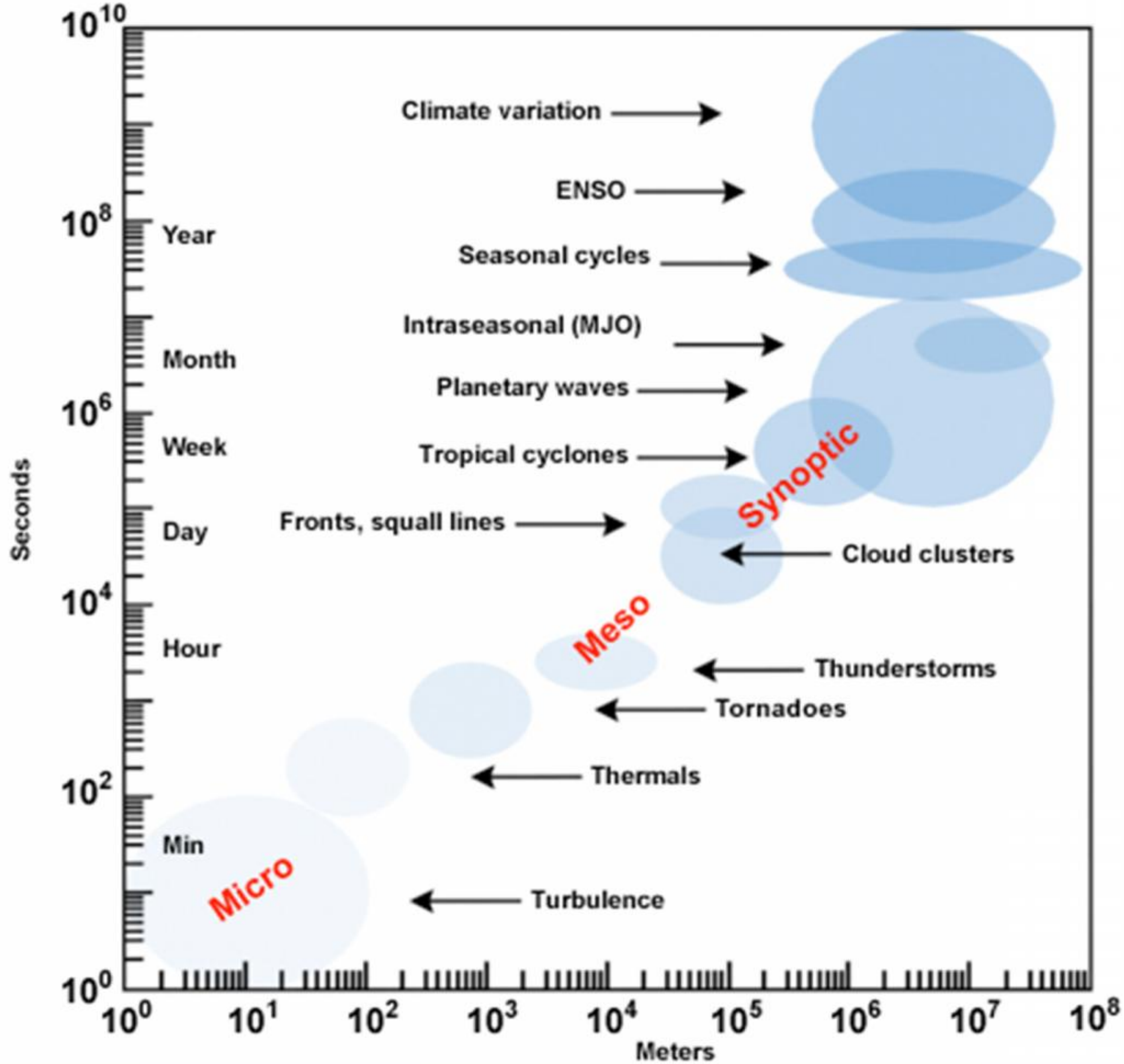
Atmospheric science challenges related to large-scale deployment of weather-dependent renewable energy

Part I: Jim Wilczak/NOAA
Part II: Sue Ellen Haupt/NCAR



Climate variation
ENSO
Seasonal cycles
Intraseasonal (MJO)
Planetary waves
Tropical cyclones
Fronts, squall lines
Cloud clusters
Thunderstorms
Tornadoes
Thermals
Turbulence
Synoptic
Meso
Micro
Year
Month
Week
Day
Hour
Min
Seconds
Meters
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}
10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10}

Outlines

Part I:

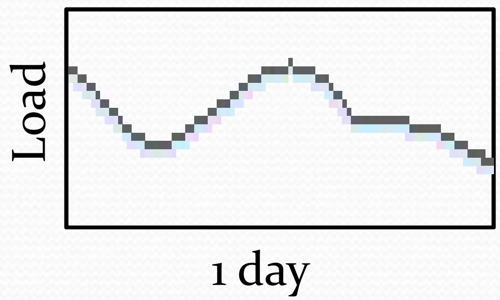
- Economics
- Instrumentation
- PBL processes
  - diurnal cycle, LLJ, shear, stability, waves
- Wake effects
- Offshore
- Forecasting/data assimilation
  - Ramp events
  - Thunderstorms

Part II:

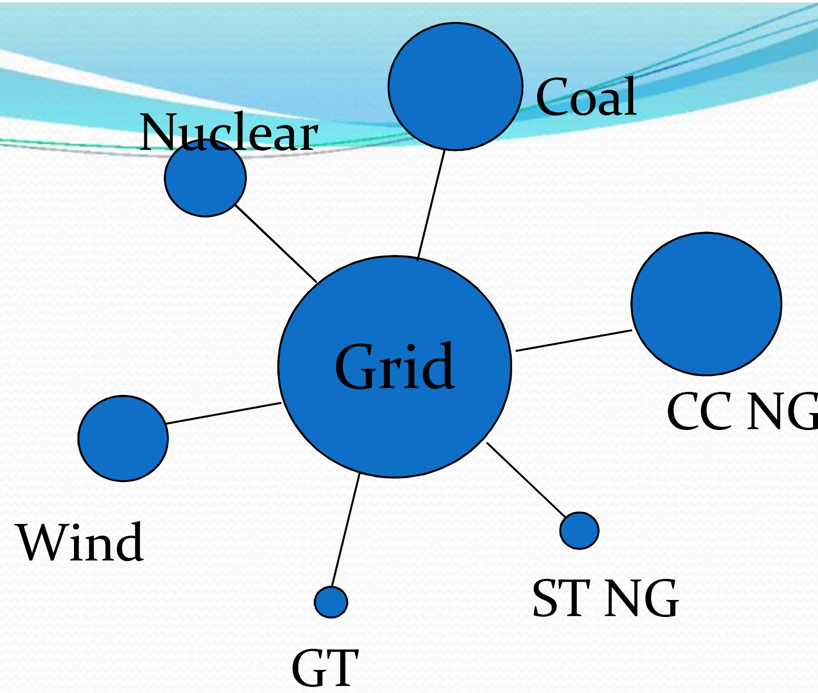
- Spatial/Temporal Variability
- Interannual variability
- Terrain effects
- Turbulence
- Models
- Terra incognita
- Wave-wind interaction
- Extreme events
- Forecasting

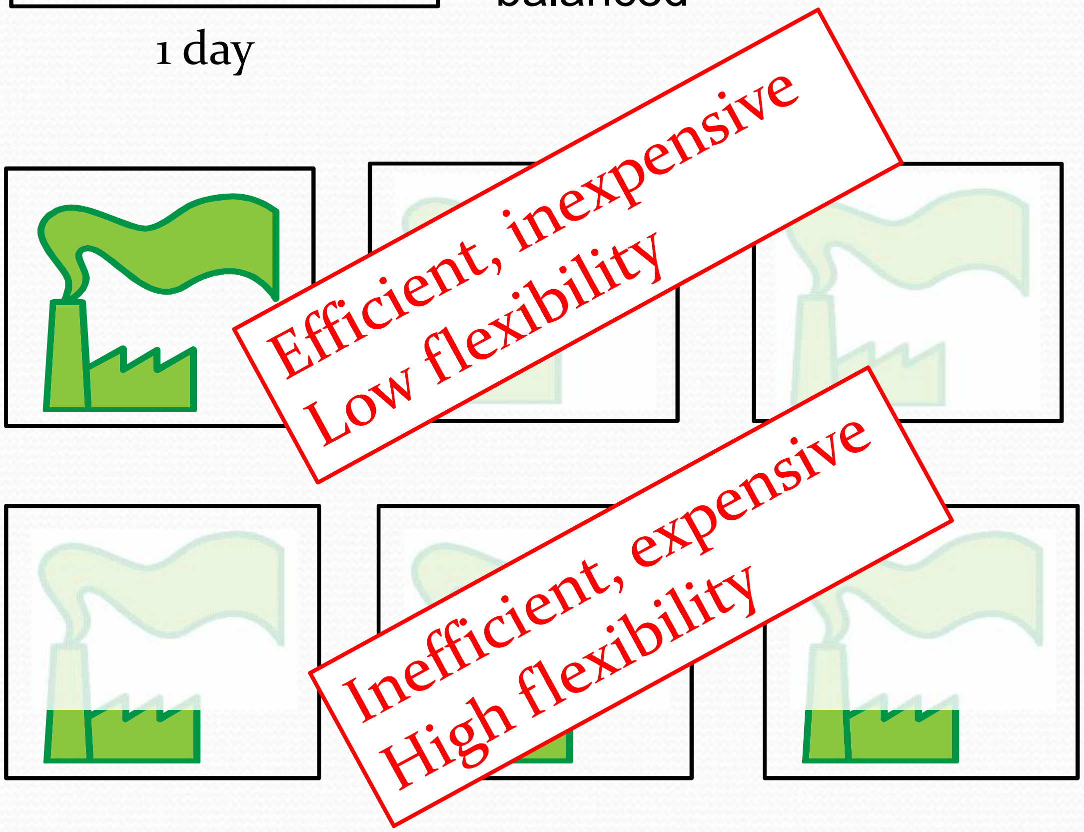
Economics

Grid Balancing



Grid operators keep demand (load) and generation closely balanced





Because of start-up costs and technical limits, can't/don't want to turn off plants for short periods of time: Nuclear: weeks; Coal and Steam Gas: ~6-24 h; CC ~hours, GT: minutes.

