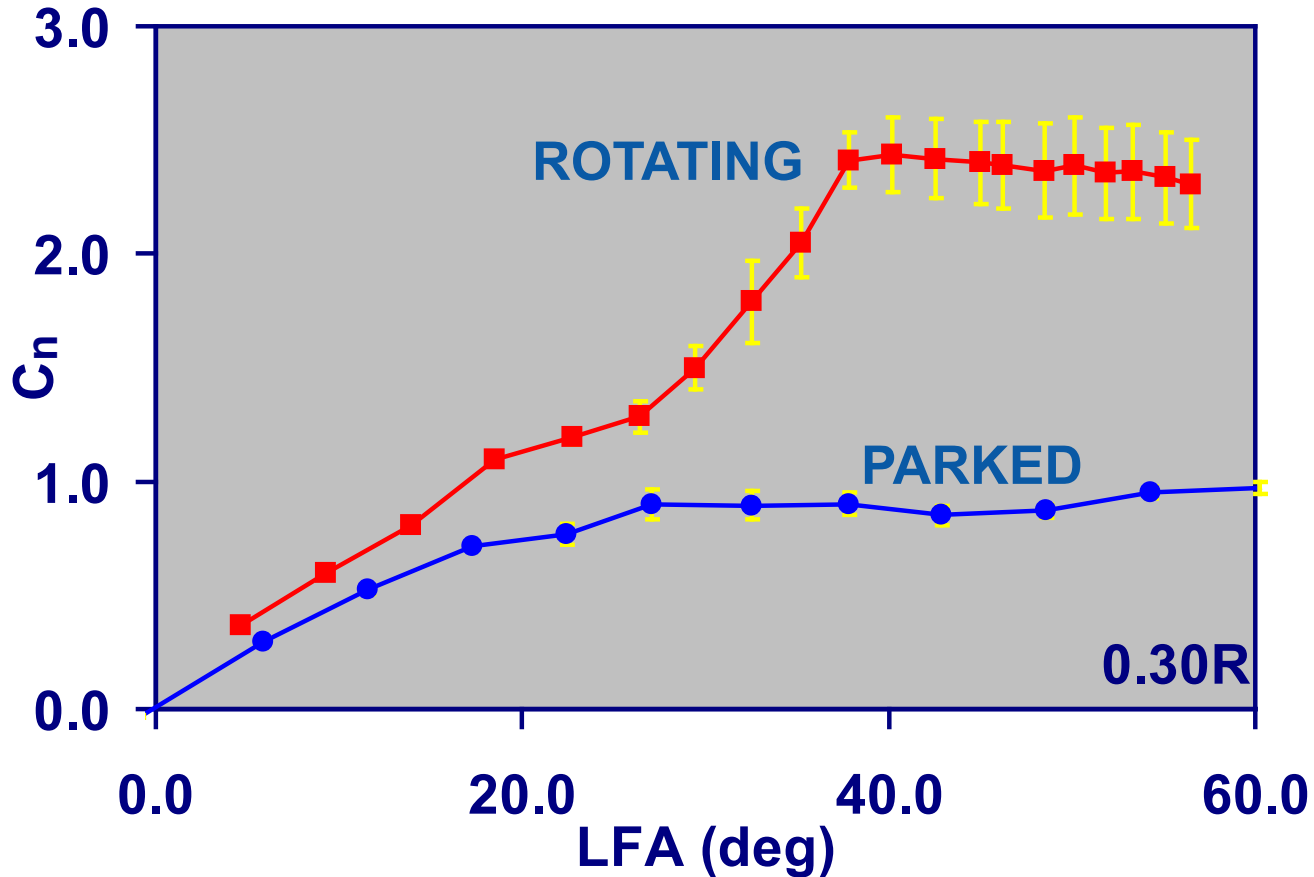
Physics and numerics

- Coupled and nonlinear
- Broad scale range
- Multiple physics

NREL UAE Phase VI Turbine in NASA Ames 80'x120'

