Atmospheric Remote Sensing for Improving Wind Energy Technology

Robert M. Banta[1] and Neil D. Kelley[3] *(presenters)*
Yelena L. Pichugina[1,2] , W. Alan Brewer

[1] Earth System Research Laboratory, National Oceanic and Atmospheric Administration

[2] Cooperative Institute for Research in the Environmental Sciences
Boulder, Colorado
[3] National Renewable Energy Laboratory
Golden, Colorado

SEAS – 3 Sept 2009

Acknowledgments

- Atmospheric Remote Sensing Branch, ESRL/CSD
  - Lidar *(inst. design to met. data interpretation)*
  - Mike Hardesty, chief
- ESRL Renewable Energy Team
  - Melinda Marquis, Betsy Weatherhead, Jim Wilczak, Stan Benjamin, Ellsworth Dutton, Joe Michalsky, John Brown, Klaus Wolter, John Schneider
- NREL / NWTC
  - Mike Robinson, Bonnie Jonkman

Atmospheric Remote Sensing Staff

Raul Alvarez

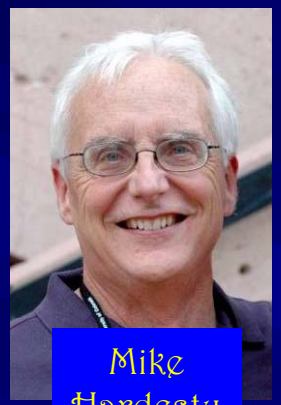
Bob Banta

Alan Brewer

Jim Churnside

Wynn Eberhard

Joanne George


Mike Hardesty

Andy Langford

Richard Marchbanks

Brandi McCarty

Yelena Pichugina

Ron Richter

Scott Sandberg

Christoph Senff

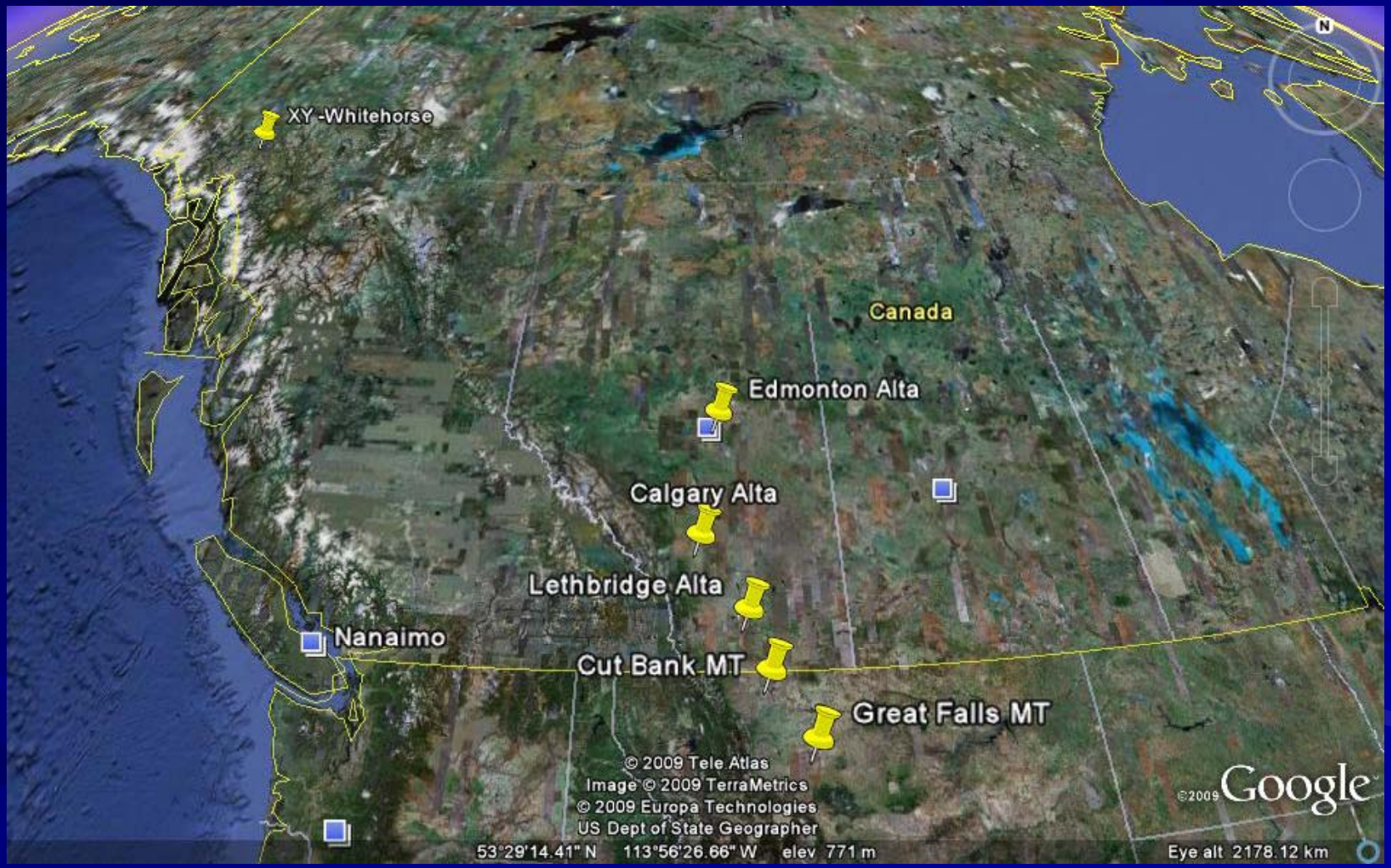
Mona Tell

Sara Tucker

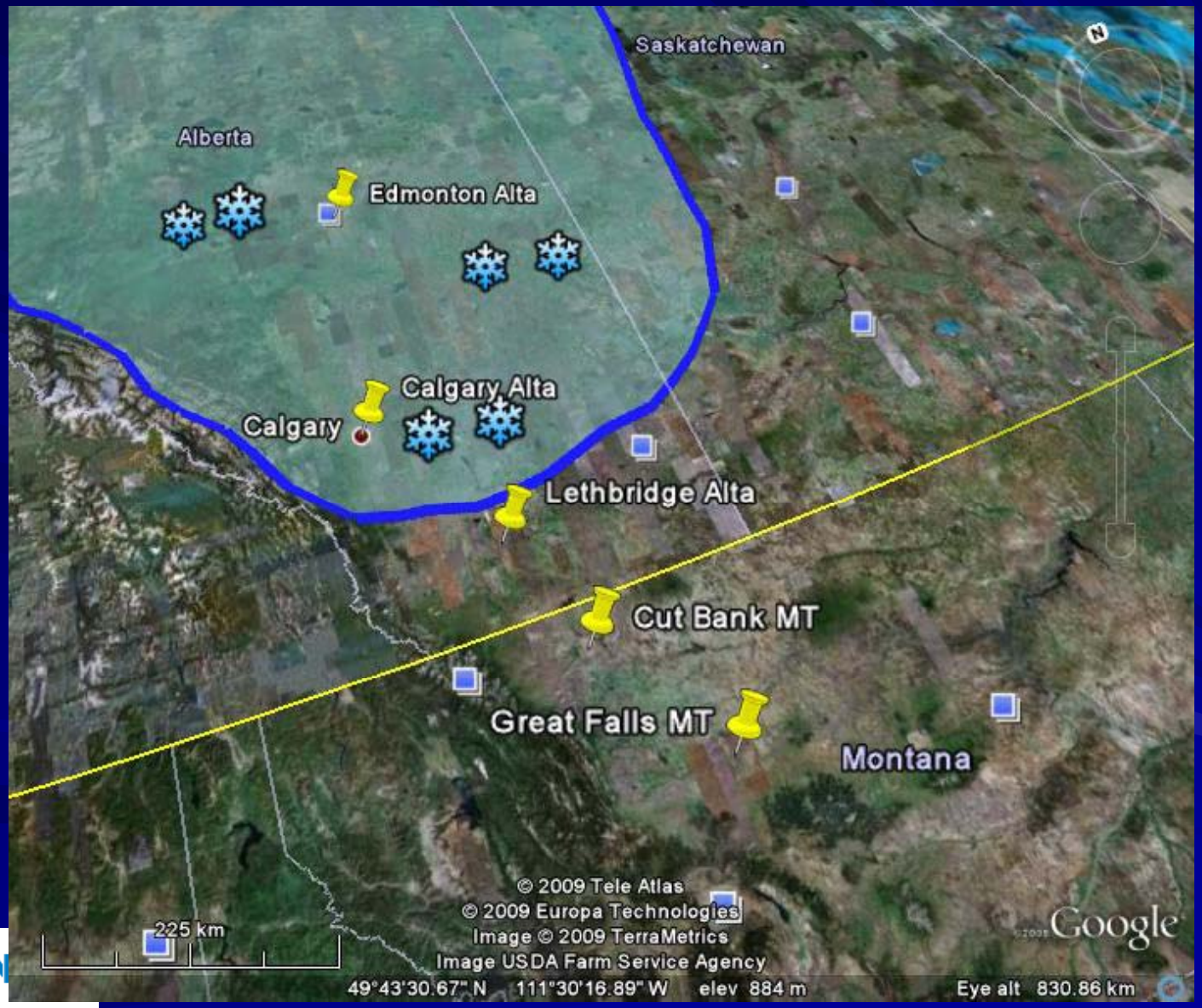
Ann Weickmann

Reality . . .

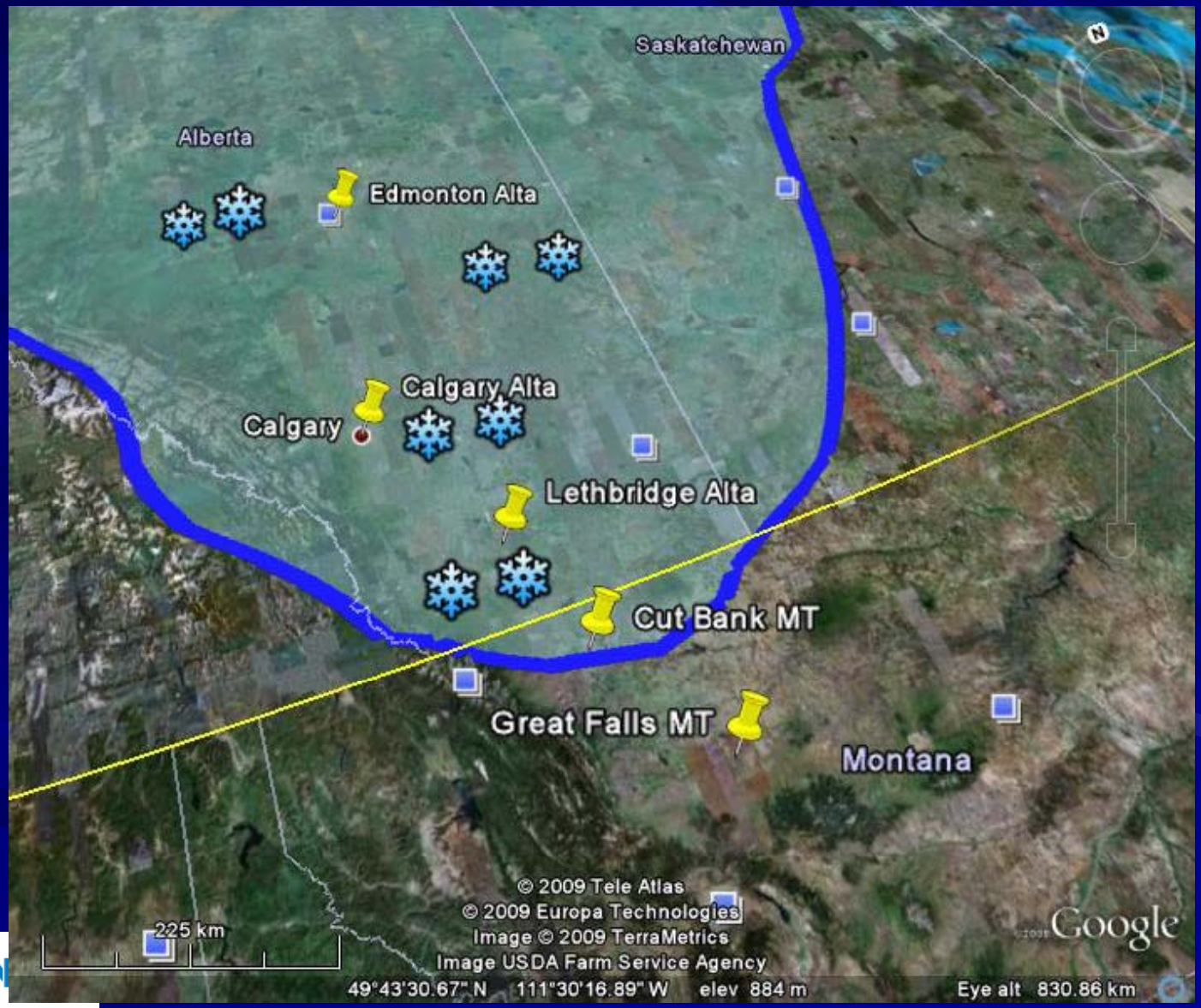
Arctic Front case study



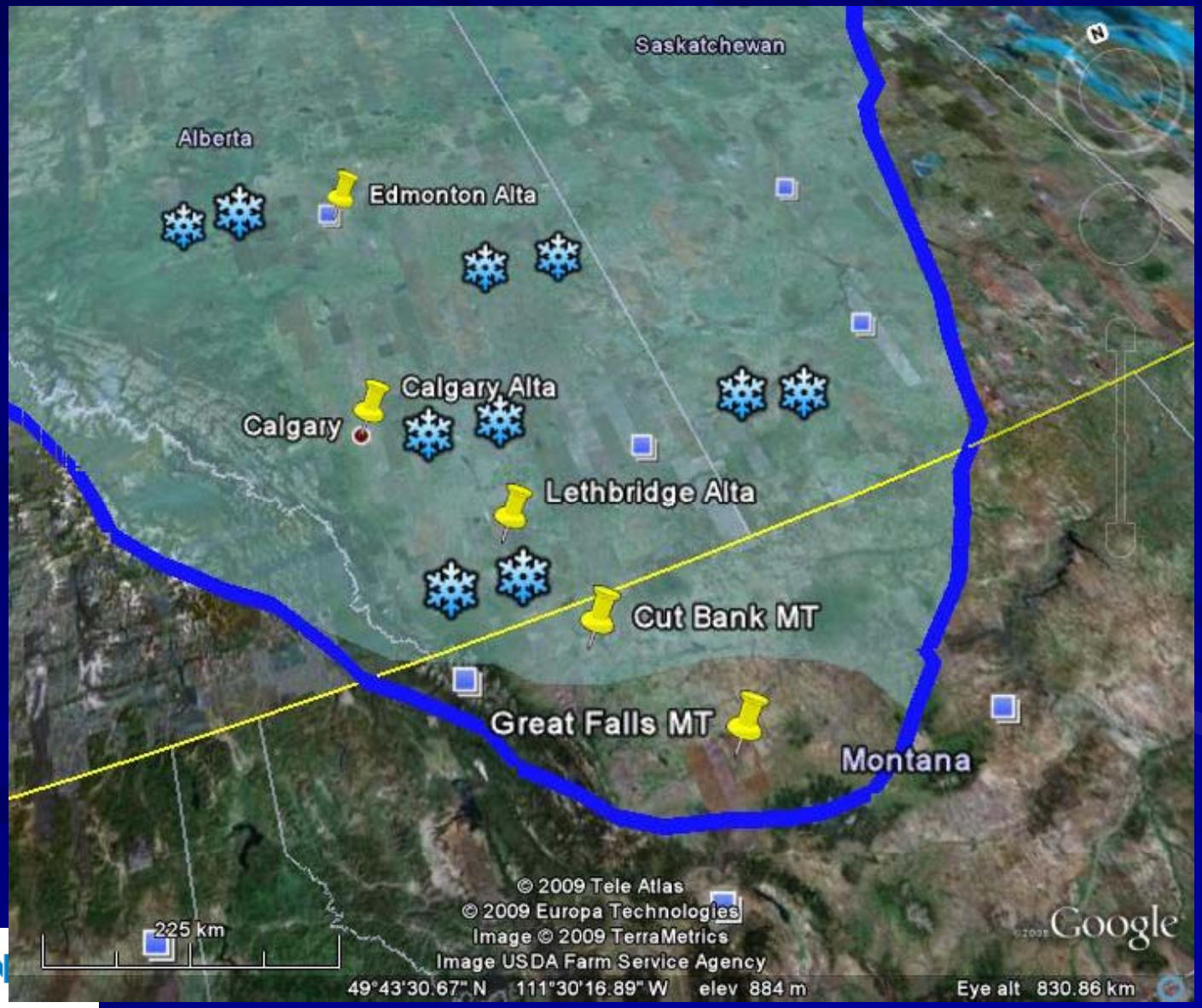
Arctic Front case study



Arctic Front case study



Arctic Front case study



Arctic Front Case

Take-home messages

- Real atmosphere teaches humility
  - “always” isn’t necessarily always
- Just when you think – have something figured out
  - Atmosphere finds a way to jump up, bite you in the rear
- Especially true if what you ‘know’ comes from model
  - Conceptual, numerical, analytical, engineering

- Essential forecast was accurate ! …front arrived as predicted
  - Bust to customer, tho = cloud-base and vsby wrong
- Changes happen after last obs., if ‘too far’ away

- *Precise wind speeds more capricious, unpredictable than Arctic Front clouds, weather*

What about wind energy ?

- *Forecasts* of winds needed
- *Characterization* of winds needed
  - Mean value, variability, extremes, vert. structure, abrupt fluctuations (incl turbulence)
- 2 special requirements
  - *Accuracy* – more precise than previous applications
  - *Above surface* – traditionally difficult to measure

Wind energy

- Wind plants (farms) must be ***economically viable - $$***
  - Estimated for one plant – 0.5 m s^{-1} difference in annual wind speed = $ 40 M per year
- Major meteorological issue:

Lack of measurements in 30-300m layer

  - High-quality, long term
  - Must include turbine layer + 'context'
  - Poor understanding of processes, flow structure in
  - " " variability on all relevant scales
  - NWP model performance unknown

- New technology, instrumentation becoming available

Observations

- ‘Lack of measurements’ does not mean no measurements exist
- Field programs of limited duration
  - Involving the new instrumentation systems

Outline

1. What's really up there ?
2. What are meteorological requirements for wind energy ?
   – range of objectives – all important
3. How to measure turbine layer
   – technological options
4. How to use the technology to address objectives
5. Summary and conclusions

Themes

- Two important aspects of the meteorology
  - Resource
  - Costs – outages, maintenance, repair
- Diurnal cycle important
- Isolated or extreme events important
- Role of numerical weather prediction
  - Need for improvements

1. What's really up there ?

Wind resource types – examples

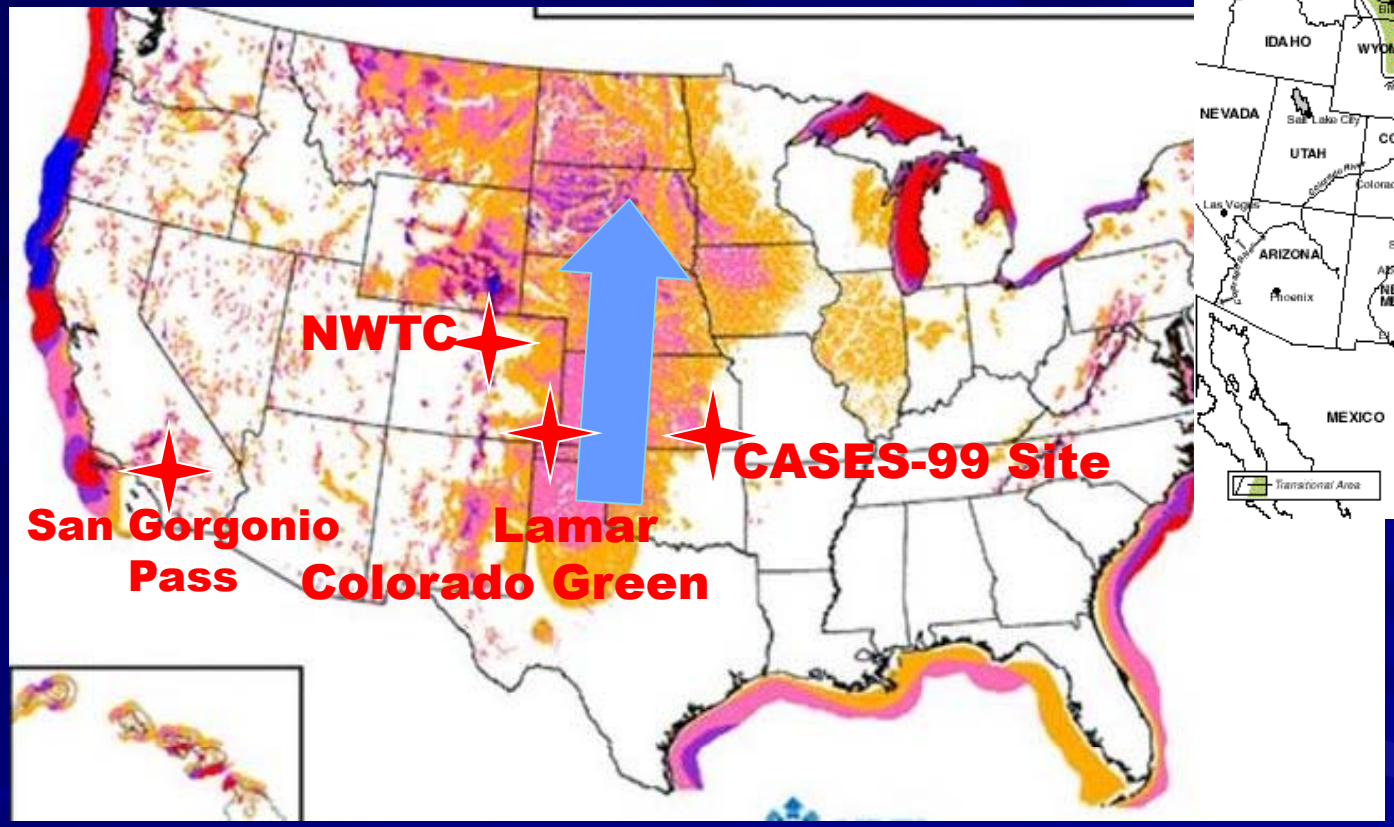
[Use Doppler lidar data, skip over description until later]

- Daytime mixed flow
- LLJs
- Complex-terrain flows

Development in diverse regions

- Variety of climate regimes
- Different types of wind resource
- Different forecasting challenges
- Different types of adverse flow conditions
  - LLJ turbulence
  - Frontal passages
  - Complex-terrain flow interactions