Plants operating at reduced capacity are less efficient (~30 % lower efficiency for CC, 15 % for coal)

Levelized Cost of Wind Energy versus Fossil Fuels

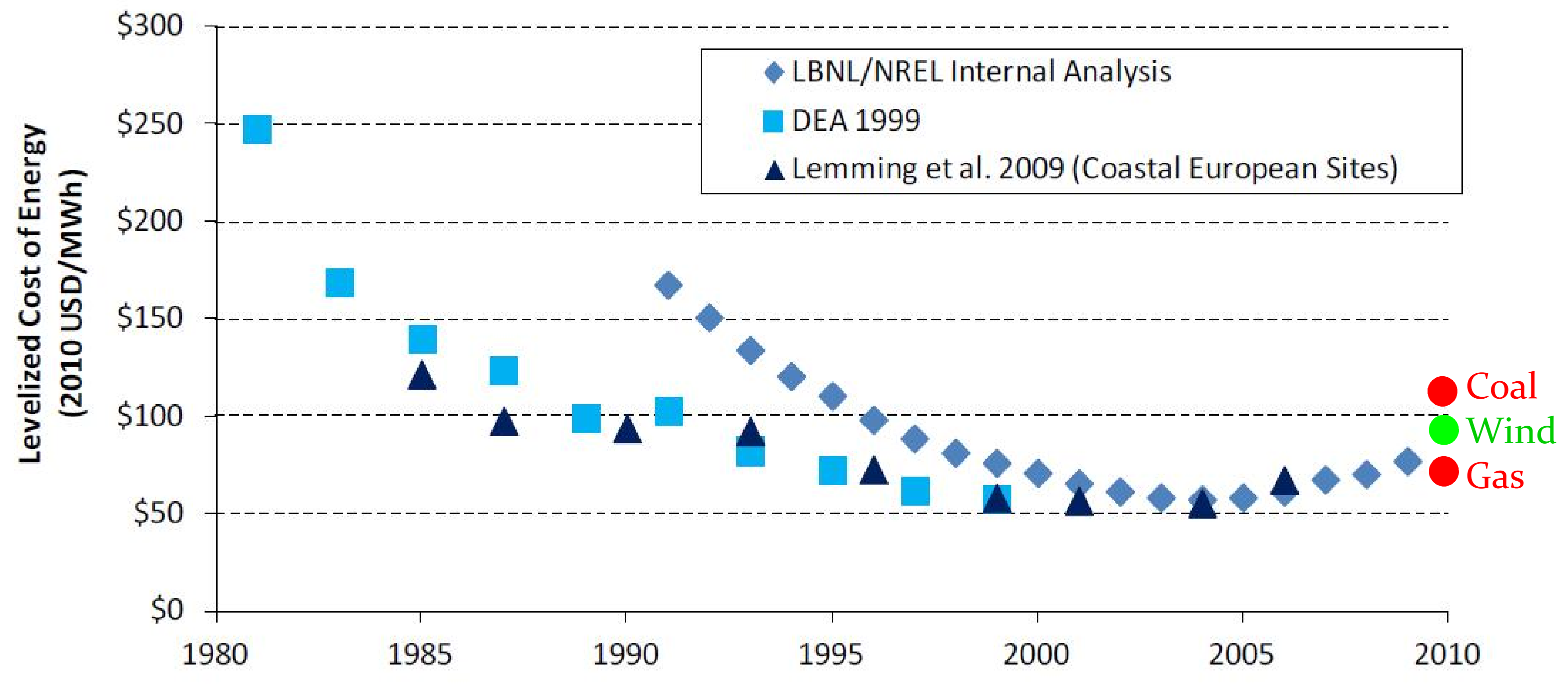
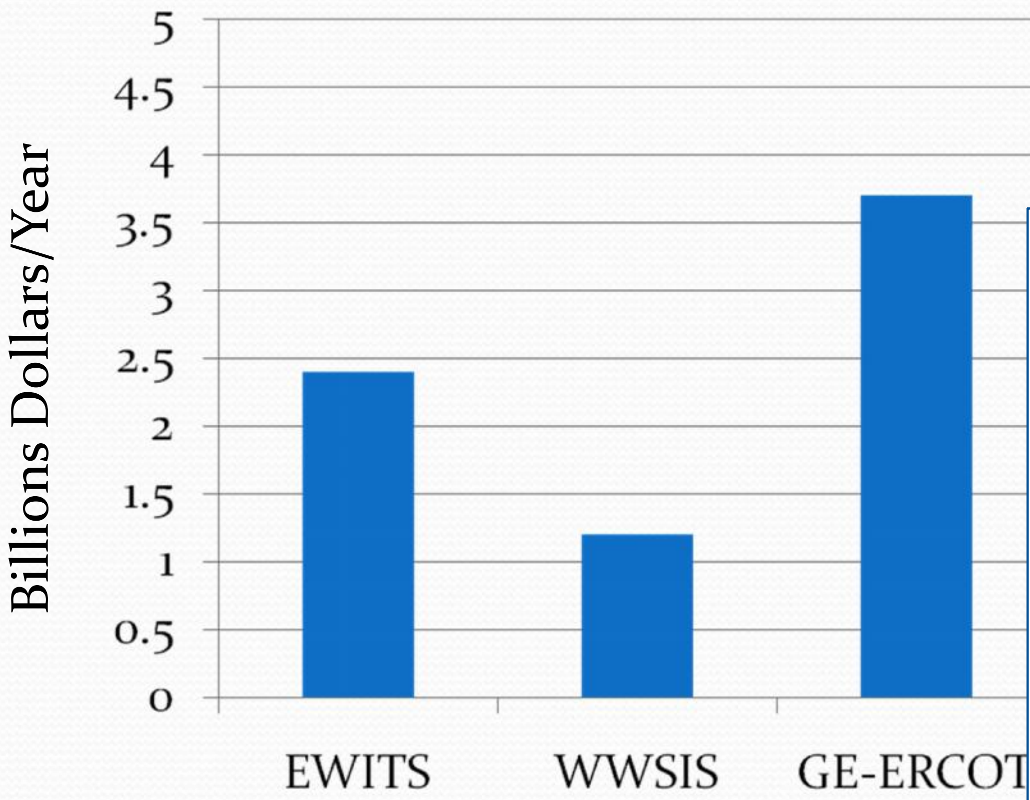
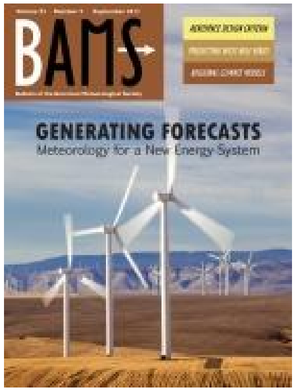


Figure 8. Estimated LCOE for wind energy from 1980 to 2009 for the United States and Europe (excluding incentives)

IEA Wind Task 26 Report (Lantz et al., 2012)
DOE/EIA Annual Energy Outlook 2012

Potential Savings

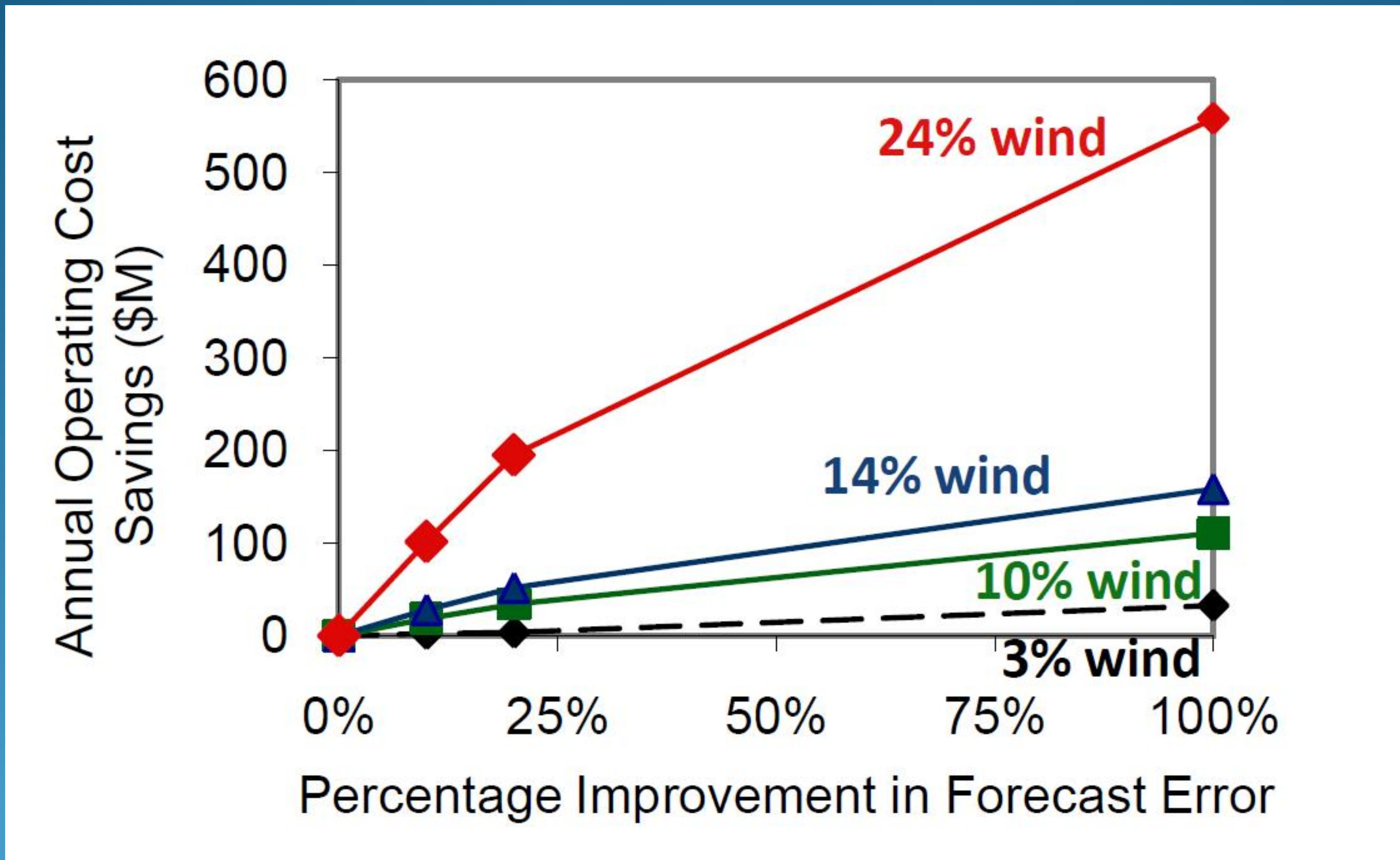




Marquis et al.,
Bull. Amer, Meteor. Soc.
Sept. 2011.