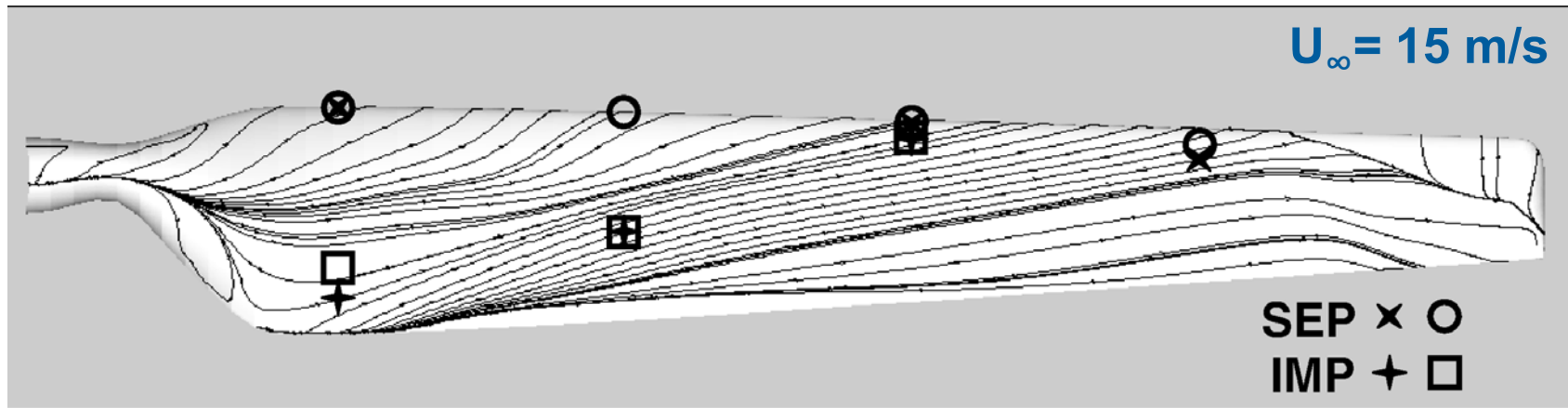


Zero Yaw – Rotational Augmentation



Max rotational augmentation of 3X parked
Deviation same as 15 – 20 % TI, ~10 Hz

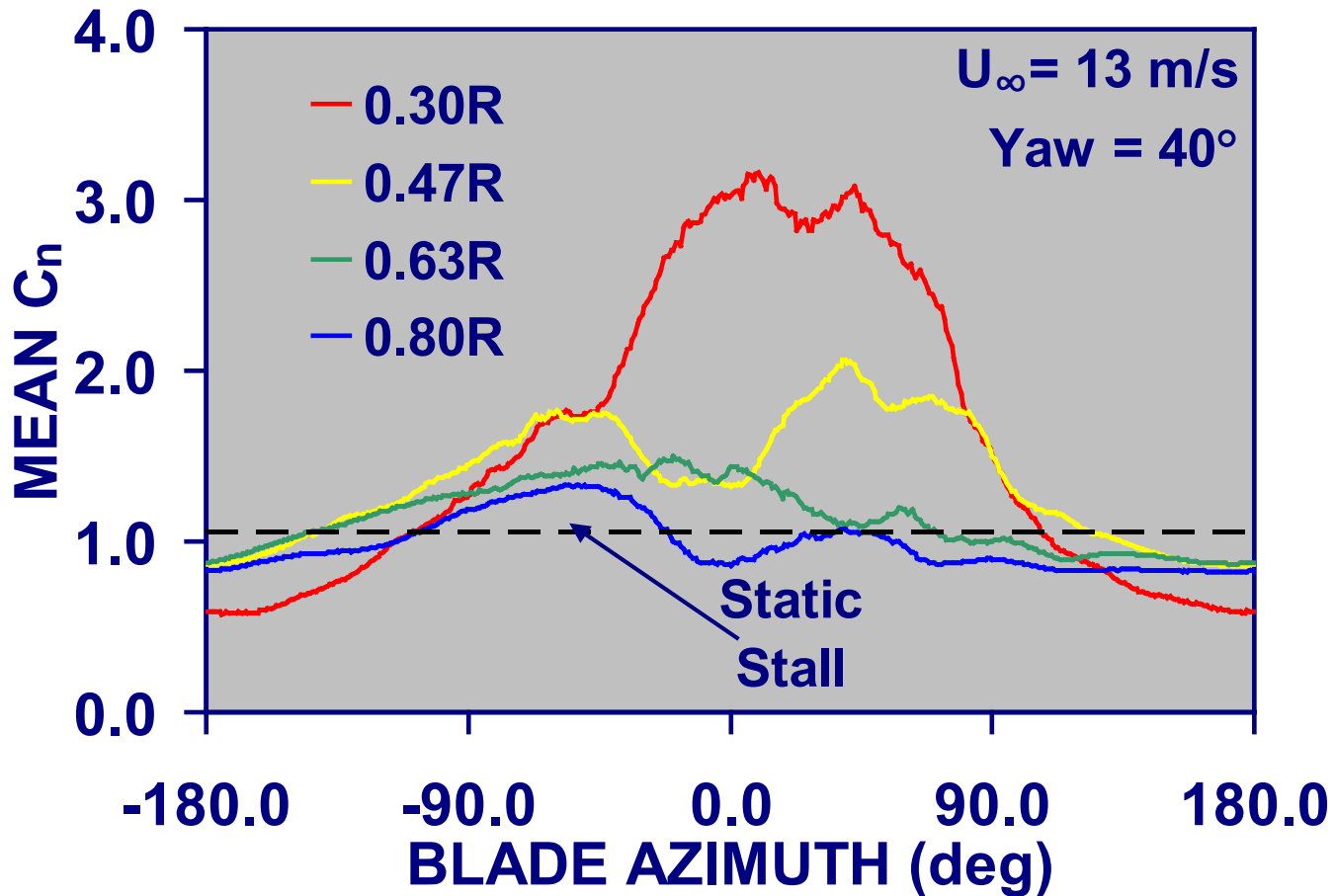
Flow Field Topology



(CFD courtesy of N. Sørensen, Risø National Laboratory)

Off-surface structures 3-D and complex
Topology responsive to operating condition

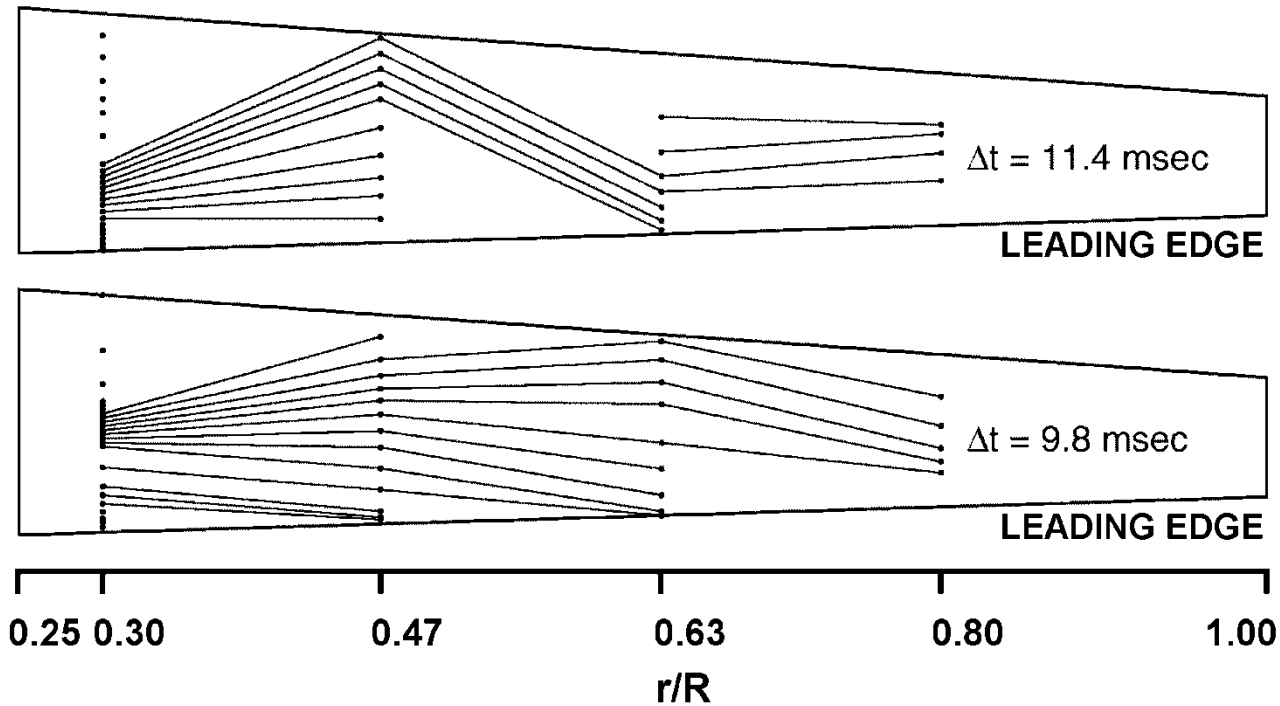
Nonzero Yaw – Dynamic Stall



Mean C_n maxima = 1.5X - 3X static stall levels

Rise times = 0.1 - 0.2 sec (1/8 - 1/4 cycle)

