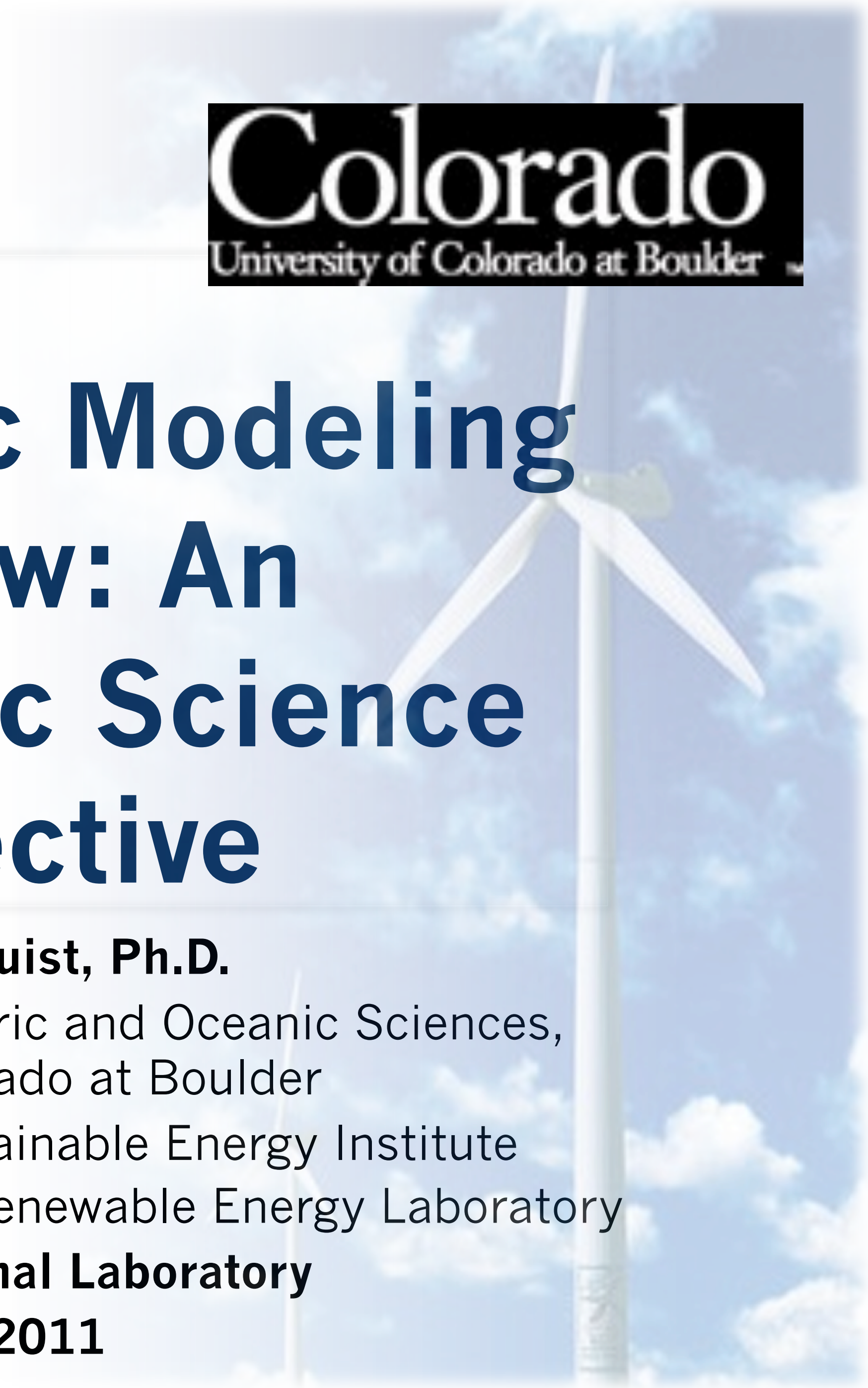

Aerodynamic Modeling Overview: An Atmospheric Science Perspective

Julie K. Lundquist, Ph.D.
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Fellow, Renewable and Sustainable Energy Institute
Joint Appointment at National Renewable Energy Laboratory

Los Alamos National Laboratory
2 March 2011

Why worry about the atmosphere?

- Complex dynamics in the lower atmosphere
- Dynamics affect:
  - Power performance
  - Maintenance Issues
  - Array & wake impacts
- Example of nested atmospheric modeling **and validation dataset**

Why couple “weather” with computational fluid dynamics model for wind energy applications?

Fluctuating power from renewables must be integrated into a constrained power grid built for scheduled power production: accurate forecasts + optimization

Rugged terrain features affect winds – which site is an optimal site over 20 years?

Turbine wakes lessen power collected in large arrays – and what are downwind impacts?

Atmospheric turbulence & shear induce premature fatigue on gears & blades, increasing maintenance and replacement costs

Consider the typical assumptions for "inflow" to a turbine-resolving model

- Neutral atmospheric stability
- Logarithmic or power law velocity profile
- Should have "spun-up" turbulence (Rod's comparison!)

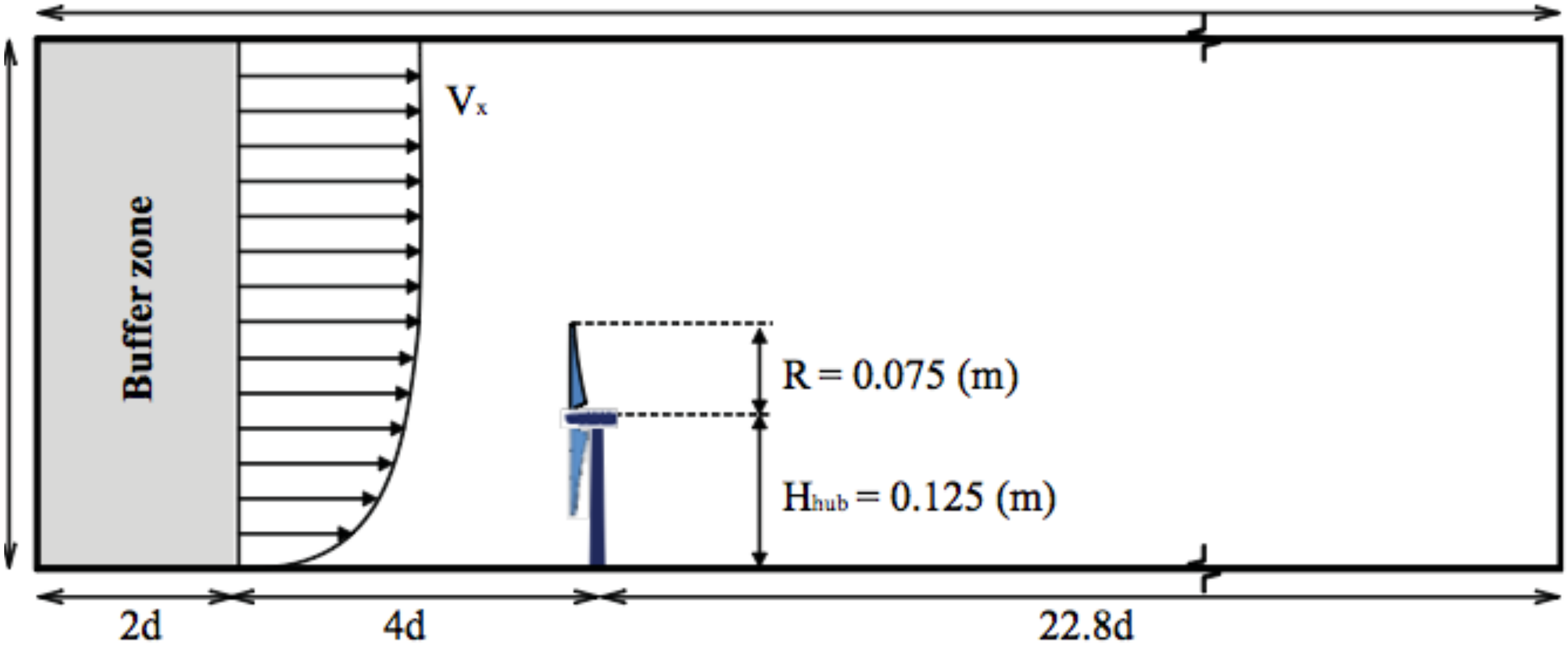
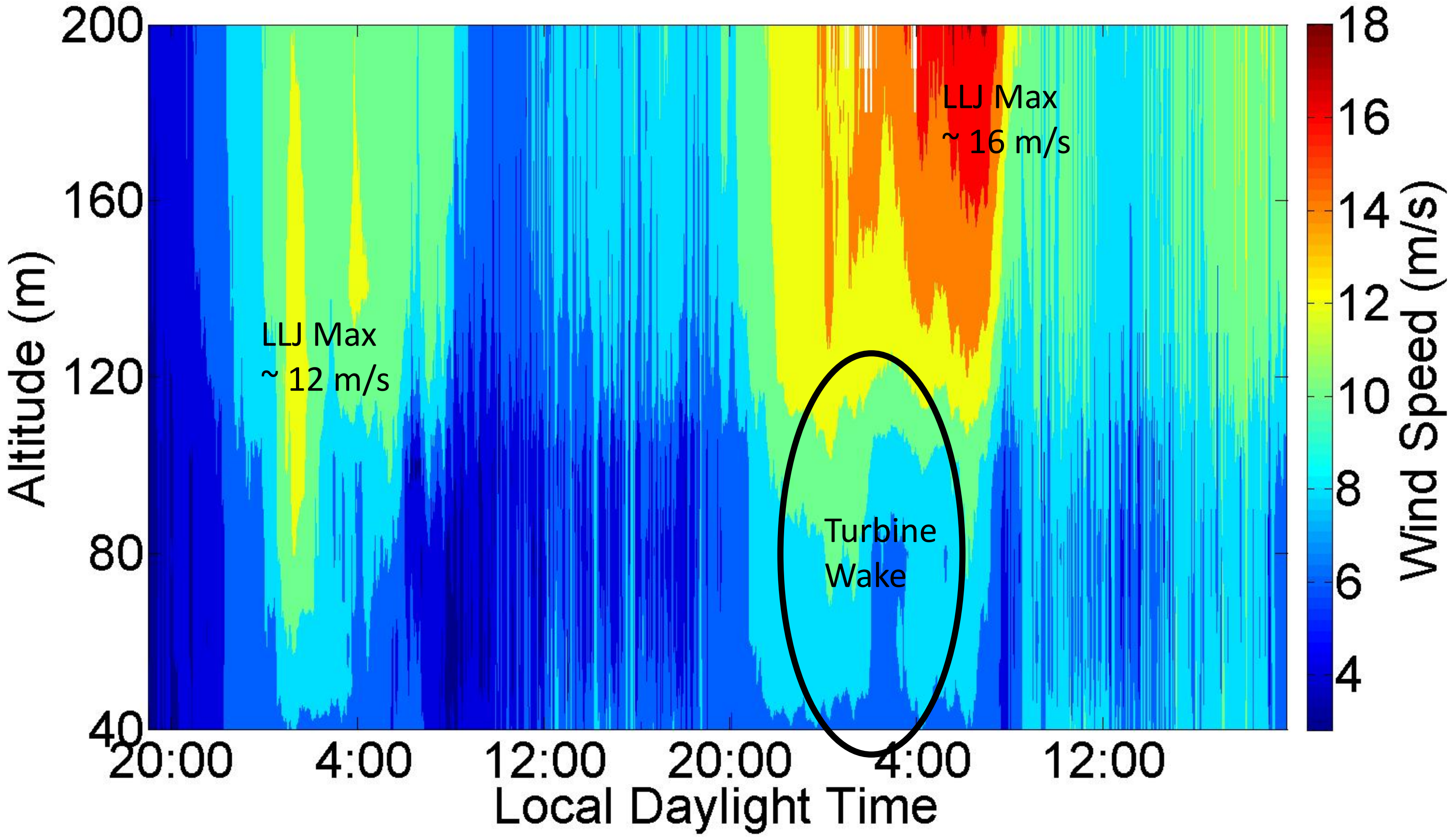


Figure from Porté-Agel, Lu, and Wu, 2010: schematic of SAFL wind tunnel, similar set-up for CFD simulations

Observed wind speed profiles (Windcube lidar, summer, midwest US) exhibit more variability than is traditionally considered in CFD