Savings between a (State-of-the-Art) SOA next-day wind forecast and a perfect forecast for a national 20% wind in 2030 scenario

Savings sensitivity to % forecast improvement



Lew et al., 2010

Economics

Key Points:

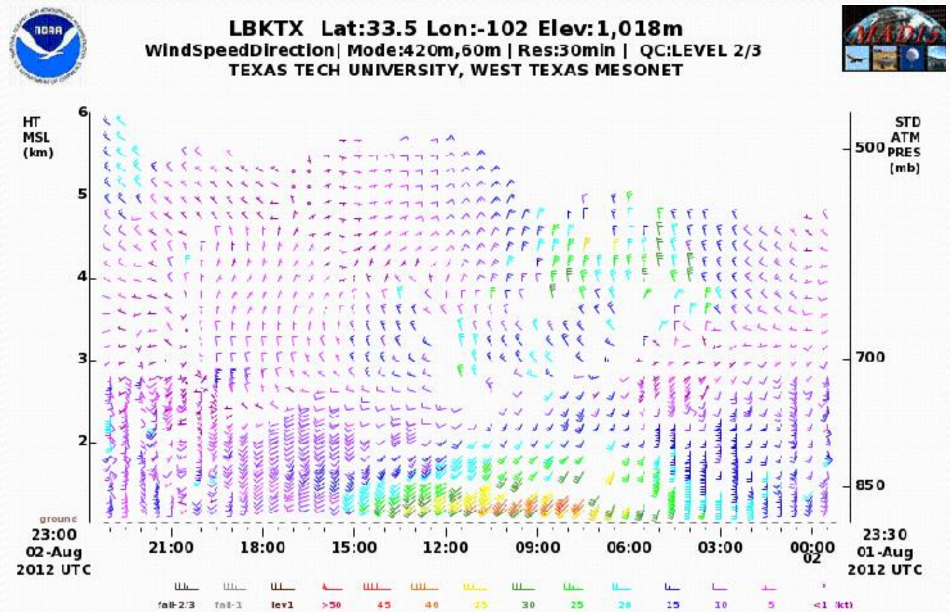
- Determining cost savings from better met info can be complicated,
  requires understanding of met and engineering/systems analysis
- Dollar savings are potentially large
- Dollar savings increase with wind penetration level
- Modest improvements in meteorological information can produce large savings
- Better met info is not an absolute necessity for WE, but it makes it cheaper!
- Useful to view all met challenges/research/information through the financial prism

Instrumentation

☺ ☺ ☺ 💣 **Radar wind profiler/RASS delivers wind and temperature profiles.**

Pros: deep layer for data assimilation, both winds and temperature.

Cons: high 1st range gate, coarse vertical resolution. Improvements to data qc needed.



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Pros: low 1st gate, high vertical resolution
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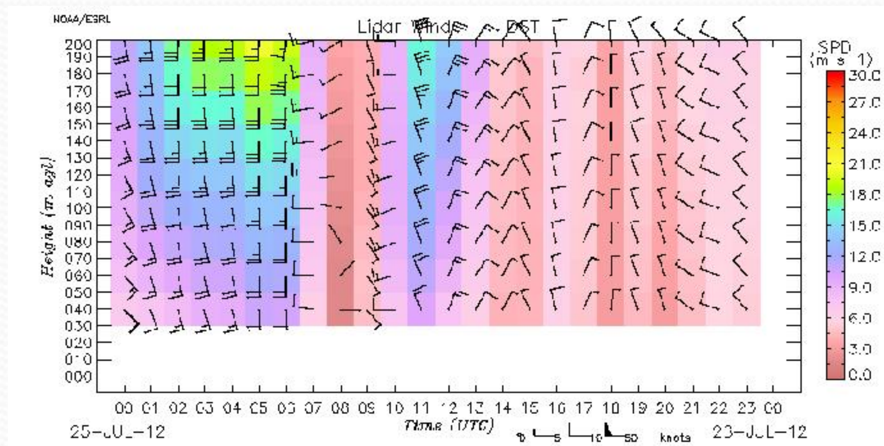

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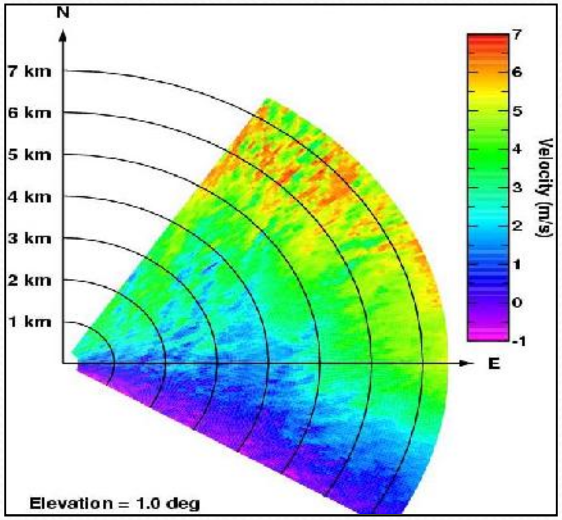
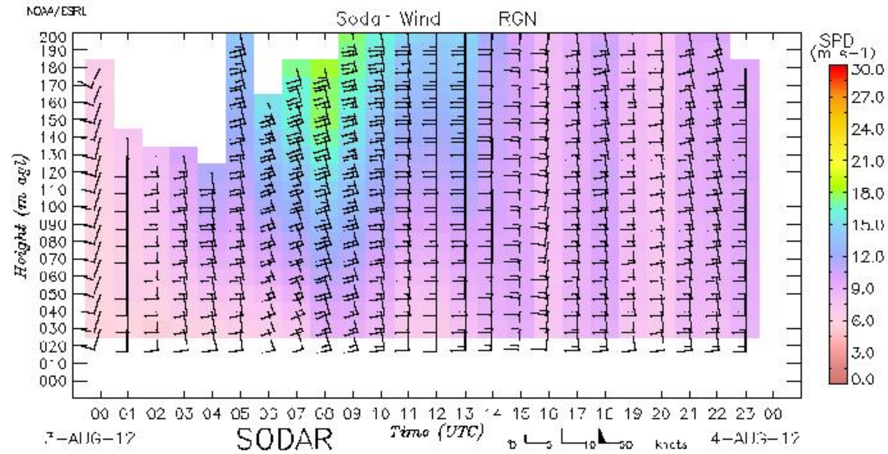
☺ ☺ ☺ 💣 **Scanning Doppler lidar** detects wind and turbulence fields.
Pros: spatial wind variations as well as vertical profile, turbulence.
Cons: No signal in extremely clean air, precip, fog. High cost. Restricted vertical range.





☺ ☺ 💣💣 **SODAR detects wind, turbulence profiles.**

Pros: High vertical resolution, low 1st gate, low cost.

Cons: Does not work well with very high wind speeds, and during stronger precipitation events. Restricted range. Noise contamination.

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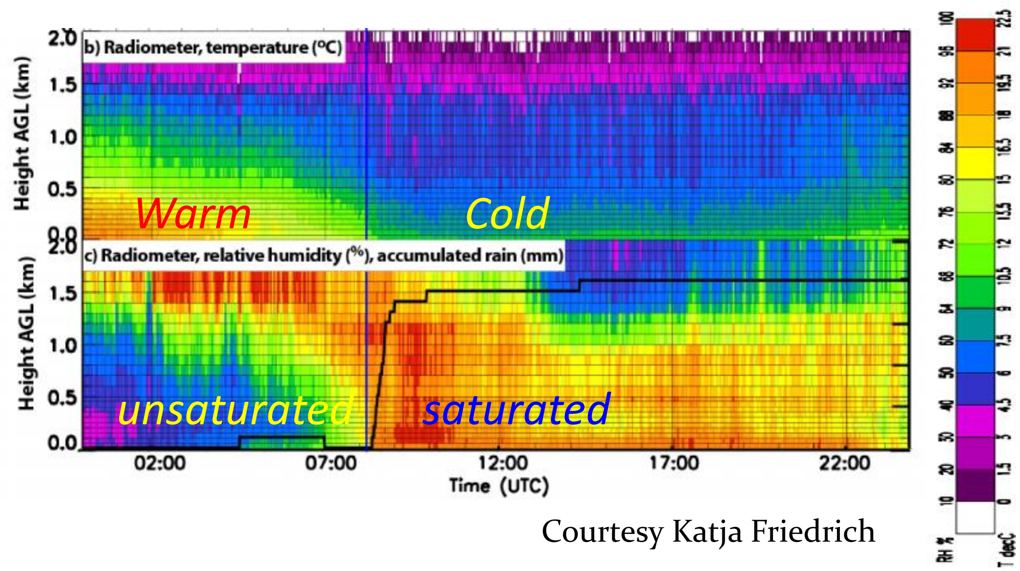

Courtesy Katja Friedrich

☺ 💣💣💣 **Radiometers** detects temperature profiles.
Pros: provides temperature and moisture profiles.
Cons: No wind information. Accuracy depends on nearby sounding.