Flow Field Topology

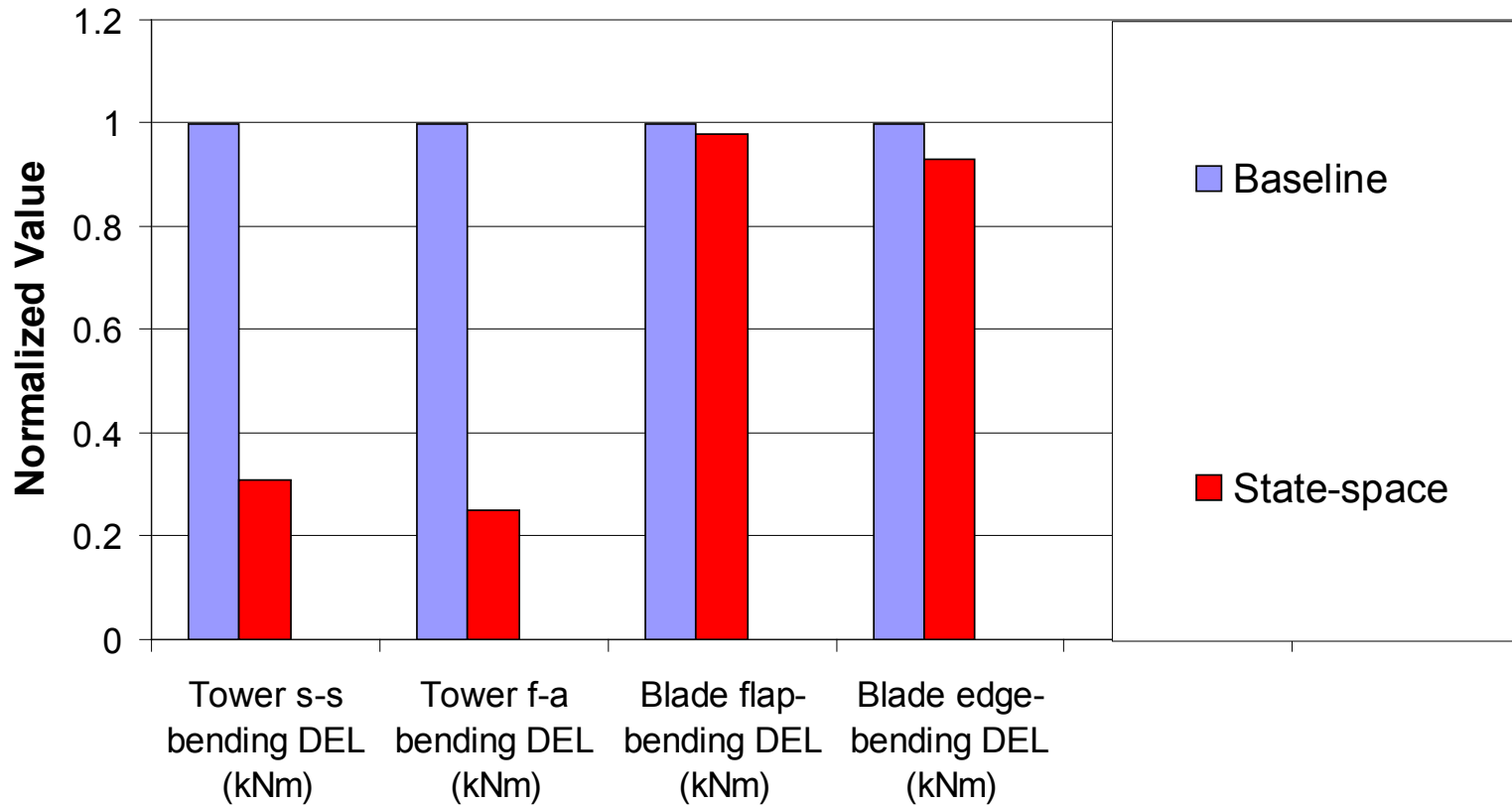


$U_\infty = 13$ m/s
Yaw = 30°

$U_\infty = 15$ m/s
Yaw = 40°

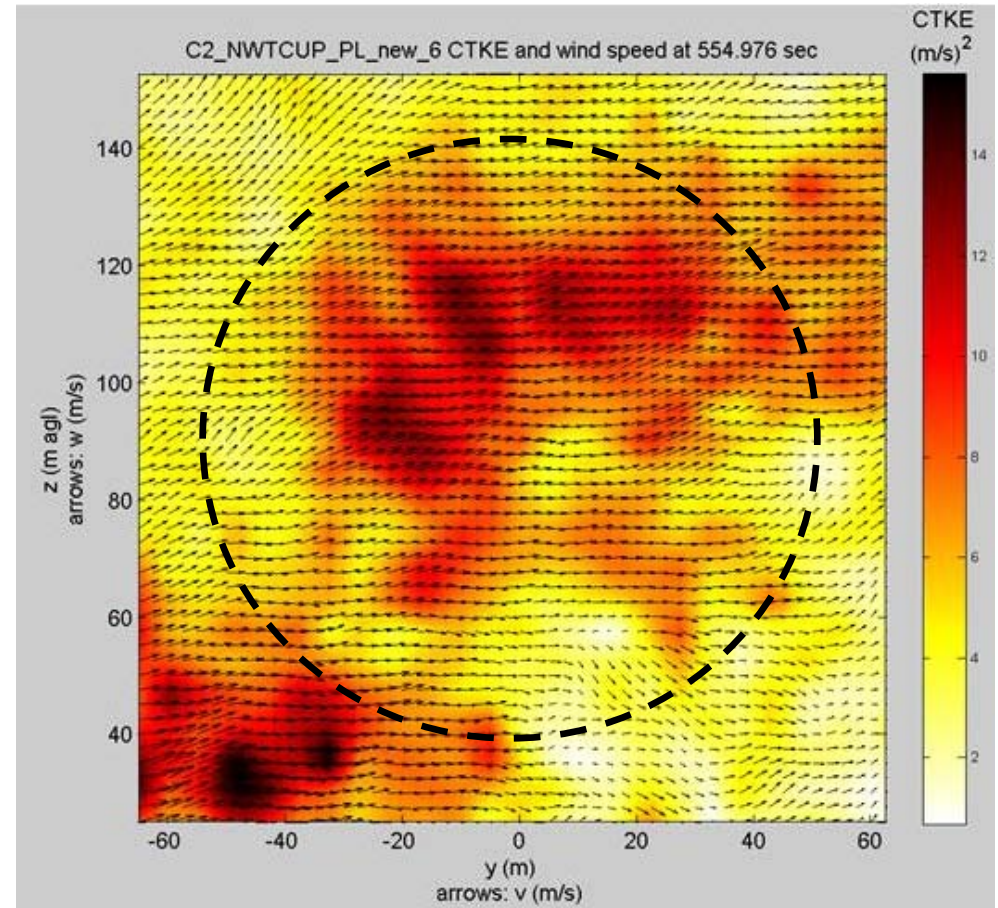
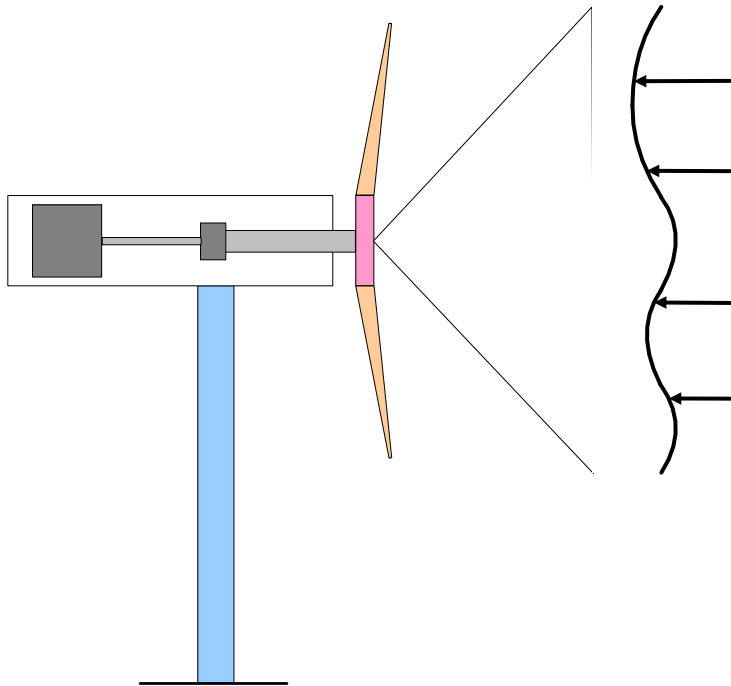
Vortex convection not radially uniform
Operating condition drives 3-D deformation

Control Effectiveness



- Test results for advanced MIMO control
- Integrated blade pitch-generator torque control