Wind resource - examples

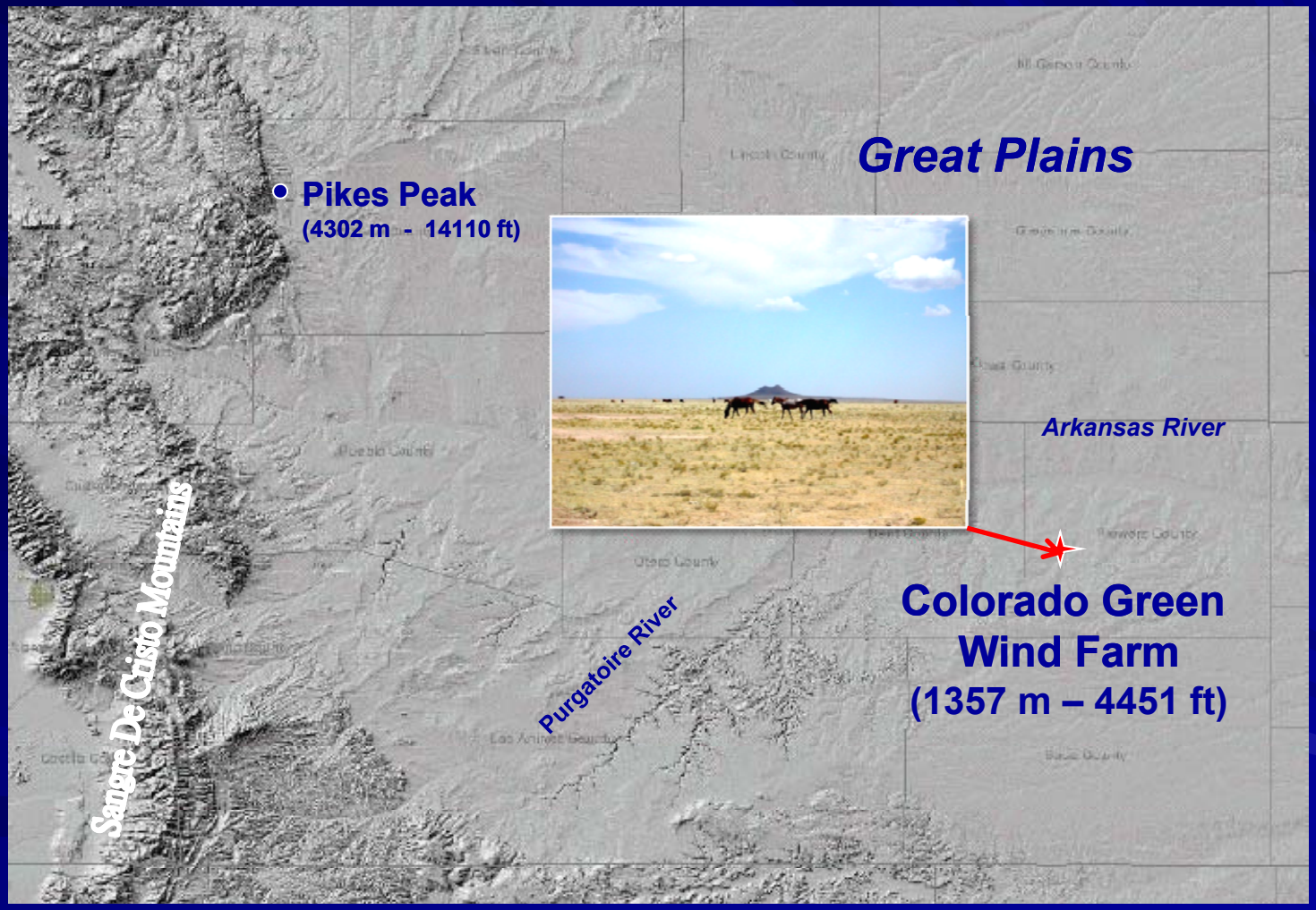


Great Plains

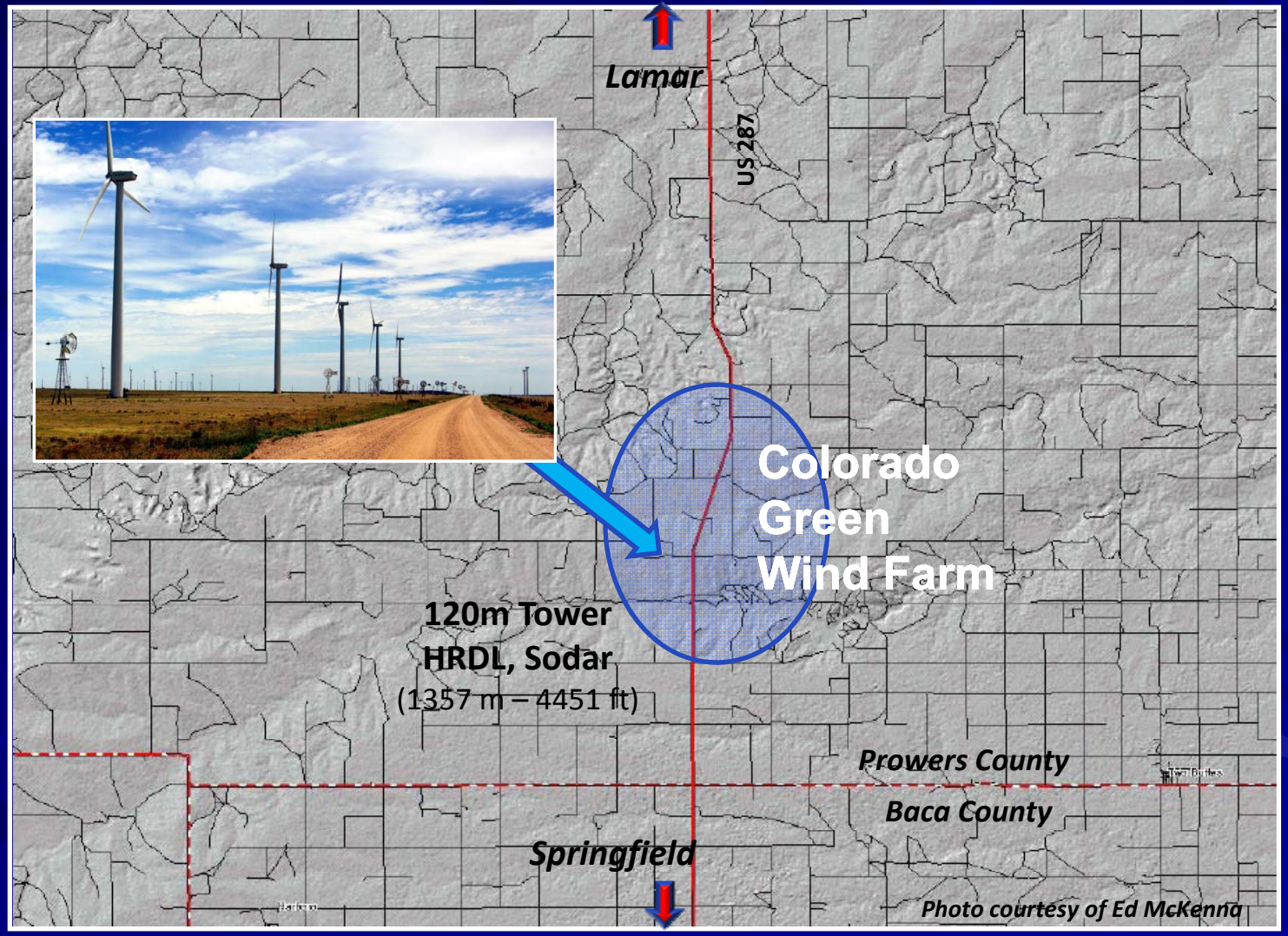
In this presentation – show ***data*** at turbine height from several of these areas, from field projects

Challenges Associated with Relatively Flat, Homogeneous Terrain

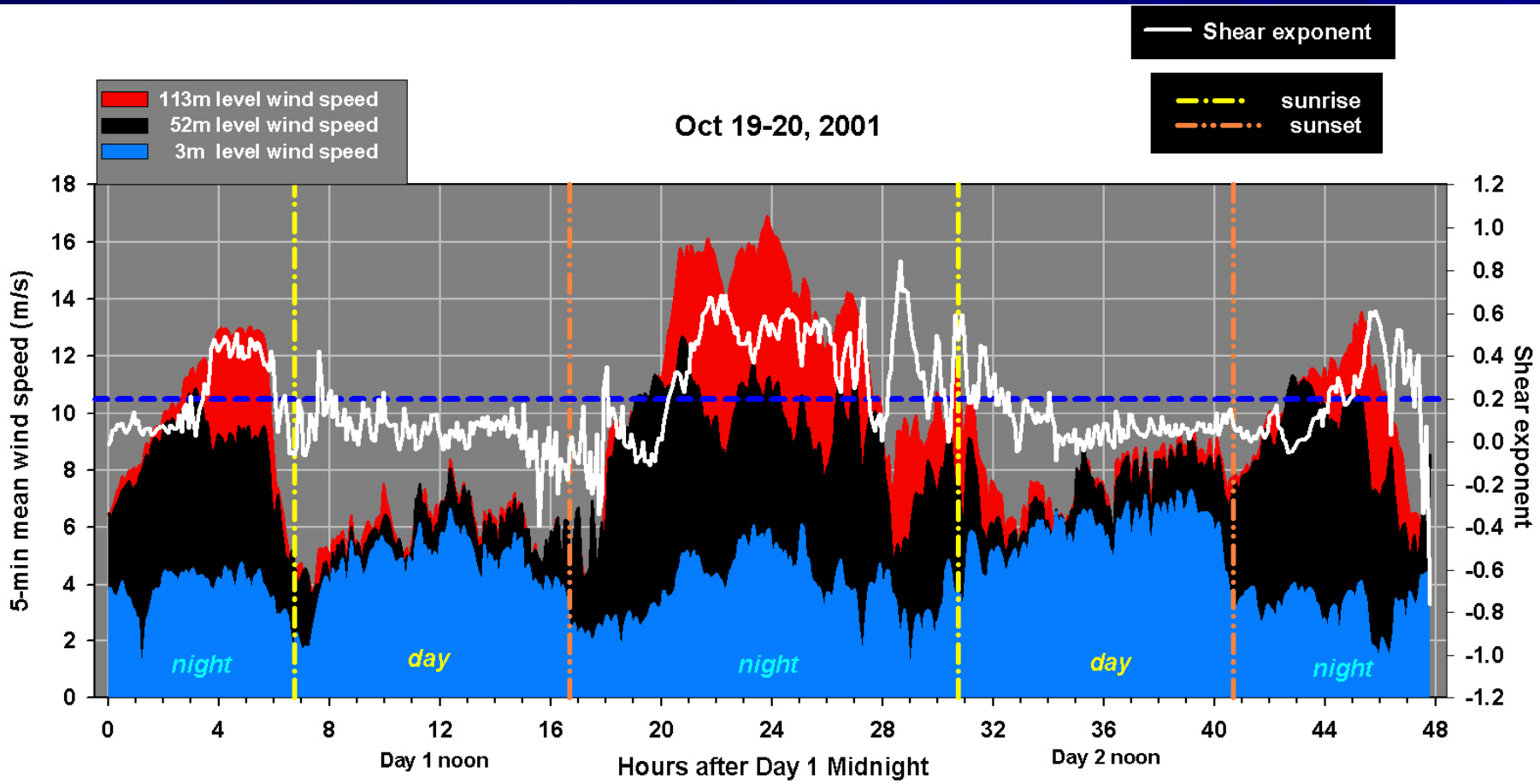
A High Plains Wind Site



Colorado Green Local Topography



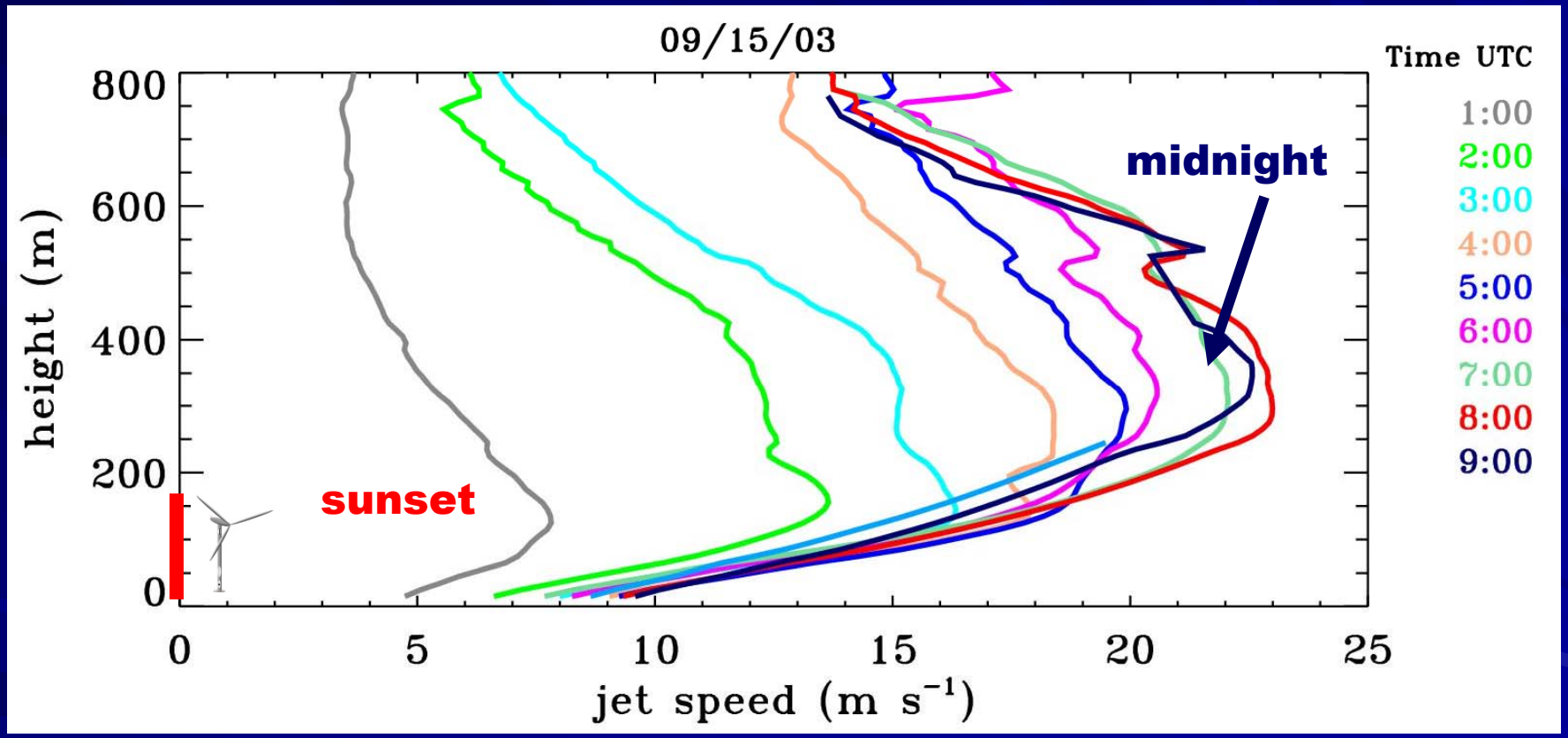
Typical 48 Hour Diurnal Variation of Wind Speeds at Three Heights Over Colorado Green Wind Farm Site



Lamar, Colorado

ESRL-NREL collaboration – September 2003

Doppler Lidar wind profiles

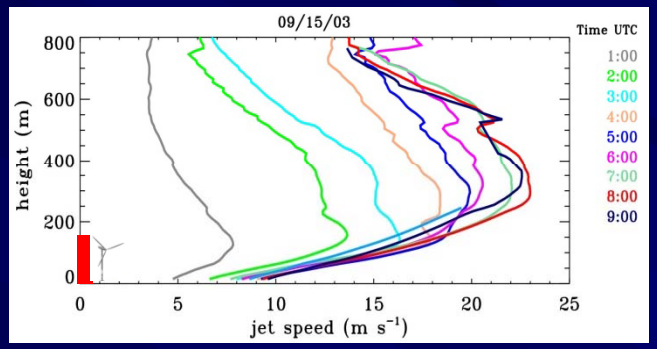


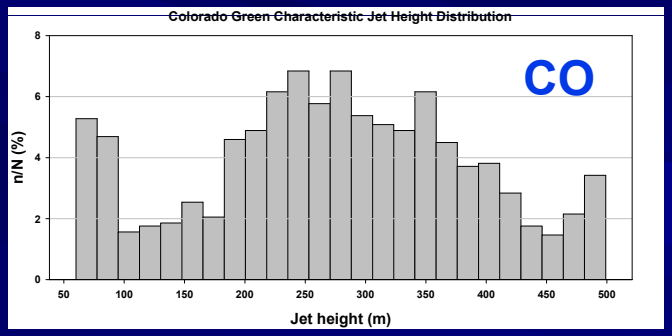
Low-level Jet –

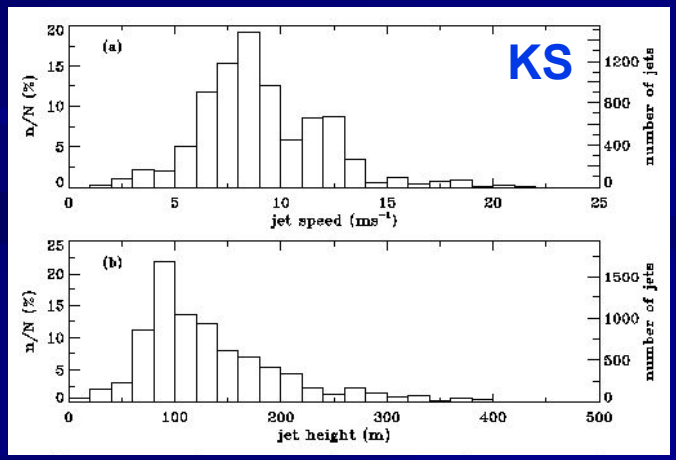
Major warm-season wind resource in the U.S. (Great Plains)

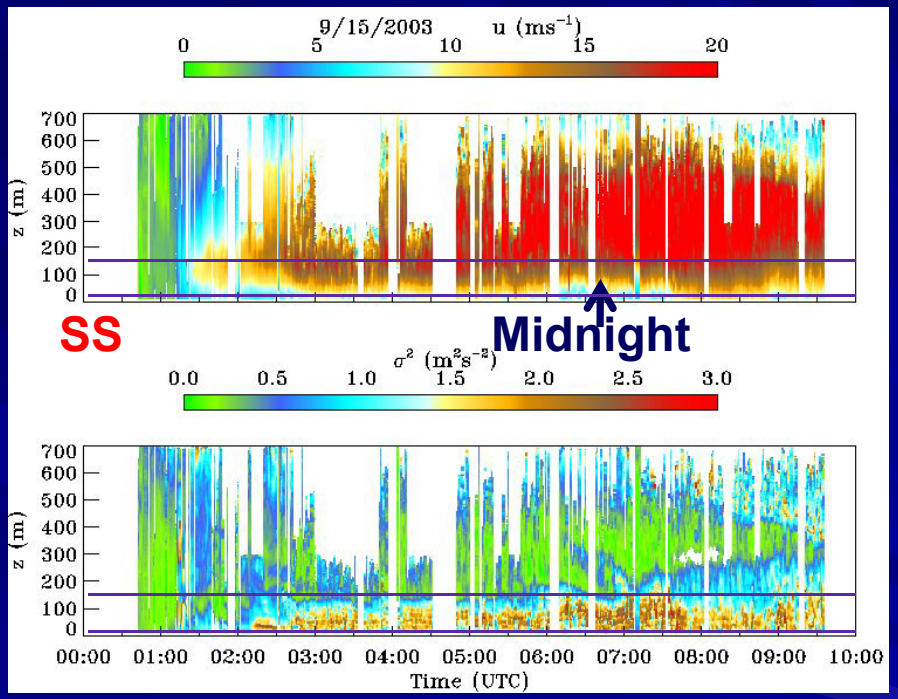
- Nocturnal acceleration aloft
- Dynamic response to surface cooling, decoupling from surface friction
- What is the nature of this resource ?
  - Mean
  - Turbulent
  - Representation in models

LLJ characteristics









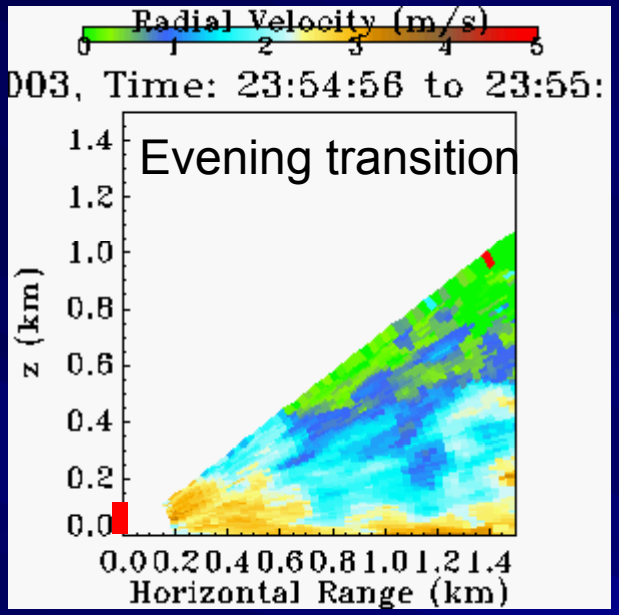
Time-height cross section

Mean wind speed

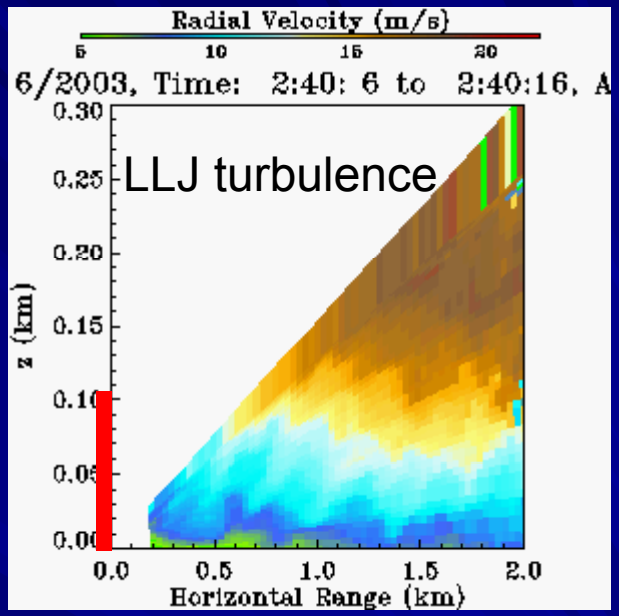
Turbulent variance

[Banta et al. 2002: Bound.-Layer Meteor., 105, 221ff]

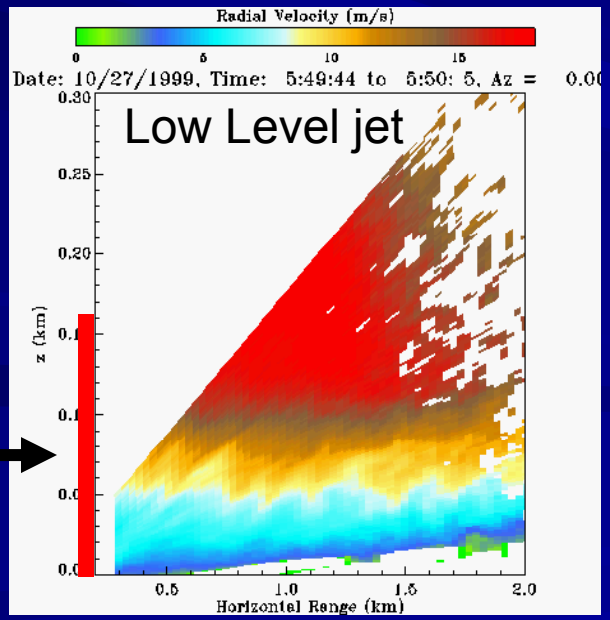
Nonstationary effects

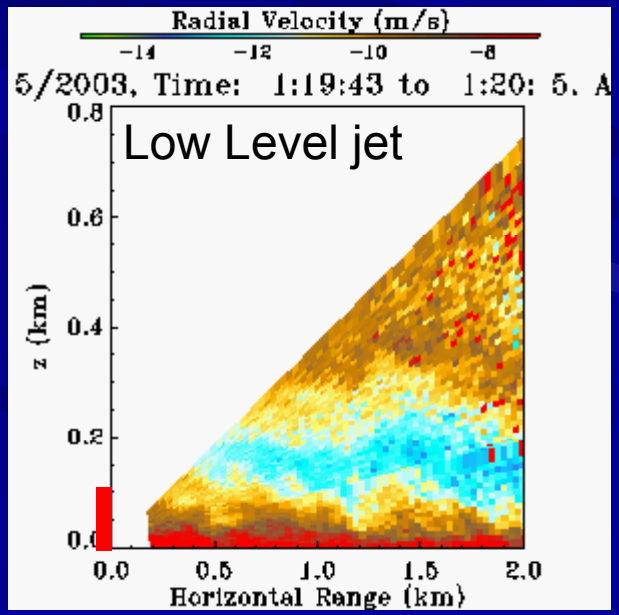


Mean wind and turbulence quantities vary in time



Turbine height (115 m)