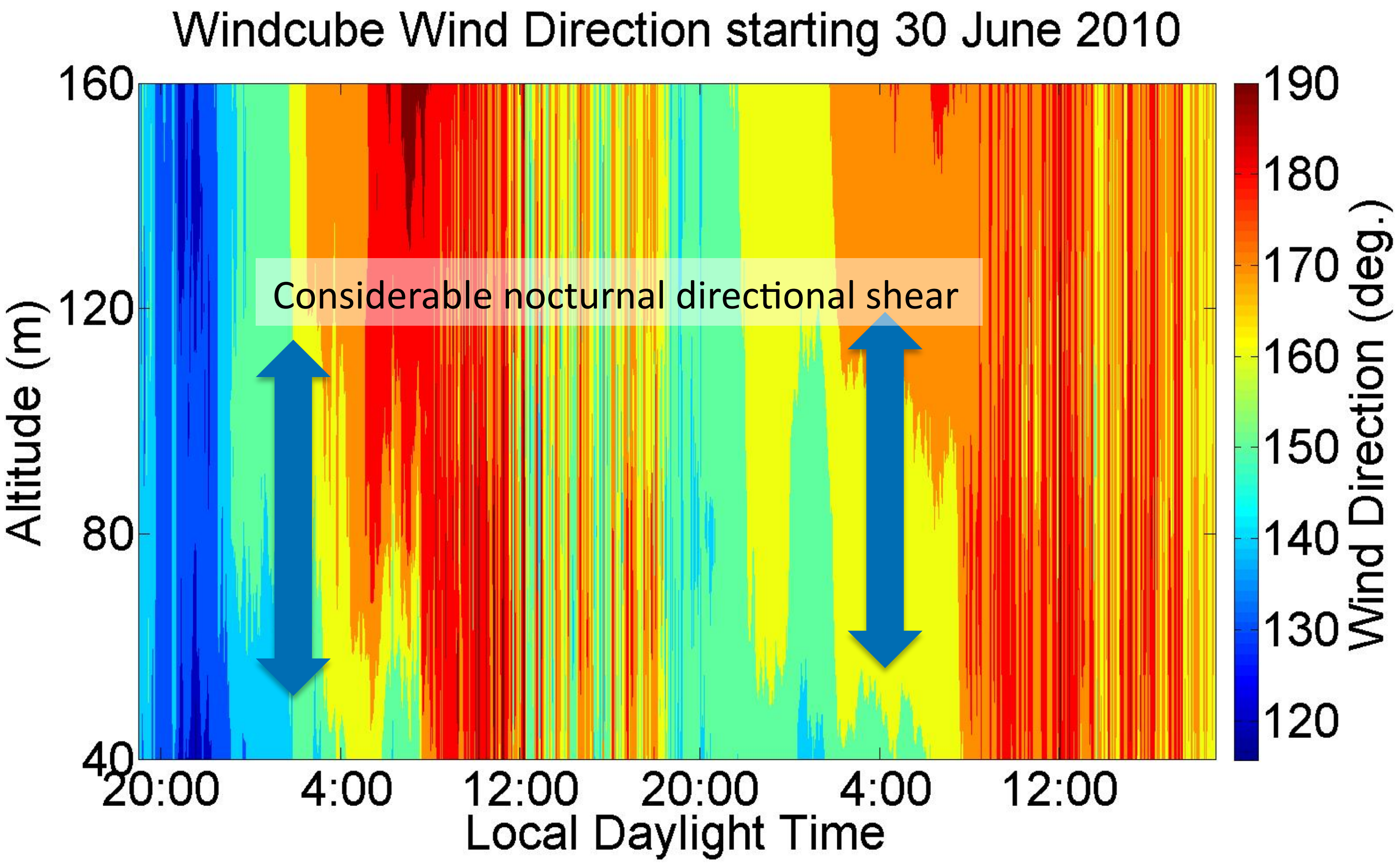


LLJ Max
~ 12 m/s

LLJ Max
~ 16 m/s

Turbine
Wake

Directional shear of 20 degrees across the rotor disk is common

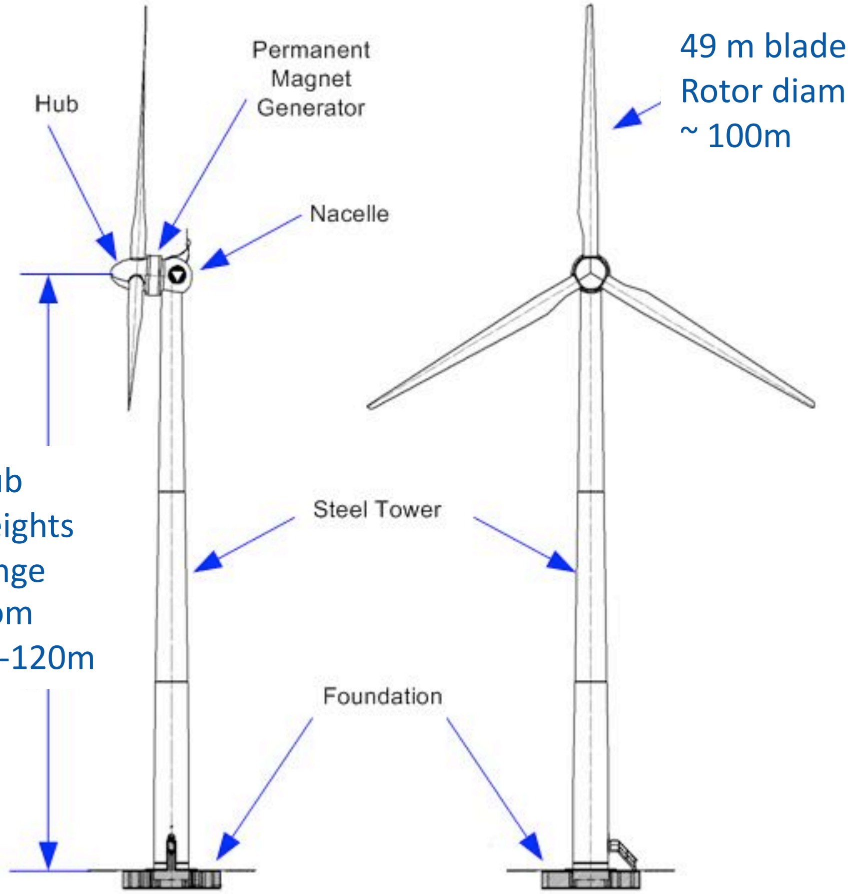

Windcube Wind Direction starting 30 June 2010

Considerable nocturnal directional shear

And these are "typical" midwestern conditions!

Modern wind turbines span heights ~ 200m, penetrating a complex atmosphere

Siemens 3.0 MW turbine

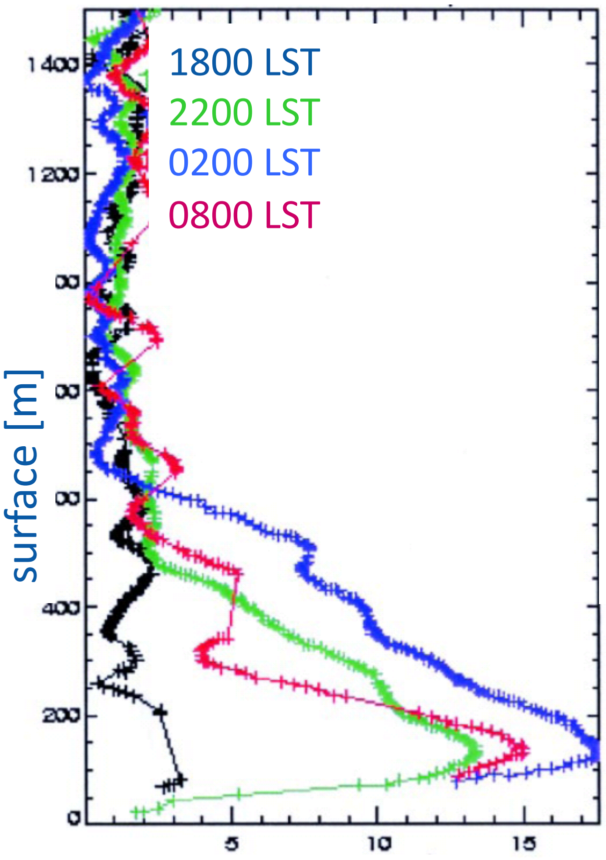


49 m blade:
Rotor diameter
~ 100m

Hub
Heights
range
from
60-120m

The dynamics of the lower atmosphere are complex, especially at night

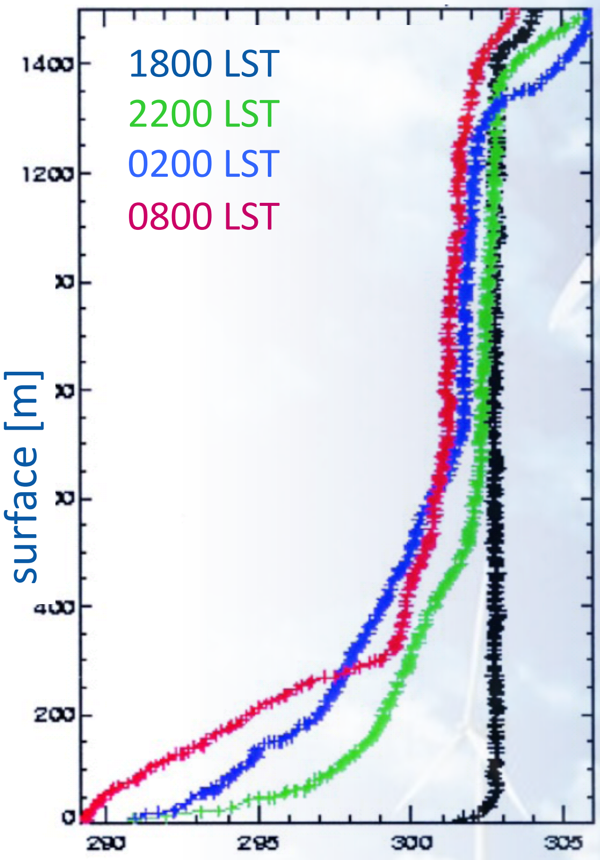
Radiosonde profiles demonstrate that the cooling of the surface overnight is accompanied by dramatic accelerations in the winds



1800 LST
2200 LST
0200 LST
0800 LST

Height above surface [m]

Wind Speed [ms^{-1}]



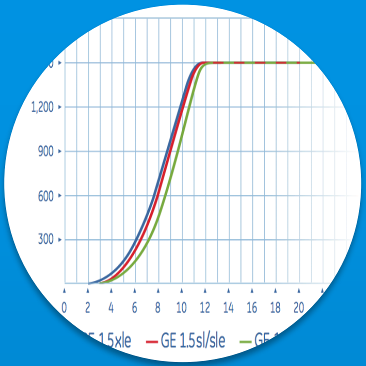
1800 LST
2200 LST
0200 LST
0800 LST

Height above surface [m]

Potential Temperature [K]

Poulos, Blumen, Fritts, Lundquist, et al., 2002

This atmospheric variability is critical for accurate aerodynamic modeling of wind turbines



Addressing Under-performance

Operations and Maintenance

Array Effects: Wake Variability

Inflow shear and turbulence

Turbine power curves can be calculated in several ways: some approaches yield more insight

IEA Standard: cup anemometer at hub height several rotor diameters upwind in non-turbulent conditions

Remote sensing: observe full profile of winds and turbulence

- **Accurate turbulence measurements**
- **Assessment of atmospheric stability**

Vertical profile of cup anemometers

EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING
AND EVALUATION

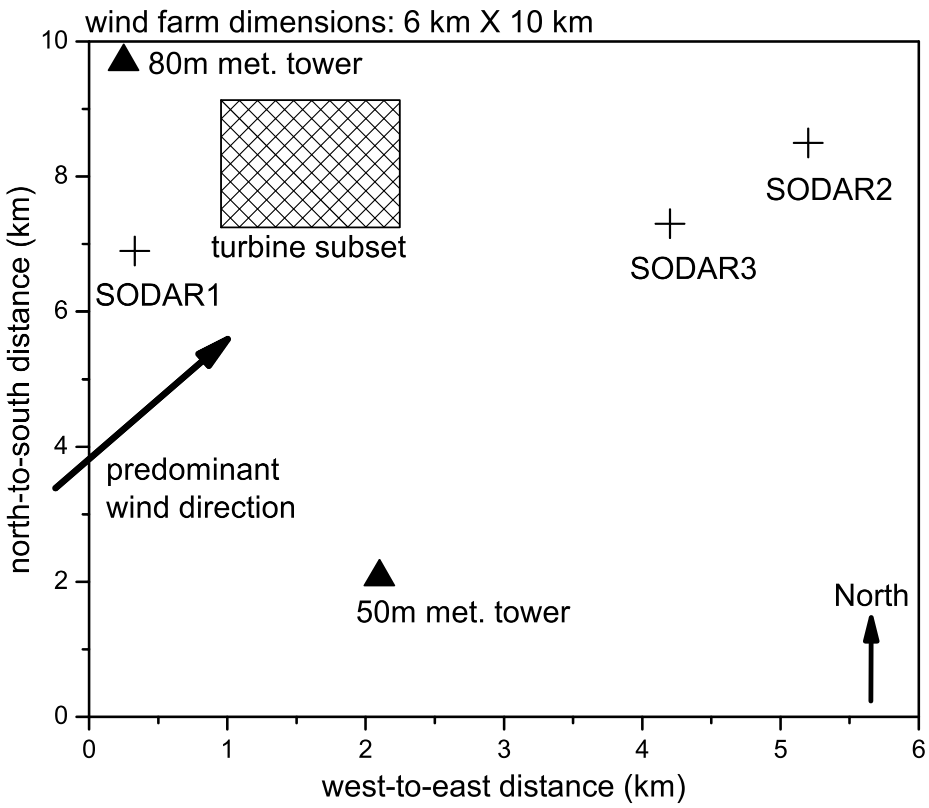
11. WIND SPEED MEASUREMENT
AND USE OF CUP ANEMOMETRY

1. EDITION 1999
second print 2003

Submitted to the Executive Committee
the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems

Doppler Sound Detection and Ranging (SODAR)

IRI deployed a SODAR in an operating wind farm; academic research surface meteorological station located nearby could define atmospheric stability



Collaboration with Iberdrola Renewables, Inc. and S. Wharton, LLNL

How to estimate stability? An off-site research measurement is compared with 3 on-site estimates