Advanced Control – Sensors/Actuators



- Real-time sensing of inflow velocity field
- Independent blade pitch actuation

Implications of Blade Flow Physics

Blade flow fields

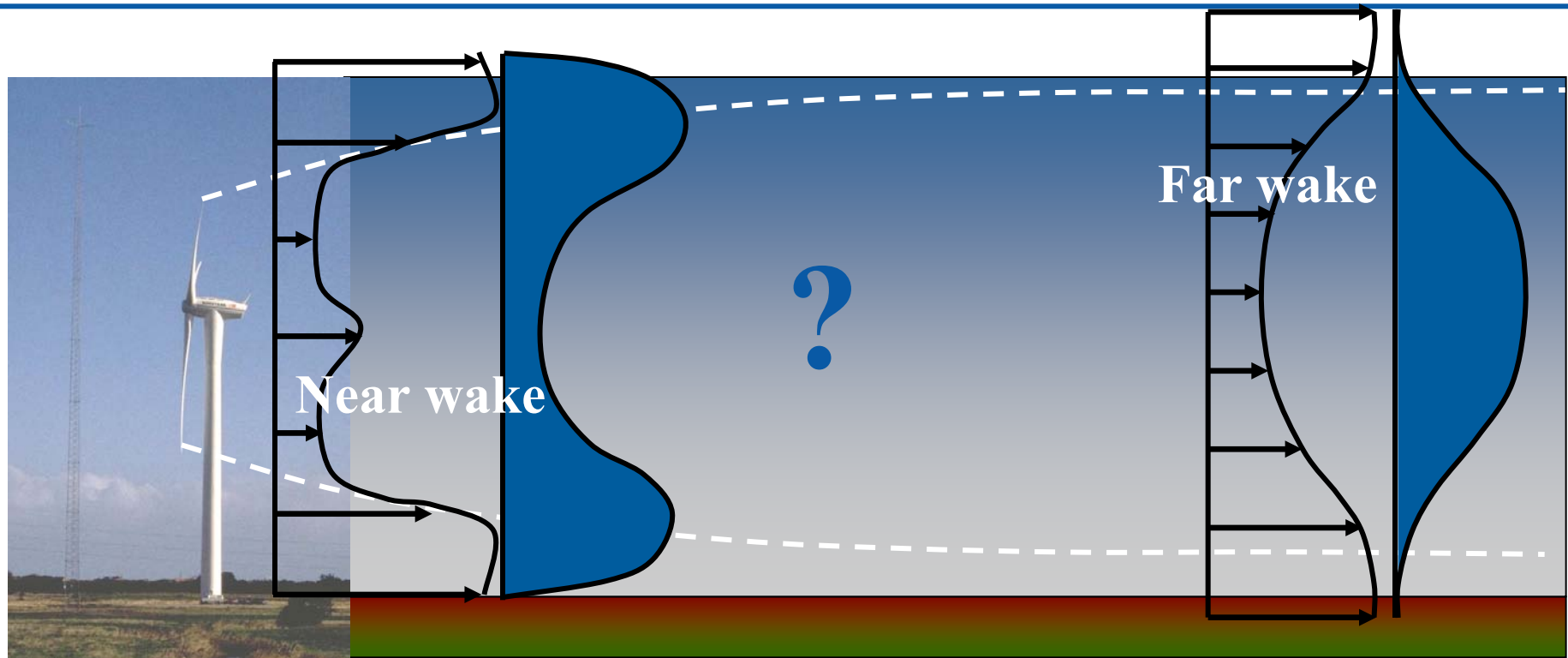
- Amplified loads
- Highly unsteady
- Large bandwidth
- Energetic vortices
- 3-D flow fields
- Commonly occur

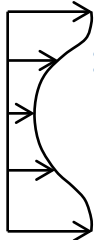
Control impacts


- Bandwidth
- Nonlinearity
- Sensors/actuators
- State identification
- Actuator authority
- Feasibility