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Cons: No wind information. Accuracy depends on nearby sounding.

☺ ☺ 💣💣 **Industry tall towers/nacelles** wind, turbulence, temperature 1 or more levels.
Pros: provides information at or near hub height. Already exist.
Cons: Difficult to obtain. Loss of data due to icing. No data in upper half of rotor plane or above.

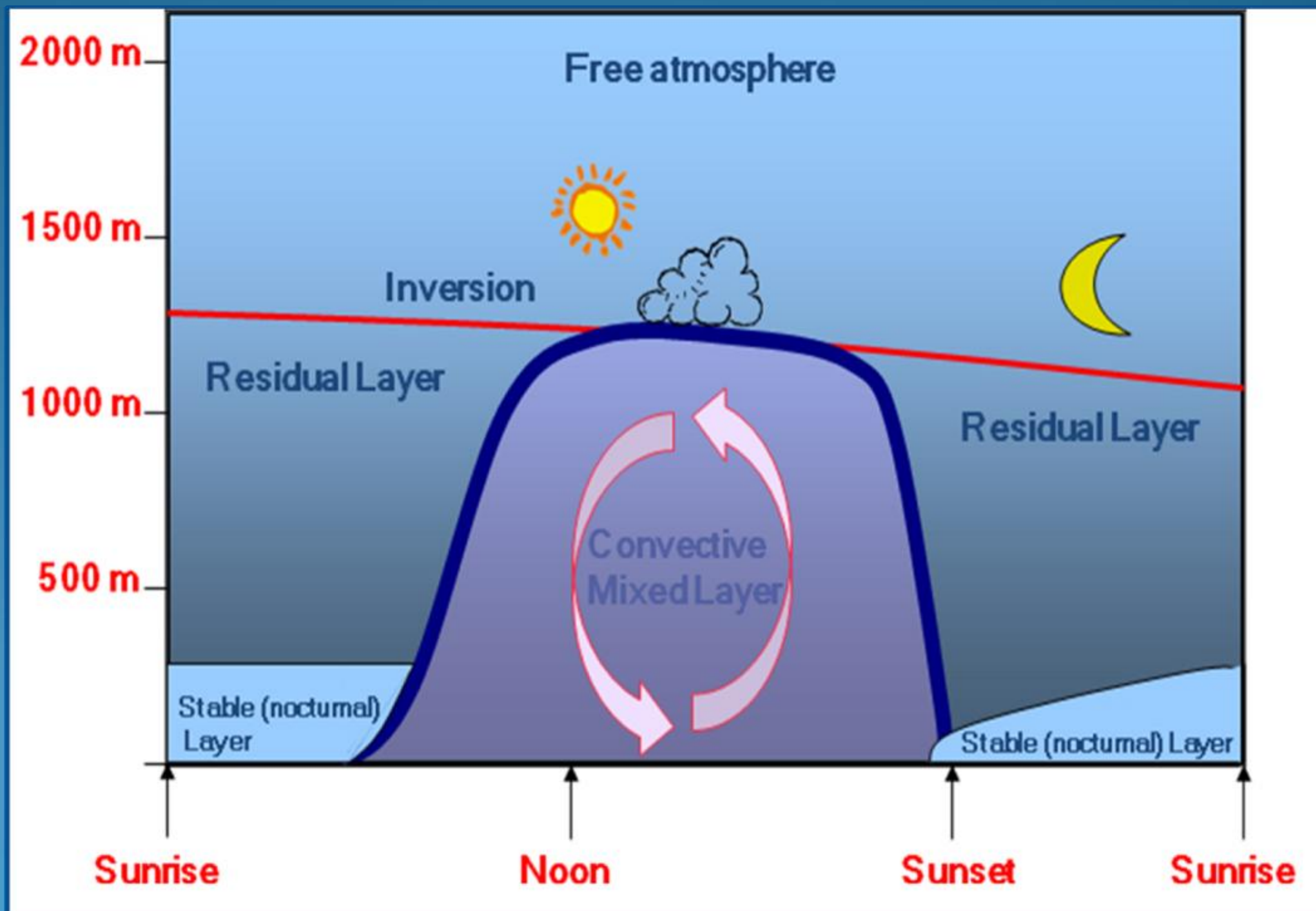
Instrumentation

Key Challenges

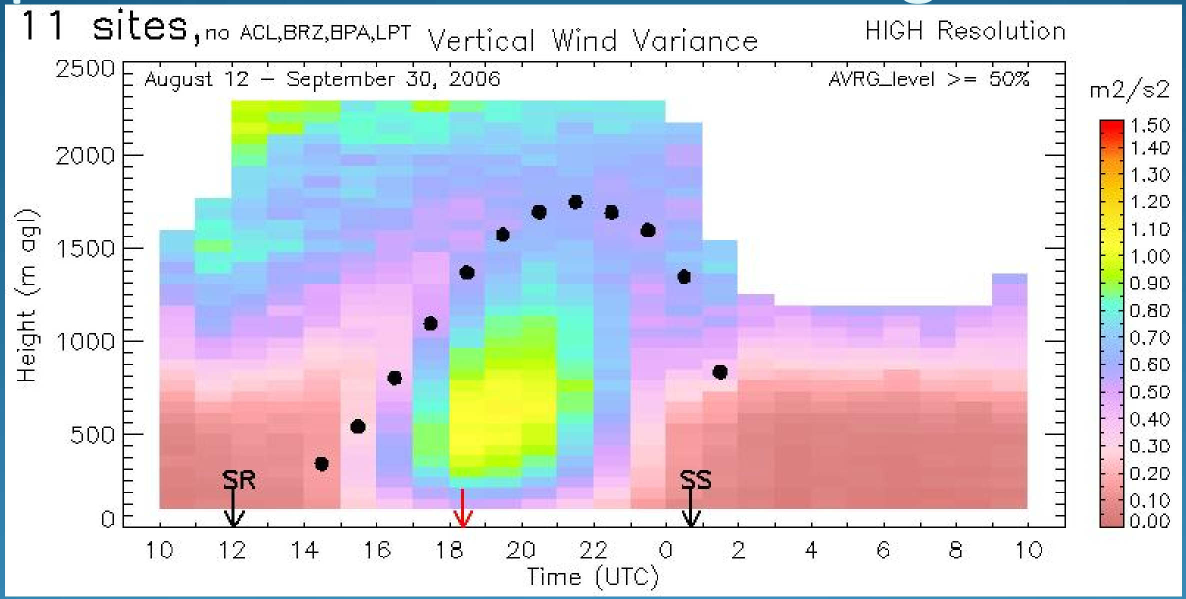
- Higher accuracy/cheaper/more easily deployed instrumentation is needed!
- Better automated QC needed especially for data assimilation
- Maintaining national networks in times of shrinking federal budgets.