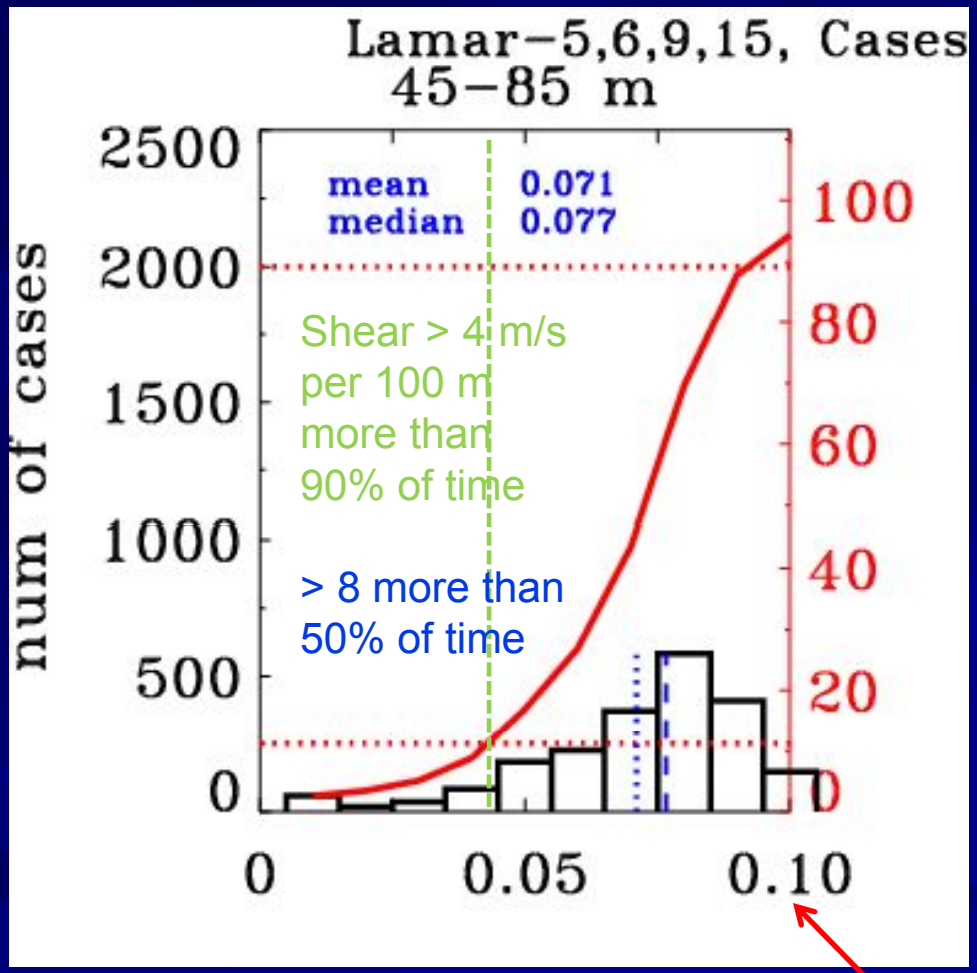


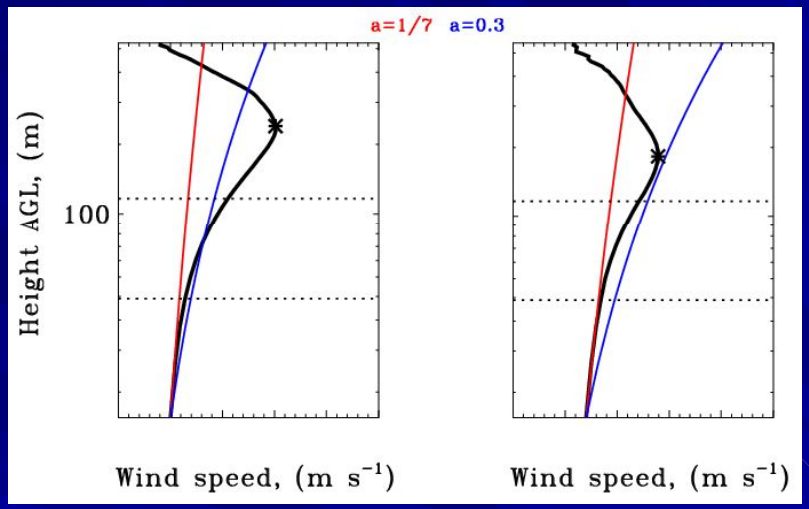


[Animations]

Colorado Green

Distribution of LLJ shear





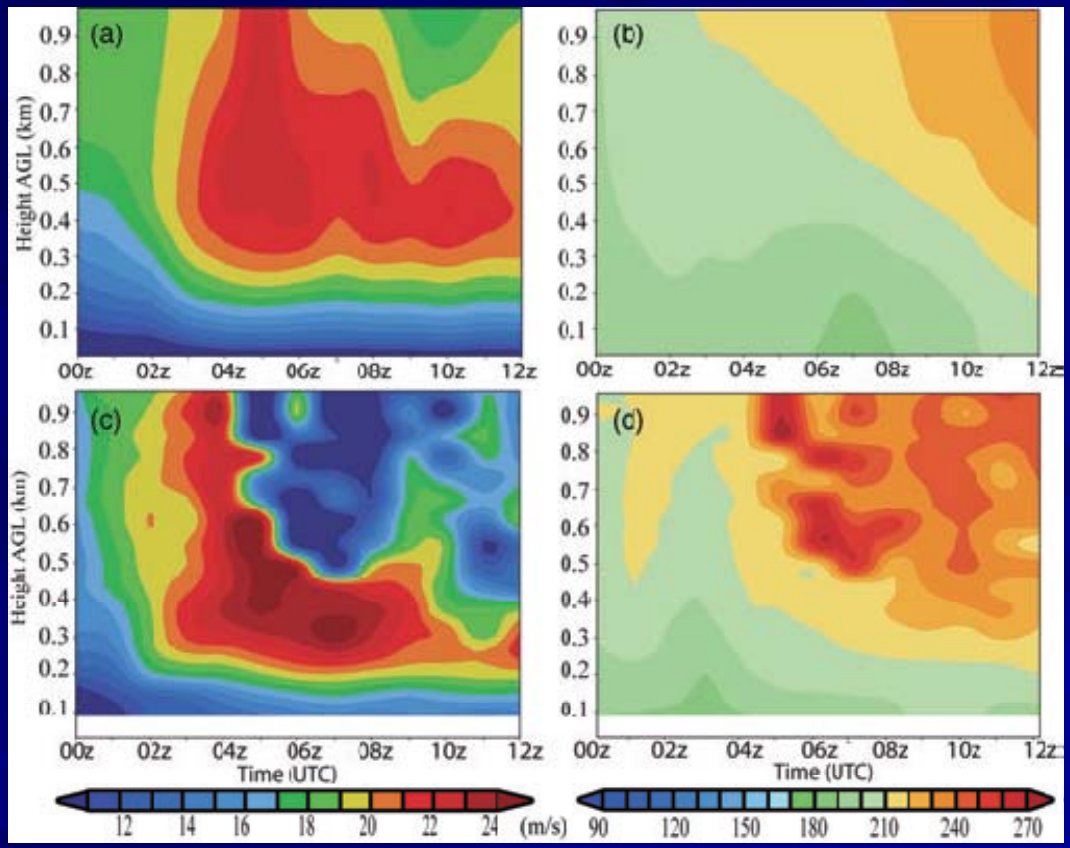
Power-law profiles not applicable to LLJ profiles

0.1 s^{-1} = 1 m/s per 10 m of height, or 10 m/s per 100 m

Model vs. observations – LLJ

Few examples in literature

Wind speed Wind direction



WRF model

Observed

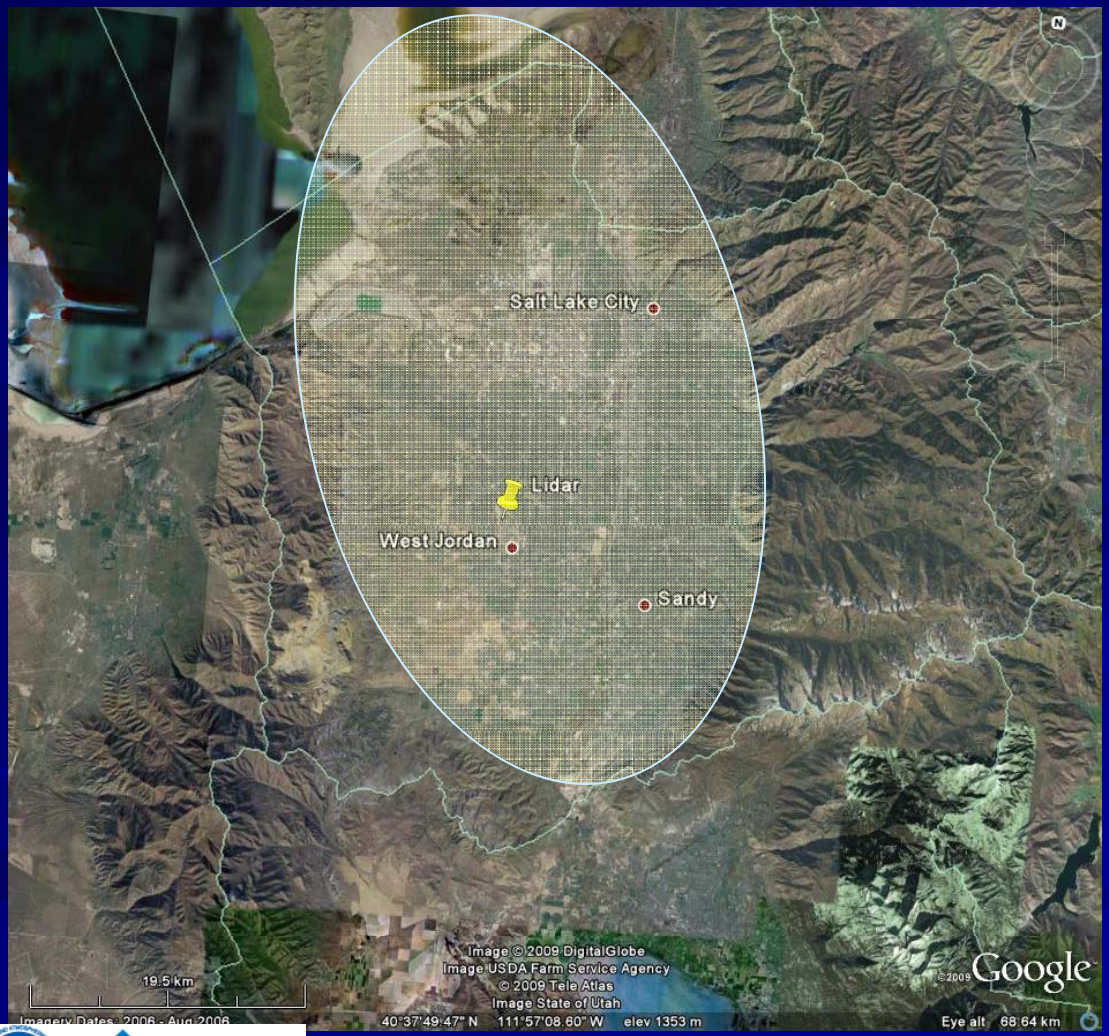
"Core of the jet tended to be higher and slower than… observed."
"…likely related to the enhanced mixing of the PBL schemes."

[Small differences = big $$]

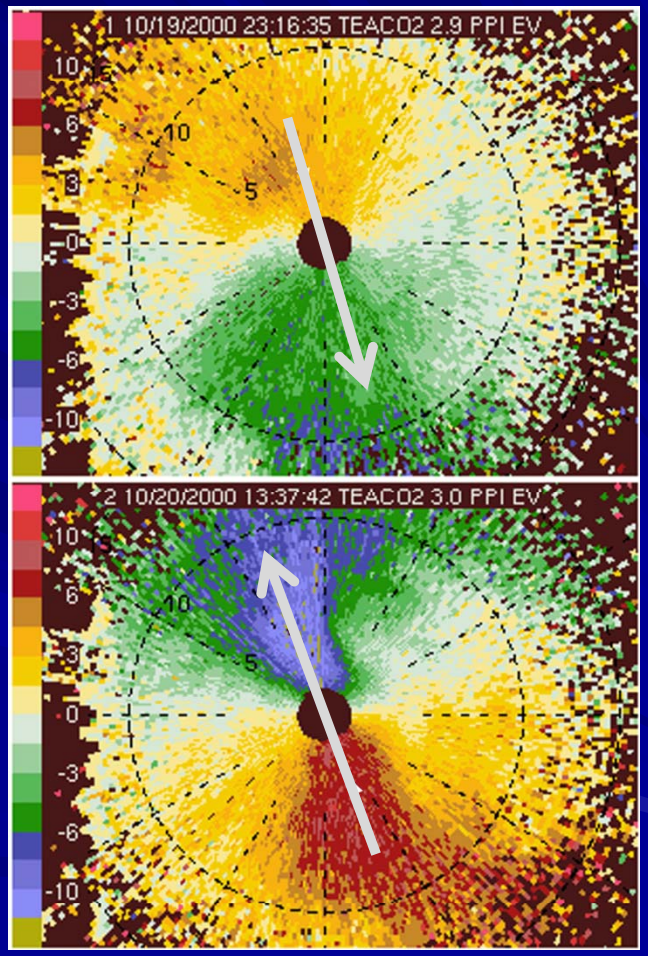
Storm et al. 2008; Wind Energy

The Challenge of Complex-terrain Sites

Great Salt Lake Basin



Daytime up-basin flow

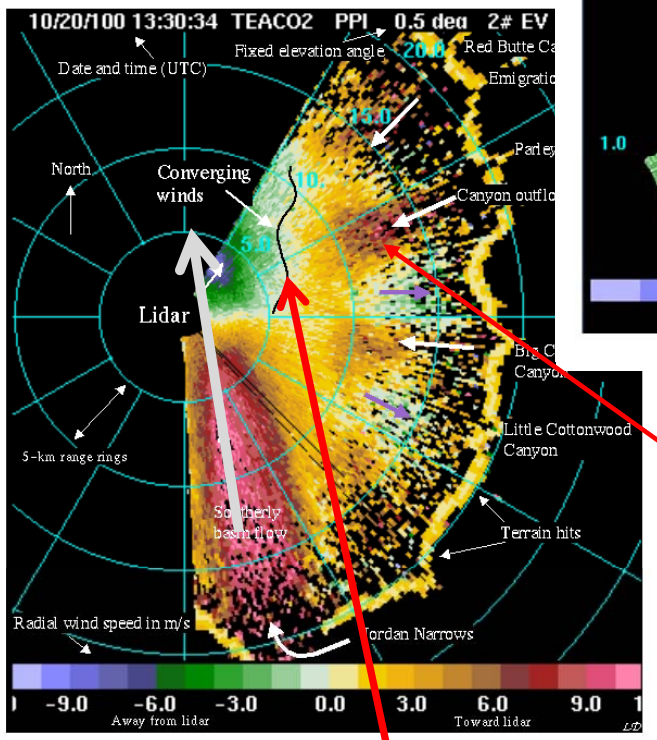


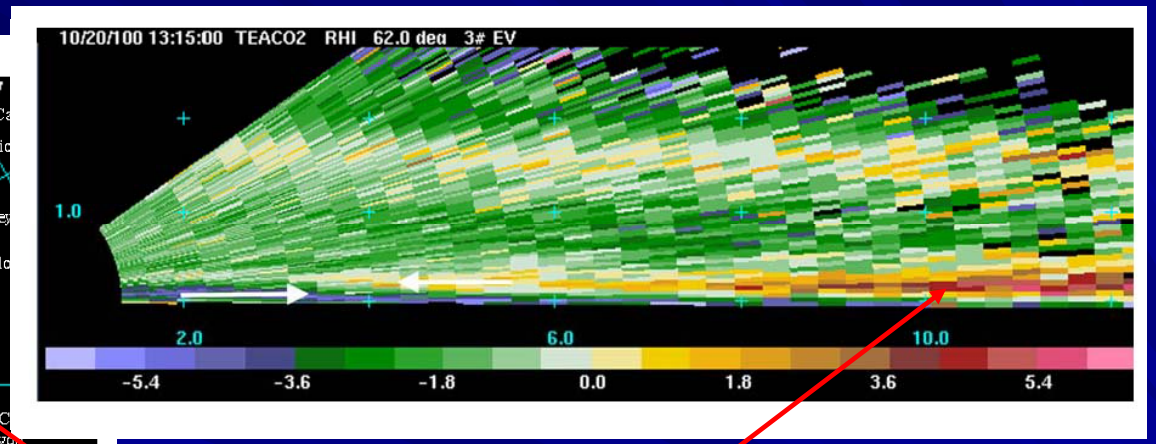
Nighttime down-basin flow

[Banta et al. 2004: J Appl Meteor., 43, 1348ff]

Complex terrain:
Locally generated flows can dominate

- Flows very complex esp. at night – but measurable





Flow exiting canyon in thin layer

CONVERGENCE

- Details of flows difficult for NWP models

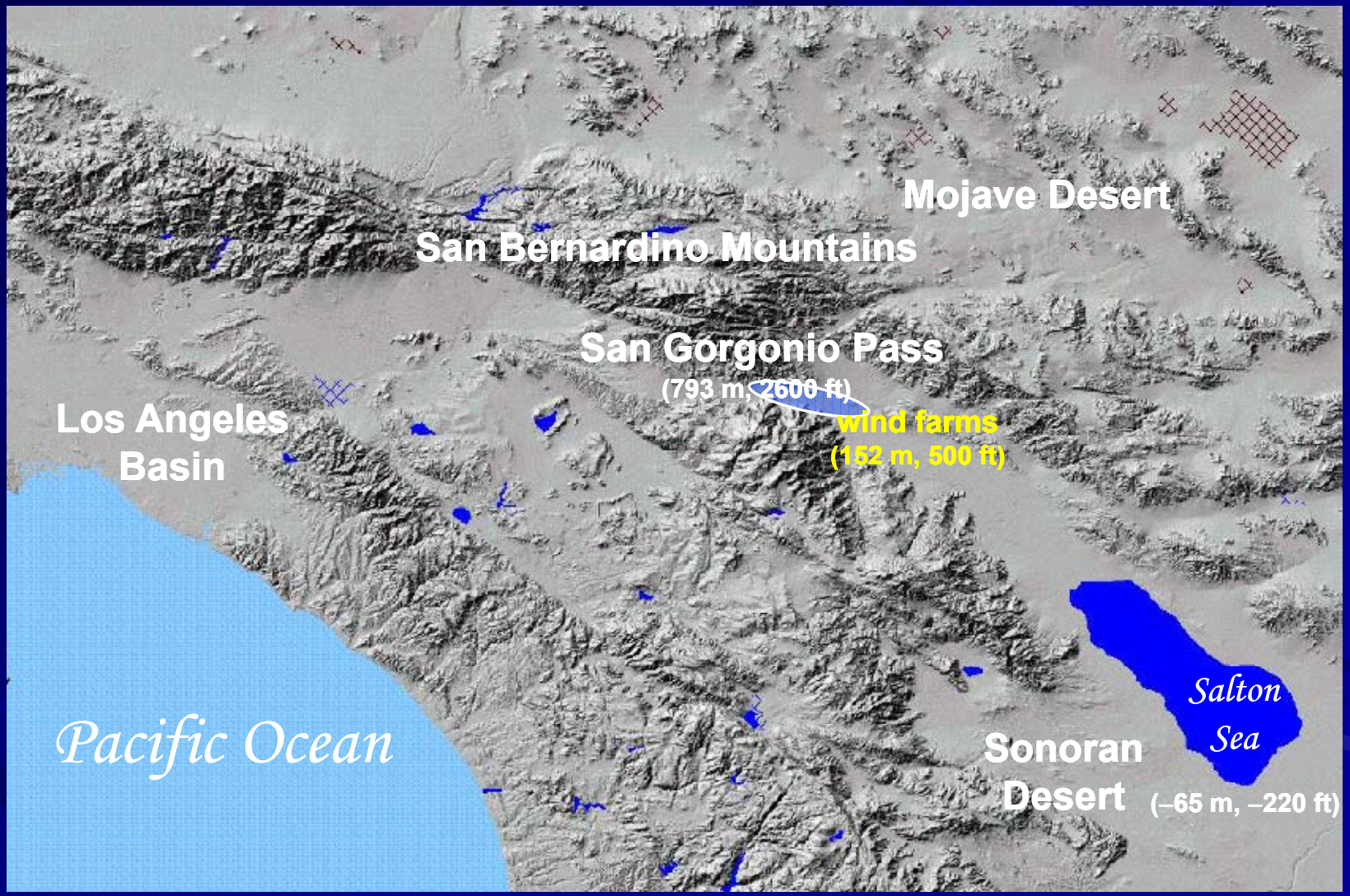
[Banta et al. 2004: J Appl Meteor., 43, 1348ff]

Wind energy applications

Two Examples . . .