Difficult to understand & predict
Challenging to control
Drive COE

Wake Structure Development



 : Axial velocity

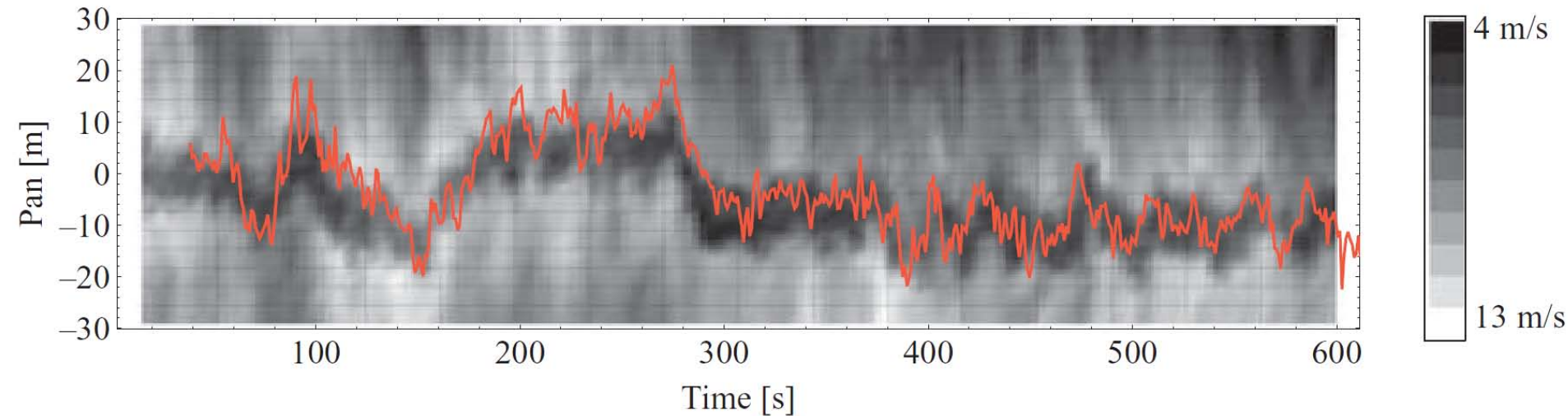
 : Turbulence intensity

Sørensen, EWEC 2007



Danmarks Tekniske Universitet

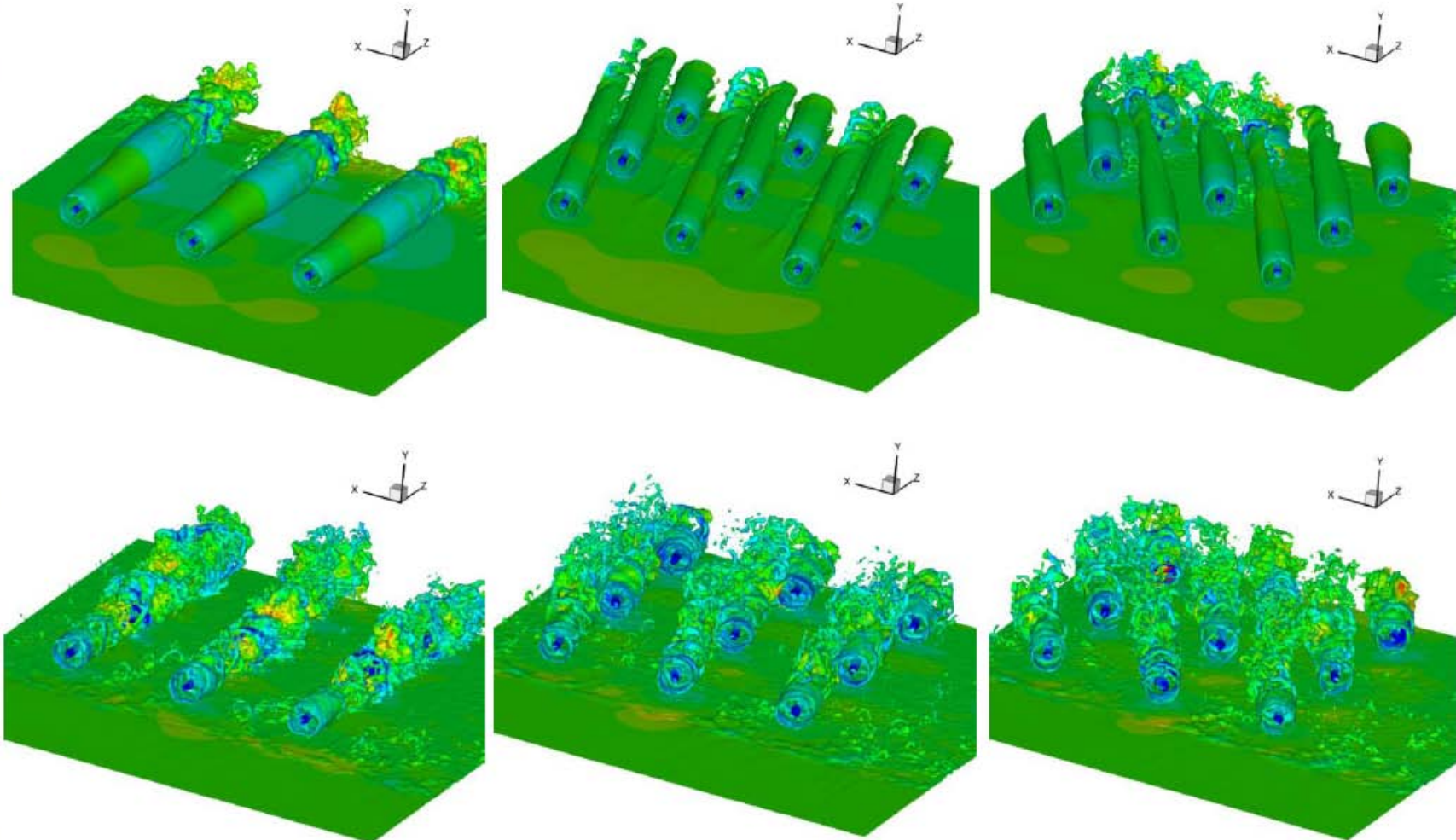
Wake Dynamics – Meandering



LIDAR (gray scale) tracks wake velocity
Model (red) assumes passive transport

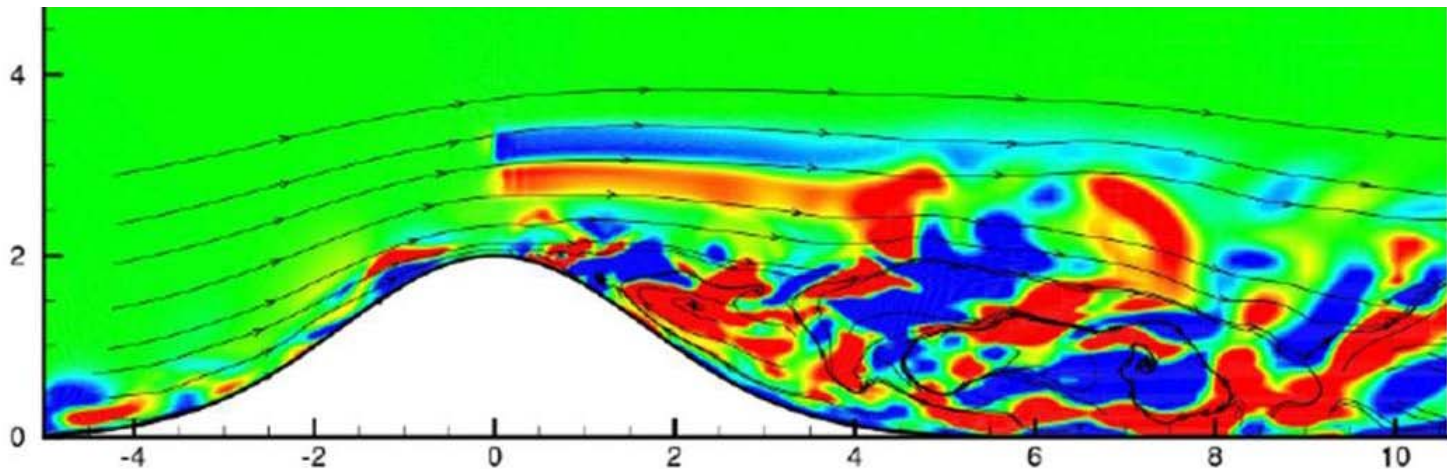
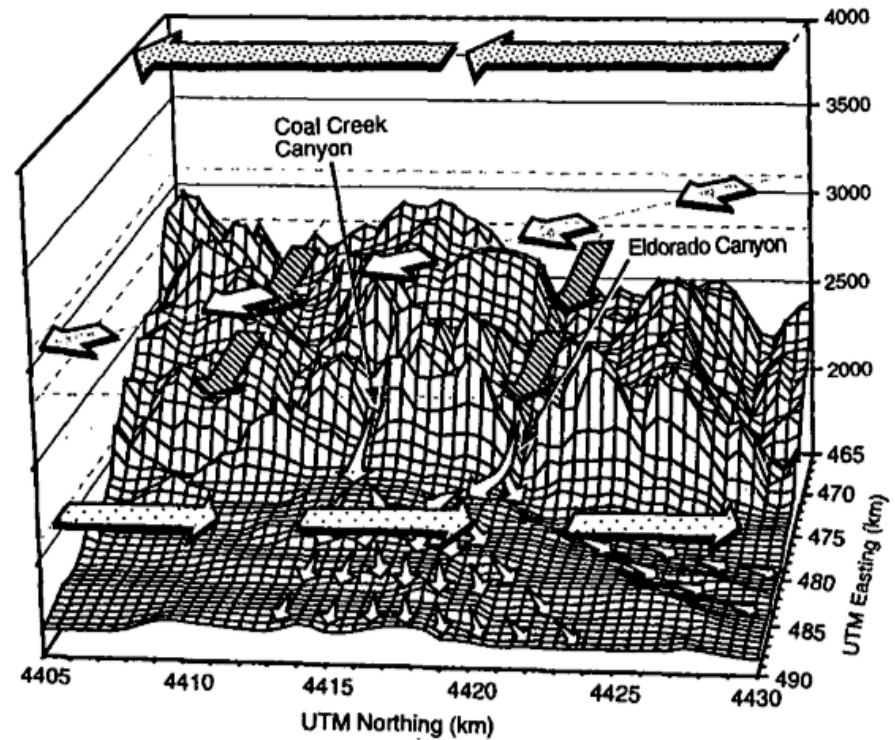
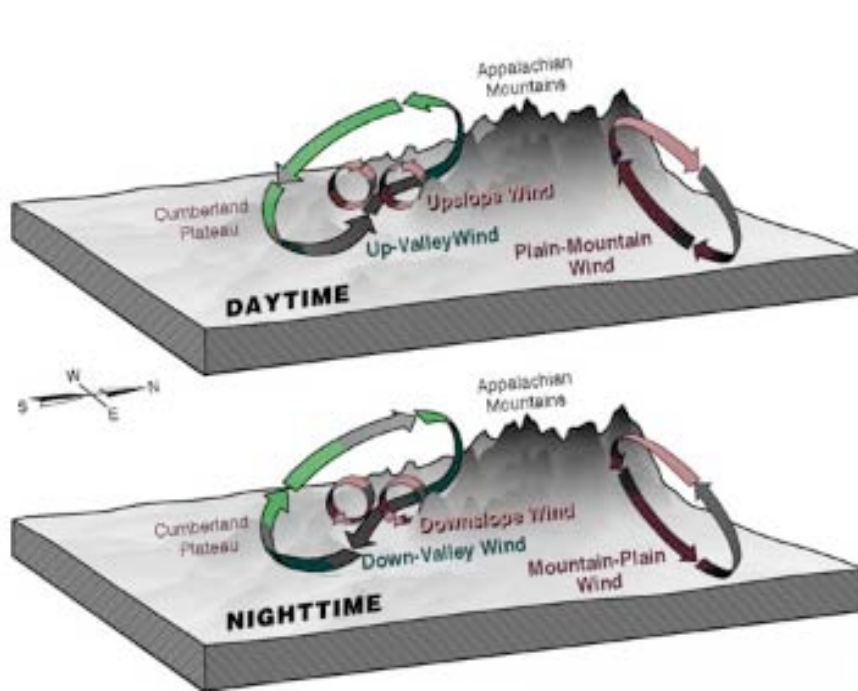
Graphic courtesy of J. Mann, Risoe-DTU