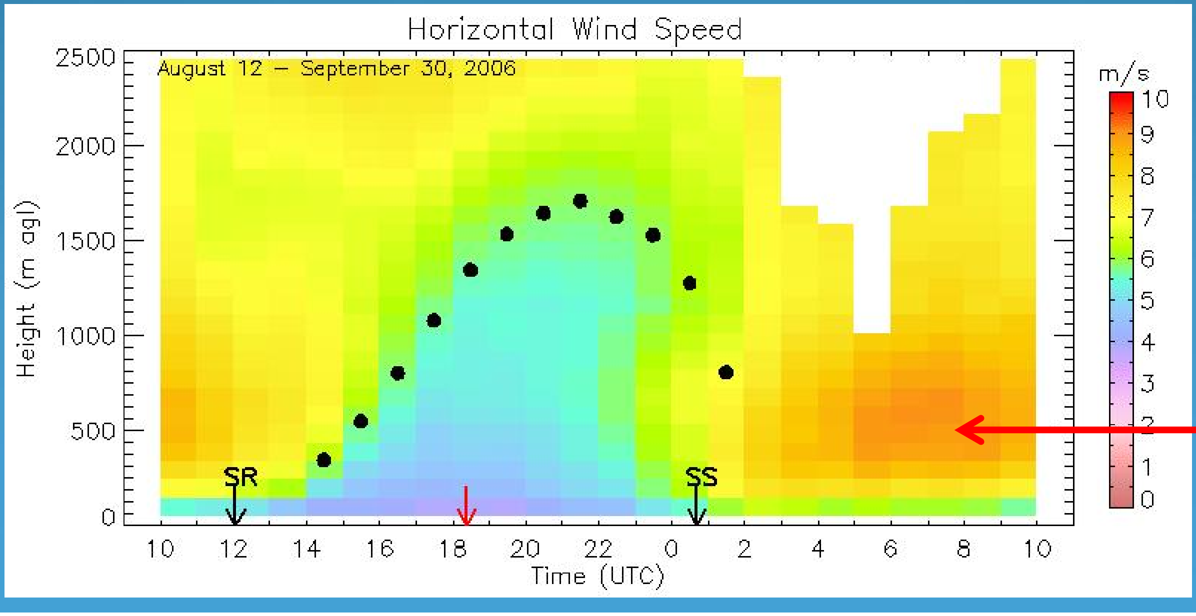
PBL Processes

Diurnal cycle
LLJ
Shear
Stability
Waves



Composite PBL – Wind Profiling Radar

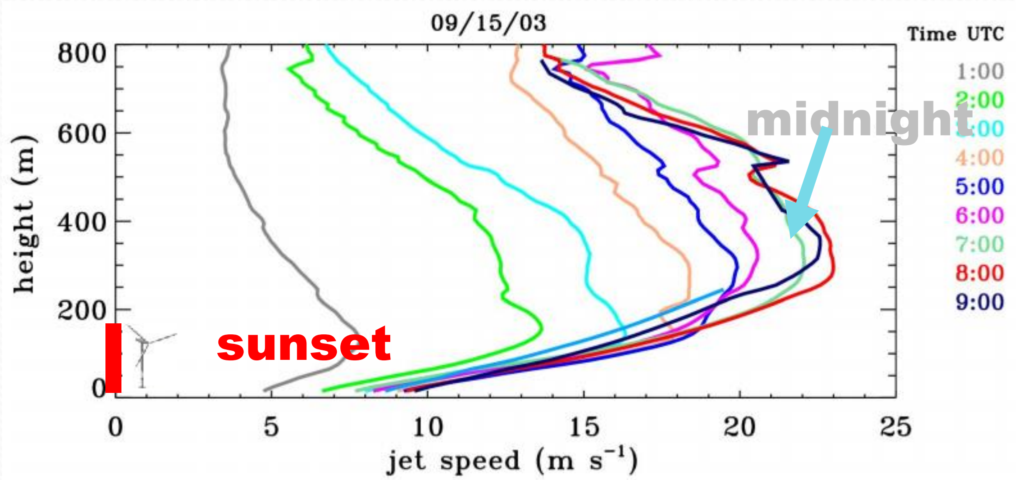


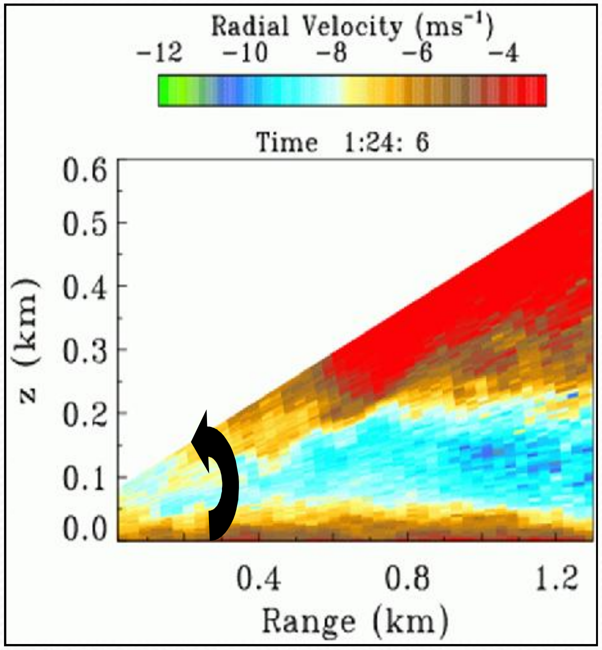


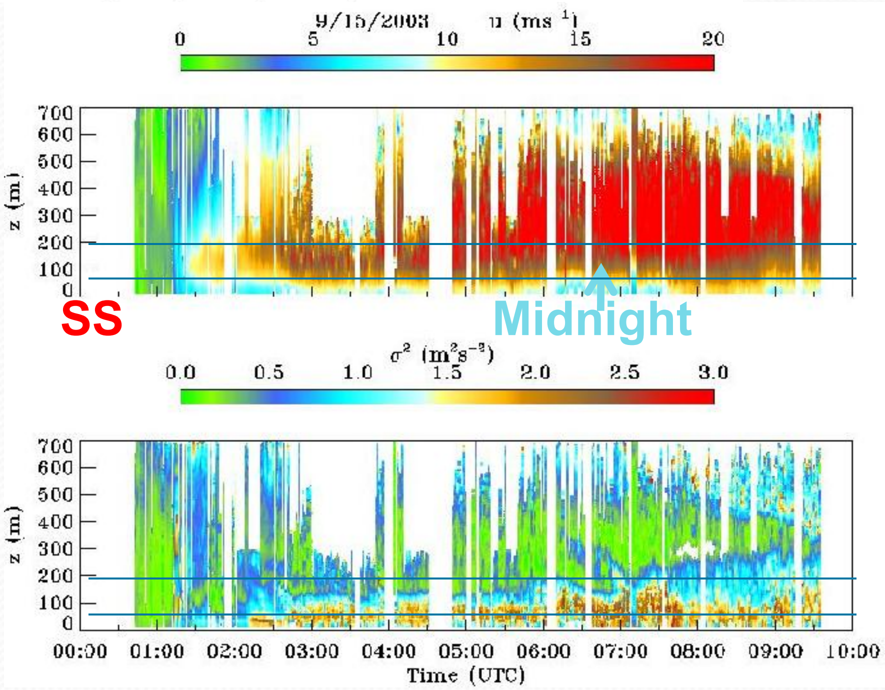
7 sites
50 days
no rain

Low Level Jet

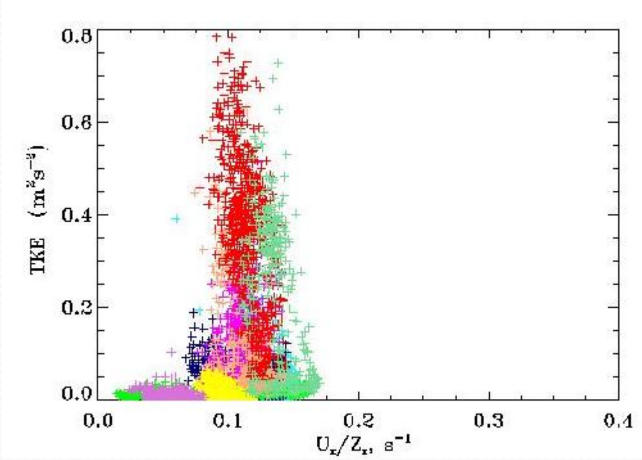
Lidar Observations of LLJ

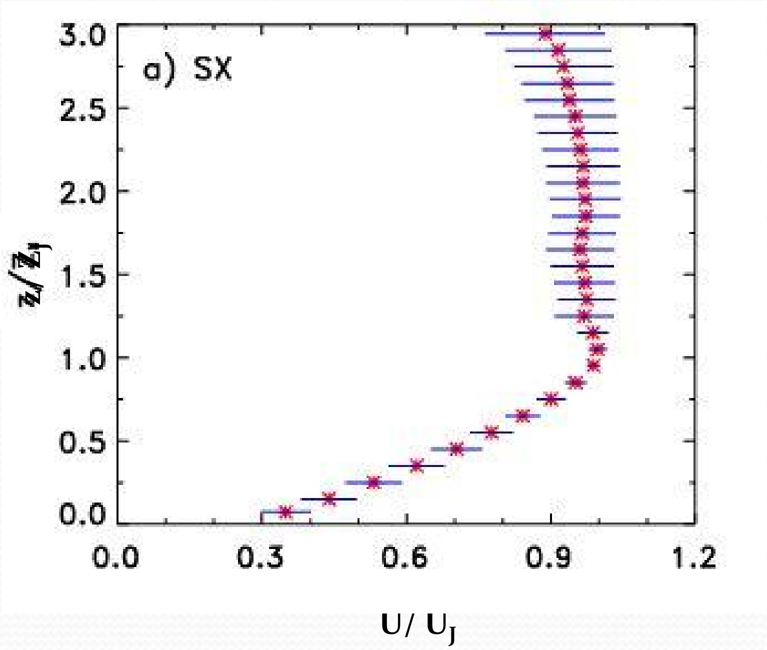






- LLJ speed U_J, and height Z_J - key velocity and length scales for the SBL
- Constant shear of 0.1 s^{-1} below jet





Composite over 6 nights

Banta, Pichugina, and Brewer, 2006: *J. Atmos. Sci.*, **63**, 2700-2719.

LLJ Geographic Variation

December 1968 William D. Bonner 835

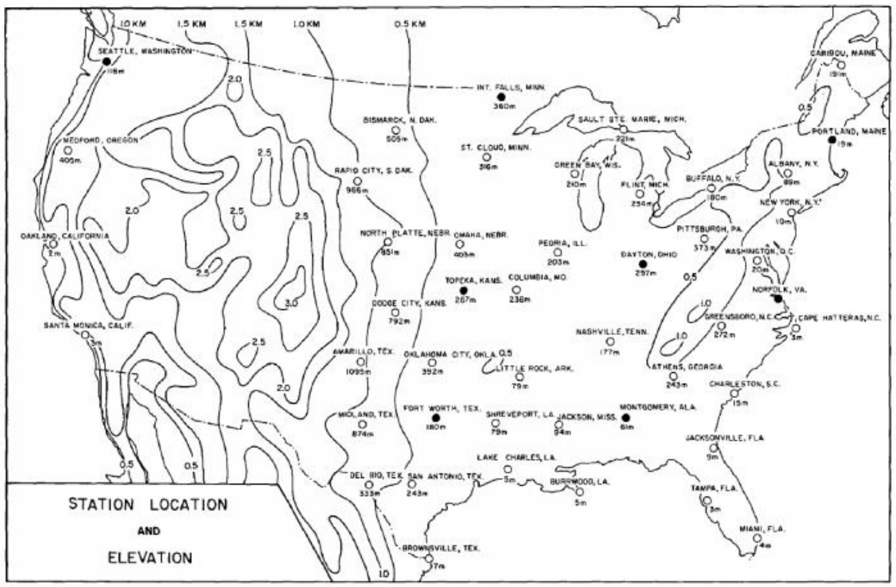


FIGURE 1.—Stations used in the machine search for low level jet observations. Station elevations are given in meters above sea level. Black circles indicate stations at which four-times-daily wind observations were examined for a 1-yr. period.