(1) Wind shear exponent, α

$$U(z) = U_R\left(\frac{z}{z_R}\right)^{\alpha}$$

U : mean horz. wind speed at height z or z_R

(2) Turbulence intensity, I_U

$$I_U = \frac{\sigma_U}{U(z)}$$

σ_U : standard dev. of mean horz. wind speed (U) at 80 m

(3) Turbulence kinetic energy, TKE

$$TKE = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

u'^2: variance of wind speed

Obukhov length, L (off-site)

$$L = -\frac{\theta_v \cdot u_*^3}{k \cdot g \cdot \overline{w'\theta_v'}}$$

θ_v : virtual potential temperature

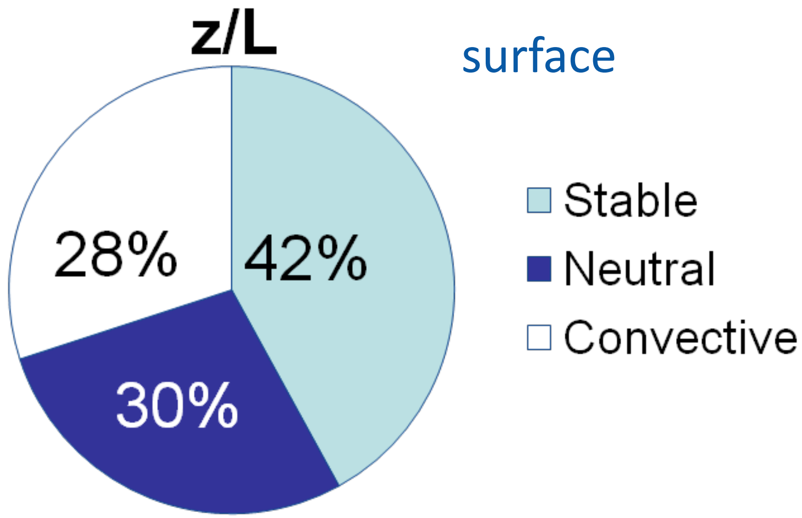
k : von Karman constant

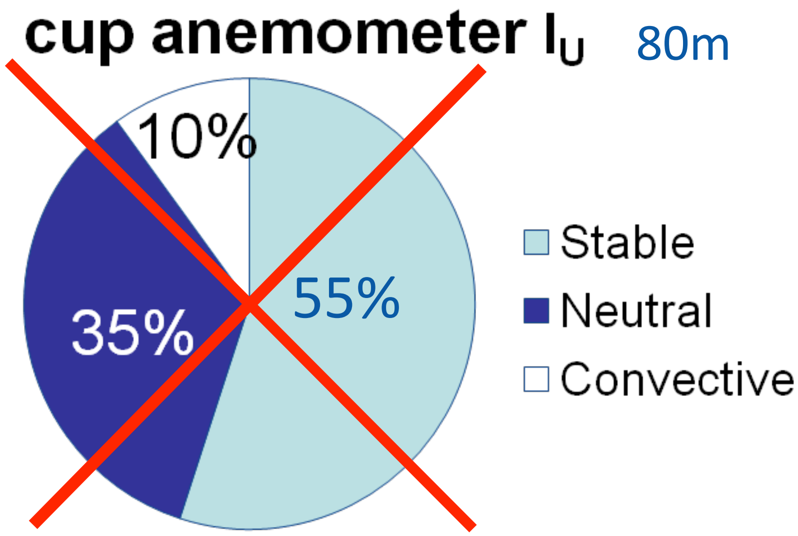
g : gravity

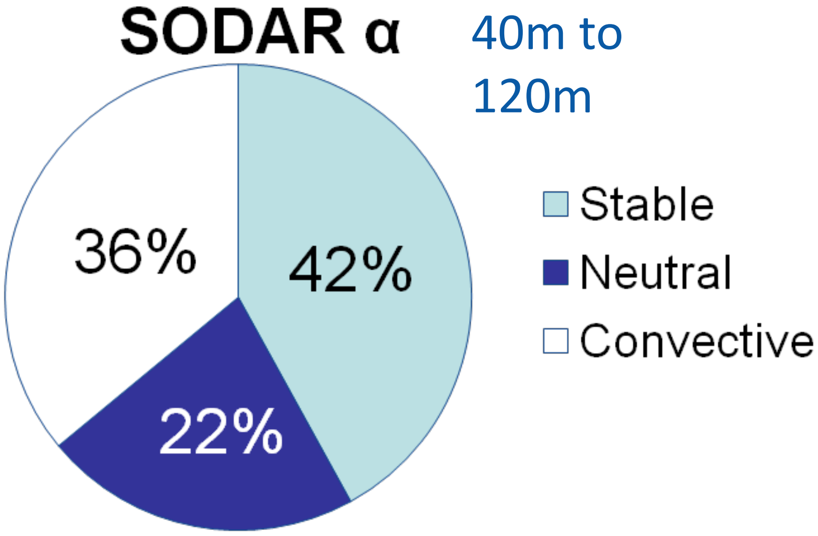
$\overline{w'\theta_v'}$: sensible heat flux

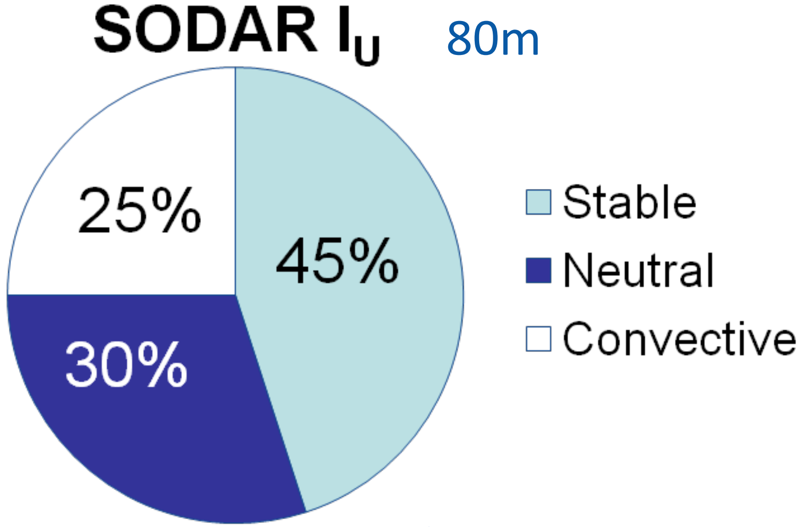
u_* : friction velocity = $(\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$

Estimates of stability from a typical cup anemometer fail to agree with more sophisticated measures





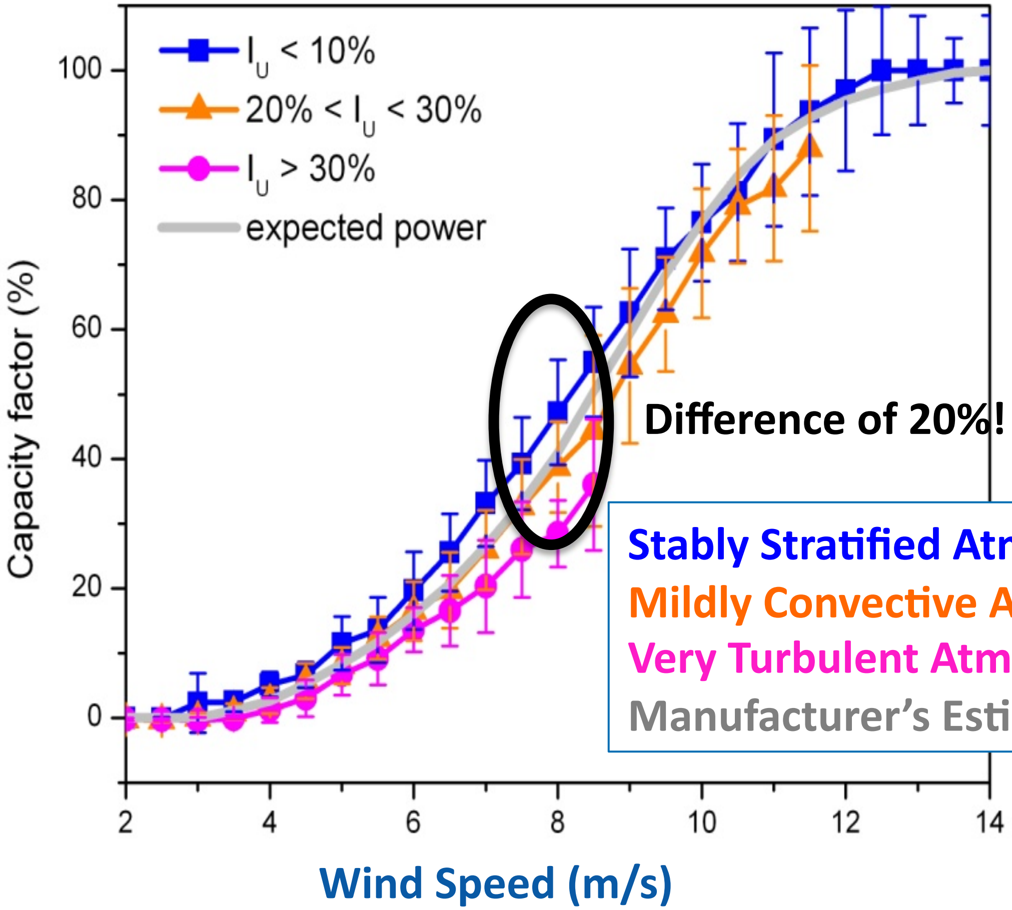




Summer (strong wind season) data, IRI West Coast North America wind farm

Power generated by turbines is dependent on wind speed – and other atmospheric conditions

Analysis based on observations from an operating wind farm with extensive and atypical meteorological instrumentation

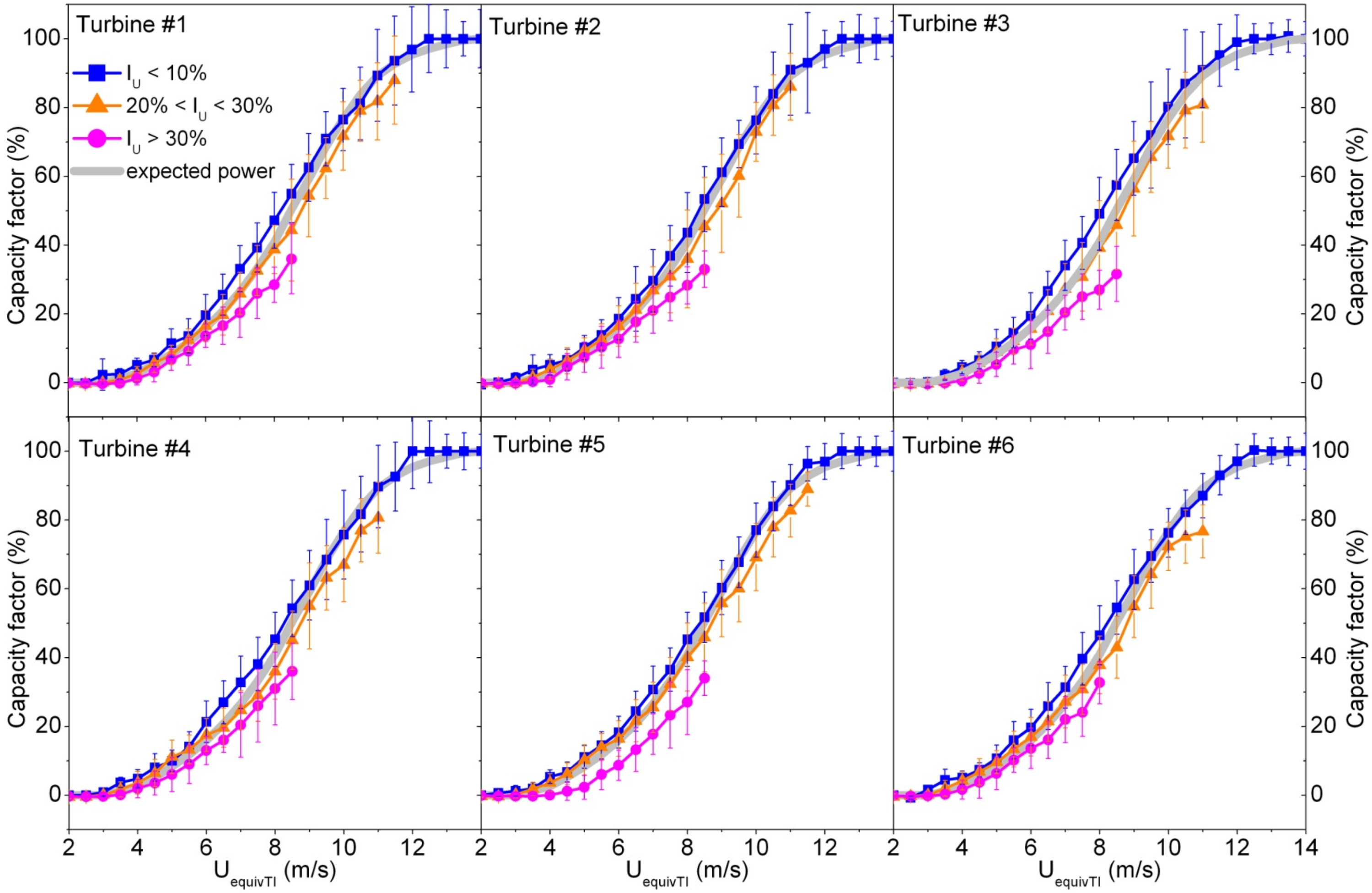


Difference of 20%!

Stably Stratified Atmosphere
Mildly Convective Atmosphere
Very Turbulent Atmosphere
Manufacturer's Estimate

Lundquist and Wharton, 2009, *IEA Experts Meeting on SODAR and LIDAR*;
Wharton, Lundquist, Sharp, Crescenti, and Zulauf, 2009, AGU Fall Meeting;
Wharton and Lundquist, 2011, in review at *Wind Energy*

In fact, all leading edge turbines show that at this wind farm, power generated is dependent on stability



Ongoing work: how does atmospheric stability impact turbine wakes and downwind turbine productivity?

Wind farm “underperformance” can in part be explained due to incomplete resource assessment

Industry must upgrade resource assessment instruments:

- SODAR stability parameters segregate wind farm data into stable, neutral and convective periods in agreement with research-grade observations
- Cup anemometers inaccurate for turbulence

Power output correlates with atmospheric stability:

- Enhanced performance during stable conditions
- Reduced performance during convective conditions

north american WINDPOWER

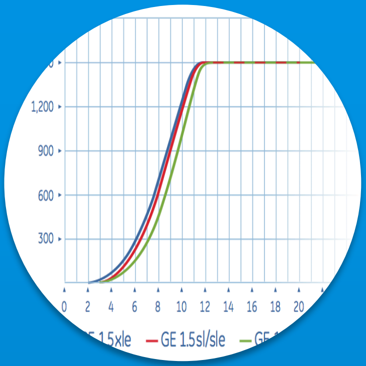
Underperformance Issues Deserve Fresh Examination

Although wind farm underperformance may have been overstated, more work needs to be done to shrink the performance gap.