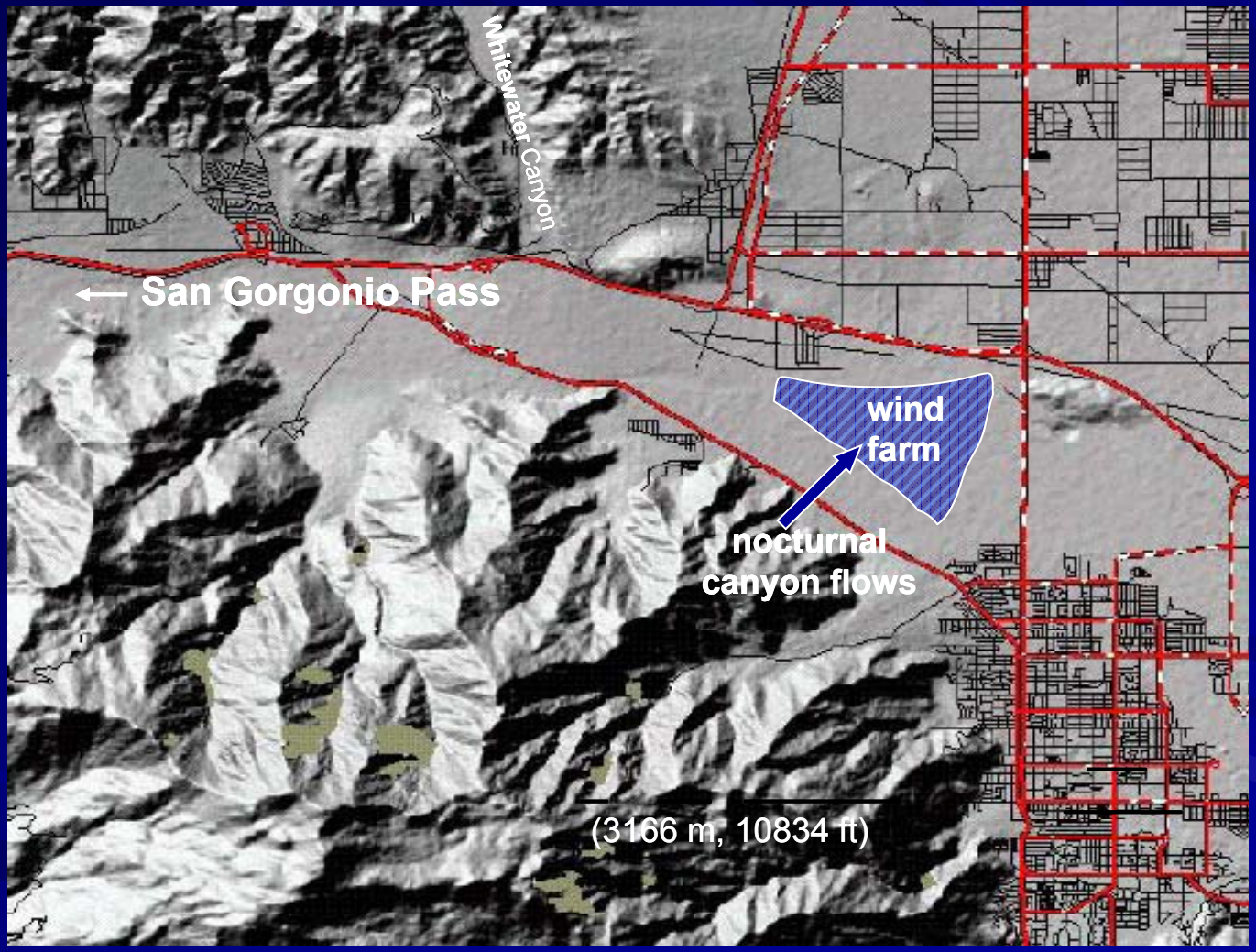
- San Gorgonio Pass near Palm Springs, California
- The National Wind Technology Center

San Gorgonio Regional Terrain



[Kelley, 1989]

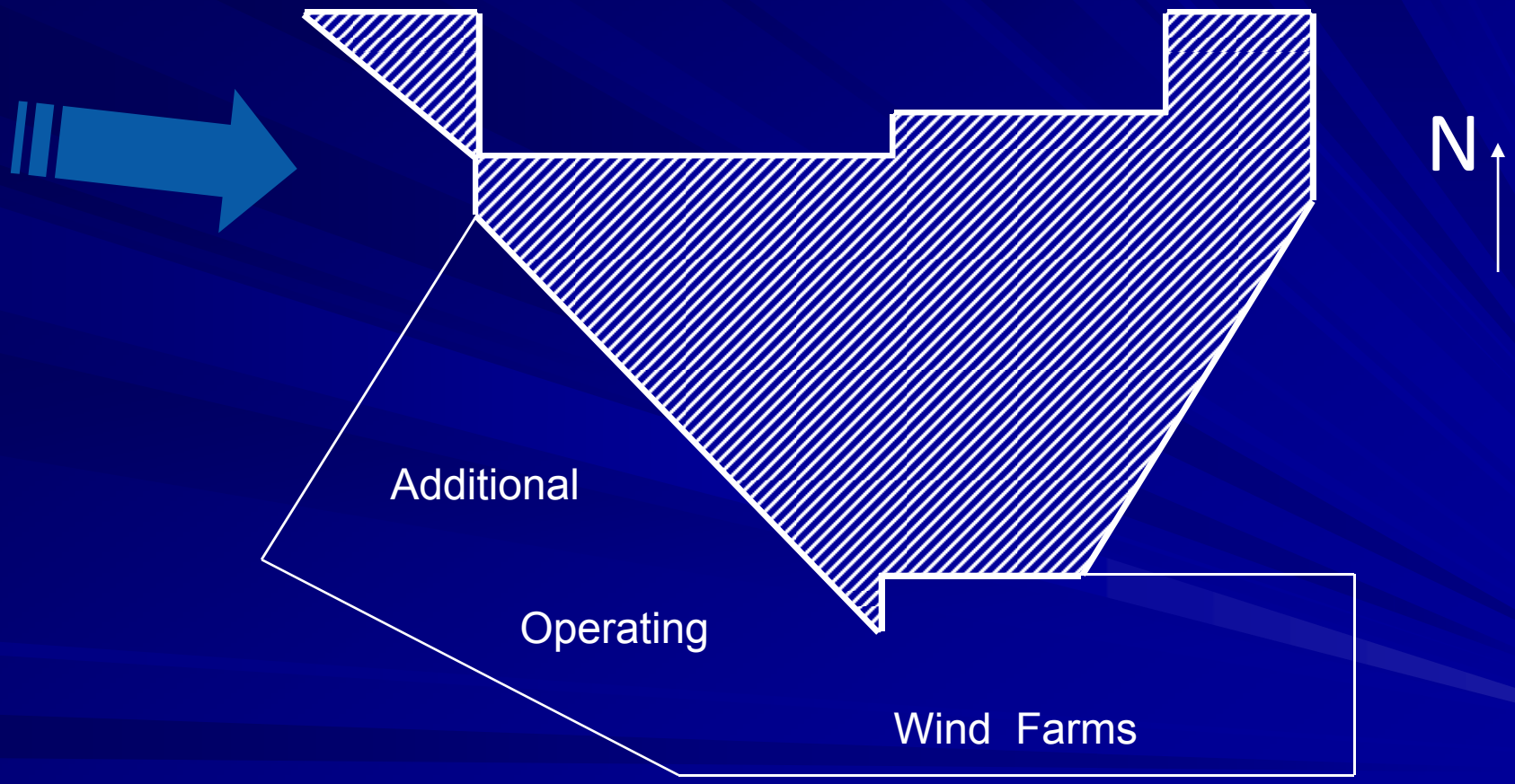
Wind Farm Nearby Topography



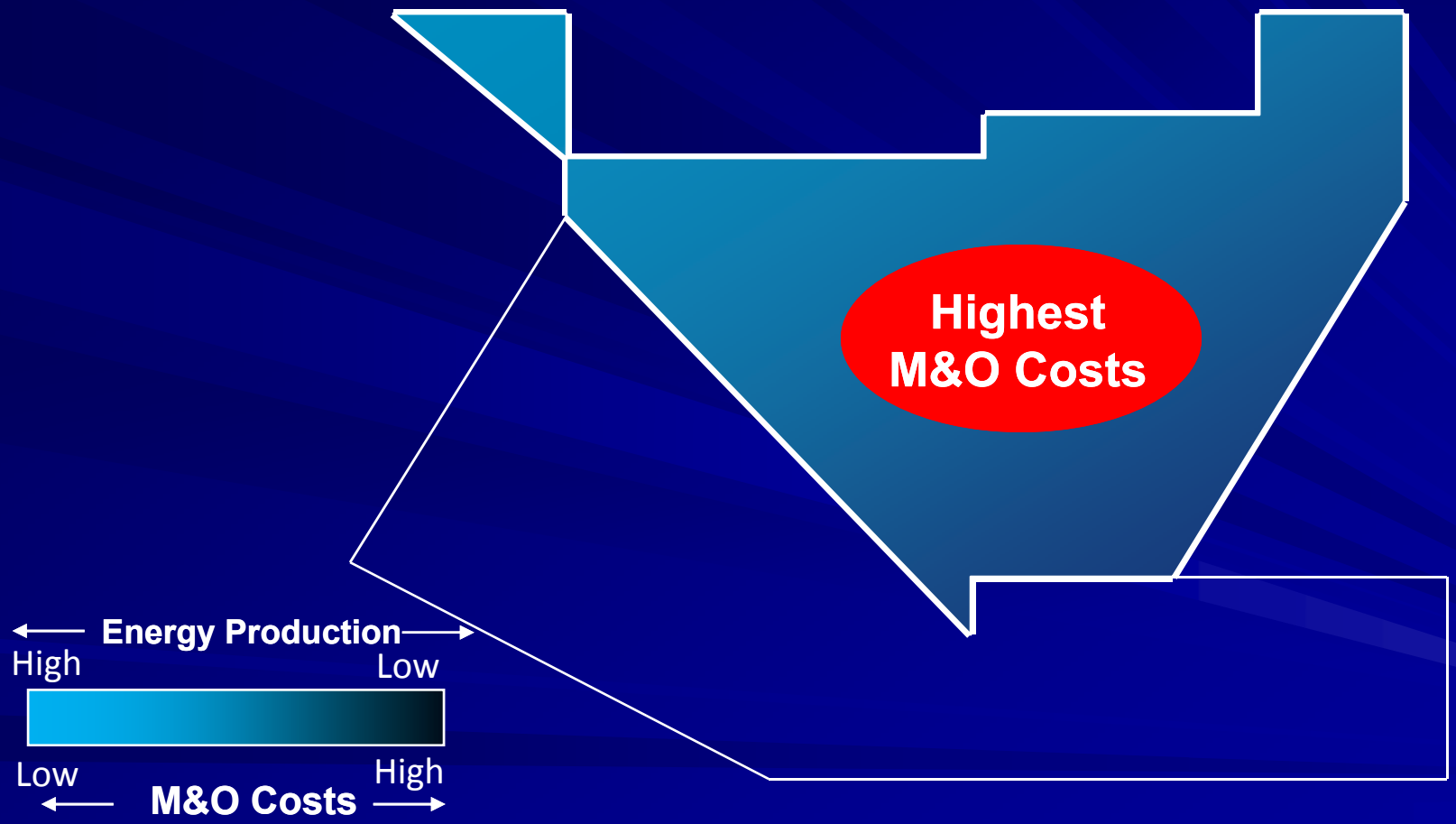
SeaWest Wind Farm San Gorgonio Pass, California

- 1000 unit wind farm of 44, 65, 108 kW wind turbines (1989-90)
- Significant number of turbine failures occurred during late evening hours
- Extensive damage to turbine yaw systems requiring extensive maintenance and replacement

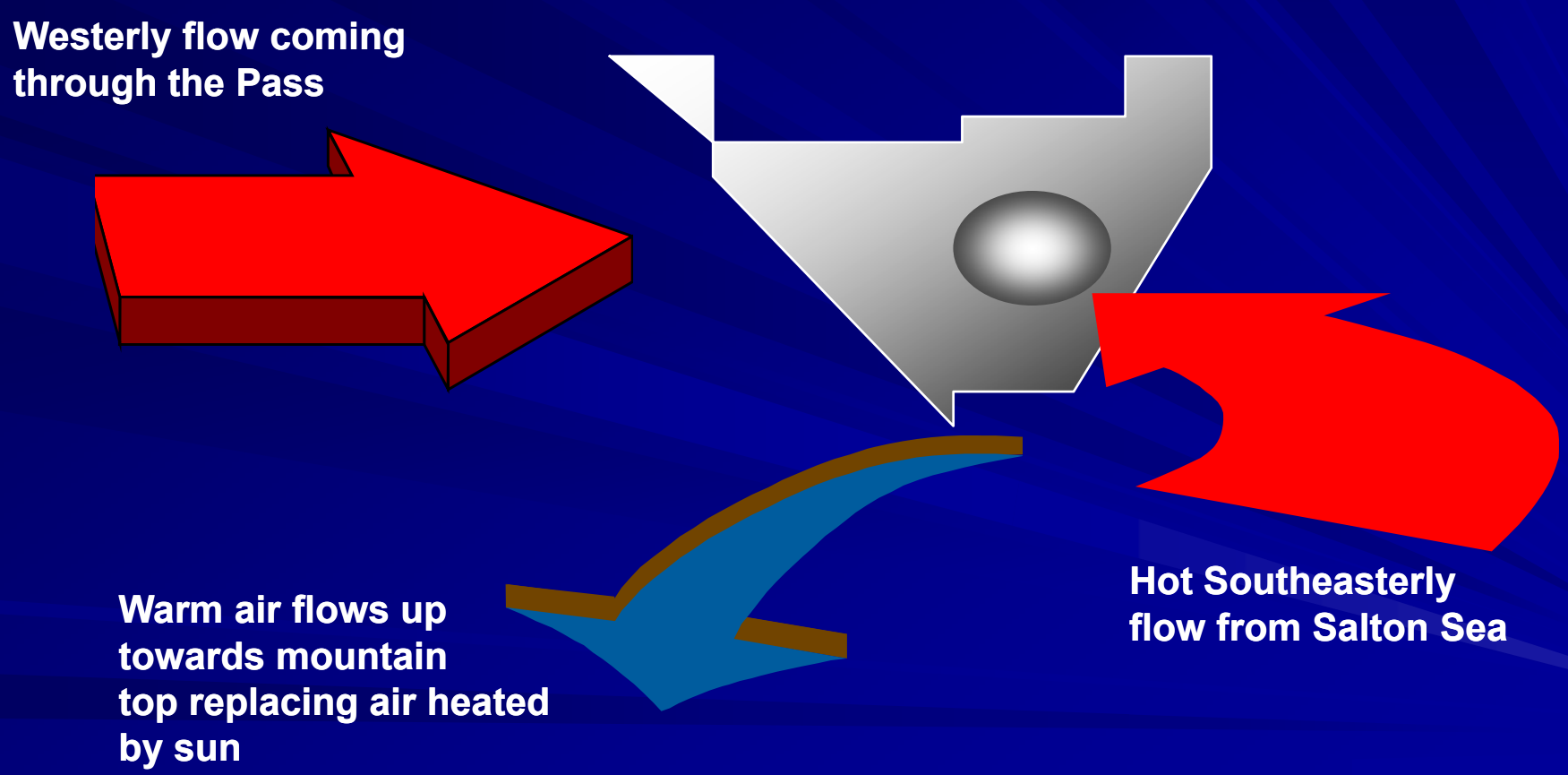
Schematic of SeaWest San Gorgonio Wind Farm Layout



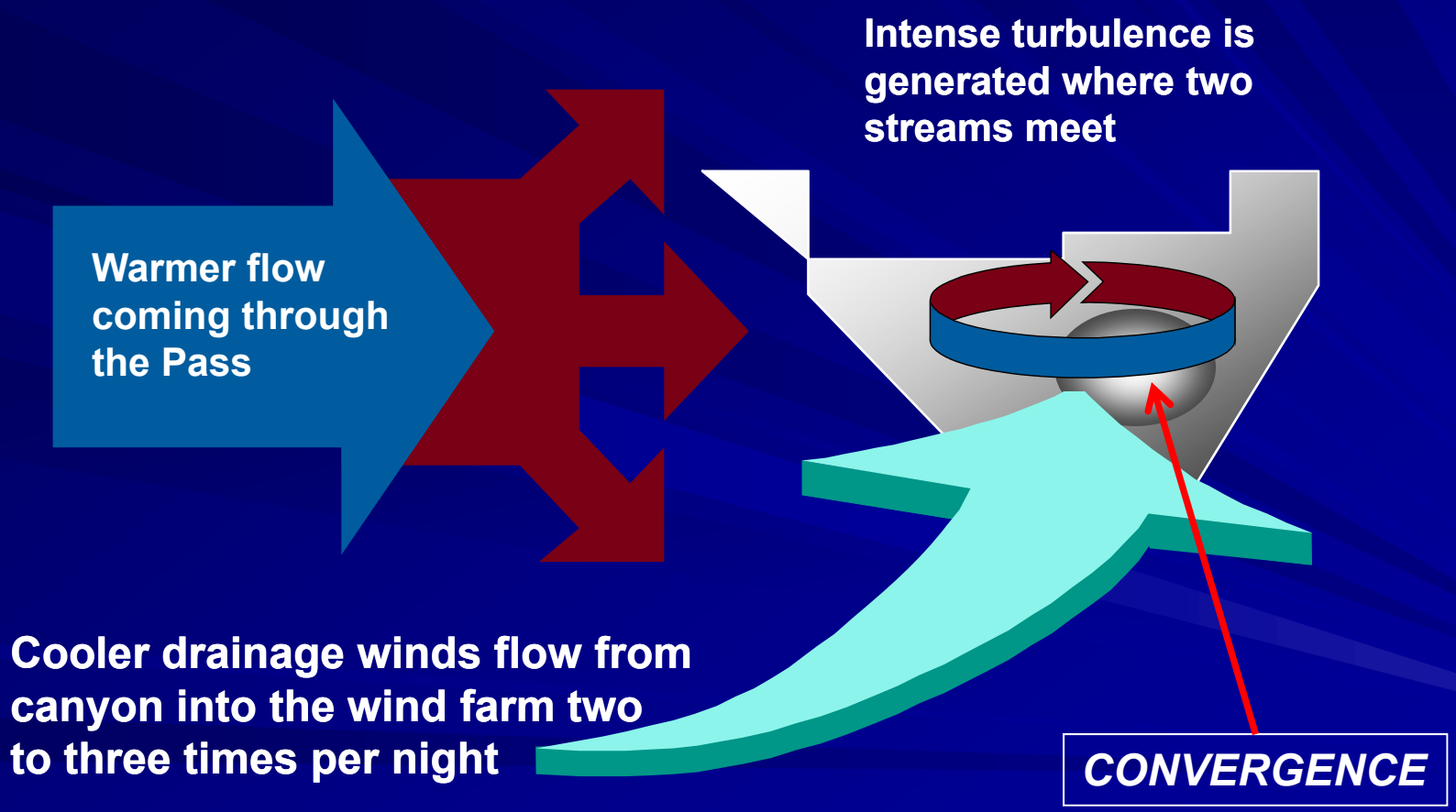
Wind Farm Energy Production and Maintenance & Operations Costs



Daytime Wind Flow Patterns Affecting the Wind Farm



Nighttime Wind Flow Patterns Affecting the Wind Farm

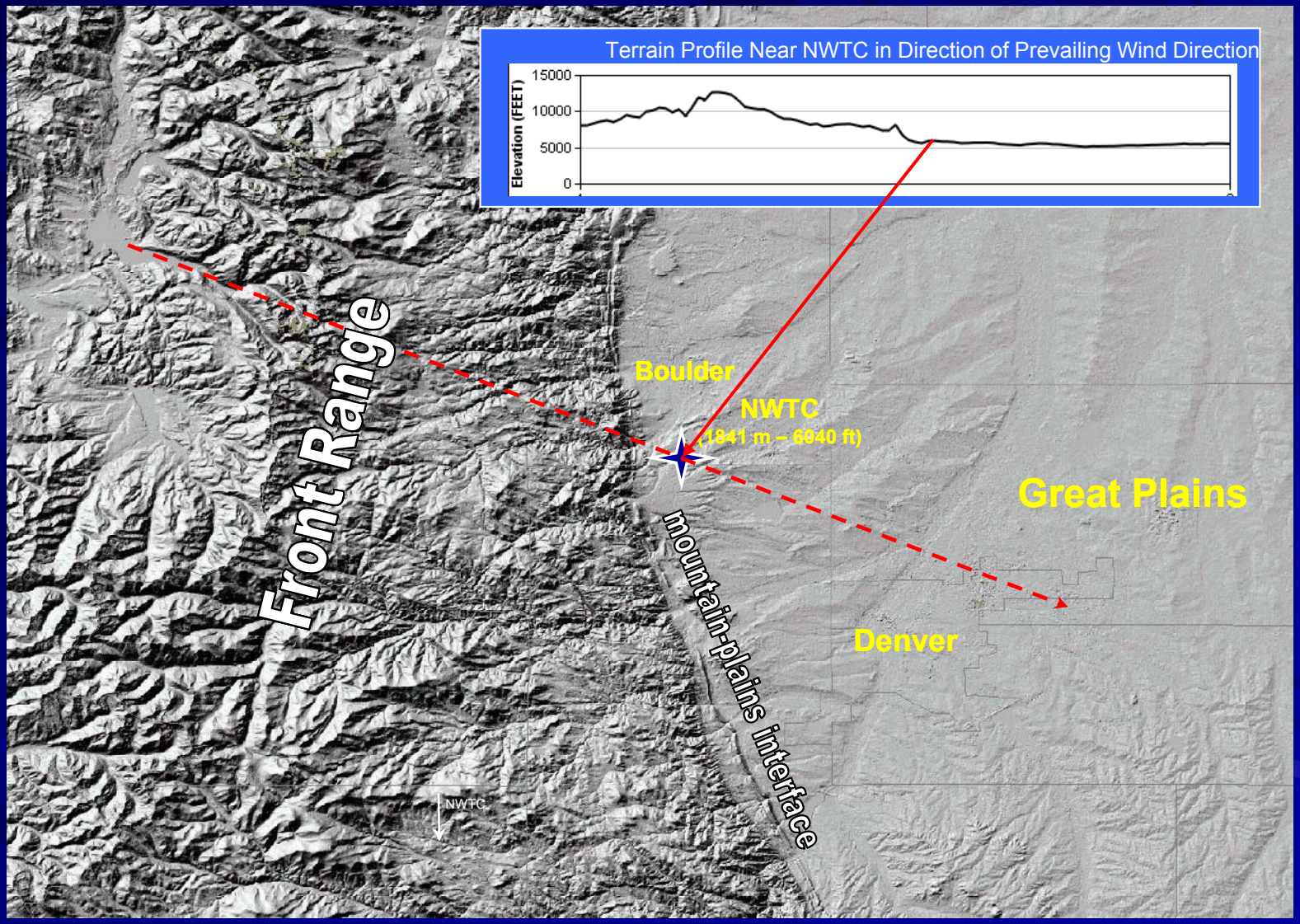


San Gorgonio Pass

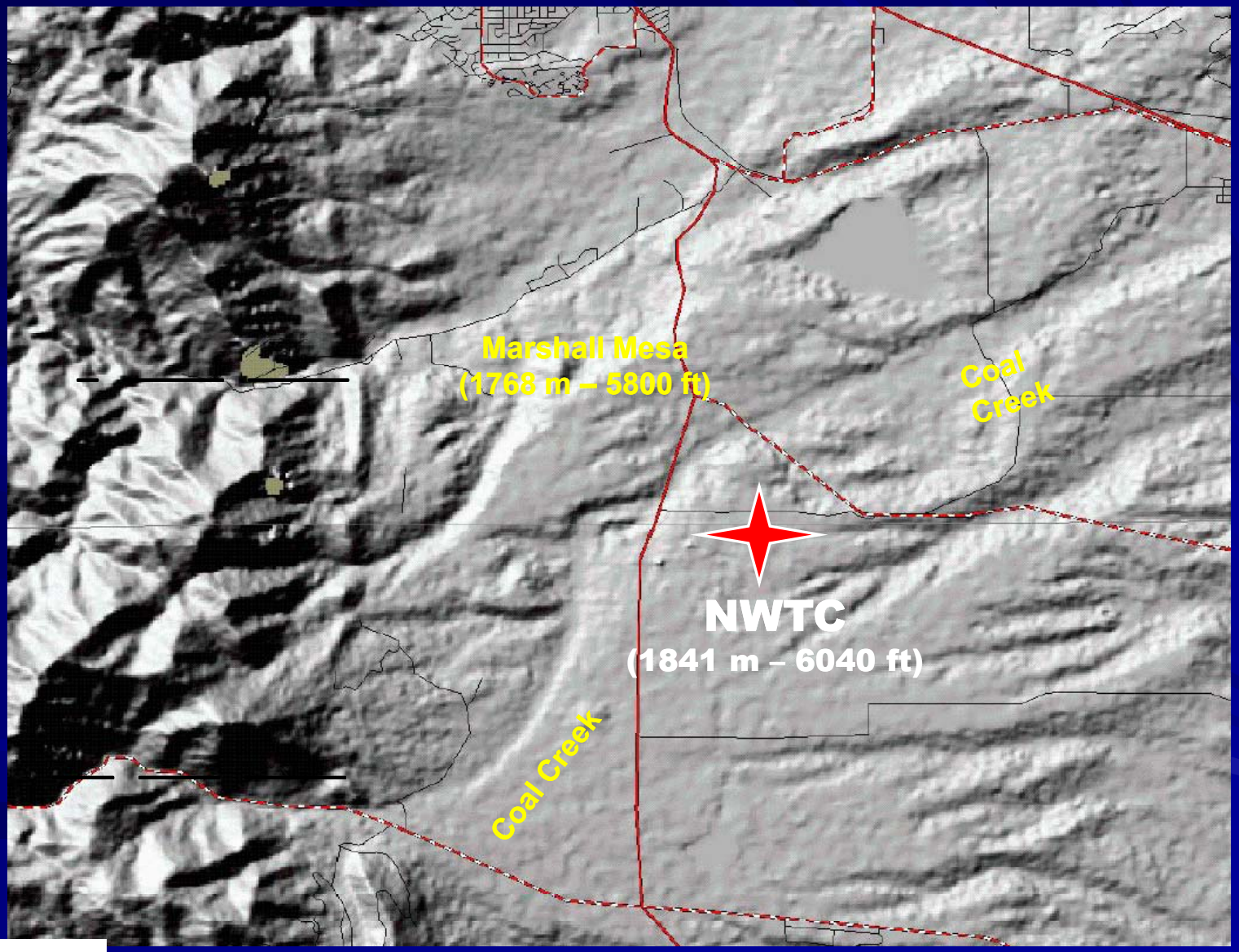
- Complex-terrain flows
  - (good news / bad news)
- Nighttime flow convergence due to local valley outflows of cold air
- Turbulence *in middle of* wind farm
  - Significant turbine outages
  - **Excess maintenance costs**