Radiosonde network

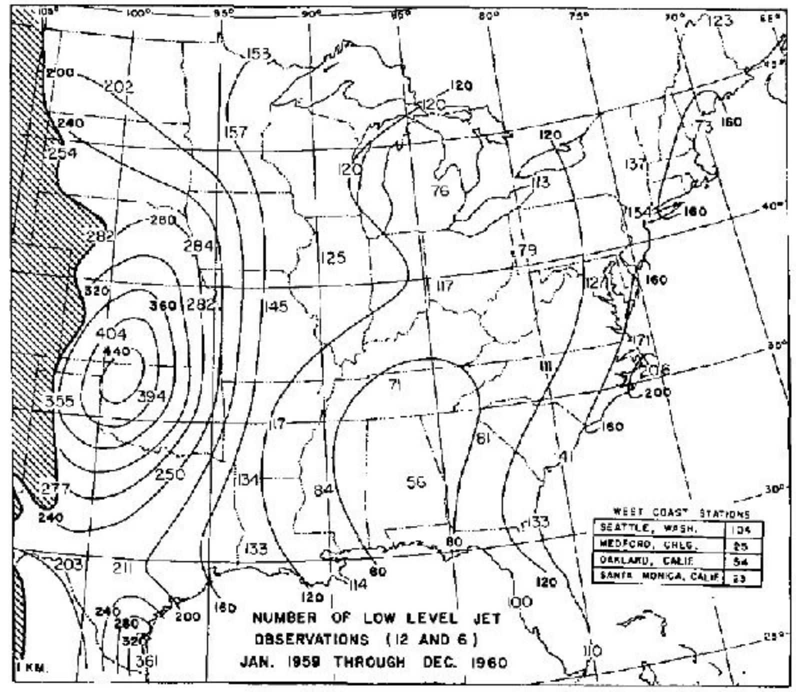
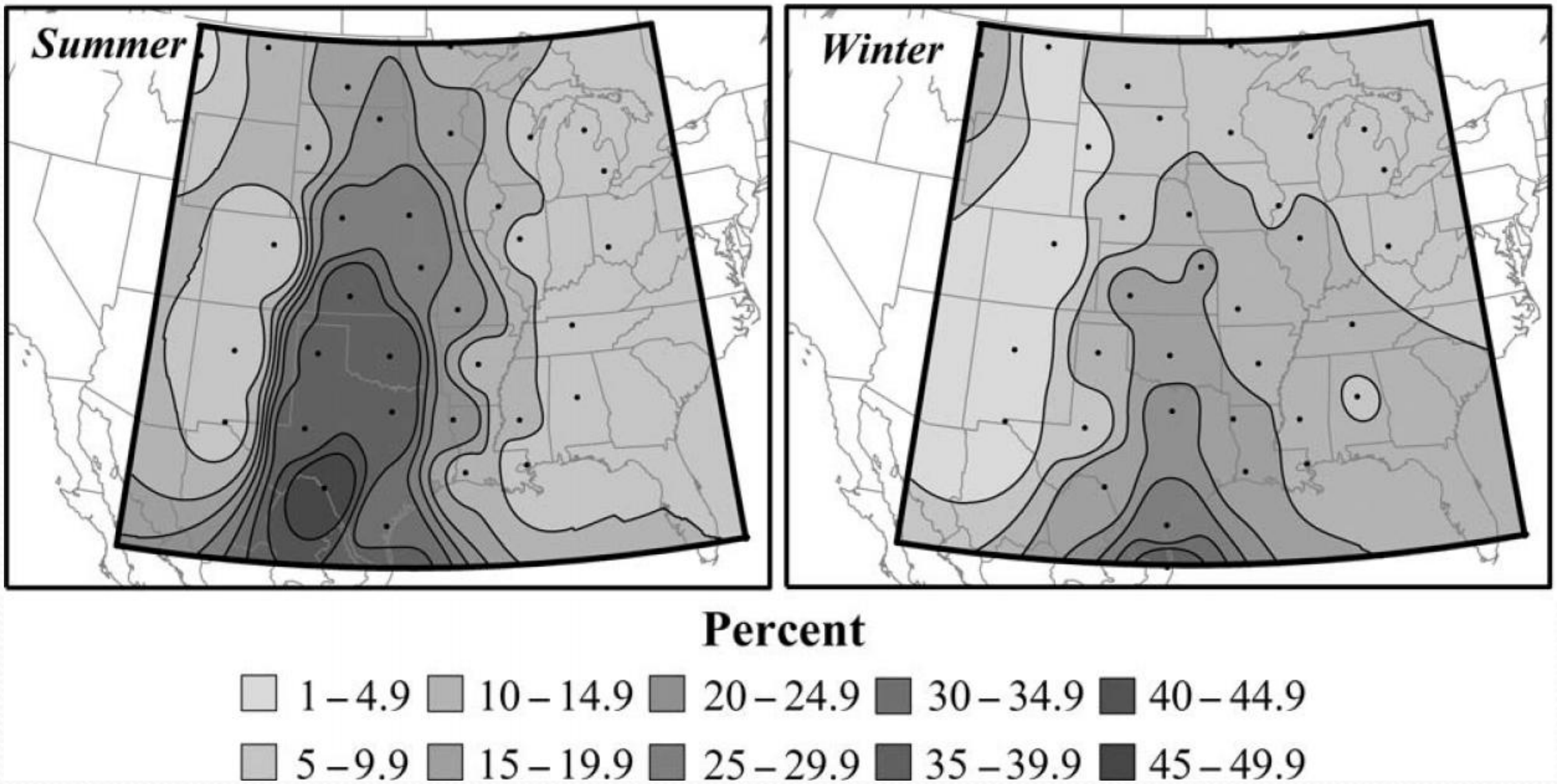


FIGURE 2.—Number of Criterion 1 low level jet observations from January 1959 through December 1960. 18 CST and 06 CST combined.

Frequency of LLJ occurrence

Bonner, 1968

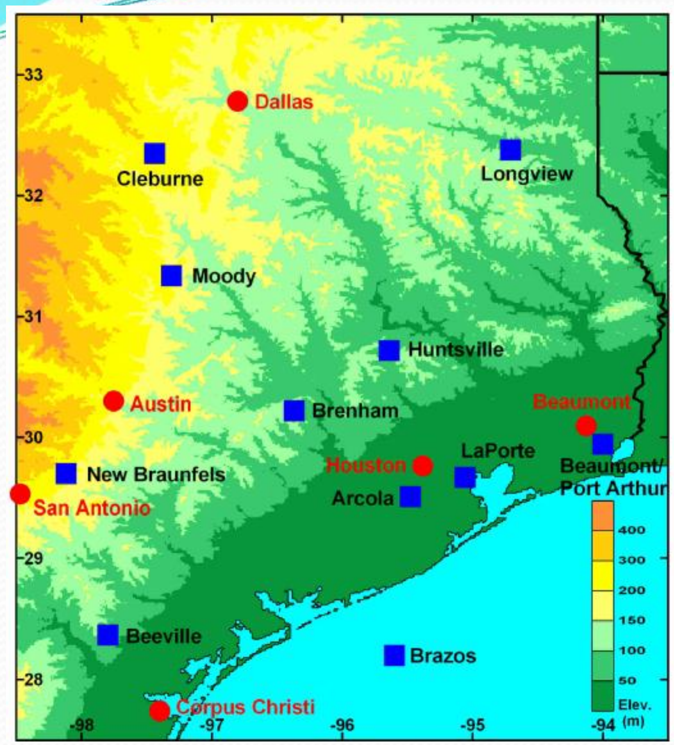
LLJ Geographic Variation - revisited



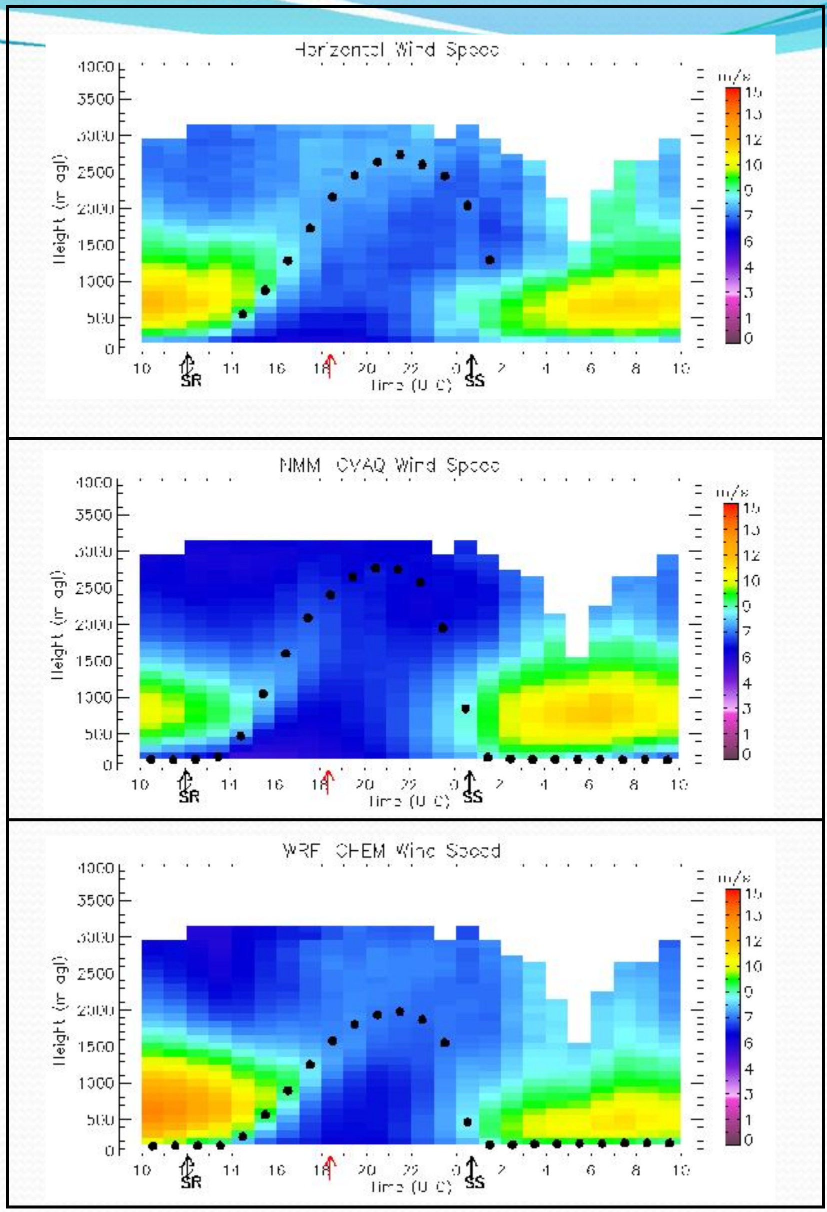
Same 2x/day radiosondes (00 UTC, 12 UTC)

What is geographical variation of Uj, Zj?
Time of onset, cessation?