IN THIS ISSUE

North American Windpower, Nov. 2010

This atmospheric variability is critical for accurate aerodynamic modeling of wind turbines



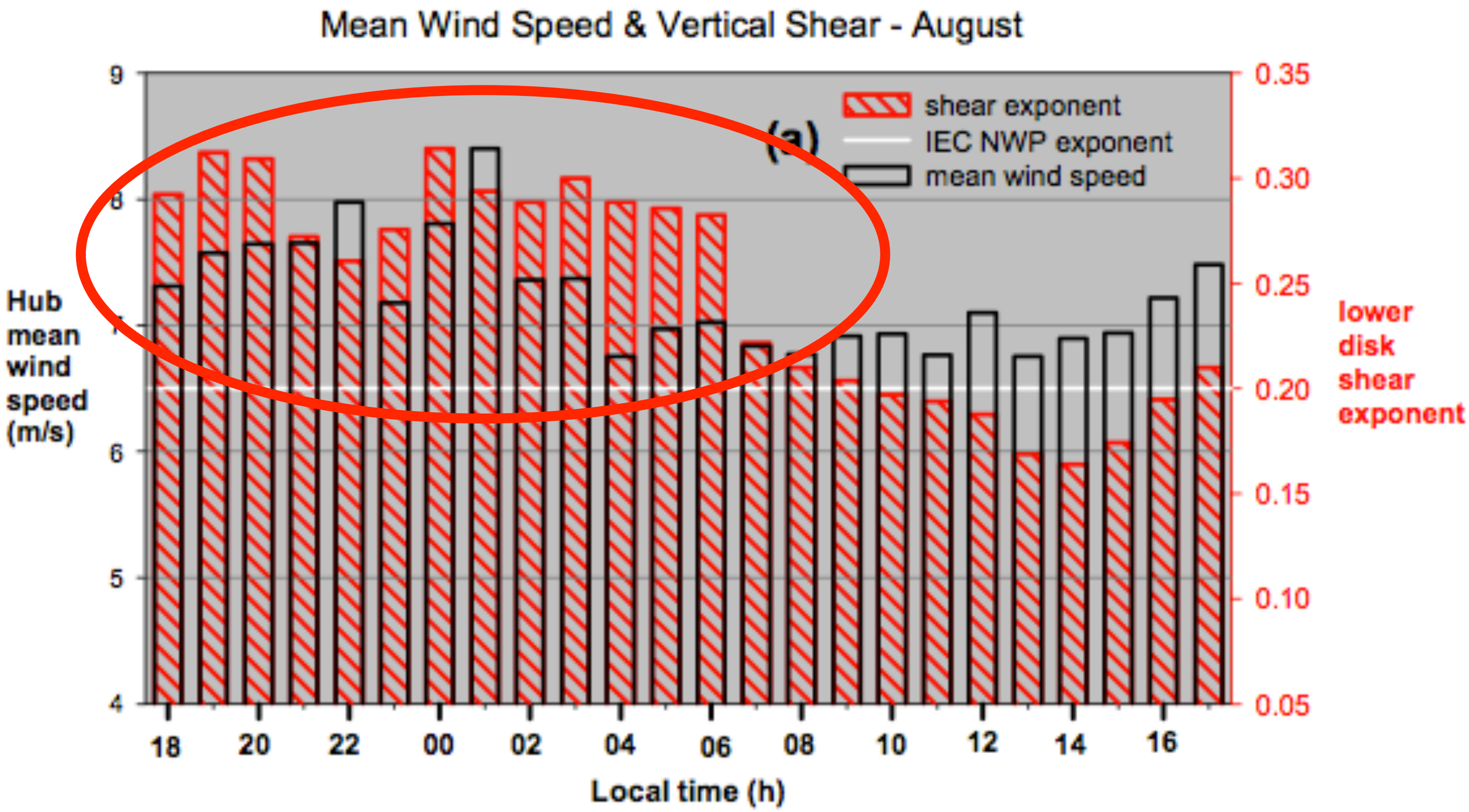
Addressing Under-performance

Operations and Maintenance

Array Effects: Wake Variability

Inflow shear and turbulence

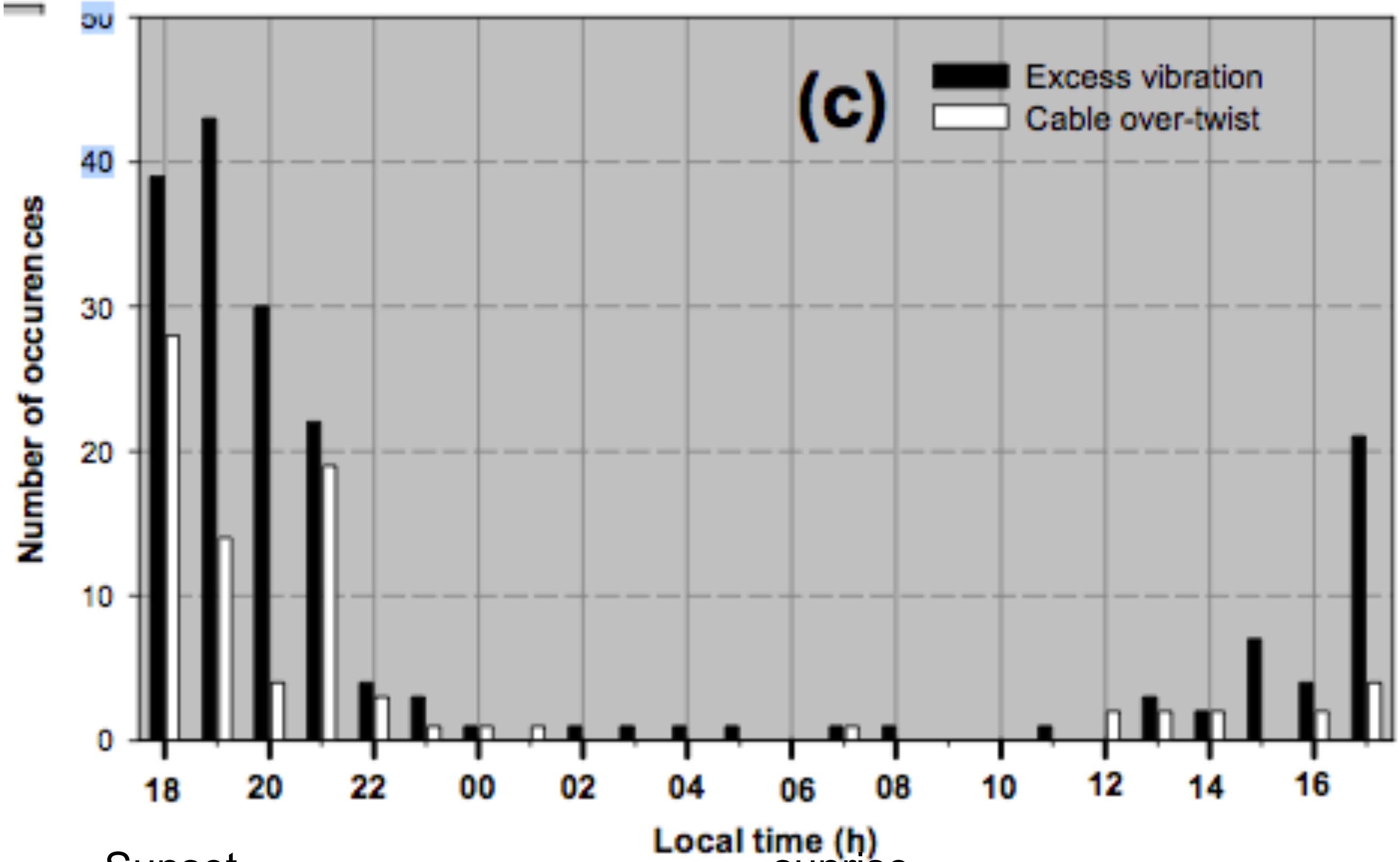
Observations indicate the atmosphere is very hard on turbines, particularly during stable conditions



Sunset sunrise

Kelley et al., 2006; see also Smith et al., 2002

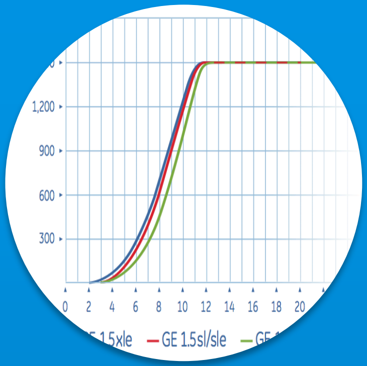
Turbine faults maximize at night during LLJ conditions



Sunset sunrise

Kelley et al., 2006; see also Smith et al., 2002

This atmospheric variability is critical for accurate aerodynamic modeling of wind turbines



Addressing Under-performance

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Array Effects: Wake Variability

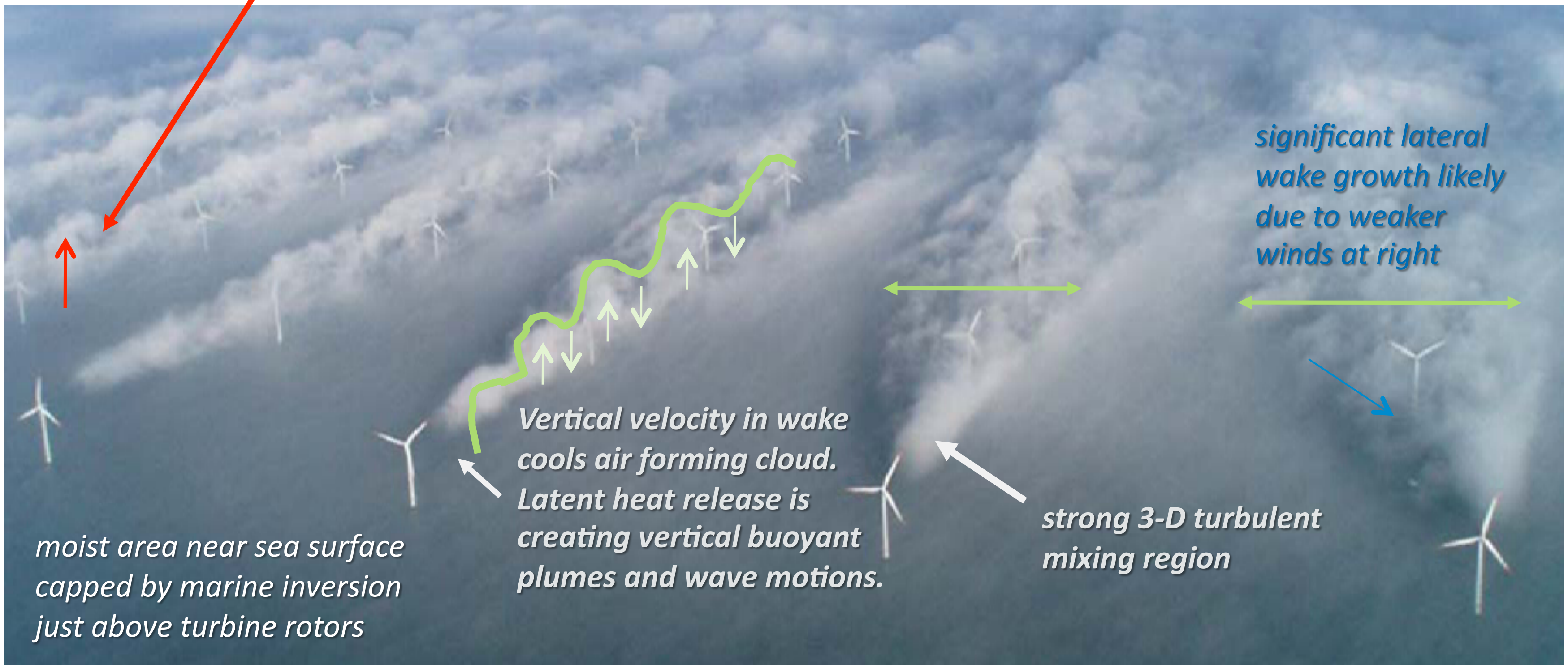
Inflow shear and turbulence

Even in this famous picture of turbine wakes, we can discern atmospheric variability

Source: UniFly A/S

Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness.

buoyant plume:
entraining dryer air, as a result of
downward momentum, temperature, and moisture fluxes
and stronger winds near the surface



significant lateral
wake growth likely
due to weaker
winds at right

Vertical velocity in wake cools air forming cloud. Latent heat release is creating vertical buoyant plumes and wave motions.

strong 3-D turbulent mixing region

moist area near sea surface
capped by marine inversion
just above turbine rotors

stronger winds ⟷ *horizontal wind speed gradient?* ⟷ *weaker winds*

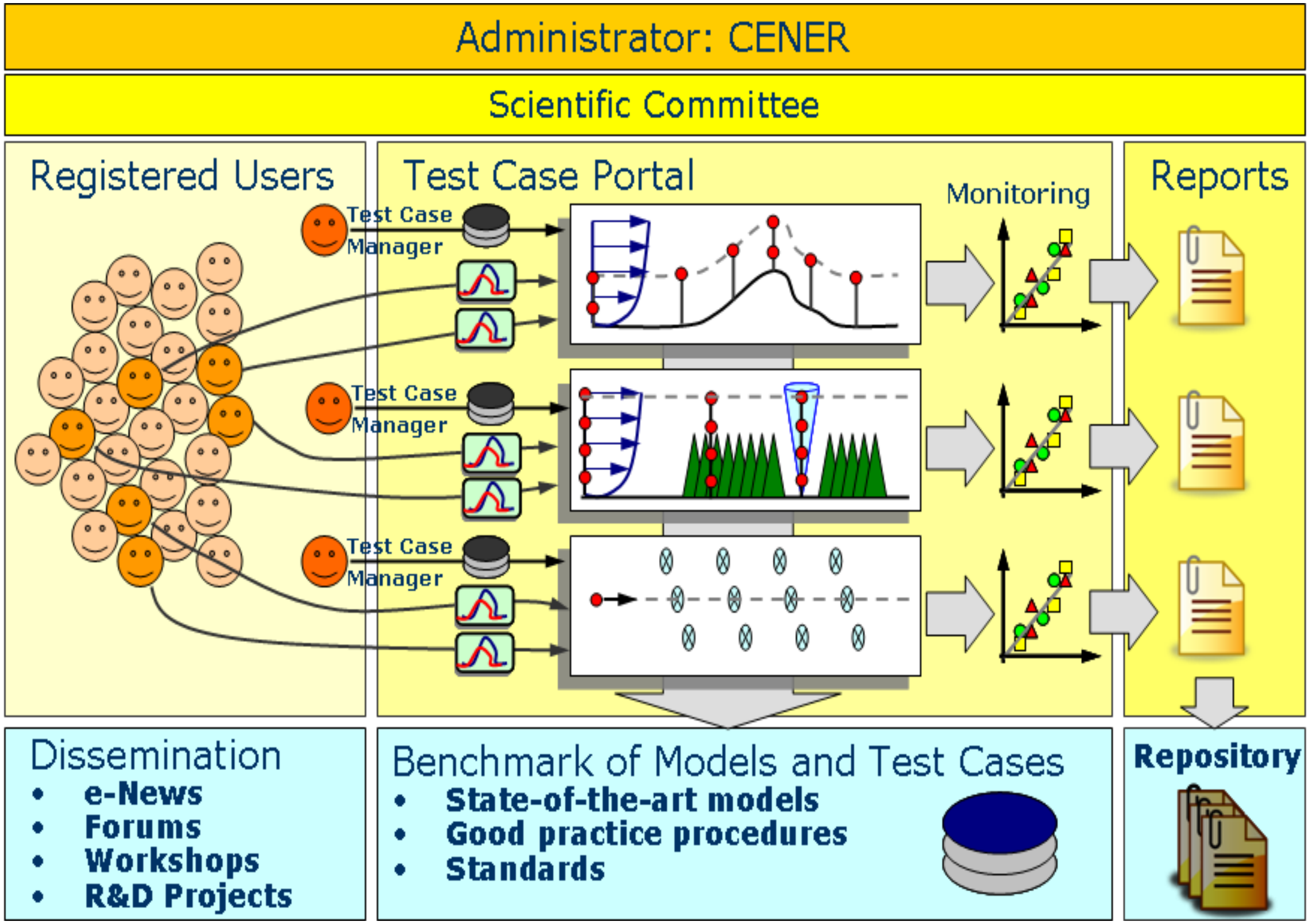
Annotation by Neil Kelley, NREL NWTC

Several teams are attempting to couple CFD models with atmospheric models to represent this variability