The NWTC:
Downwind of Very Complex Terrain

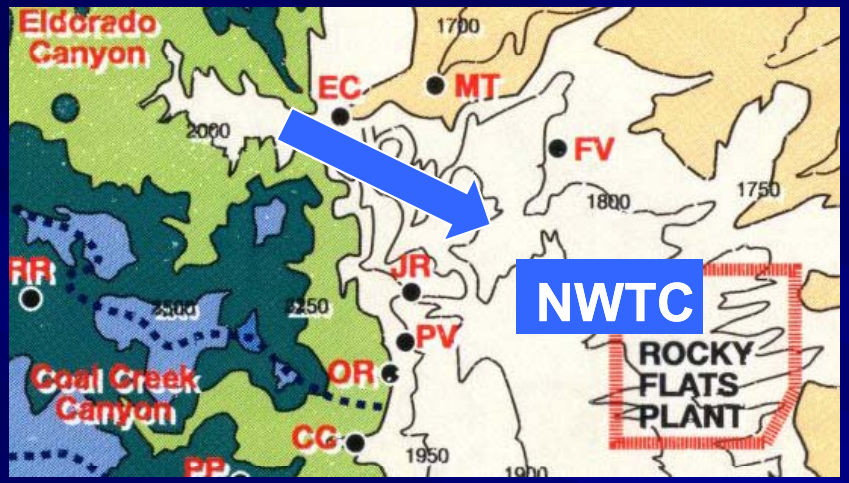
NWTC Regional Topography



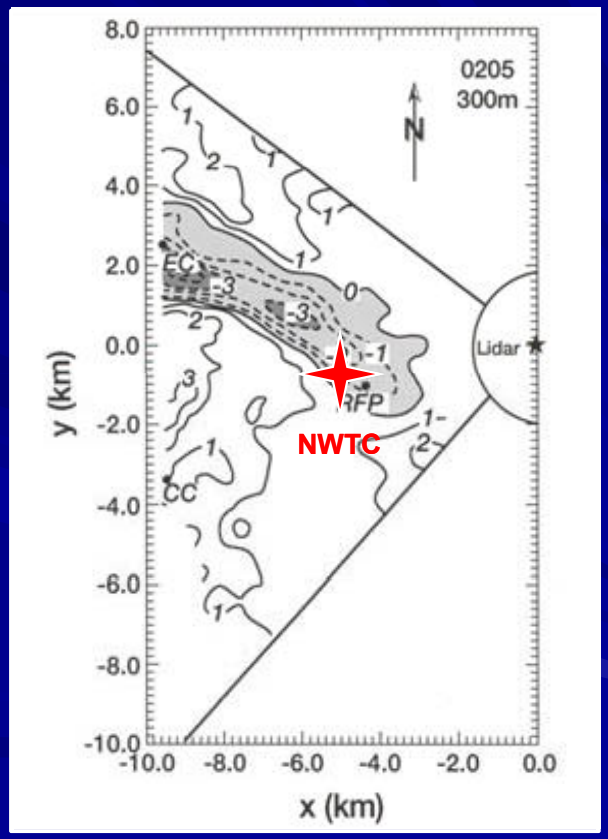
NWTC Local Topography



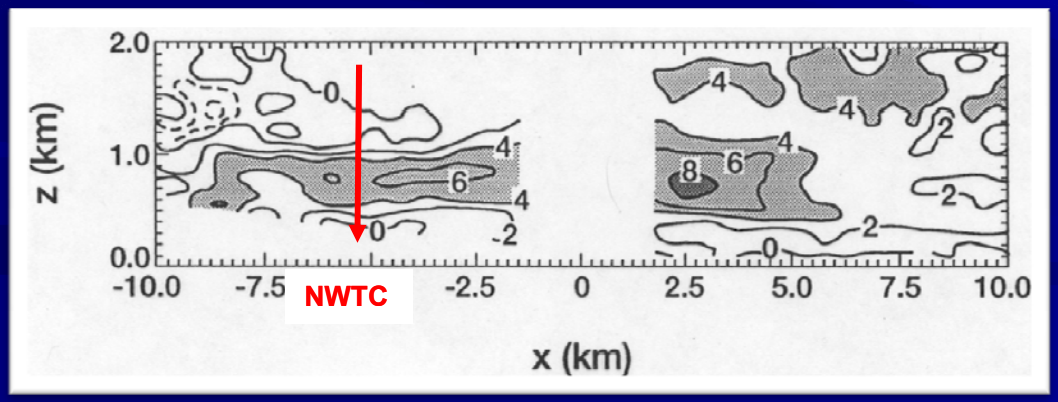
Lidar-Observed Nocturnal Downslope Jet Structure Influencing Wind Conditions at NWTC



Downwind Horizontal Structure at 300 m Height



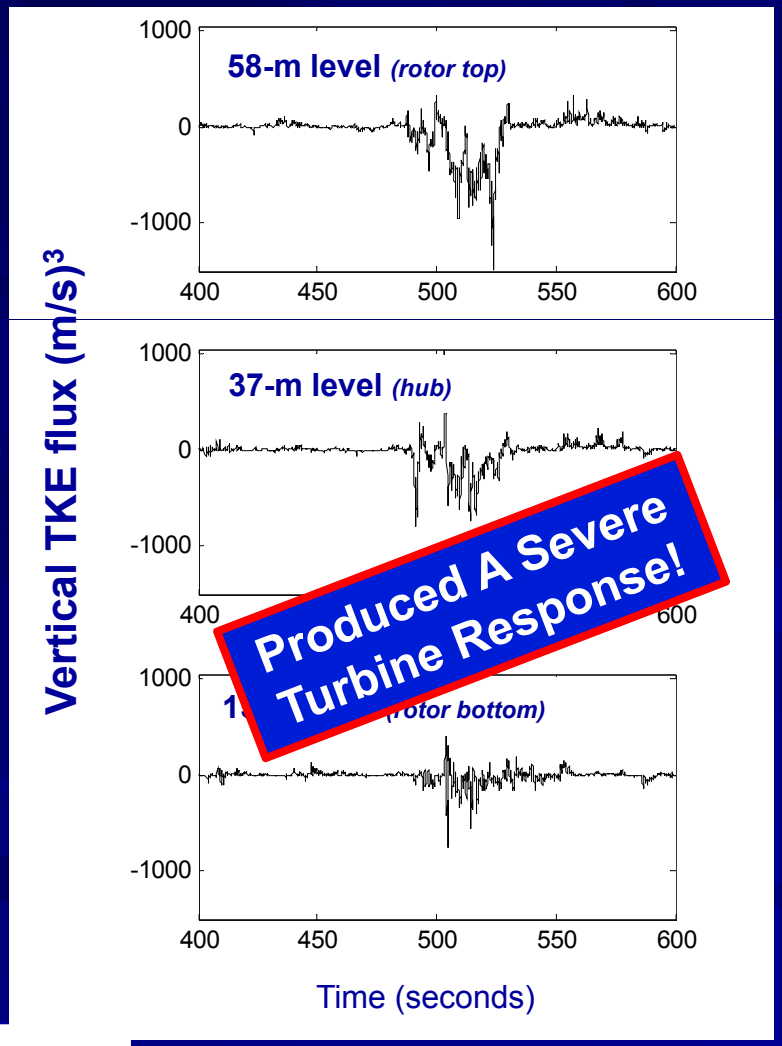
Downwind Vertical Structure



[Banta et al. 1996: J Appl Meteor., 35, 330ff]

Nocturnal Downslope Jet Structures Transport Intense Turbulent Energy From the Jet Above and Into the Turbine Rotors

Measured NWTC ART Turbine Inflow



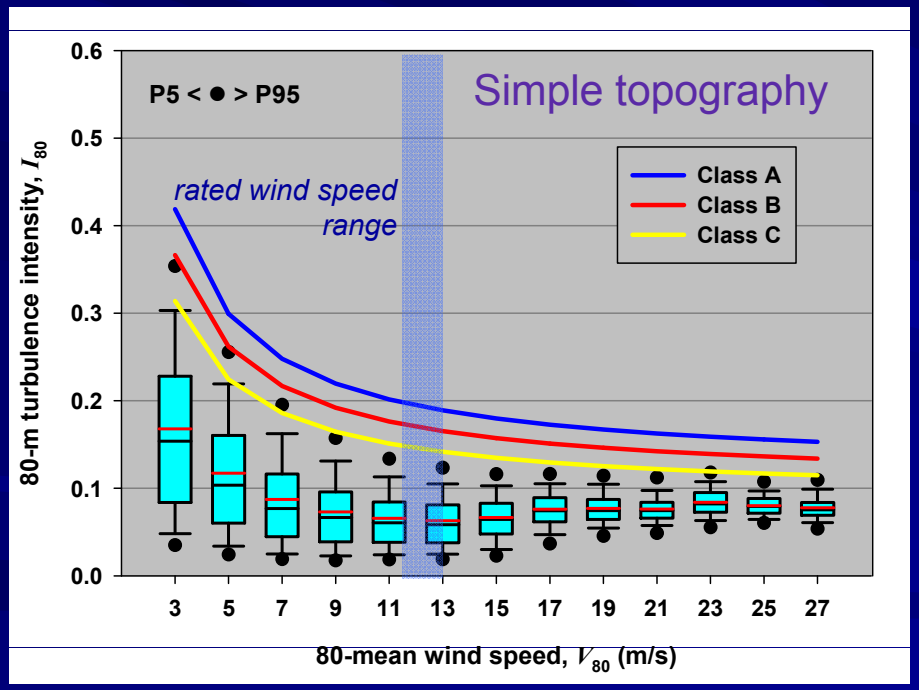
- Turbulence in isolated events
- May occur 1-2 x per night, a few nights per week
- Hardware damage over time
- Essentially unpredictable

Kelley, N.D., et al, 2002

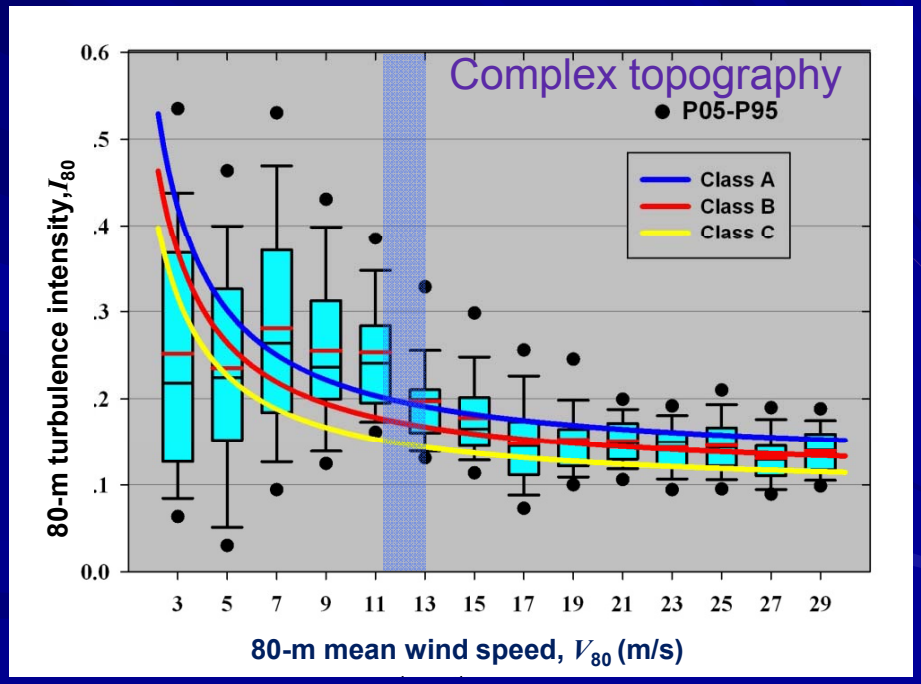
The Impact of Local Terrain Is Important

Observed Variation of Turbulence Intensities with Wind Speed at 80-m Hub Height

Colorado Green Wind Farm

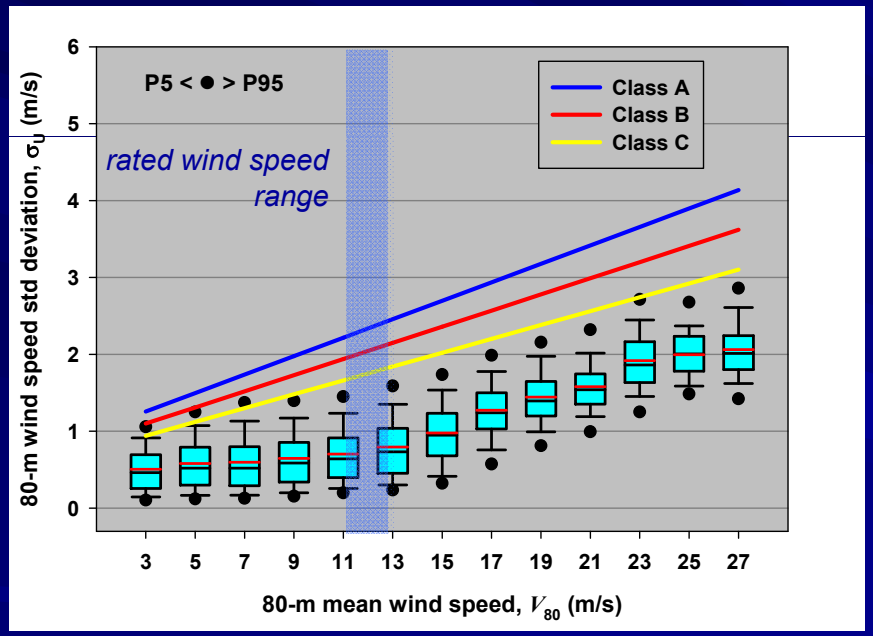


NWTC

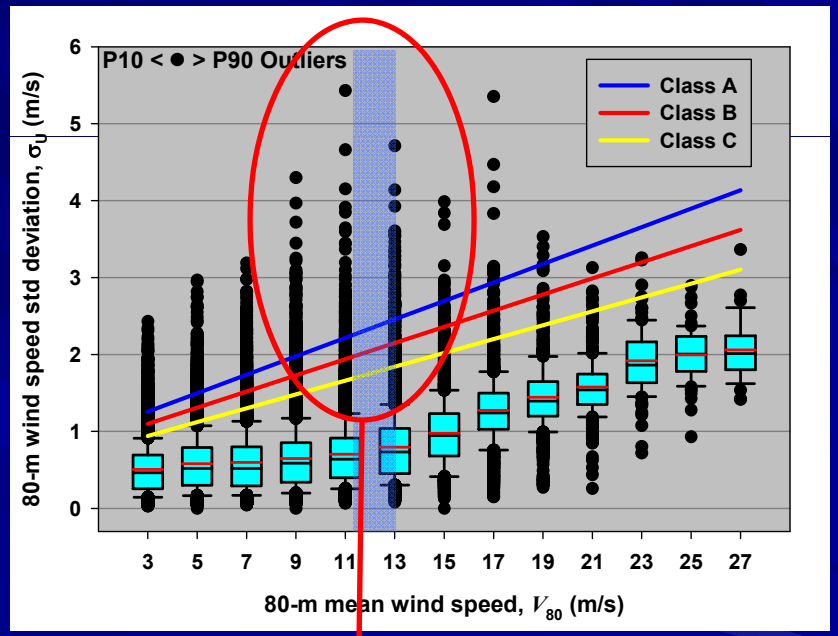


Closer Look at Conditions Experienced at the Colorado Green Wind Farm Site:

Turbulence level distributions that occur more than 5% but less than 95% of the time . . .



HOWEVER if we look at the highest turbulent events that occur less than 10% of the time . . .



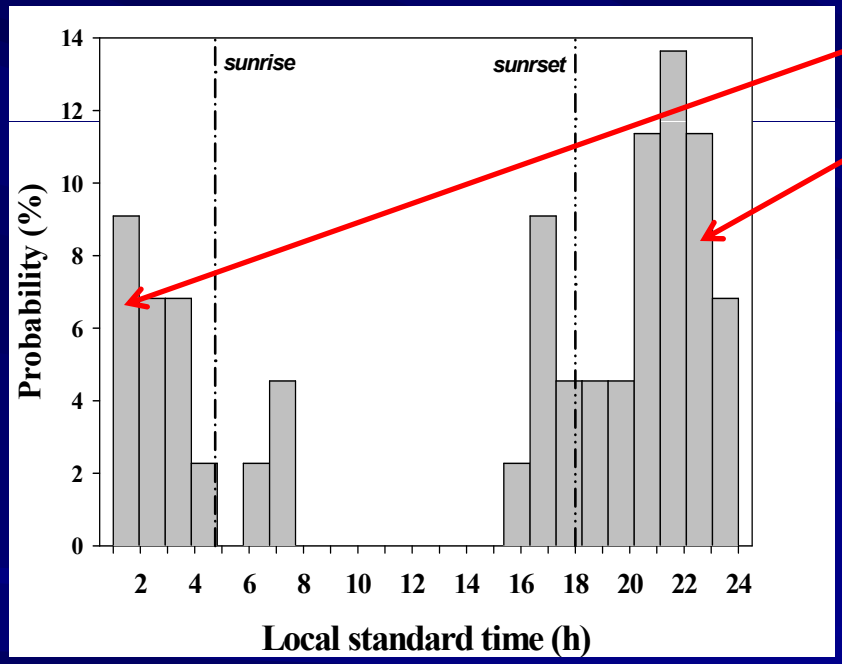
Looks like an IEC Class II B or C design would be acceptable!

These are intense turbulent periods that are occurring when the turbine is operating near rated power and which can induce large structural loads!

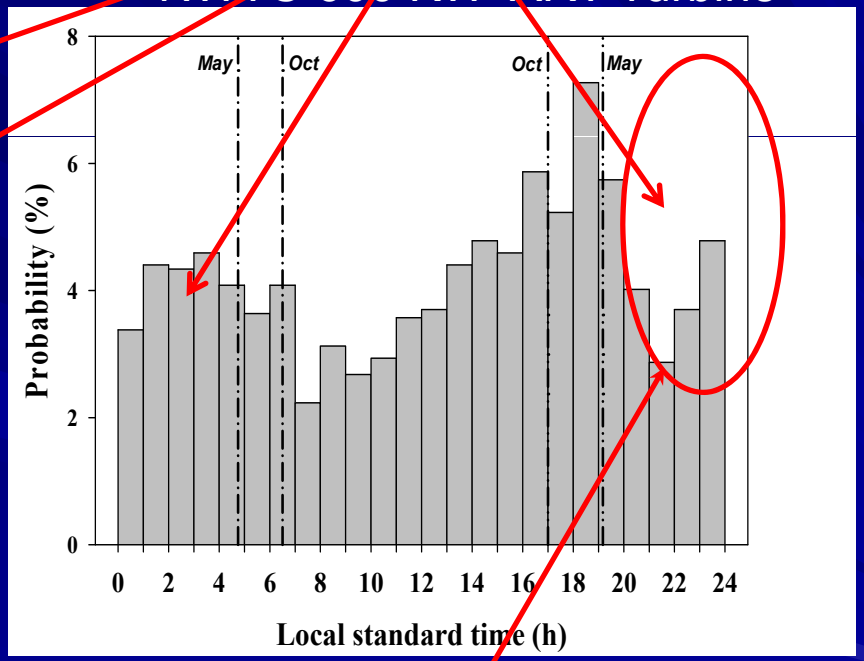
Consequences:

Peak turbine wear and tear (fatigue damage and turbine shutdowns) Occur Diurnally

San Gorgonio Pass Wind Farm – Row 37



NWTC 600 KW ART Turbine



Turbine unable to operate much of the time due to severity of turbulent conditions

2. What are meteorological Requirements for WE ?

Range of objectives

Range of objectives

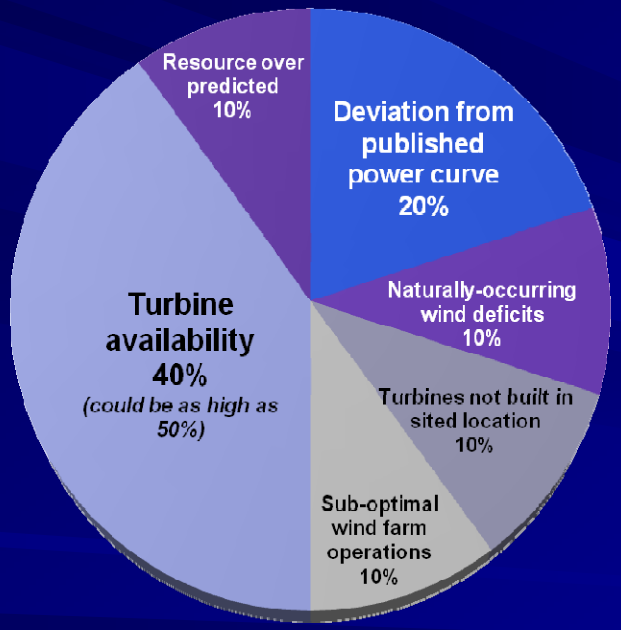
- Hardware design criteria
- Siting – regional, local
- Array effects – internal, external
- Climatology
- Operations – forecasting
- Numerical weather prediction
  - Important tool for *all applications*

Meteorological processes- Impact

- **Siting** (plant-, turbine scales)
- Wind **forecasts** → estimates of production, interaction with electrical grid
  - 'Hour ahead' (~1-6 hr)
  - 'Day ahead' (~16-48 hr) < *confidence ?* >
- **Underperformance of arrays** of turbines
  - Wake, other aerodynamic effects
- **Turbulence**, wind shear –
  - Strong stresses on hardware
  - Excess maintenance costs

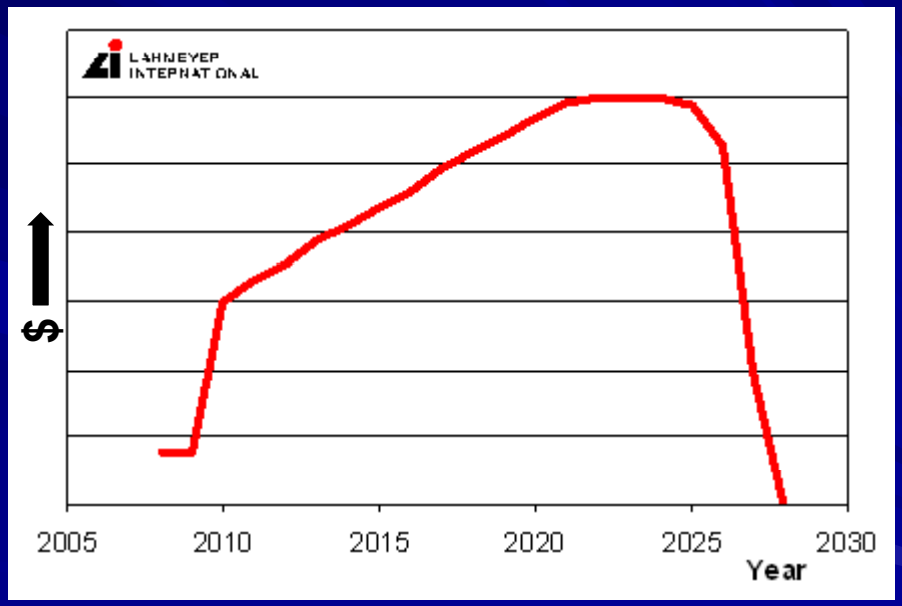
The Local Atmospheric Operating Environment Influences . . .