Walters et al., 2008



TexAQS 2006 wind profiler network



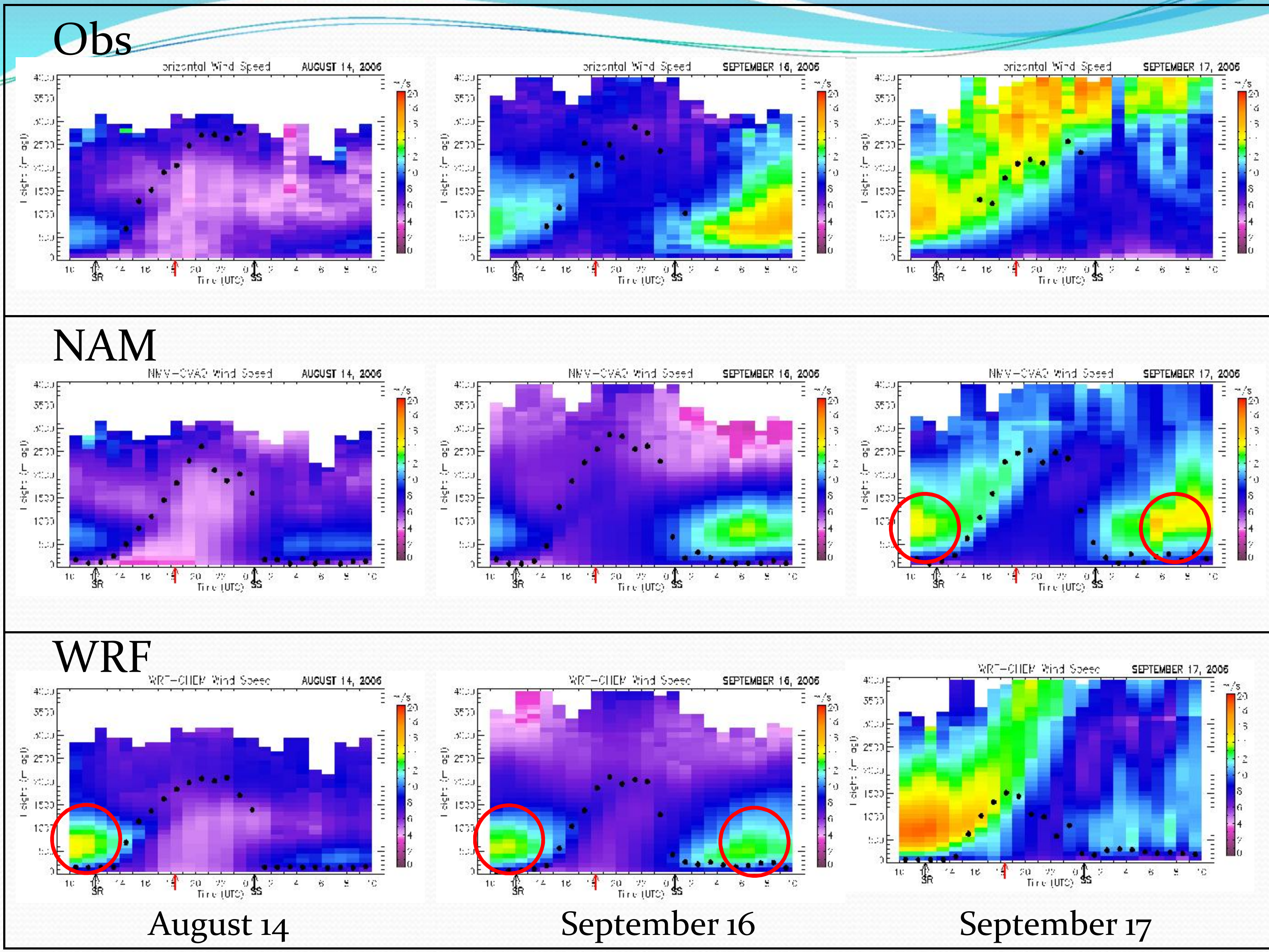
Obs

NAM

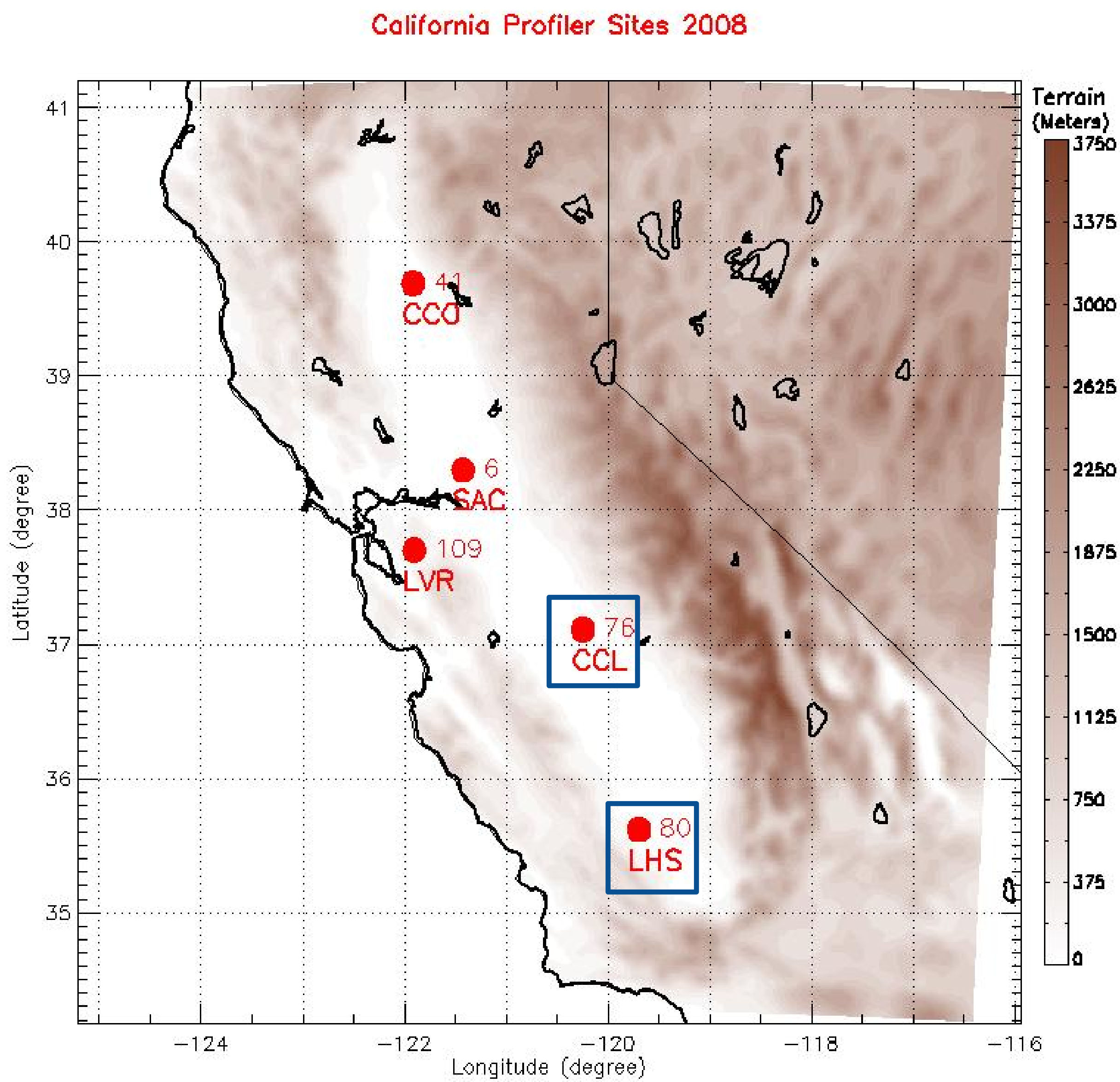
WRF

Composite of 17 LLJ days, all sites

Wilczak et al., 2009

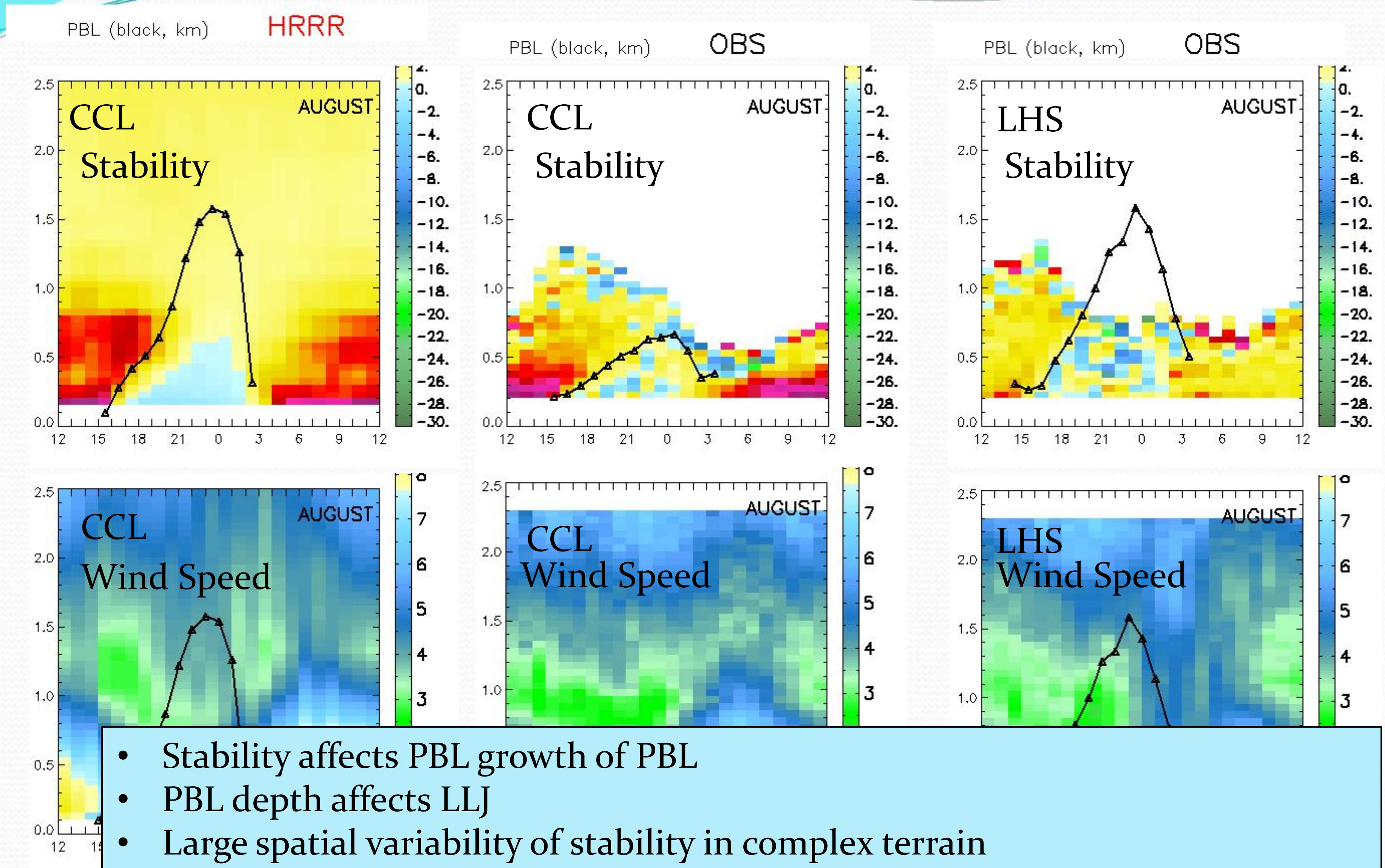


Obs
NAM
WRF
AUGUST 14, 2006
SEPTEMBER 16, 2006
SEPTEMBER 17, 2006
m/s
Time (UTC)
SR
SS
August 14
September 16
September 17



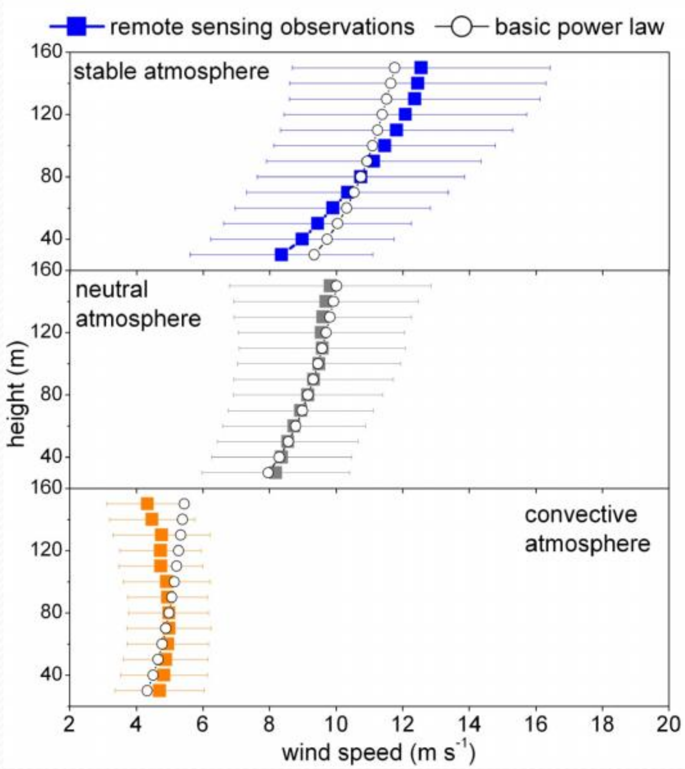
California Profiler Sites 2008
Terrain
(Meters)
3750
3375
3000
2625
2250
1875
1500
1125
750
375
0
41
40
39
38
37
36
35
Latitude (degree)
-124
-122
-120
-118
-116
Longitude (degree)
41
CCO
6
SAC
109