- **LANL**: WindBlade with TURBSIM (Rod’s presentation this morning) and WRF
- **LLNL**: cgWind (Overture/cgIns) with WRF
- **NREL**: OpenFOAM with WRF
- and others (industry, Risø, ECN)

The diversity of approaches emphasizes utility of open collaboration and intercomparisons

Multiple mechanisms for intercomparison: IEA TASK 31 WAKEBENCH, coordinated by Spain's National Renewable Energy Centre (CENER)



WRF offers a framework for nesting LES within numerical weather prediction, convenient for coupling with CFD

WRF THE WEATHER RESEARCH & FORECASTING MODEL

- Community atmospheric modeling system used by NOAA/NCEP, FAA, DoD, DoE, among others
- Based at NCAR w/ contributions from around the world
- Multiple physics options for microphysics, cloud processes, surface-atmosphere interaction, boundary-layer turbulence, and LES subgridscale models
- Support for multiple one- and two-way nesting
- Terrain-following coordinates; but an immersed boundary method has been implemented and is being evaluated with complex terrain observations (Lundquist, Chow, and Lundquist, 2010, *MWR*)
- **Issues: vertical coordinate system (pressure levels), multiple physics options, always evolving**

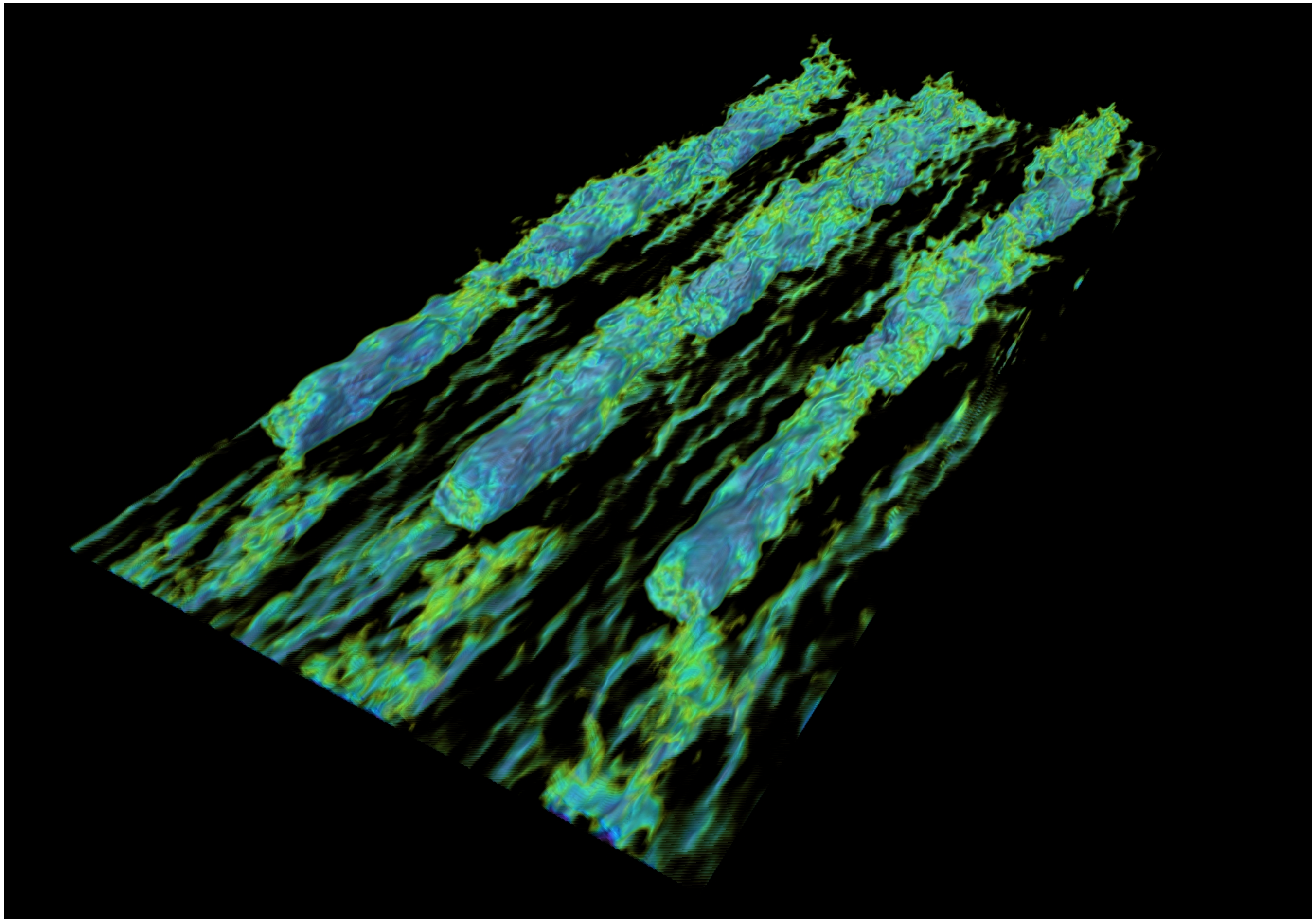
How does the blade develop a wake? How does the wake evolve?

- Models must capture interaction of realistic atmospheric turbulence with the blade
- These LES simulations match experimental data of power production loss in wakes within 4%
- Ongoing work builds on this model to reduce wake power losses and improve overall wind farm power production

Actuator line model of a wind turbine in OpenFOAM

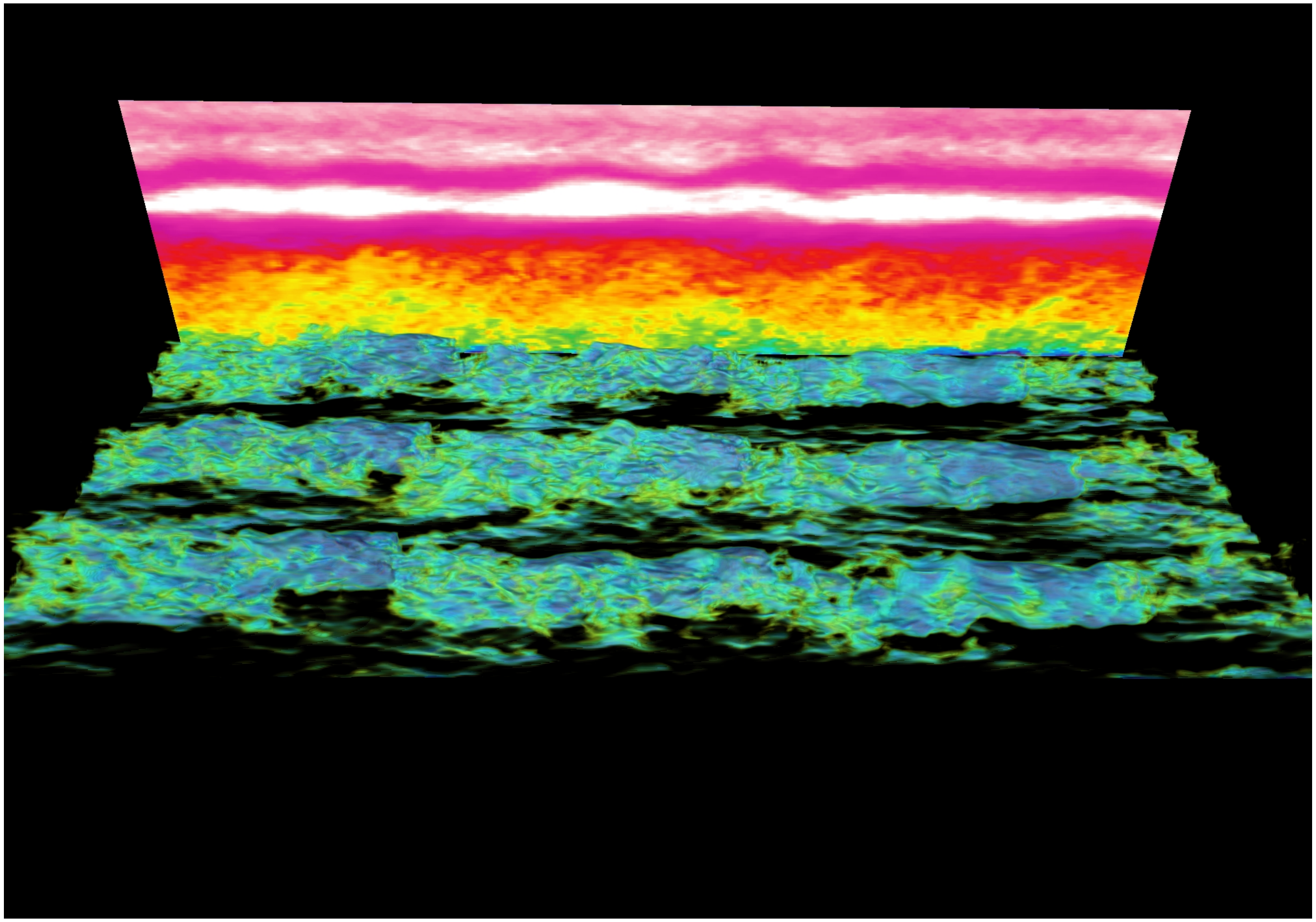
Churchfield et al., 2009 (NREL)

Next steps: include multiple turbines in a more realistic atmospheric flow



Contours of streamwise velocity Churchfield et al., 2010; OpenFOAM

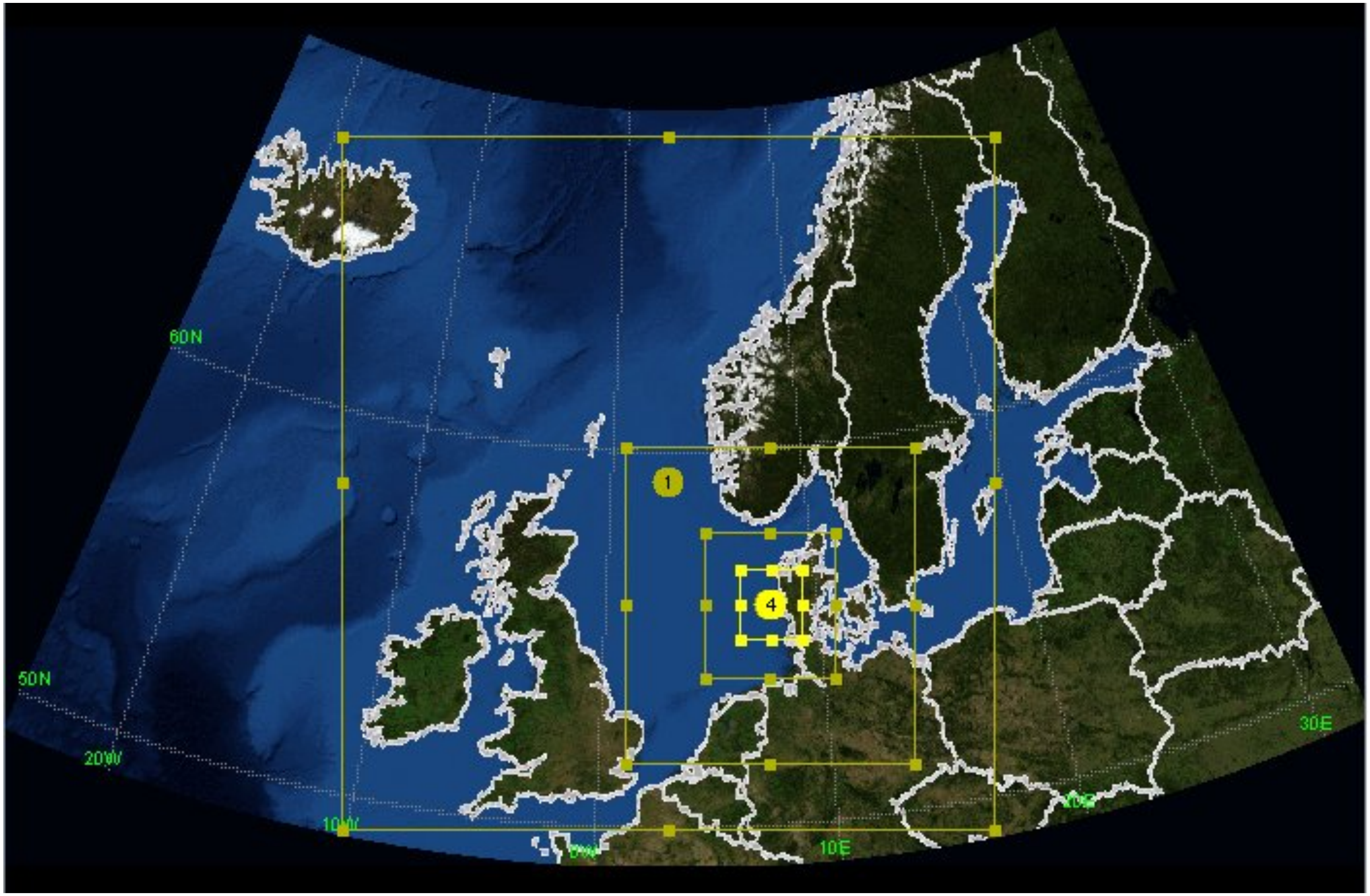
9 turbines in neutral atmospheric boundary layer with jet wind profile