9 turbine park simulation

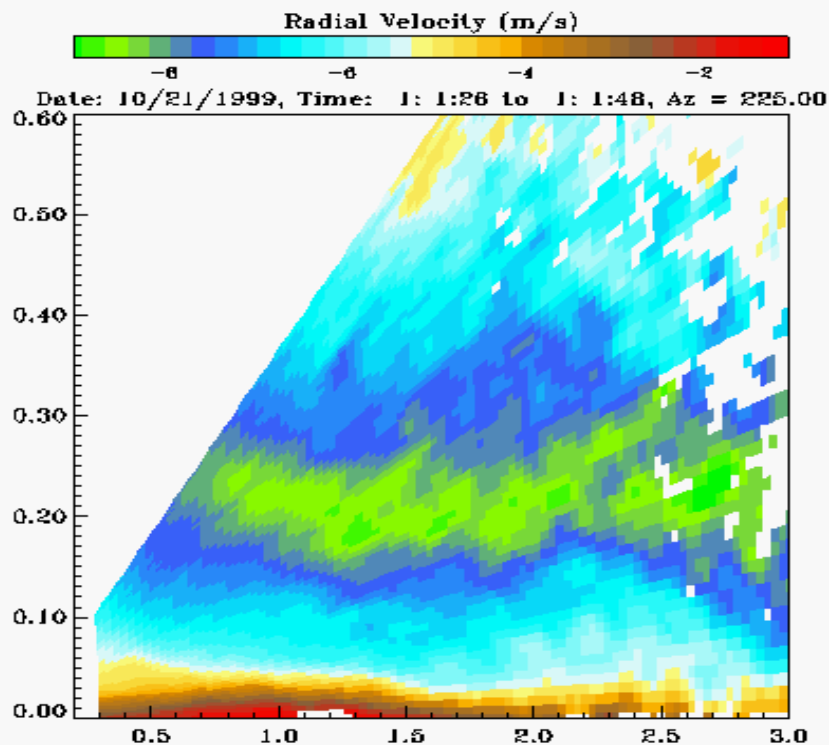
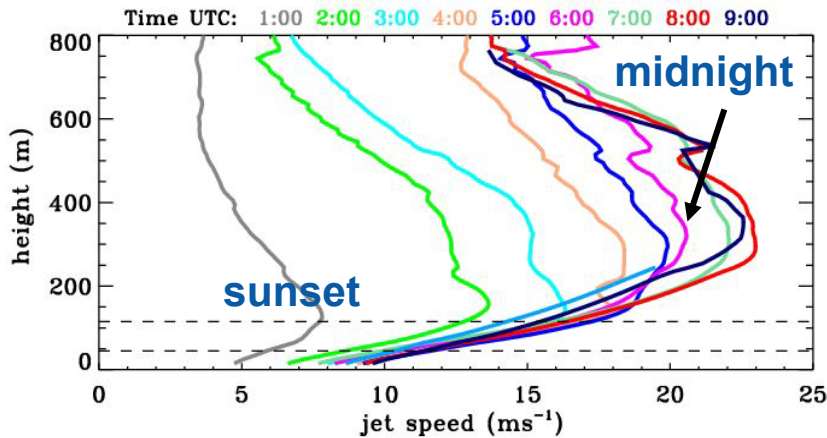


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Complex Topography Effects



Planetary Boundary Layer (PBL)



**Turbine, wind farm, PBL;
similar dimensional scales
Farm / inflow interactions not
quantified
Characterization & prediction
remain an issue**

**Detailed inflow information
required for turbine design and
optimized control**

Diurnal variation

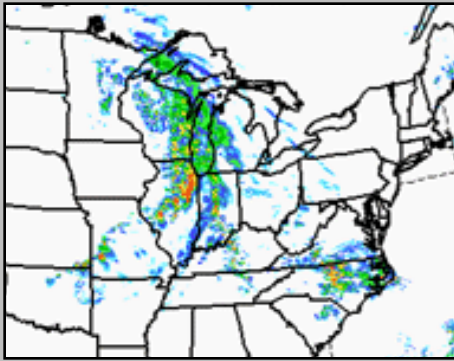
Growing concerns include:

- Quality of the downwind resource
- Microclimatology changes
- Agriculture impacts
- Permitting