Power Production Losses



Source: American Wind Energy Association

Maintenance & Repair Cost Trends



Expected M&R Costs Over 20 year turbine lifetime

Courtesy: Matthias Henke, Lahmeyer International

Array effects

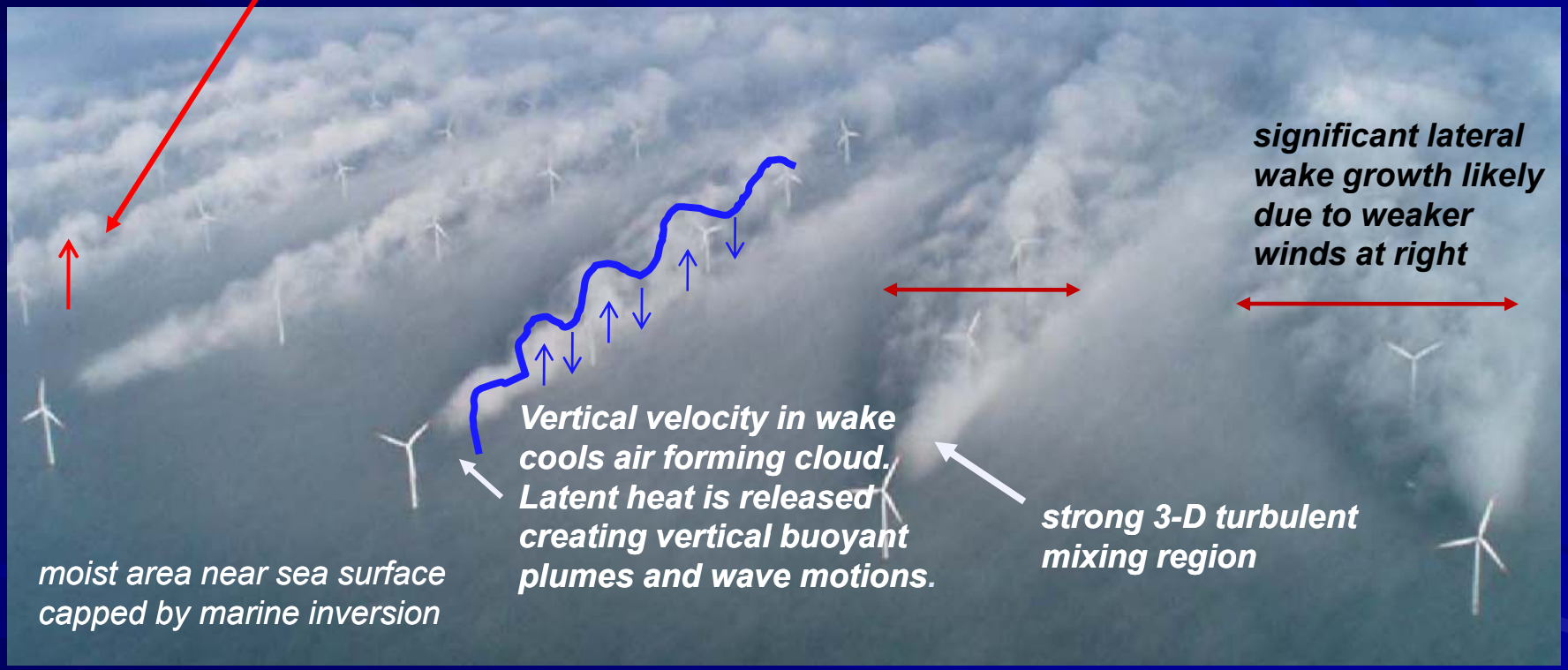
- Losses / inefficiencies very important
- Amenable to research using remote sensing technology

Wind Farm Wake Visualization

Horns Rev Off-Shore Wind Farm Denmark

Wakes are Complex

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



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

conceptual analysis by N. Kelley, NREL

Need for Remotely Sensed Measurements

- Impractical = in-situ measurements of wind characteristics at heights of current (80-120 m) and future wind turbine rotors (200 m)
- Details of vertical boundary-layer structure over candidate sites and operating wind farms:
  - important from both a resource and operational viewpoints
- Regional as well as local measurements are required to meet the needs of resource assessment, R&D, and operational numerical weather prediction
- Reliable, autonomous, and cost effective remote sensing instrumentation will need to be developed

Technology options

3. How can we measure the turbine layer ?

Instrumentation Available for Wind Energy Technology

- Tower / in situ – traditional, and **The** accepted Reference
- Remotely Sensed
  - Sodar (acoustic)
  - Radar wind profiler (RF)
  - Optical
    - Lidar
    - Microwave radiometry

In situ

- **Advantages**
  - Excellent time series, temporal coverage possible
  - Instrumentation often simpler
  - Many measureables can be collocated
  - Accessibility to instrumentation
  - Procedures familiar
  - Interpretation straightforward
- **Disadvantages**
  - Coverage limited to one point, or a line
  - Interference by platform (including tower) can be a concern

Banta, R.M., 2008: presentation at Mountain Weather Workshop; Amer. Meteor. Soc.

Sodar

- Transmits audible sound pulses into atmosphere
- Scattering targets are fine-scale temperature gradients
  - Most often fluctuations generated by turbulence

Commercially-Available Sodars

Representative Examples of Mini-Sodars

Second Wind
Triton

ASC
4000

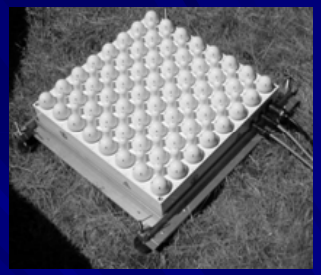
ART
VT-1

Scintec
SFAS

	Mini-Sodars	Mid-Range Sodars
Nominal operating frequency	4500 Hz	2000 Hz
Measurement range	15-200 m	30-1000 m
Minimum vertical resolution	5-10 m	20 m
Averaging times	2 to 60 minutes	2 to 60 minutes
Claimed accuracy	0.3 to 0.5 m/s	0.3 to 0.5 m/s

Sodar

(acoustic)



Advantages

- Inexpensive, deployable in arrays
- Frequent profiles of wind and turbulence-related quantities
- Layers visible
- Transportable
- Relatively inexpensive
- Autonomous operation
- Moderate level of technical expertise required to obtain best results
- Temperature profiles with Radio Acoustic Sounding Systems (RASS)

Disadvantages

- Coverage can be incomplete under certain atmospheric conditions
- Interpretation often challenging
- Not useful in noisy environments
- Sound pulse annoying to neighbors
- Sampling volume increases with height
- Atmospheric absorption losses, strong winds can limit maximum measureable altitude

Banta, R.M., 2008: presentation at Mountain Weather Workshop; Amer. Meteor. Soc.

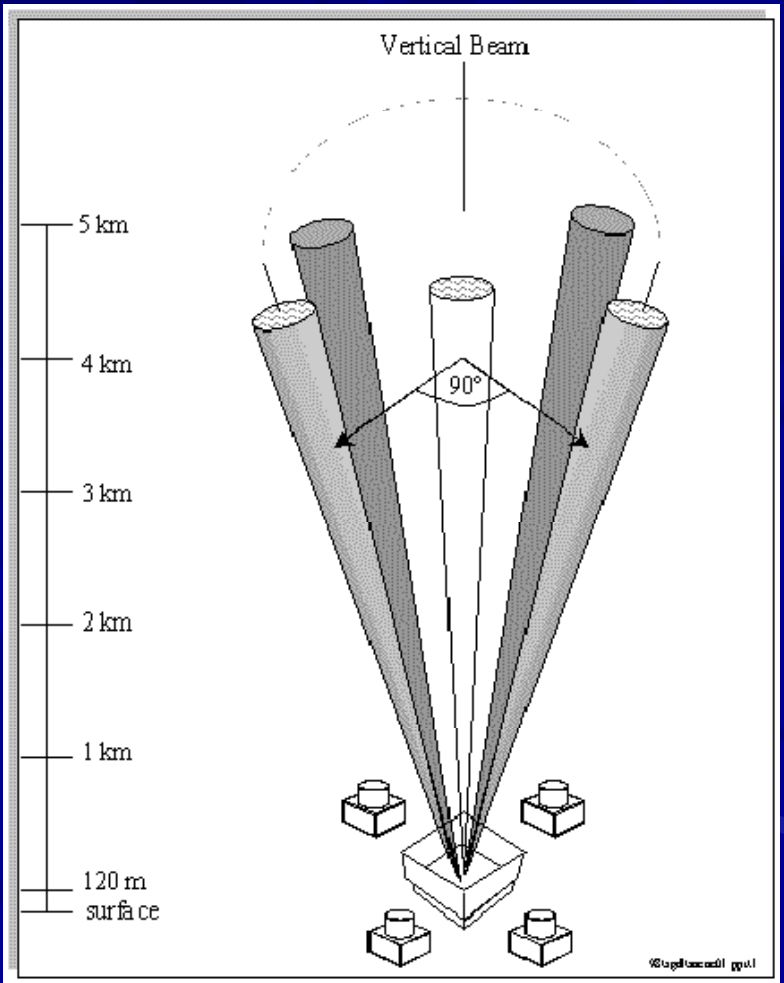
New Developments in Acoustic Profiling

- Multi-frequency operation for improved performance
- Combined acoustic/UHF-RF (RASS) profilers
  - *improved wind speed measurement performance under a wide range of atmospheric conditions*
  - *Coincident vertical temperature profile*

Boundary-Layer Profiler

Approx typical values

- Radio-frequency signal
- Scatterers mostly humidity fluctuations, gradients
- Min height ~120 m
- Max height ~4 km
- Δz ~ 40 m
- 20-30 min average
- ~1 m s^{-1} precision



Radar wind profiler

(radio frequency)

Advantages

- Frequent wind profiles
- Suitable for assimilation
- Reflectivity also useful
- Freq z_i meas.
- Rel. inexpensive – can deploy in arrays, use for traj calc's
- Unattended operation
- All weather

Disadvantages

- Minimum range,
- resolution coarse for some app's (e.g., SBL, slope flows) (*but RIM*)
- Spatial separation (3 or 5 beam config)
- Susceptible to RF interference, esp urban
- Side-lobe effects
- Migrating-bird contamination

Banta, R.M., 2008: presentation at Mountain Weather Workshop; Amer. Meteor. Soc.

Optical Remote Sensing

(light energy)

- Continuous wave lidar
- Pulsed lidar
  - Lidars transmit light signal (UV, visible, or IR)
  - Scattering targets = aerosol particles, air molecules
- Radiometer

Commercially-Available Lidars for Wind Energy Applications

Examples

Continuous Wave (CW) Lidar

QinetiQ
Zephyr

Pulsed Coherent Lidars

Wind Profiling Lidar

NRG/Leosphere
WindCube

Scanning Lidars

Lockheed-Martin
WindTracer

HALO
Photonics

Continuous Wave Lidars

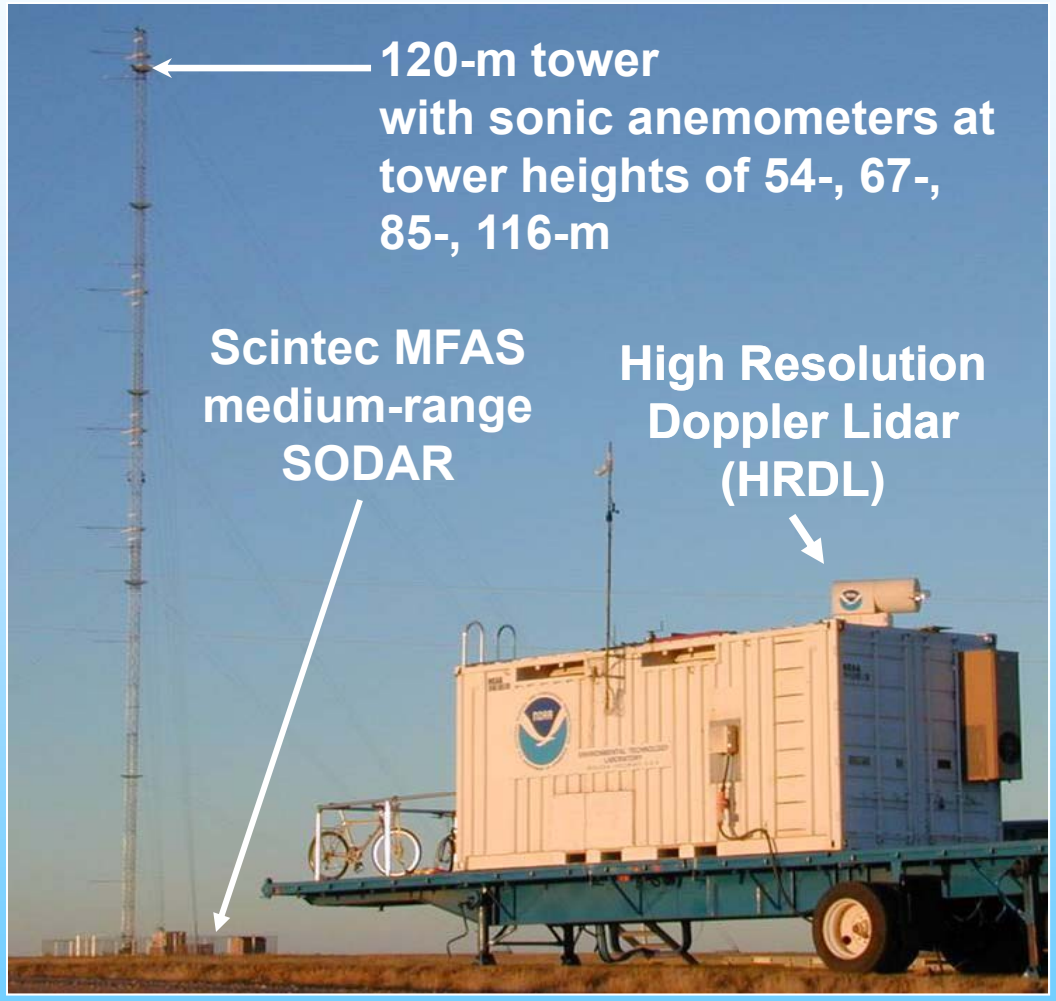
Advantages

- Continuous emissions of infrared light energy
- Line-of-sight **radial** wind speeds made within a single focused region along the beam
- Very narrow beam diameter
- Useful for highly detailed measurements of a limited spatial area
- High sampling rate possible
- Relatively inexpensive
- Can be used for real-time turbine control applications

Disadvantages

- Vertical range limited by aerosol concentration & distribution
- Limited cloud penetration; attenuation by fog, rain
- Limited number of measurement heights available (typically 5)
- Significant time required to complete a 5-level wind profile
- Sampling volume increases with height
- Profiles limited to 200 m

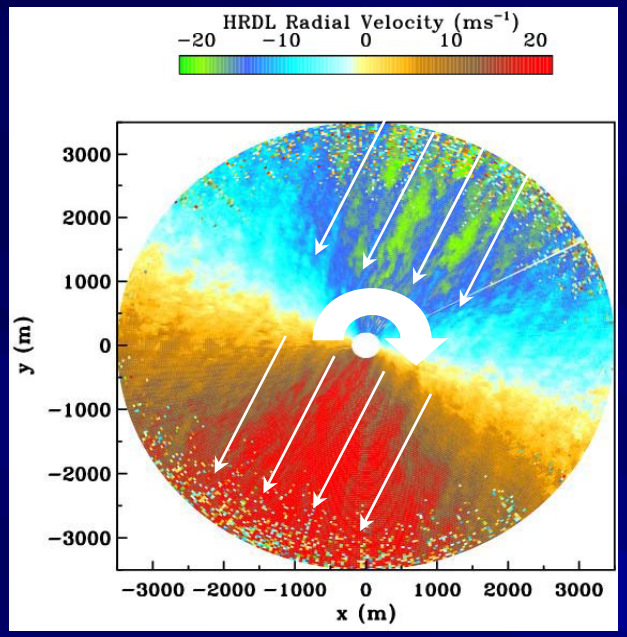
Pulsed Coherent Research Lidar



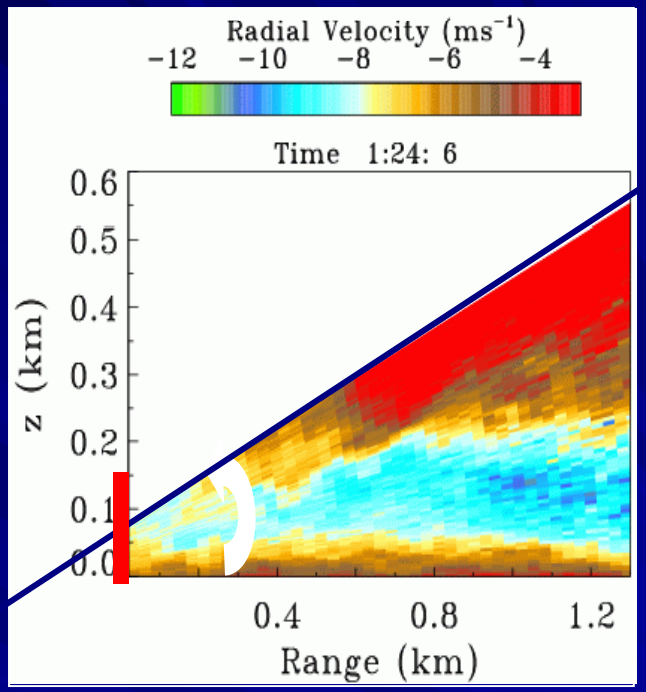
HRDL technical parameters	
Wavelength	2.02 μm
Pulse energy	1.5 mJ
Pulse rate	200/s
Range resolution	**30 m**
Velocity resolution	**~ 0.1 m/s**
Time resolution	0.5 s
Minimum range	**0.2 km**
Maximum range	**3 km**
Beam width range	6 to 28 cm

Lamar Low-Level Jet Project

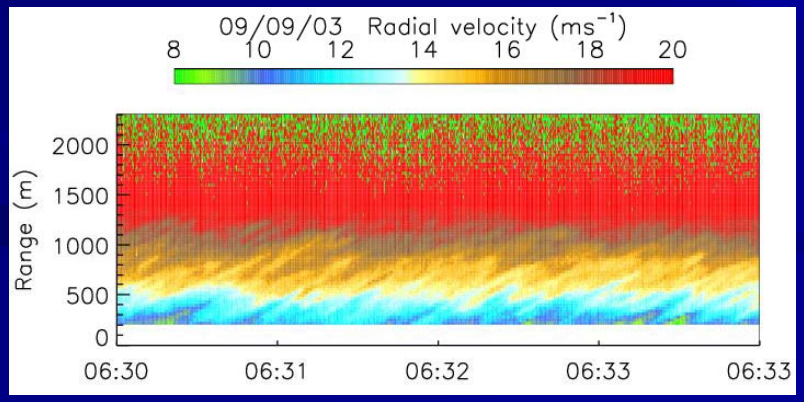
Lidar measurements = Types of scan



Conical scans



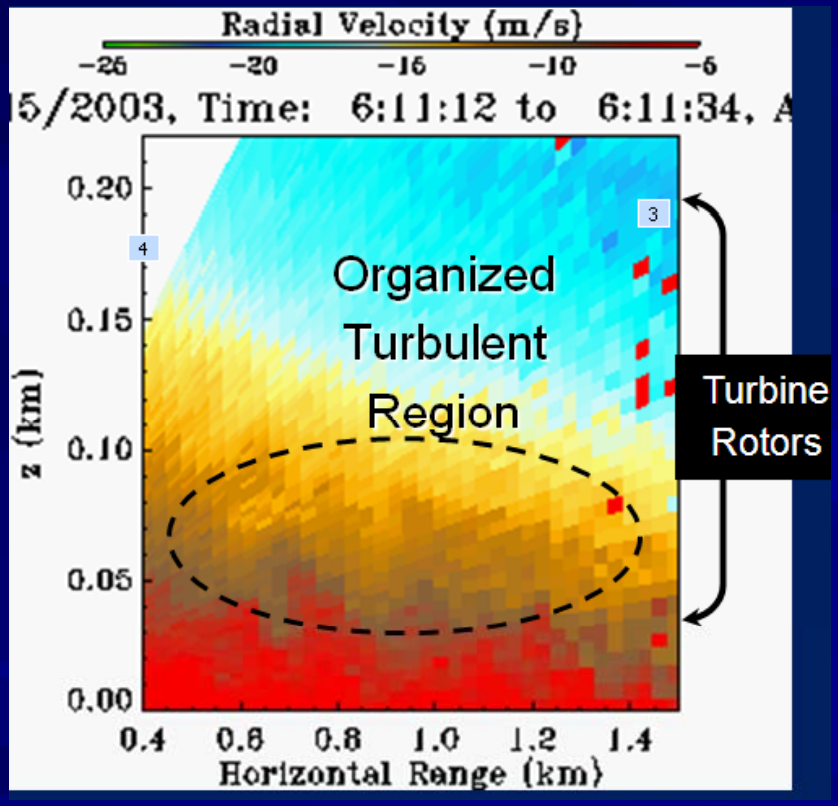
Vertical-slice scans



Fixed-beam "scan"

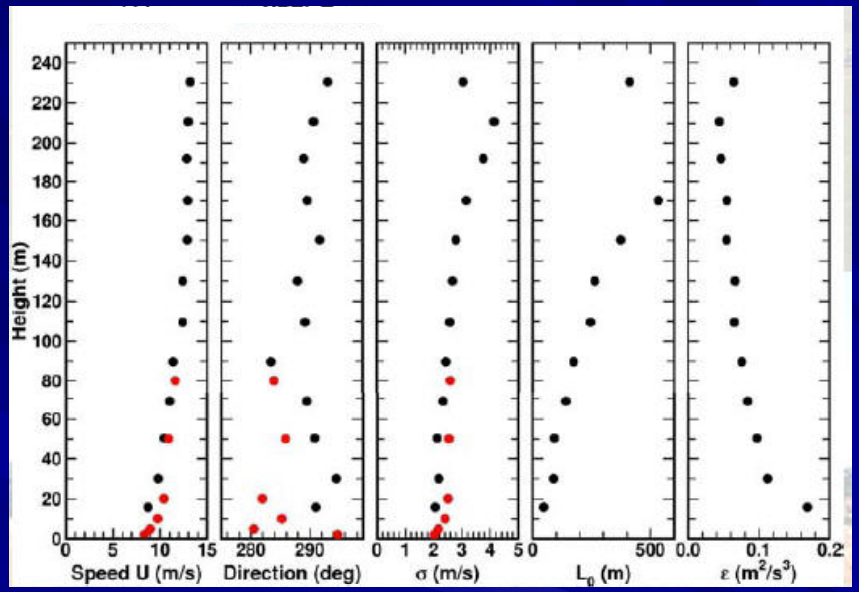
Scanning Coherent Lidar Measurement Examples

Wind/Turbulence Structures At Colorado Green Wind Site



Vertical scan example

Profiles of Turbulence Scaling Parameters Observed Above the NWTC



Frehlich, R. and Kelley, N., 2008

● LIDAR ● NWTC TOWER

Derived from a volume scan

Pulsed Coherent Lidar

(scanning)

Advantages

- Finely detailed flow near terrain (narrow beam, no sidelobes)
- Clear air sampling
- High temporal and spatial resolution
- Scans a volume of space
- Detailed model evaluation
- Aerosol – BL height, cloud base
- Versatile
- Some unattended lidars available (backscatter and Doppler)

Disadvantages

- Vertical range limited by aerosol concentration & size distribution
- Expensive
- Research lidar systems require expert technicians
- Limited cloud penetration; attenuation by fog, rain
- Low sampling rate

Banta, R.M., 2008: presentation at Mountain Weather Workshop; Amer. Meteor. Soc.