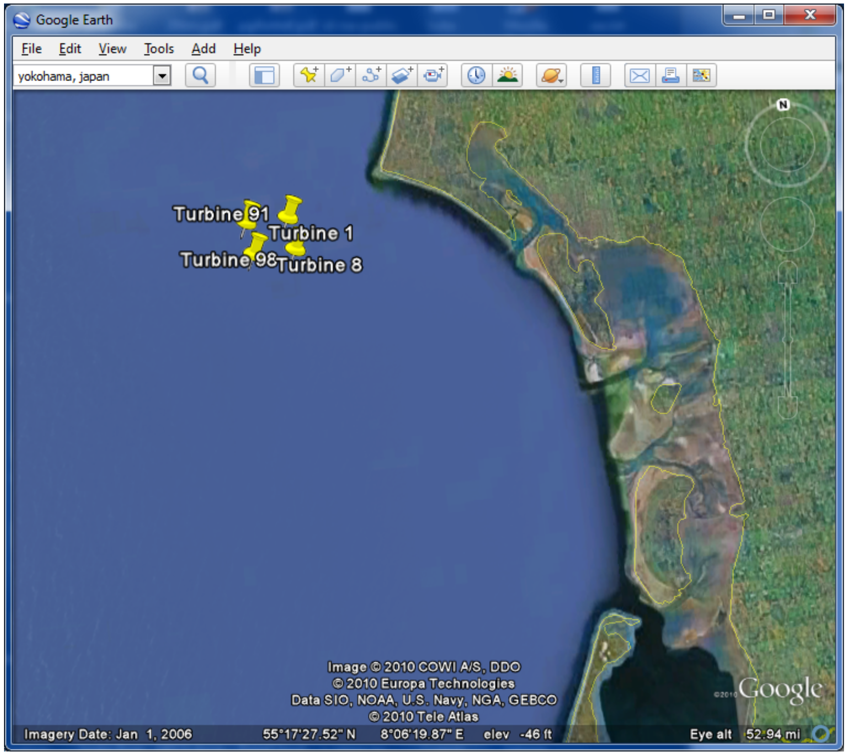
Contours of streamwise velocity; back plane shows wind profile

Churchfield et al., 2010; OpenFOAM

Initial WRF Simulations for the Horns Rev domain build on several nests to ensure incorporation of “weather”



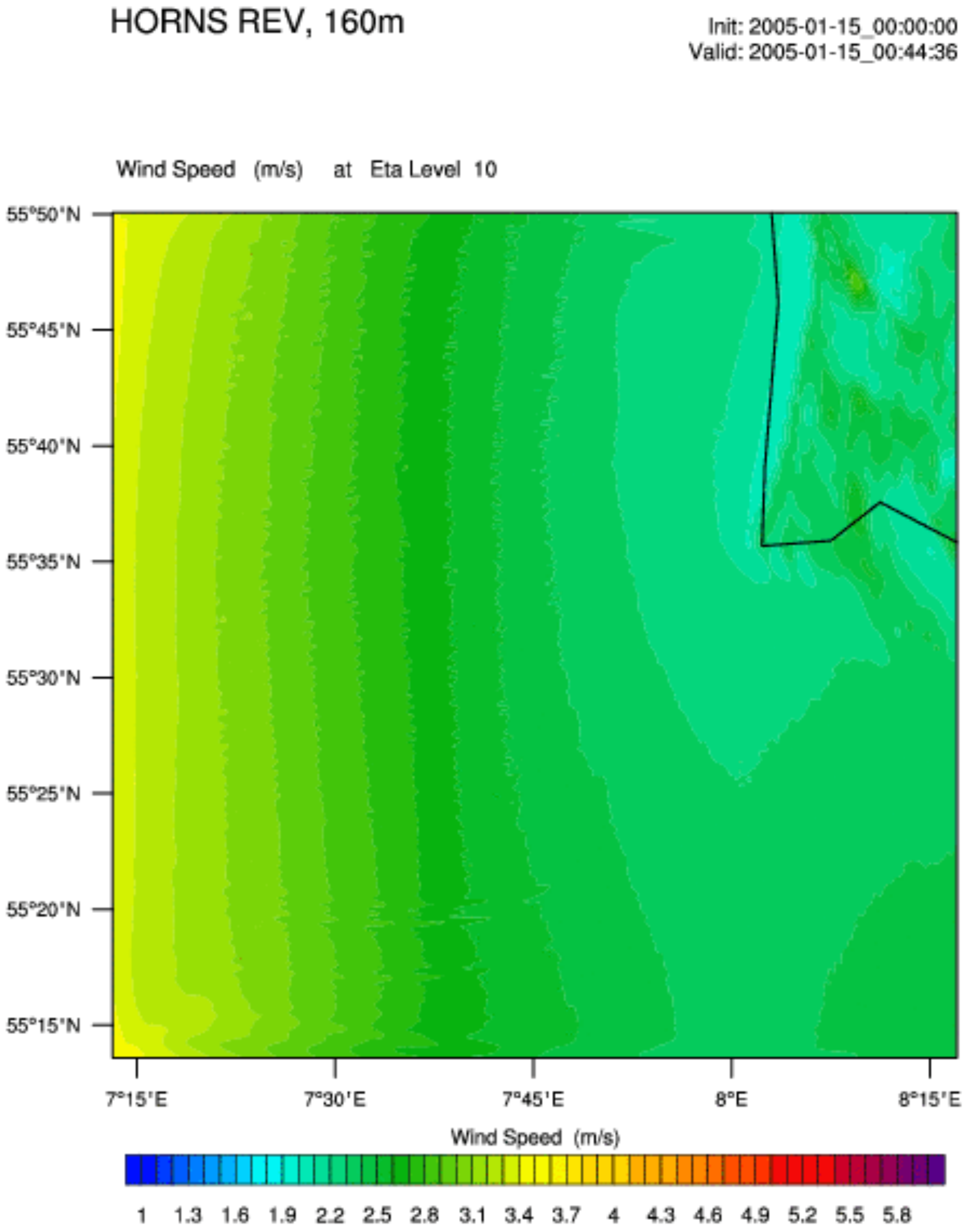
Horns Rev is just off the coast



Turbines off shore

© Horst Looschelders

Initial LES simulations of offshore farm

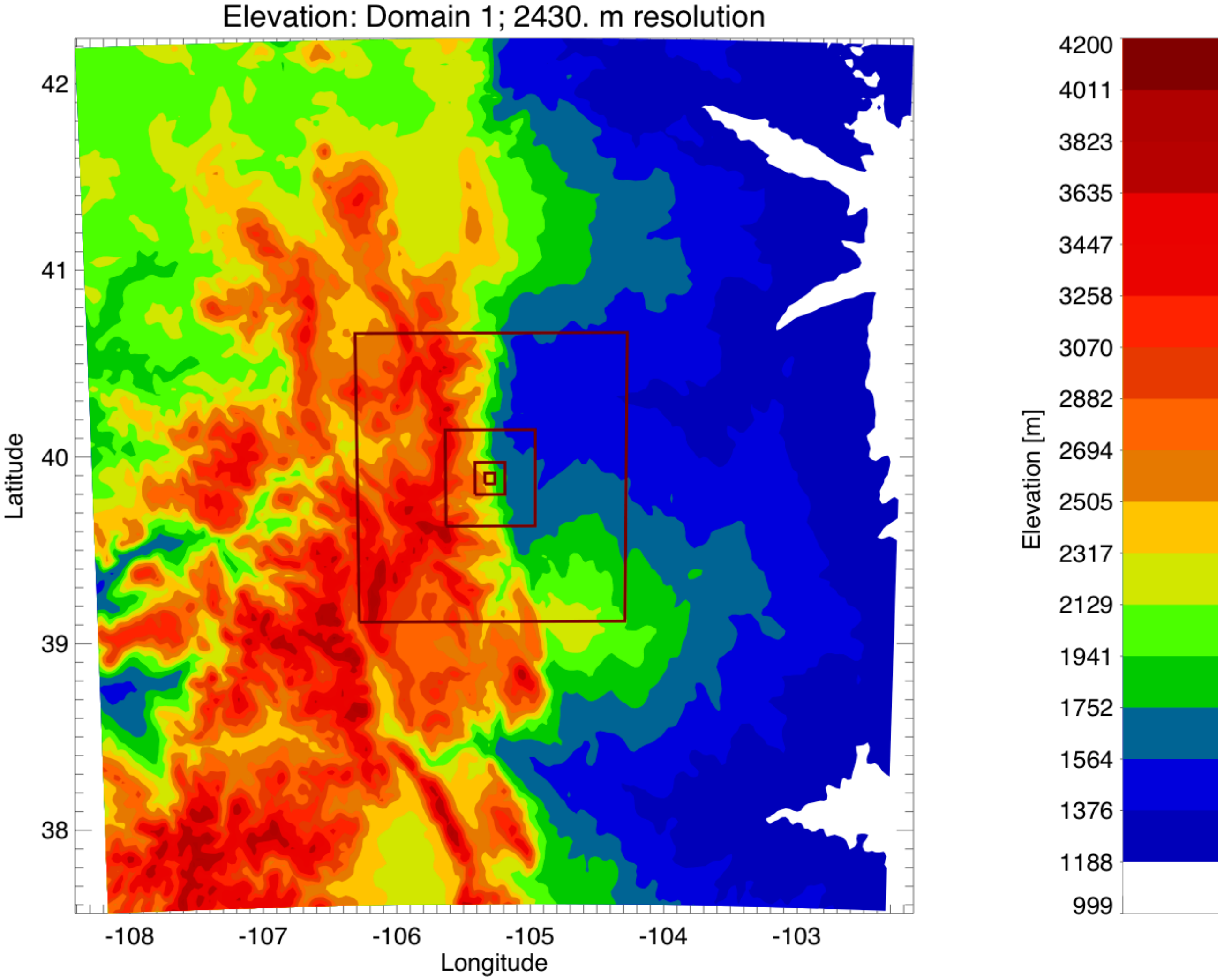


160-m WRF LES nest, 4th nest, driven by ECMWF for two hours

Have identified four optimal test cases from Horns Rev 2005 data, based on:

- **Wind direction**
- **Wind speed (7-9 m/s)**
- **# turbines functioning**

Other domains may be more challenging: Colorado domain of nested WRF/WRF-LES simulations for comparison to wake observations at NWTC