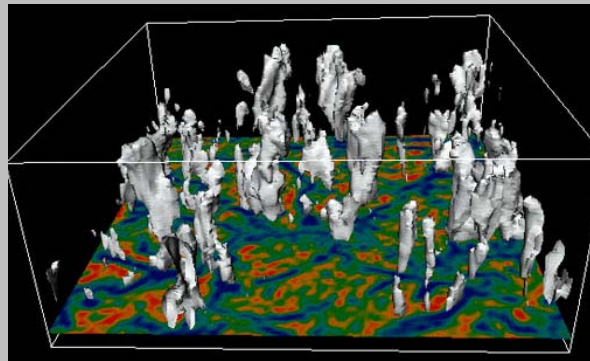
Unification Across Models & Scales

Treating Multi-Scale Flow Interactions Among Models

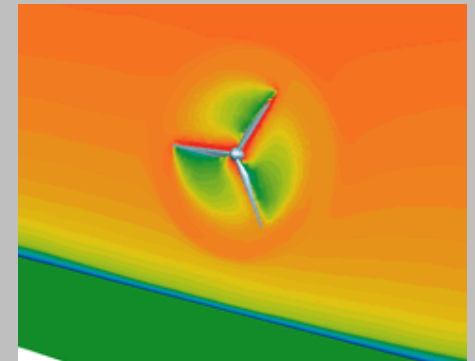
Mesoscale Models



LES Models



CFD Models

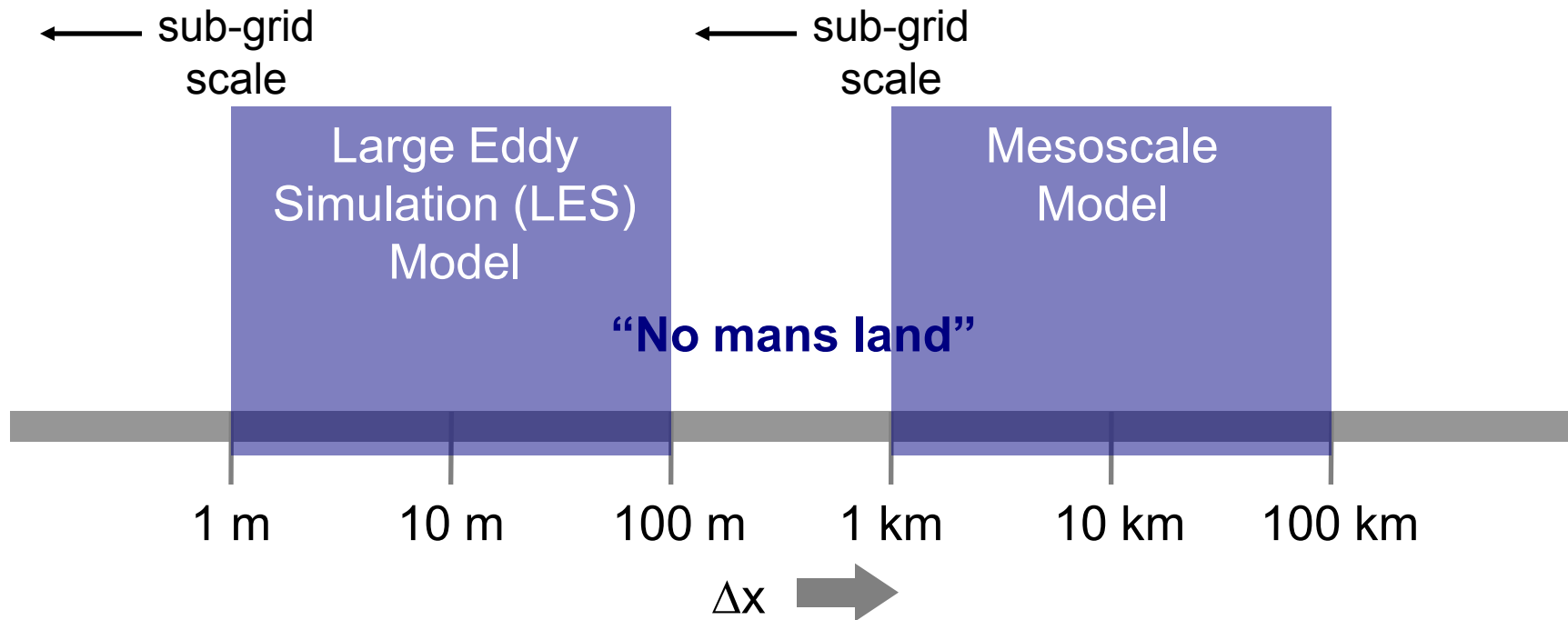


temporal and spatially varying BCs

parameterizations

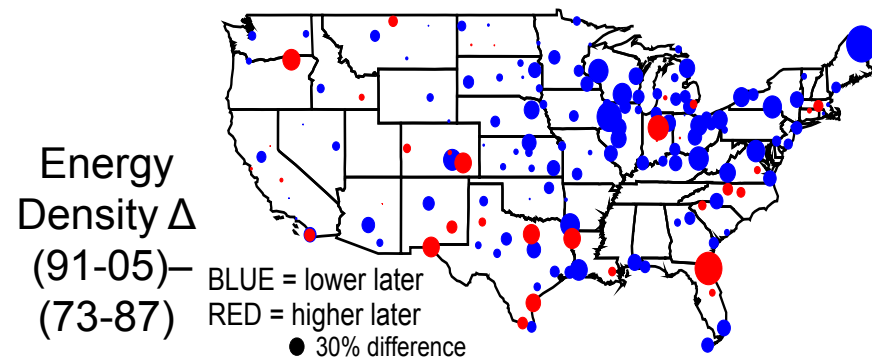
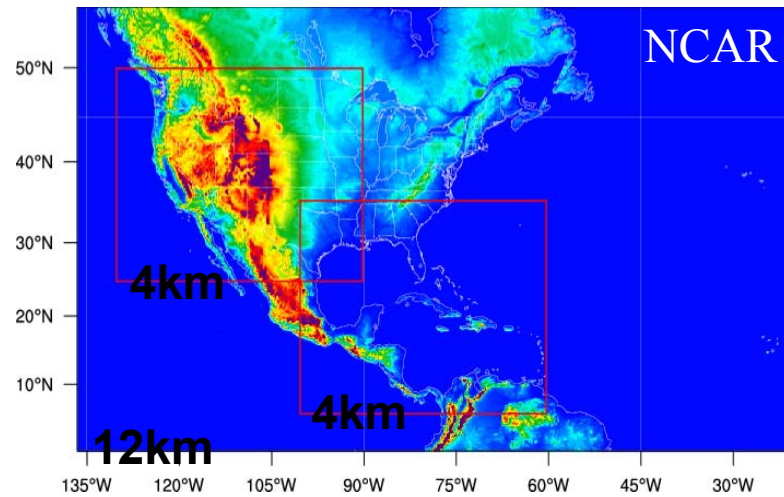
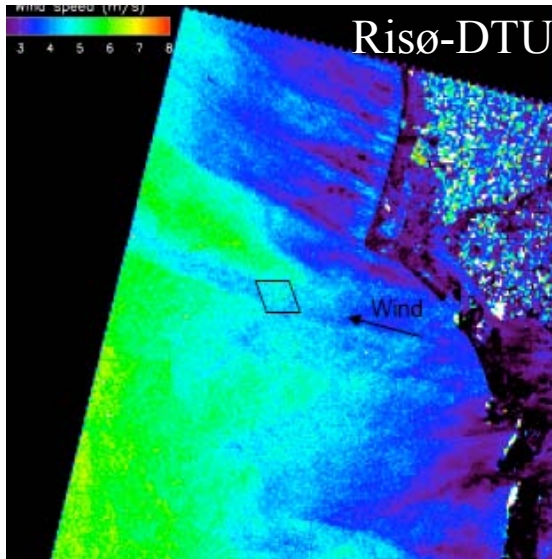
Mesoscale, LES and CFD models normally run separately
LES and CFD models use constant or periodic boundary conditions
Some work already underway in linking these types of models
Include terrain and variable land-use into LES models

PBL Parameterizations



Models cover multiple spatial scales, but not all encompassing
For $\Delta x < 1$ km, but problems exist – e.g., “double booking” turbulence