Vertical Temperature Profile Measurements

- Needed for local initialization of NWP modeling
- May be used in conjunction with wind profiles in the future for determining vertical stability of boundary layer as part of turbulence warning system for turbine loads control
- Instruments include:
  - Radio Acoustic Sounding System (RASS)
  - Microwave radiometer profilers

Commercially-Available Microwave Radiometer Profilers

Examples

Radiometer-Physics HATPRO

- temperature profiles
- humidity profiles
- liquid profiles

Radiometrics MP-3000A

- temperature profiles
- humidity profiles
- liquid profiles

Kipp & Zonen MP 5-H

- temperature profiles

4. Measurements to address objectives

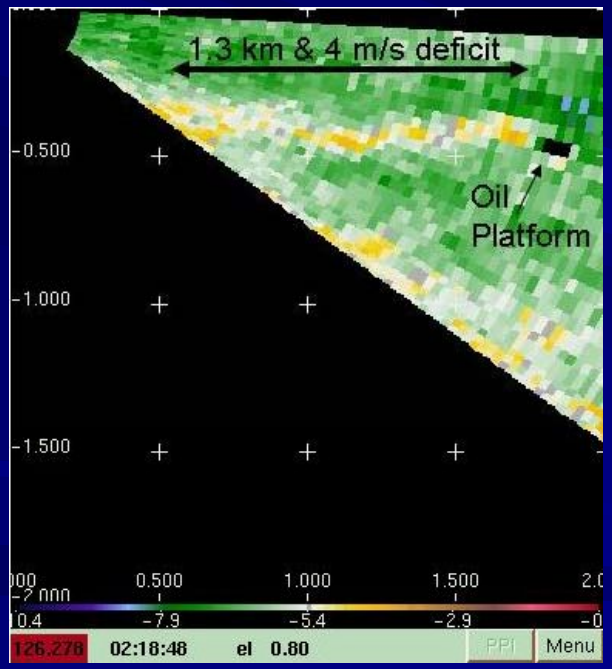
- Provide information for turbine design criteria
- Assess potential wind energy sites
- Use to improve wind farm performance and reliability

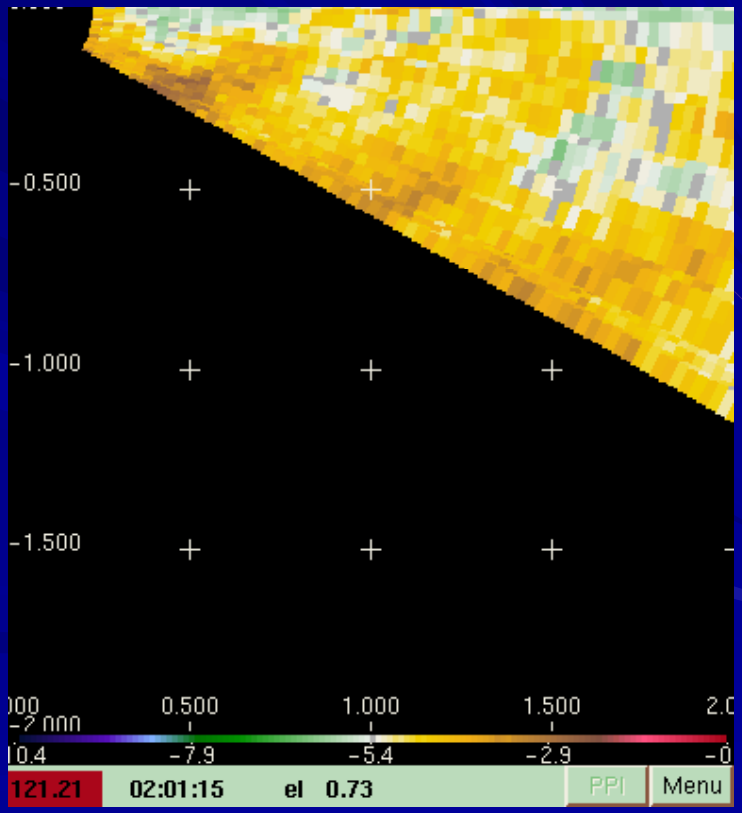
Uses of Remote Sensing

- For the initial resource assessment
  - *Use a combination of tower and remote sensing to establish if a sufficient capacity factor would exist (resource)*
  - *Use remote sensing to characterize the turbine operating environment: shears, turbulent structures, etc. (potential cost issues)*
- For the micrositing of the wind farm
  - *Identify localized flow regimes due to terrain or other features that would impact turbine operations*
  - *Use numerical flow simulations using remotely sensed boundary-layer measurements for initializations and validation*
- For wind farm operations
  - *Initialize short term mesoscale prediction models with local values*
  - *Early detection of ramping events occurring upstream of the wind farm*
  - *Use lidar measurements for real-time turbine power production and loads control*

Measurements of wakes

- Scanning capability of Doppler lidar – able to sample wake characteristics





Images courtesy W. Alan Brewer

Forecasting

Operations / forecasting

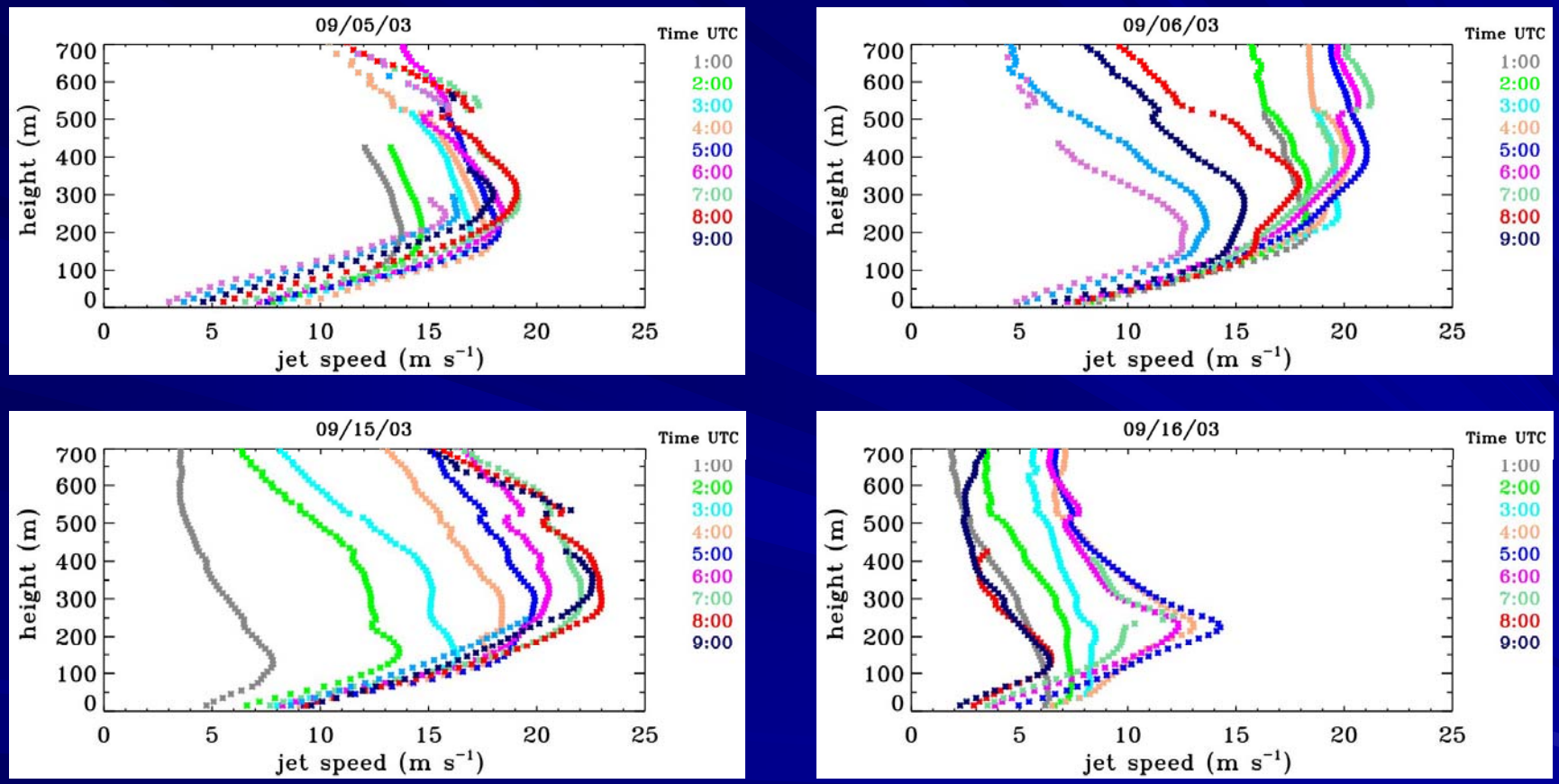
- "Day-ahead forecasting"
  - LLJ example
- "Hour-ahead" forecasting
- Need for measurements (esp hour-ahead)
- Need for NWP improvement (esp day-ahead)

An Example of a Forecasting Challenge:

The Nocturnal Low-Level Jet

LLJ nocturnal evolution

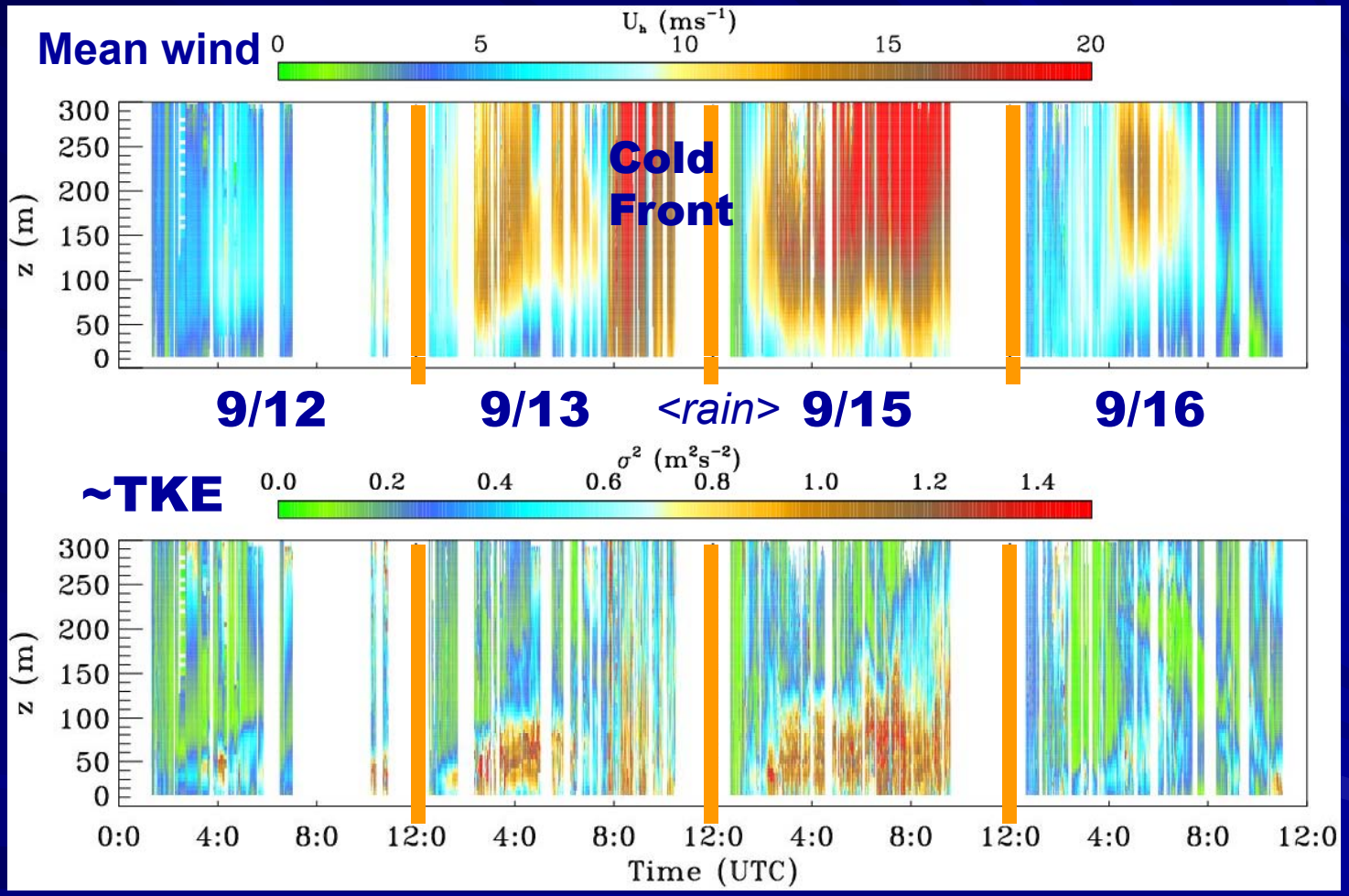
different behavior on different nights



Temporal variability… Each night different – need to forecast differences

Conditions on 4 of 5 successive days

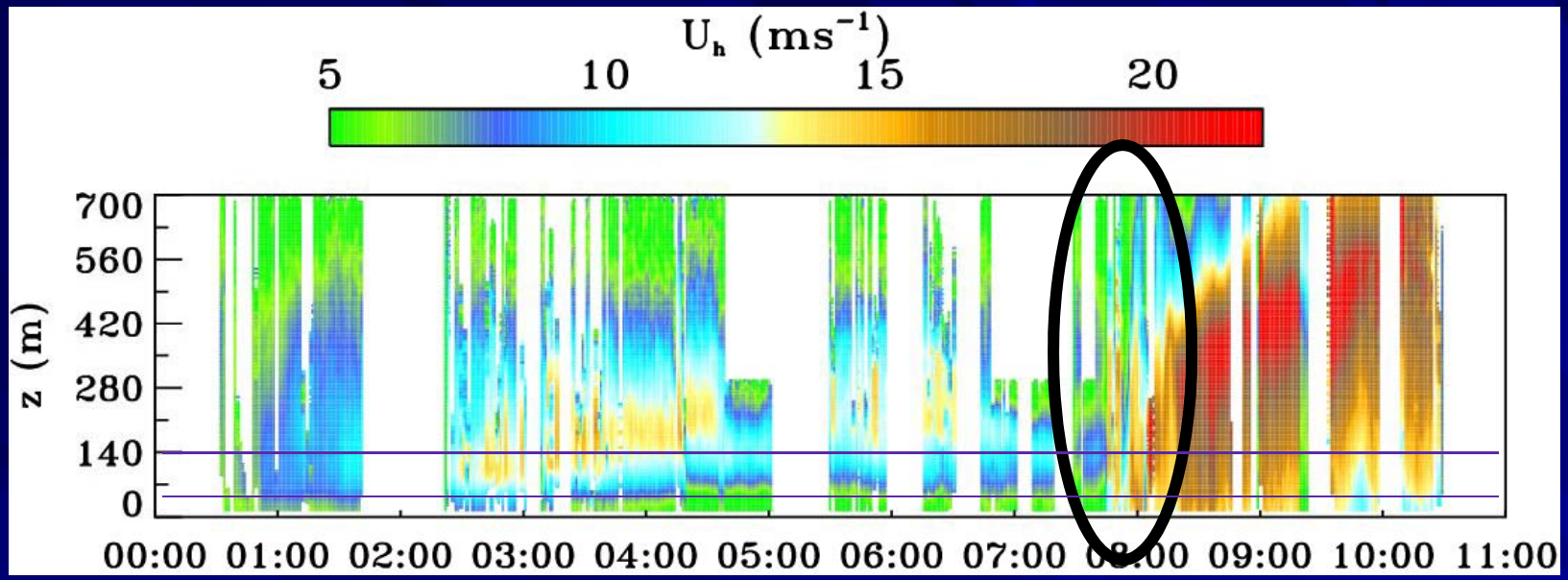
– wide variation, challenging forecasts



Mean and turbulent evolution need to be documented, tested vs. models

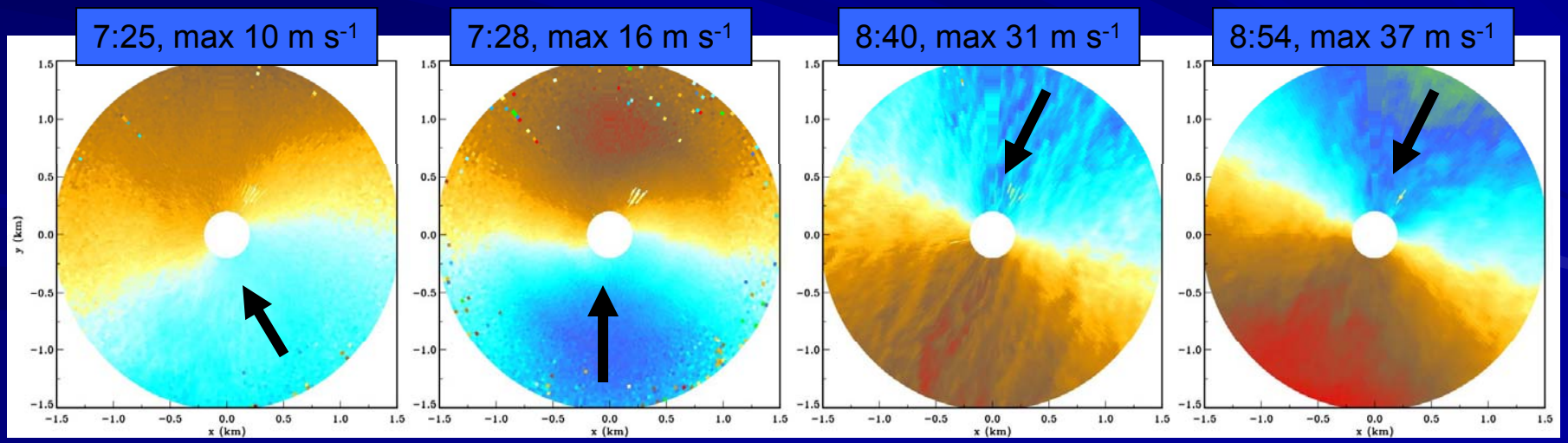
(Cold Front on 9/13 – Pichugina et al)

Closer look, frontal passage night



direction changed from SSE to NNW

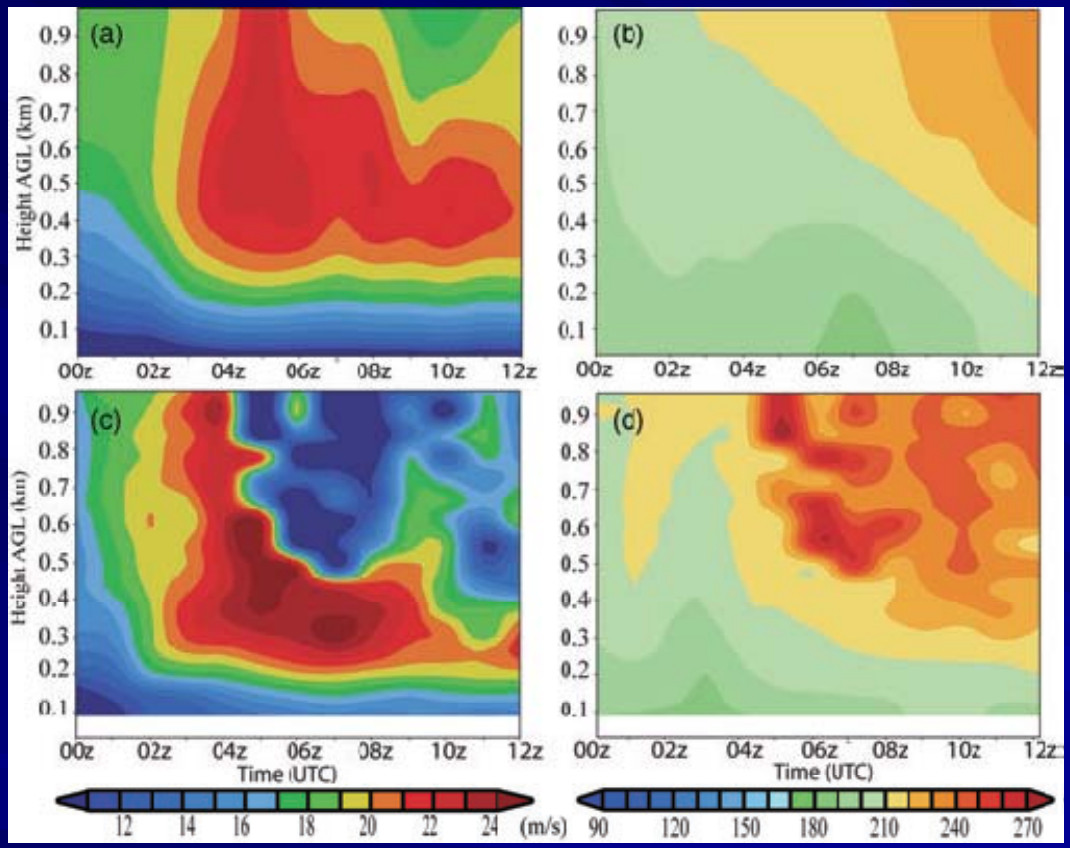
wind speed increased from 10-15 m s^{-1} to 20-27 m s^{-1}.



Model vs. observations – LLJ

(Reminder = model improvement needed)

Wind speed Wind direction



WRF model

Observed

"Core of the jet tended to be higher and slower than… observed."
"…likely related to the enhanced mixing of the PBL schemes."

[Small differences = big $$]

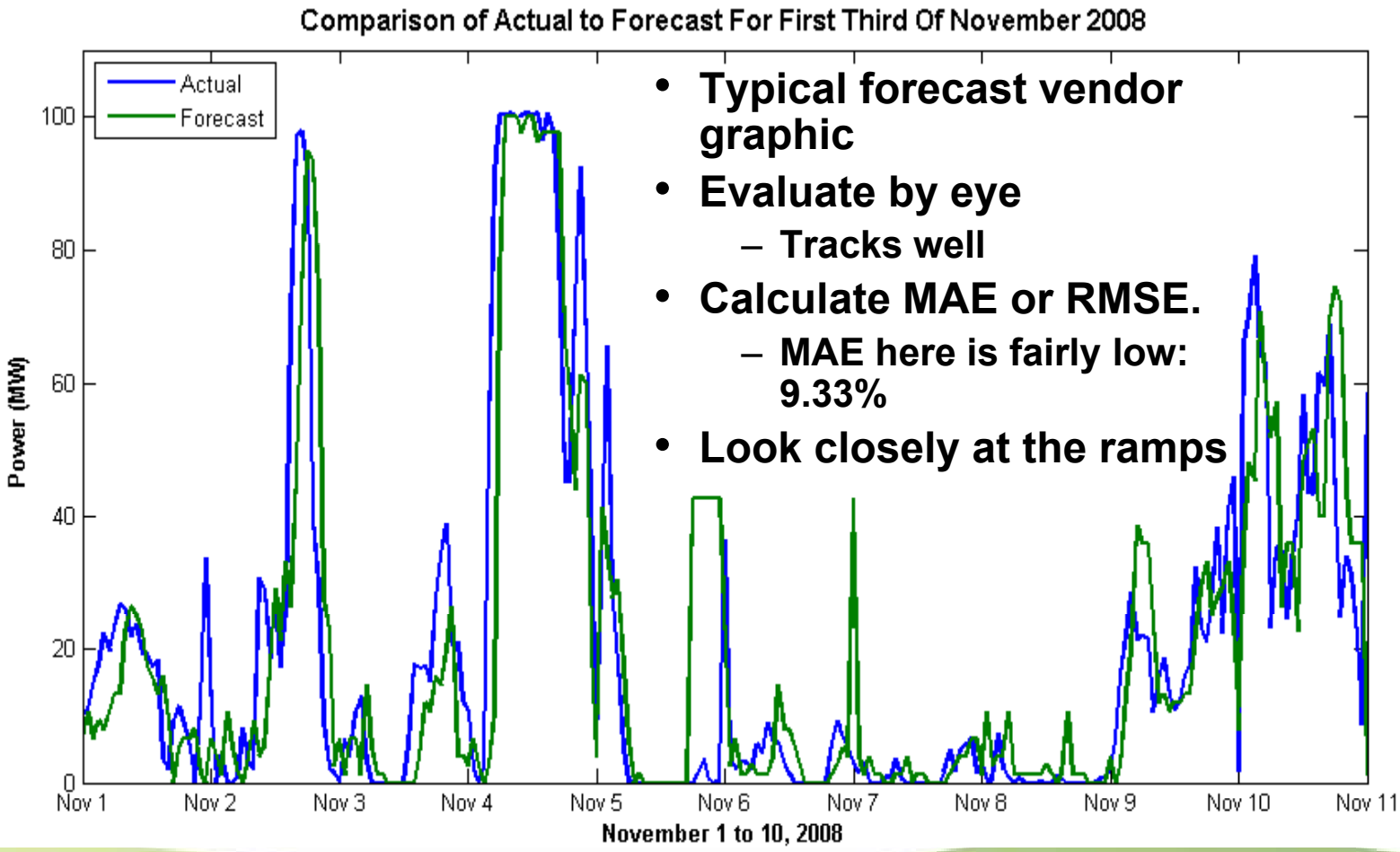
Storm et al. 2008; Wind Energy

Day-ahead (12-36 hr) forecast

- Numerical model predictions important
- Regional arrays of remote-sensing sites to profile wind, temperature to define met. context
- Involves day-night transitions
  - Driven by surface heating/cooling cycle
  - Need to be improved in NWP models
- Processes controlling LLJ
  - Speed, height, timing, turbulence
  - Stable Atmospheric Boundary Layer (SBL)
  - Acknowledged weakness in NWP models

Hour-ahead:

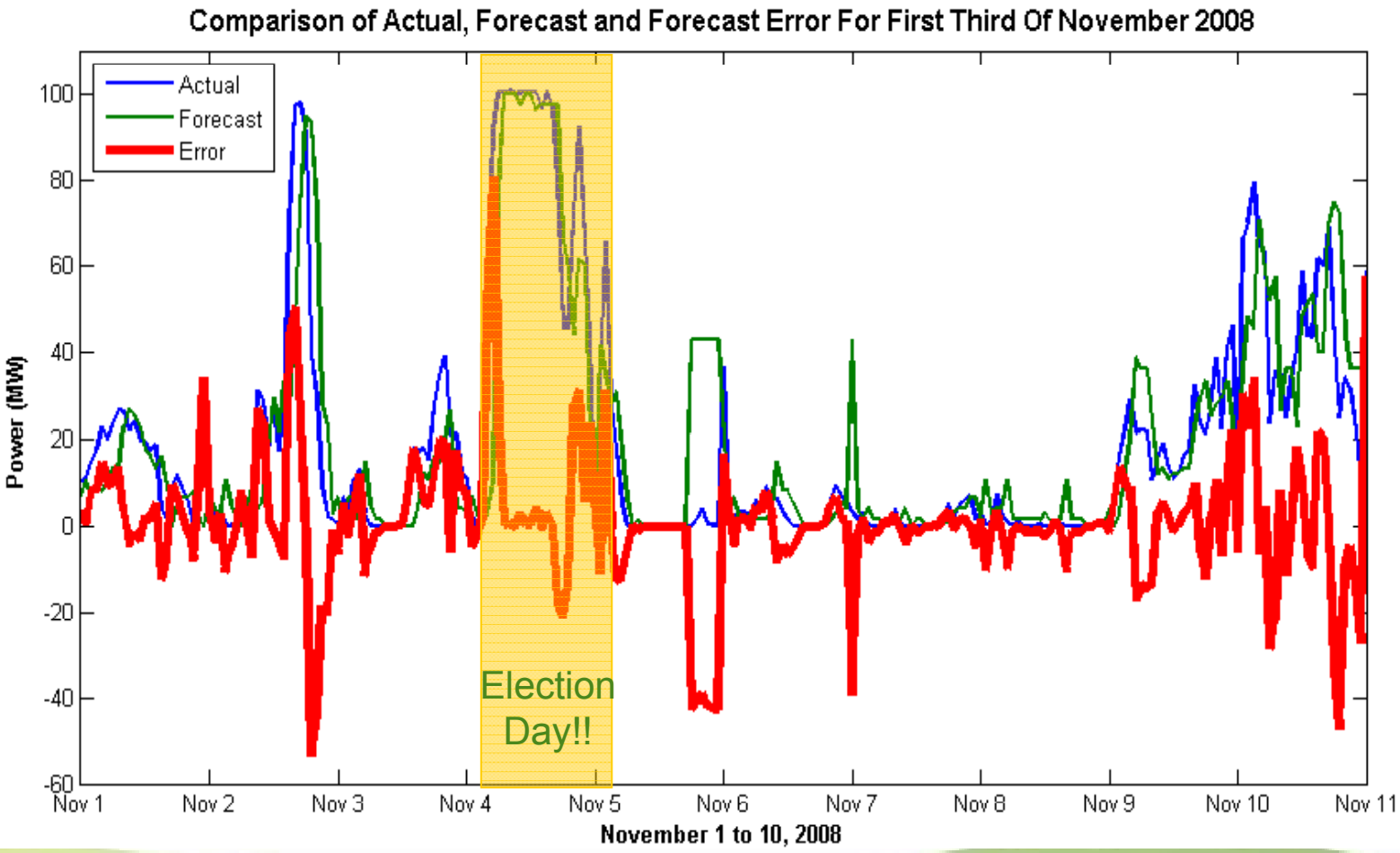
How do we evaluate a forecast?