D1: $\Delta x = 2430\text{m}$

D2: $\Delta x = 810\text{m}$

D3: $\Delta x = 270\text{m}$

D4: $\Delta x = 90\text{m}$

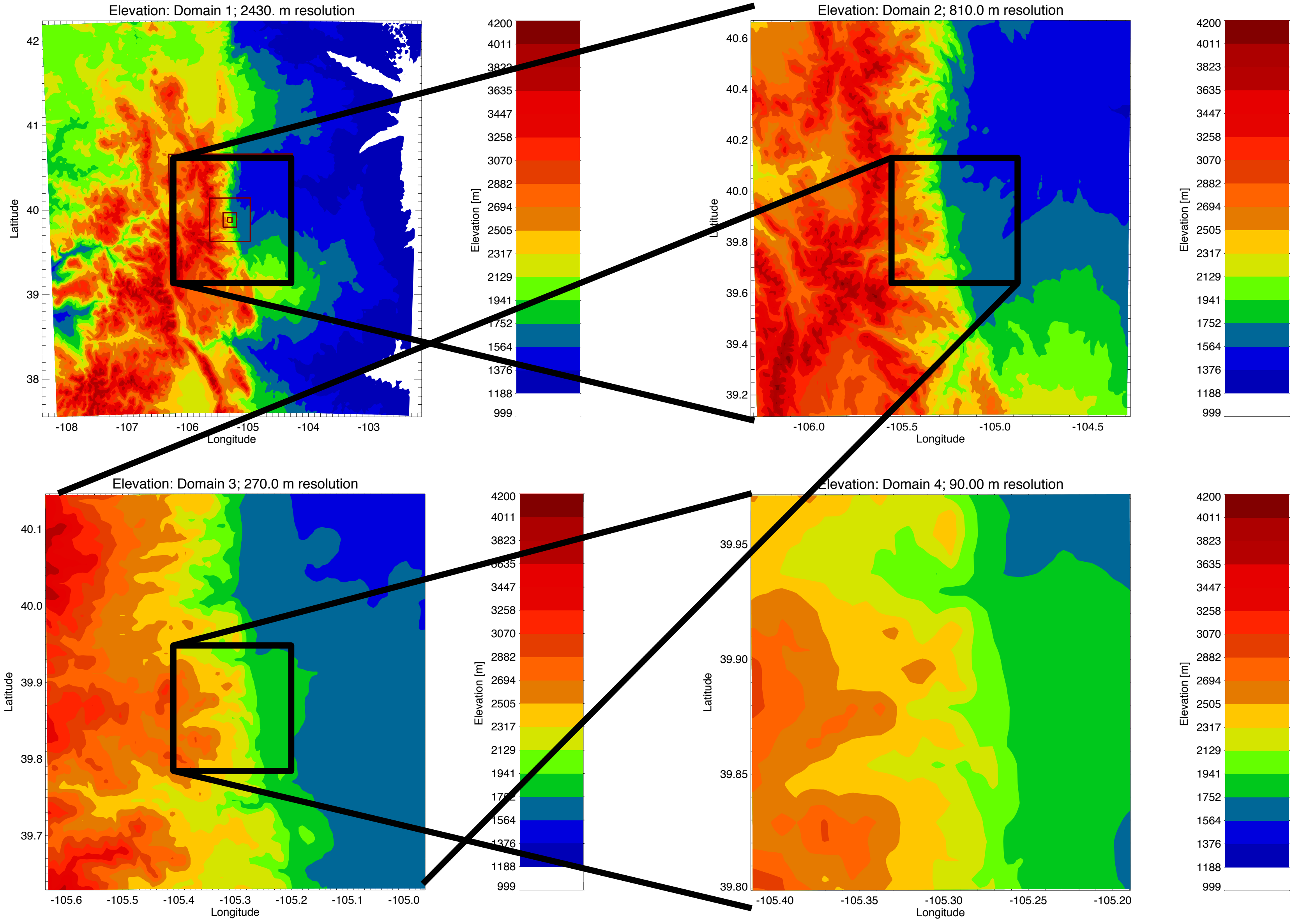
D5: $\Delta x = 30\text{m}$

D6: $\Delta x = 10\text{m}$

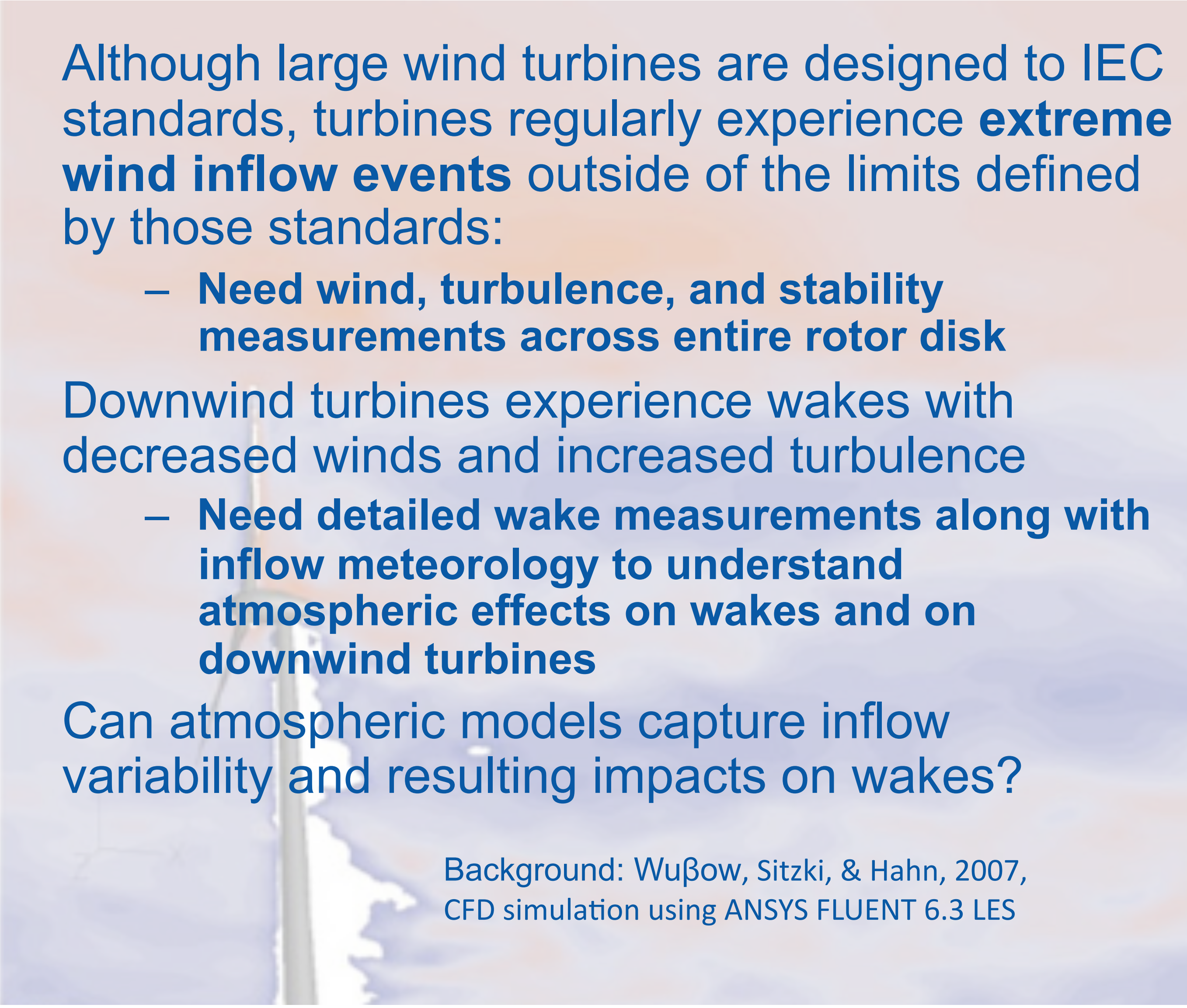
LES domains (D3+) use nonlinear backscatter with anisotropy model to capture stability effects

Challenges include complex topography and appropriate spin-up for LES turbulence

Nesting LES domains within mesoscale WRF simulations



TWICS: Turbine Wake and Inflow Characterization Study



Although large wind turbines are designed to IEC standards, turbines regularly experience **extreme wind inflow events** outside of the limits defined by those standards:

- **Need wind, turbulence, and stability measurements across entire rotor disk**

Downwind turbines experience wakes with decreased winds and increased turbulence

- **Need detailed wake measurements along with inflow meteorology to understand atmospheric effects on wakes and on downwind turbines**

Can atmospheric models capture inflow variability and resulting impacts on wakes?

Background: Wuβow, Sitzki, & Hahn, 2007,
CFD simulation using ANSYS FLUENT 6.3 LES

NOAA

NREL

Lawrence Livermore National Laboratory
Science in the National Interest

U.S. DEPARTMENT OF ENERGY

Characterizing turbine inflow and turbine wakes with Doppler LIDAR at a modern 2.3 MW turbine: couple models (left) with observations (right)

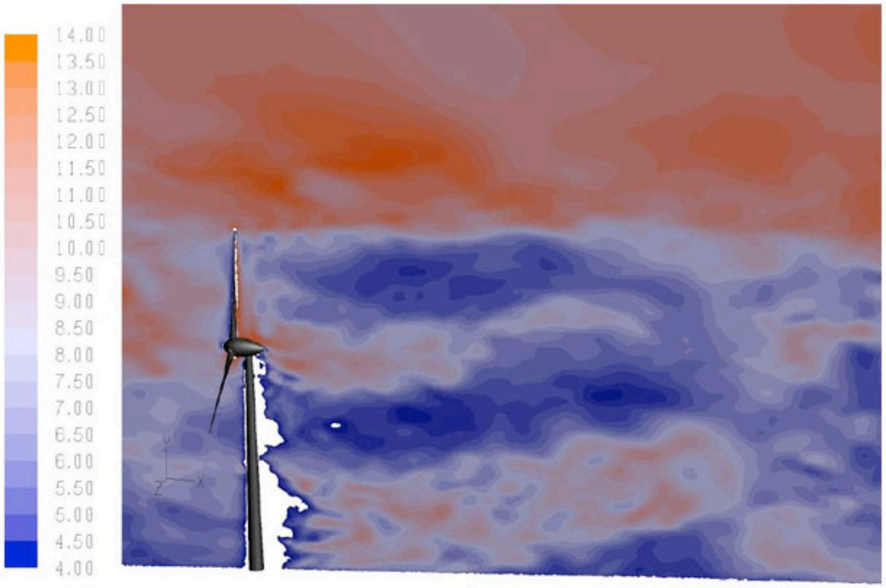
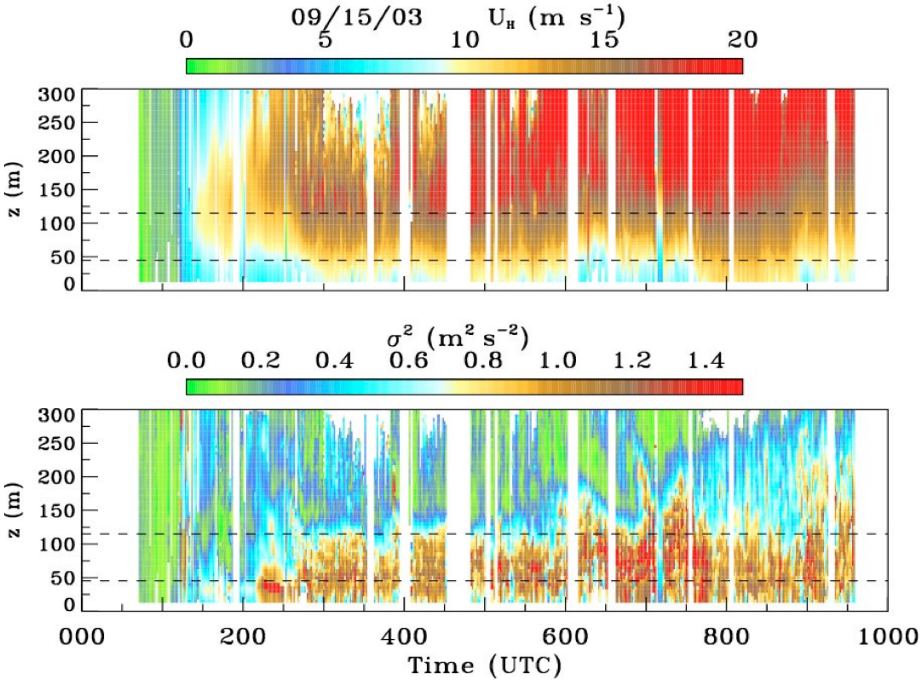


Figure 2: Contours of velocity magnitude in m/s at an average v_{in} of 10m/s at hub height (snapshot in a vertical plane).

Wuβow, Sitzki, & Hahn, 2007,
CFD simulation using ANSYS FLUENT 6.3 LES

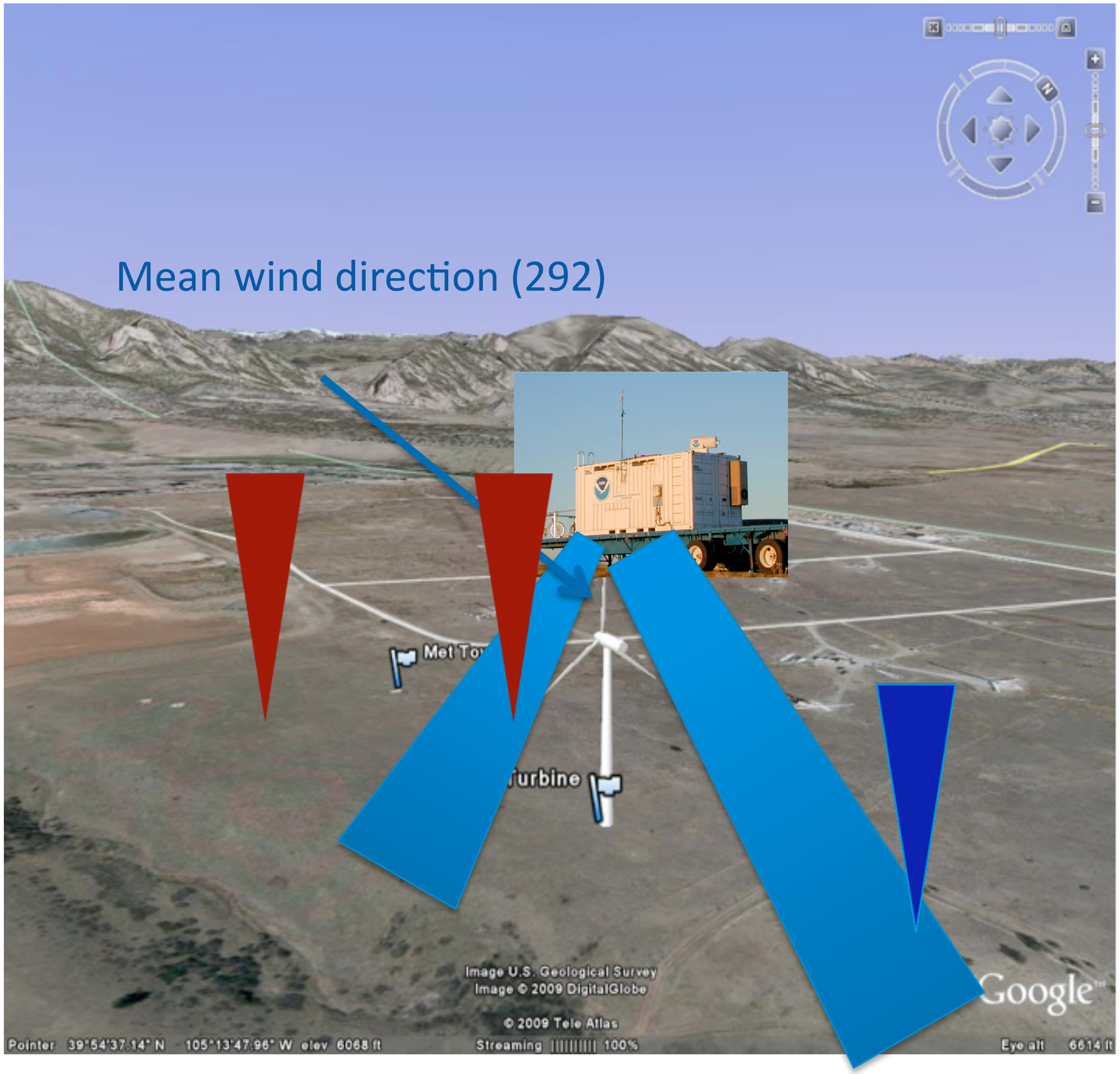


Kelley et al., 2006: streamwise velocity and velocity variance from HRDL

Project Plan: Deploy NOAA's High Resolution Doppler Lidar at NREL's National Wind Technology Center (April 2011) to characterize inflow and wake from the Siemens 2.3 MW turbine; model with WRF and WRF-LES

TWICS field plan (as of 3/2011)