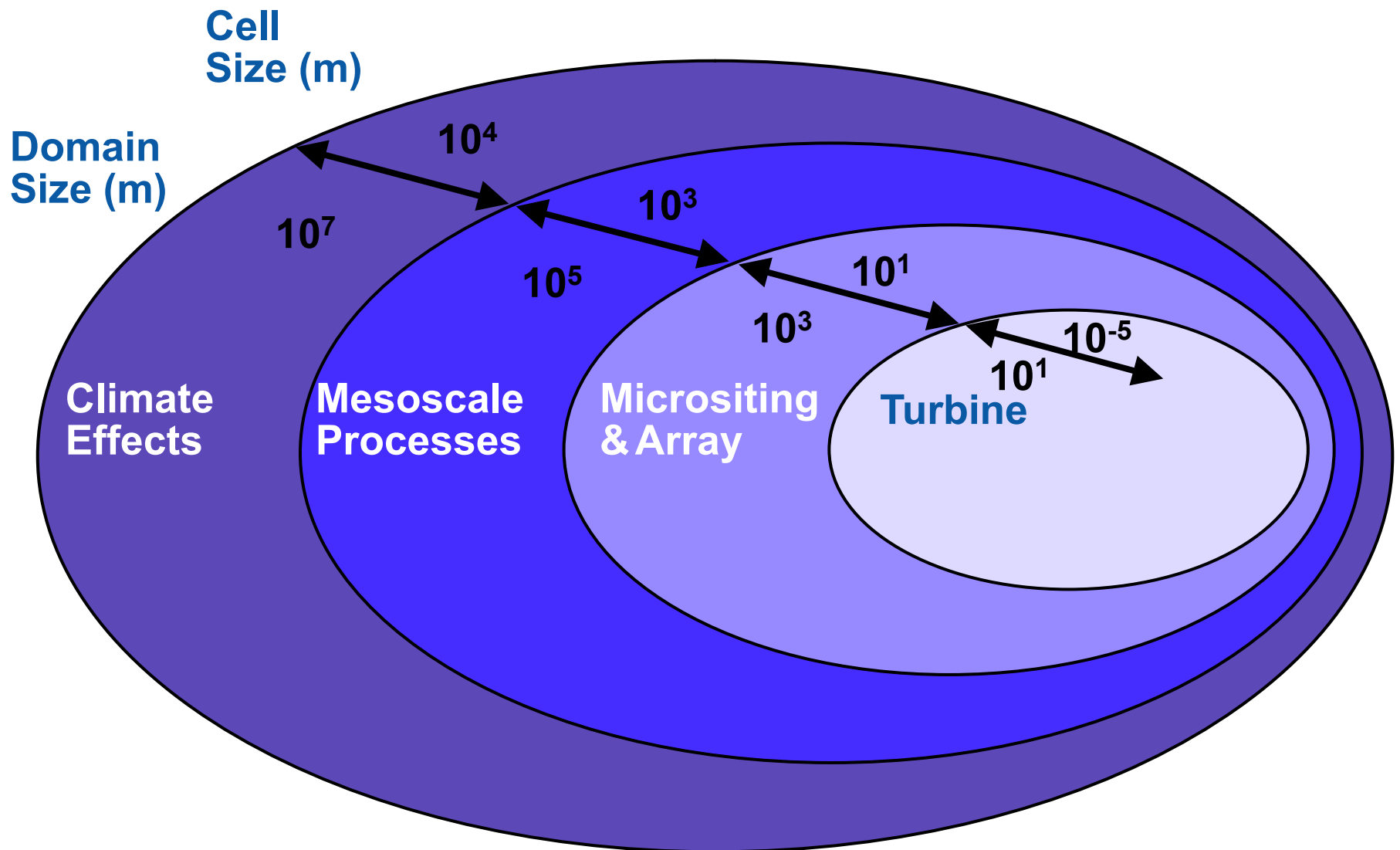
Climate Effects



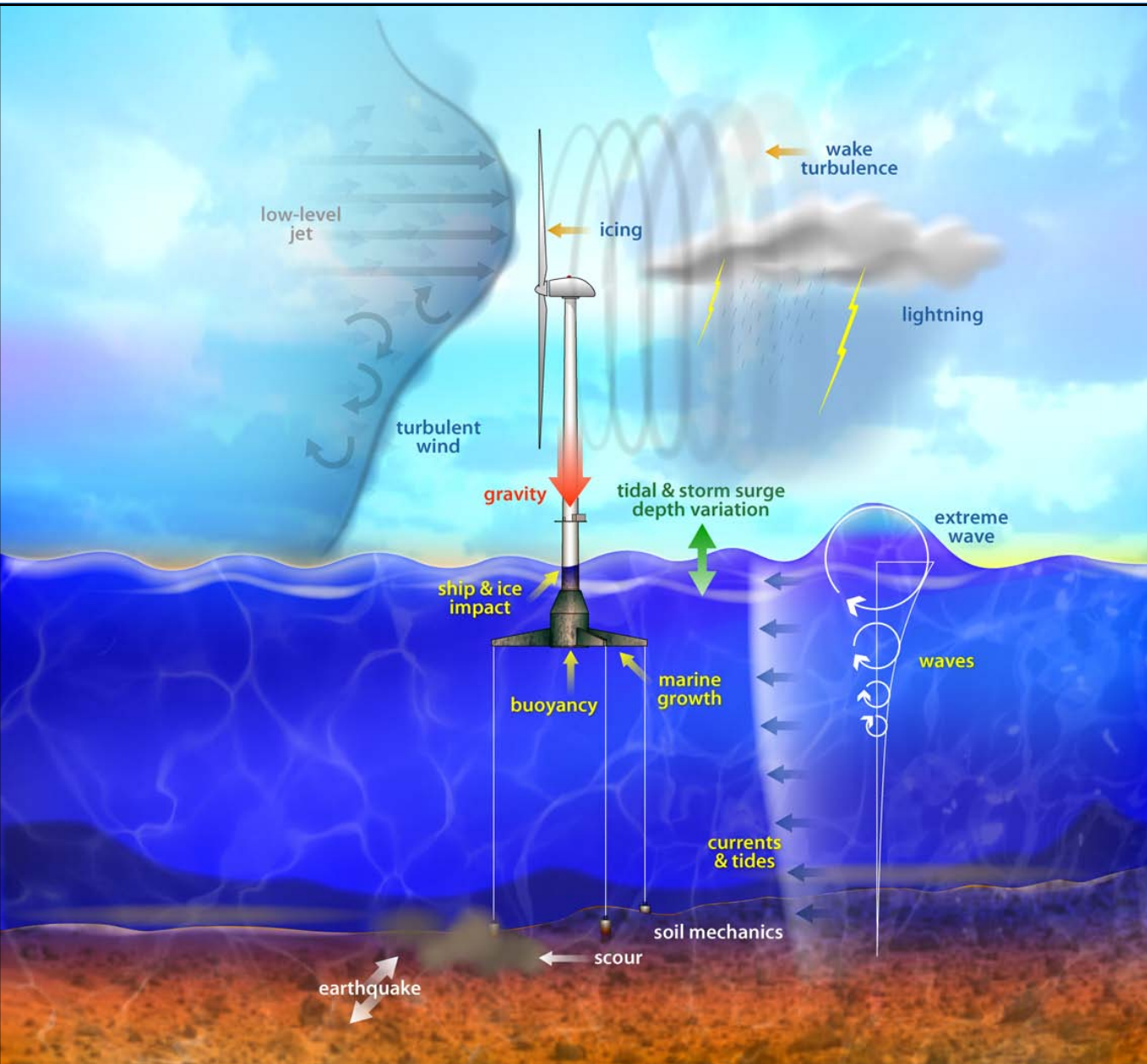
Climate effects

- Understand and predict wind resource variability
- Wind plant and local/regional/global climate

Computational Modeling Scales



Deep Water Modeling Requirements



Fully coupled aero-hydro-servo-elastic interaction

Wind-Inflow:

- discrete events
- turbulence

Waves:

- regular
- irregular

Aerodynamics:

- induction
- rotational augmentation
- skewed wake
- dynamic stall

Hydrodynamics:

- scattering
- radiation
- hydrostatics

Structural dynamics:

- gravity / inertia
- elasticity
- foundations / moorings

Control system:

- yaw, torque, pitch

Large Facility Requirements



PIX #13889

A 45-meter wind turbine blade undergoing fatigue testing at the NWTC, July 2004.

New Large Blade Test Facilities:

- Boston, MA with Massachusetts Technology Collaborative
- Corpus Christy, TX with University of Houston

DOE NOI for 5-15 MW Dynamometer



PIX #12414

Multi-MW Turbines at NWTCC



DOE 1.5 MW

PIX #17694

DOE 1.5 MW GE Turbine:

- Model: GE 1.5SLE
- Tower Height: 80 m
- Rotor Diameter: 77 m
- DOE owned; used for research and education



Siemens 2.3 MW

PIX #17720

Siemens 2.3 MW Turbine:

- Model: SWT-2.3-101
- Tower Height: 80 m
- Rotor Diameter: 101 m
- Siemens owned and operated
- Multi-year R&D CRADA; aerodynamics and rotor performance

Questions?

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