- **Typical forecast vendor graphic**
- **Evaluate by eye**
  - **Tracks well**
- **Calculate MAE or RMSE.**
  - **MAE here is fairly low: 9.33%**
- **Look closely at the ramps**

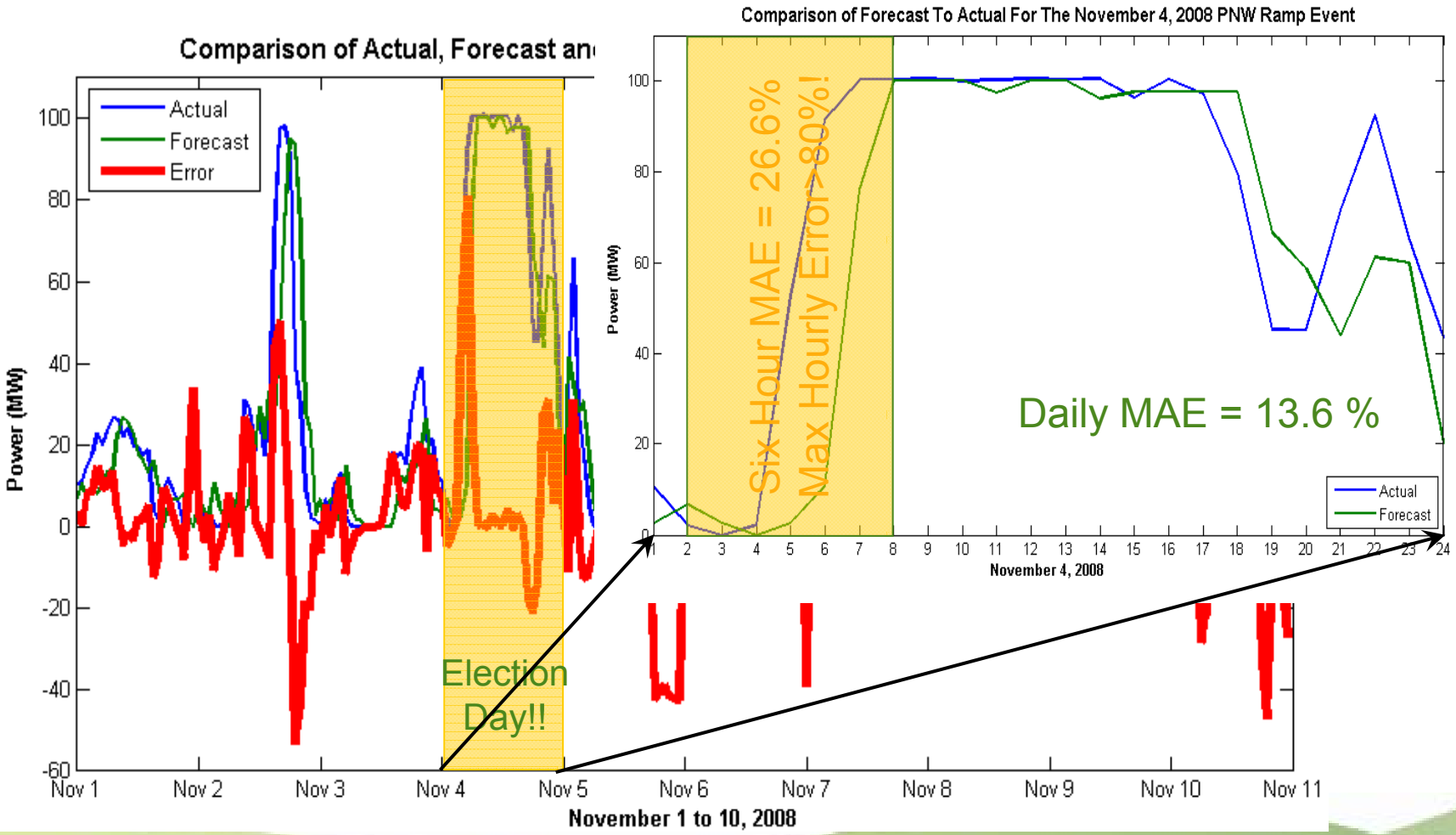
Courtesy Justin Sharp, Iberdrola Renewables

Plotting Hourly Error is Revealing

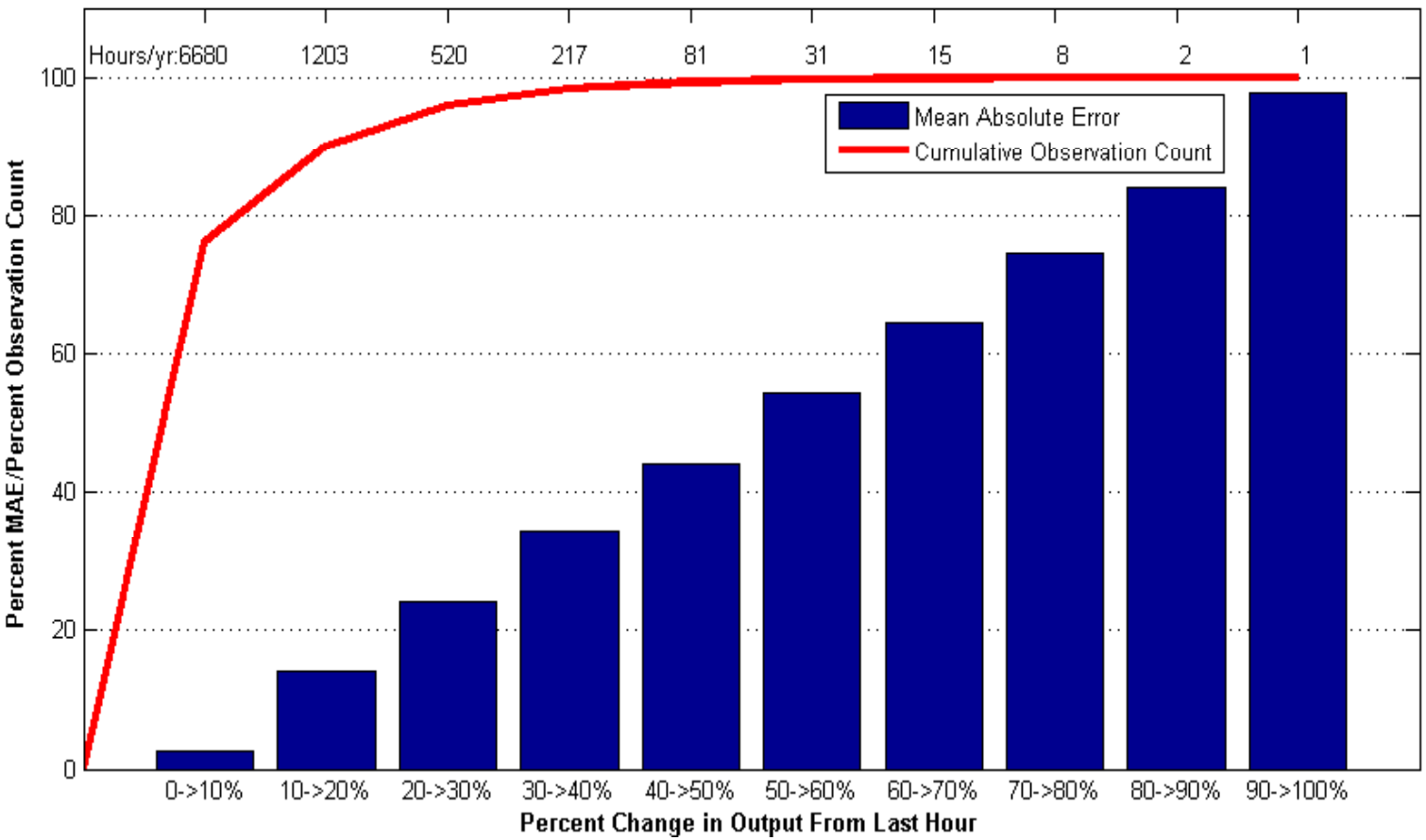


Courtesy Justin Sharp, Iberdrola Renewables

Plotting Hourly Error is Revealing



Courtesy Justin Sharp, Iberdrola Renewables



- Typical measures of forecasting effectiveness give equal weight for periods with little change to output and ramp events.
- Amount of time with stable output far exceeds the amount of time for ramp events
- Forecast accuracy is easily obtained during periods of no change
- Current automated forecasts typically lag ramp events creating problems associated with large imbalances

Courtesy Justin Sharp, Iberdrola Renewables

Hour-ahead (>1 ~ 6 hr) forecasts

- Hard to beat persistence
- Lots of $$ at stake
- Need for good local-area measurements

The Value of Better Short-range Forecasts

- Example: Better forecasting (scheduling) reduces reserve needs
  - Bonneville Power proposed $12/MWh Wind Integration Charge (WIC) based upon 2008 scheduling accuracy
    - Approx $73M/yr cost to the wind industry in their control area
  - Rate adopted was ~$5.70/MWh
    - Savings of $34.6M/yr to BPA area wind operators
  - A major driver in the decrease was forecasting improvements that Iberdrola has realized by staffing a 24x7 forecasting desk
- High wind penetration reduces need for carbon-based generation
  - Better short-range forecasting is a piece of low hanging fruit to reduce integration problems

Courtesy Justin Sharp, Iberdrola Renewables

5. Summary and conclusions

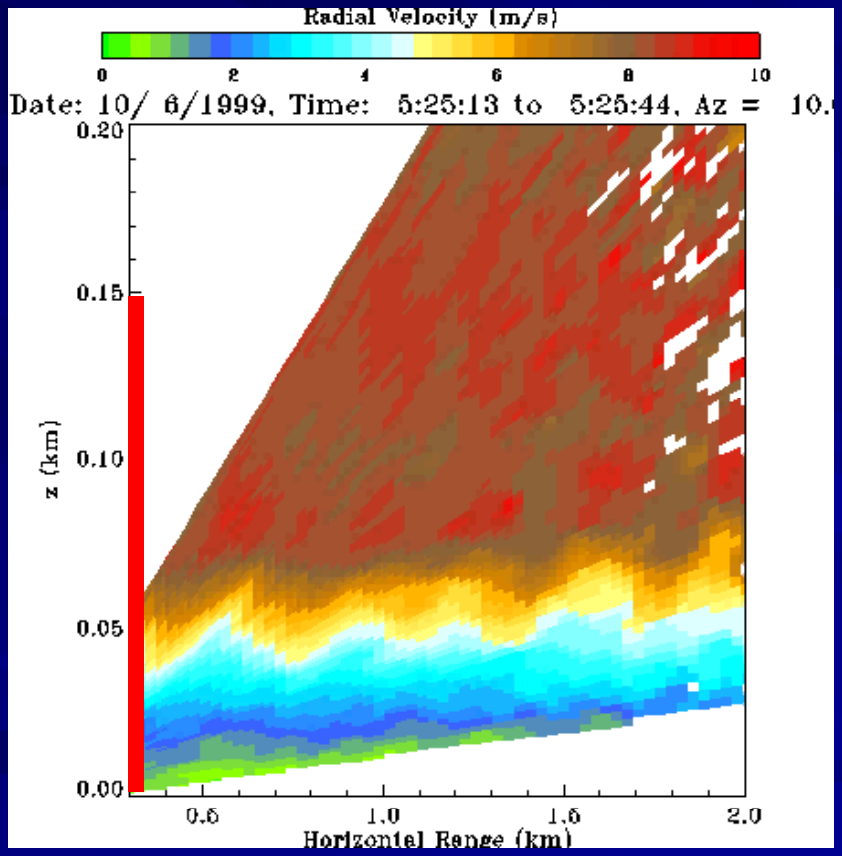
Outlook - meteorologically

- Time window of opportunity – explosive development of WE (favorable ‘opinion polls’)
- Wind energy / variable source “detractors”
- Could envision pessimistic scenario:
  - Costs, poor understanding of atmosphere, inadequate predictions
  - Public disillusionment with wind energy
  - Avoidable if took time now to get proper measurements, improve forecast models
- Instrument deployments: learn from previous experience
  - Not reinvent previous findings
  - Not repeat past mistakes

Wind-resource research needs

- Most urgent need – measurements in the 30 - 300+ m layer
  - Wind, temperature, turbulence profiles
  - Carefully planned deployment
  - Understand meteorological processes controlling SBL, LLJ structure, intensity, behavior
- Use measurements to verify model output, improve representation of modeled physical processes (including parameterizations)
- Accuracy of predictions more important than any previous applications

Thank you !!



[Animation]

LLJ impact: strong shear produces turbulence, wave activity

*Newsom and Banta 2003: J. Atmos. Sci, **60**,16-33.*

References
and for further information…

References

NOAA/ESRL White Paper

Marquis, M., J. Wilczak, R. Banta, S. Benjamin, J. Brown, E. Dutton, J. McGinley, A. MacDonald, J. Michalsky, Y. Pichugina, J. Schneider, K. Wolter, C. Kutscher, and M. Robinson, 2008: NOAA/ESRL's potential contributions to solving the Nation's energy-climate crisis through renewable energy development.

Journal Articles

Banta, R.M., R.K. Newsom, J.K. Lundquist, Y.L. Pichugina, R.L. Coulter, and L. Mahrt, 2002: Nocturnal low-level jet characteristics over Kansas during CASES-99. *Boundary-Layer Meteor.*, **105**, 221-252.

Banta, R.M., Y.L. Pichugina, and R.K. Newsom, 2003: Relationship between low-level jet properties and turbulence kinetic energy in the nocturnal stable boundary layer. *J. Atmos. Sci.*, **60**, 2549-2555.

Banta, R.M., L.S. Darby, J.D. Fast, J.O. Pinto, C.D. Whiteman, W.J. Shaw, and B.D. Orr, 2004: Nocturnal low-level jet in a mountain basin complex. Part I: Evolution and implications to other flow features. *J. Appl. Meteor.*, **43**, 1348-1365.

Banta, R.M., Y.L. Pichugina, and W.A. Brewer, 2006: Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. *J. Atmos. Sci.*, **63**, 2700-2719.

Banta, R.M., 2008: Stable boundary layer regimes from the perspective of the low-level jet. Special Issue, *Acta Geophysica*, **56**, 58-87.

Emeis, S., M. Harris, and R.M. Banta, 2007: Boundary-layer anemometry by optical remote sensing for wind energy applications. *Meteorologische Zeitschrift*, **16**, 337-347.

For further reference…

Newsom, R.K., and R.M. Banta, 2003: Shear-flow instability in the stable nocturnal boundary layer as observed by Doppler lidar during CASES-99. *J. Atmos. Sci.*, **30**, 16-33.

Pichugina, Y.L., R.M. Banta, B. Jonkman, N.D. Kelley, R.K. Newsom, S.C. Tucker, and W.A. Brewer, 2008: Horizontal-velocity and variance measurements in the stable boundary layer using Doppler-lidar: Sensitivity to averaging procedures. *J. Atmos. Ocean. Technol.*, **24**, 1307–1327.

Pichugina, Y.L., and R.M. Banta, 2009: Stable boundary-layer depth from high-resolution measurements of the mean wind profile. *J. Appl. Meteor. Climatol.*, **48**, *in press*.

Storm, B., J. Dudhia, S. Basu, A. Swift, and I. Giammanco, 2008: Evaluation of the Weather Research and Forecasting Model on forecasting low-level jets: Implications for wind energy. *Wind Energ.* DOI: 10.1002/we.288.

Tucker, S.C., W.A. Brewer, R.M. Banta, C.J. Senff, S.P. Sandberg, D.C. Law, A.M. Weickmann, and R. M. Hardesty, 2009: Doppler lidar estimation of mixing height using turbulence, shear, and aerosol profiles. *J. Atmos. Oceanic Technol.*, **25**, *in press*.

Reports and Conference Papers

Banta R.M., Y L Pichugina, N.D. Kelley, B. Jonkman, and W.A. Brewer, 2008: Low-level jet scaling of the stable boundary layer over the United States Great Plains, *18th Symposium on Boundary Layers and Turbulence, Stockholm, Sweden, June 2008, Amer. Meteor Soc.*

For further information…

Banta R.M., Y.L. Pichugina, N.D Kelley, B.J. Jonkman, and W.A. Brewer, 2008: Doppler lidar measurements of the Great Plains low-level jet: Applications to wind energy. *14th International Symposium for the Advancement of Boundary layer Remote Sensing,* 23-25 June, Risø National Laboratory, DTU, Roskilde, Denmark, pp.4

Frehlich, R., Kelley, N., 2008: Measurements of Wind and Turbulence Profiles with Scanning Doppler Lidar for Wind Energy Applications, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* **1**, 42-47.

Hand, M.M., Kelley, N.D., Balas, M.J., 2003: Identification of Wind Turbine Response to Turbulent Inflow Structures, NREL/CP-500-33465.

Kelley, N.D., 1989: An Initial Look at the Dynamics of the Microscale Flow Field within a Large Wind Farm in Response to Variations in the Natural Inflow, NREL/TP-257-3591.

Kelley, N.D., Wright, A.D.,1991: A Comparison of Predicted and Observed Turbulent Wind Fields Present in Natural and Internal Wind Park Environments, NREL/TP-257-4508.

Kelley, N.D., M. Shirazi, D. Jager, S. Wilde, J. Adams, M. Buhl, P. Sullivan, and E. Patton, 2004: Lamar Low-Level Jet Project Interim Report, NREL/TP-500-34593.

For further information… cont'd

Kelley, N.D., 1993: Defining the Normal Turbine Inflow Within a Wind Park Environment, NREL/TP-442-5619.

Kelley, N.D., Hand, M.M., Larwood, S., McKenna, E., 2002: The NREL Large-Scale Turbine Inflow and Response Experiment – Preliminary Results. *2002 ASME Wind Energy Symposium, Jan 14-17, 2002, Reno, NV.* , 412-426.

Kelley, N.D., Jonkman, B.J., Scott, G.N., 2006: Great Plains Turbulence Environment: Its Origins, Impact and Simulation, NREL/CP-500-41253.

Kelley, N.D., B.J. Jonkman, G.N. Scott, Y.L. Pichugina, 2007: Comparing Pulsed Doppler Lidar with Sodar and Direct Measurements for Wind Assessment. *NREL/CP-500-41792, Golden, CO: National Renewable Energy Laboratory.*

Pichugina, Y.L., R.M. Banta, N.D. Kelley, 2005: Application of High Resolution Doppler Lidar data for wind energy assessment. *Symposium on Lidar Atmospheric Applications*, 9-13 January 2005, San-Diego, CA , *Amer. Meteor Soc.*

Pichugina Y L., R.M. Banta, W.A. Brewer, 2006. The application of High Resolution Doppler Lidar data for wind-energy assessment. *AWEA/WINDPOWER* Conference, June 4-7, Pittsburgh, PA.

Pichugina Y.L., R.M. Banta, N.D. Kelley, B.J. Jonkman, W.A. Brewer, S.P. Sandberg, and J.L. Machol, 2007: Advantage of the High Resolution Doppler Lidar measurements for nighttime boundary layer study and wind-energy applications. Preprints, *14th Coherent Laser Radar Conference,* 8-13 July, 2007, Snowmass, CO, 4 pp,

For further information… cont'd

Pichugina Y.L., R.M. Banta, N.D. Kelley and W.A. Brewer , 2007: Advancing wind energy research through new remote sensing technologies**.** Proceedings, *WINDPOWER 2007 conference*, June 3-6, Los Angeles, CA.

Pichugina Y.L, R M. Banta, and W.A. Brewer, Kelley N.D., 2007. Analysis of the southern Colorado low-level jet by High Resolution Doppler Lidar data. Comparison to the Great Plains LLJ climatology. *3d Symposium on Lidar Atmospheric Applications*, 14-18 January 2007, San-Antonio, Texas, paper 5.6, *Amer. Meteor Soc.*

Pichugina Y.L., R.M. Banta, W.A. Brewer, N.D. Kelley, R.K. Newsom, 2008: Doppler lidar study of nocturnal boundary layer structure. Preprints, *24th International Laser Radar Conference*, 23-27 July, 2008, Boulder, CO., 4 pp.

Pichugina Y.L., R.M. Banta, N.D. Kelley, W.A. Brewer, S.P. Sandberg, and J.L. Machol, B.J. Jonkman, 2008: Remote sensing of the nocturnal Boundary Layer for Wind Energy applications. *14th International Symposium for the Advancement of Boundary layer Remote Sensing*, 23-25 June, Risø National Laboratory, DTU, Roskilde, Denmark, pp.4

Pichugina Y.L, R.M. Banta, N.D. Kelley, W.A. Brewer, S.P. Sandberg, and J.L. Machol, B.J. Jonkman, 2009: Lidar measurements of extreme inflow events for wind energy operations, *4th Symposium on Lidar Atmos. Applic., AMS,* 11-15 January, Phoenix, AZ, *Amer. Meteor Soc.*

Pichugina Y.L, R.M. Banta, N.D. Kelley, W.A. Brewer, S.P. Sandberg, R.M. Hardesty and B.J. Jonkman, 2009: Lidar study of the nocturnal boundary layer at the heights of modern wind turbines. Preprints, *15th Coherent Laser Radar Conference,* 22-26 June, 2009, Toulouse, France, 4 pp.