Lundquist (CUB, NREL), Kelley/Clifton (NREL), Banta/Pichugina/Brewer (NOAA), Mirocha (LLNL)



135m met tower, 6+ sonics, T profiles

NOAA HRDL LIDAR

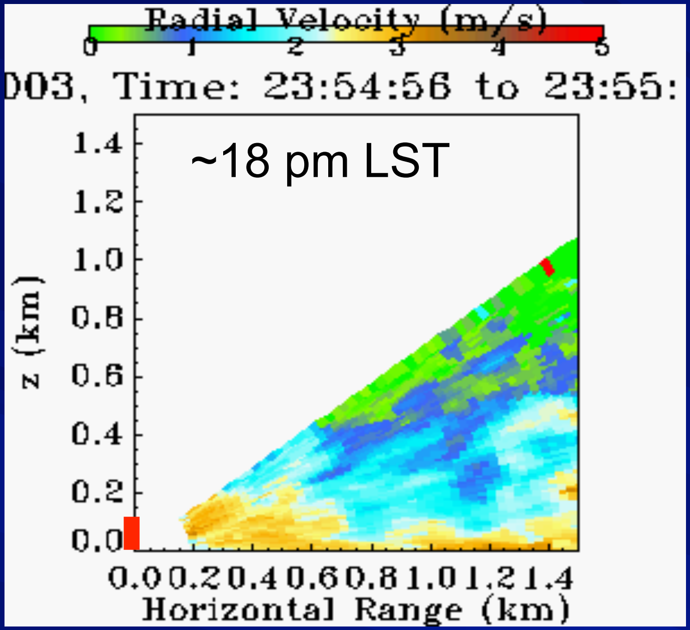
2 NREL SODAR

CU WindCube LIDAR

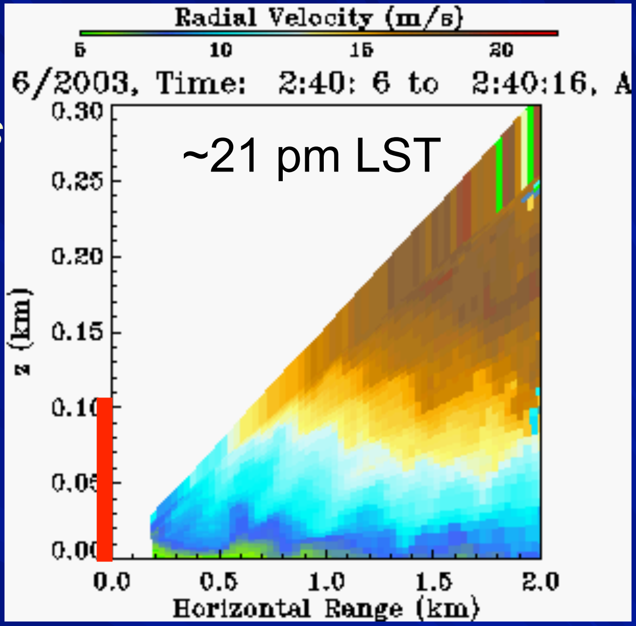
Two-week IOP April/ May 2011

Plan subject to change

Examples of HRDL observations of atmospheric complexity



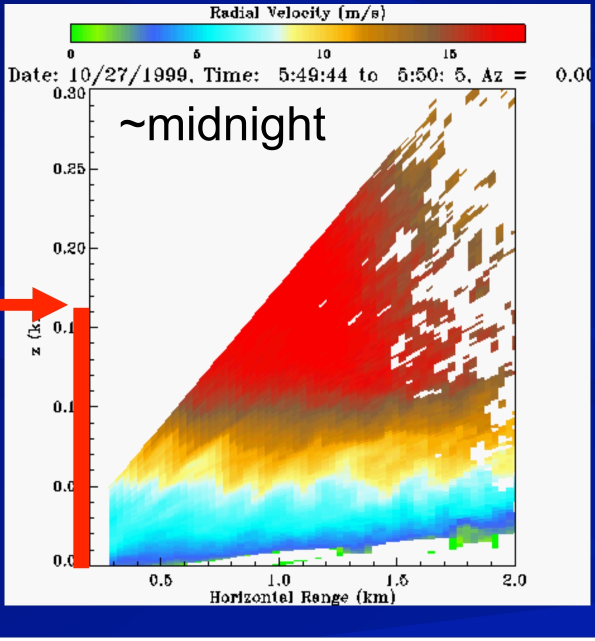
Mean wind and turbulence quantities vary in time

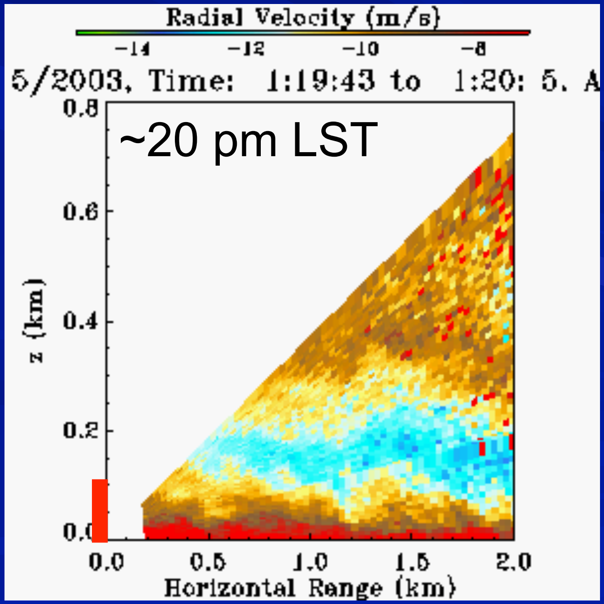


Evening transition

LLJ development

Turbine height (115 m)





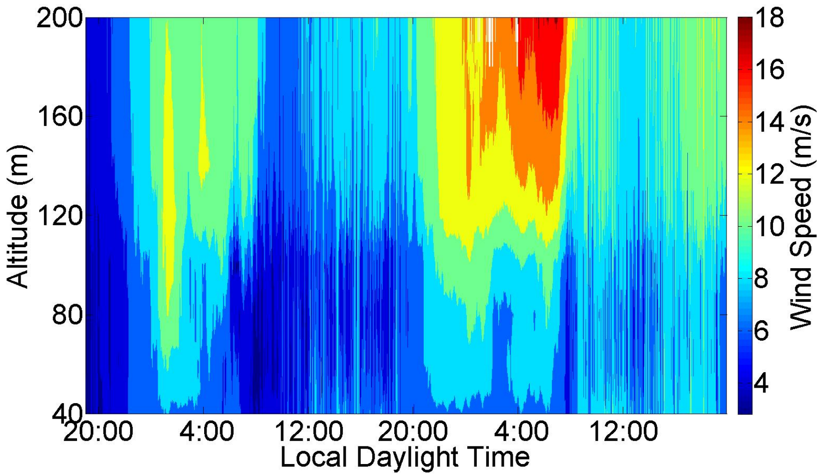
Images courtesy Banta & Pichugina, NOAA/ESRL

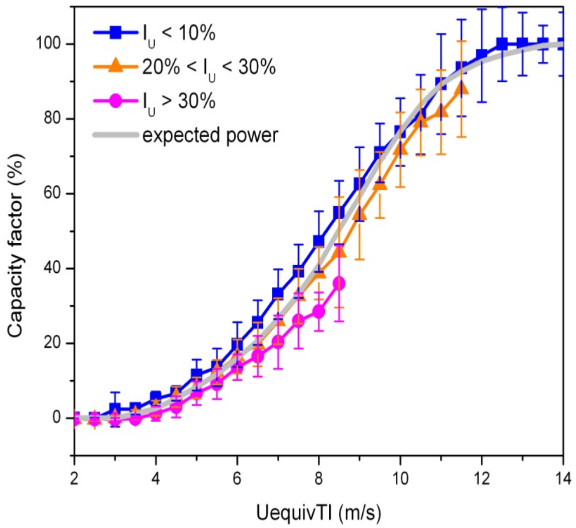
Why worry about the atmosphere?

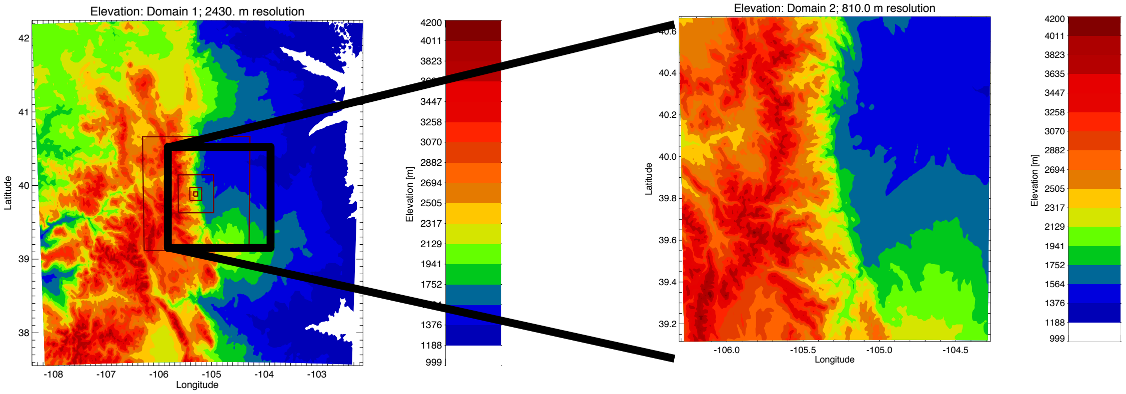
- Lower atmosphere enjoys complex dynamics due to diurnal cycle

- Dynamics affect:
  - Power performance
  - Maintenance Issues
  - Array & wake impacts

- Example of nested atmospheric modeling







Thanks for your attention

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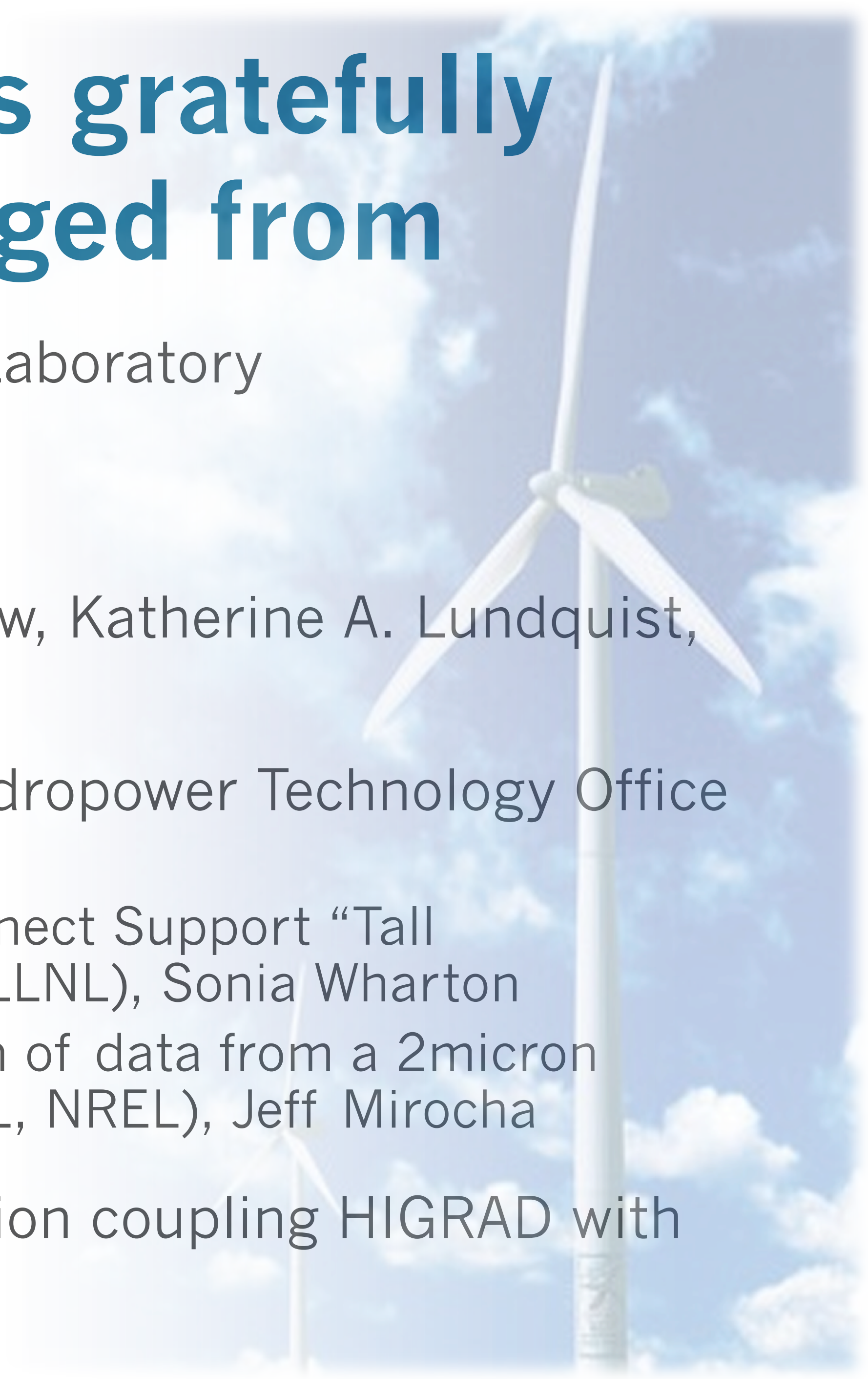
303/384-7046 (@NWTC)

Contributions gratefully acknowledged from



- National Renewable Energy Laboratory
  - Supercomputing capabilities
  - Joint Appointment support
- UC Berkeley: Prof. Fotini Chow, Katherine A. Lundquist, Nikola Marjanovic
- Dept of Energy Wind and Hydropower Technology Office for research funding:
  - Renewable Systems Interconnect Support "Tall Turbines" (subcontract with LLNL), Sonia Wharton
  - 20% by 2030: "Incorporation of data from a 2micron lidar" (subcontract with LLNL, NREL), Jeff Mirocha
- LANL for research collaboration coupling HIGRAD with WRF (Rod Linn)