LVR
76
CCL
80
LHS

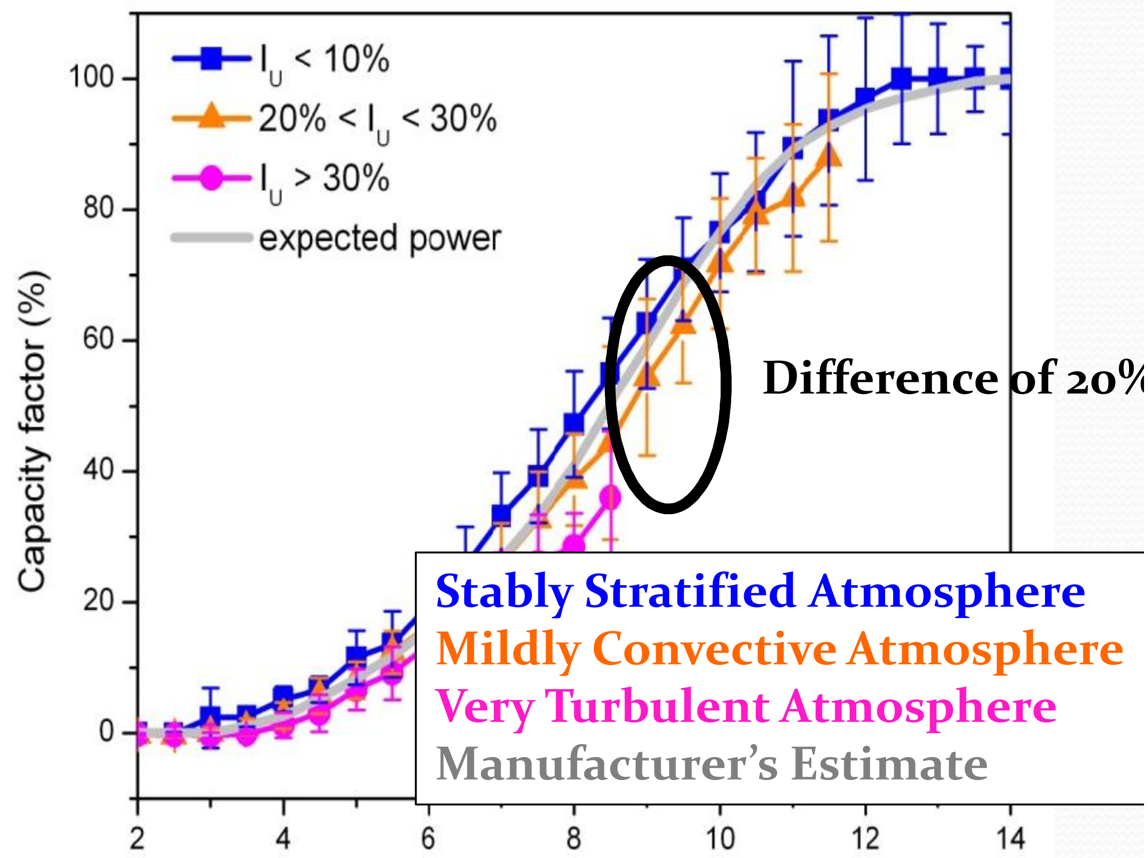
August 2010 Radar Wind Profiler Composite



- Stability affects PBL growth of PBL
- PBL depth affects LLJ
- Large spatial variability of stability in complex terrain
- Models have greater difficulty on simulating climatology of stability, PBL, LLJ

Power production by the leading turbine varies with atmospheric stability



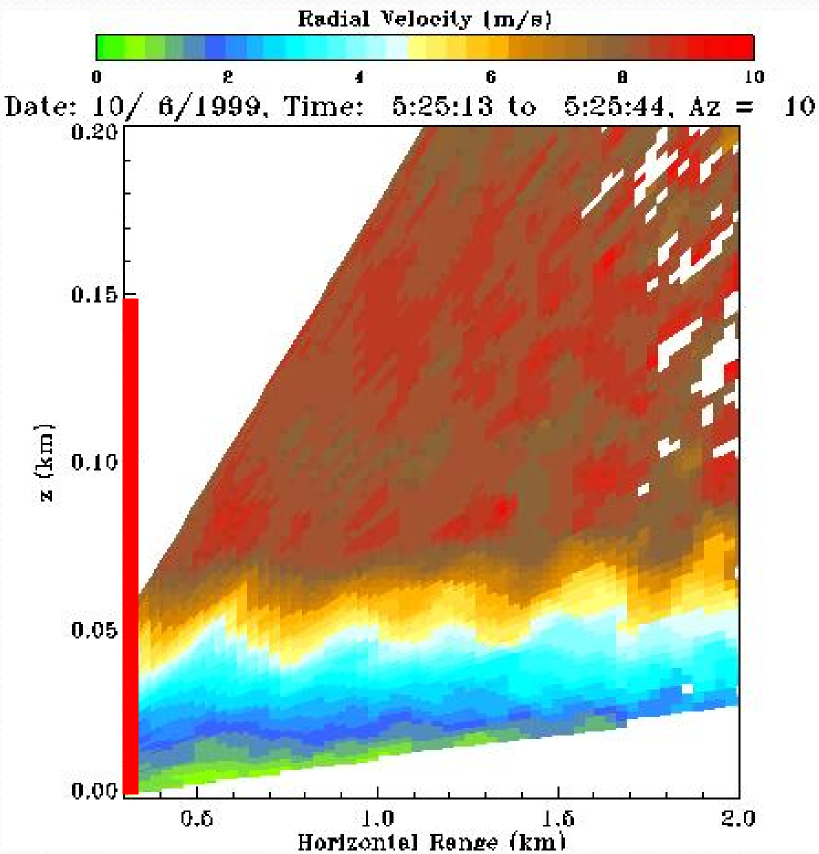


Based on SCADA and SODAR data from an operating wind farm, West Coast North America

Stability stratification by SODAR I_U

Wharton and Lundquist, 2012,
Environmental Research Letters

Waves



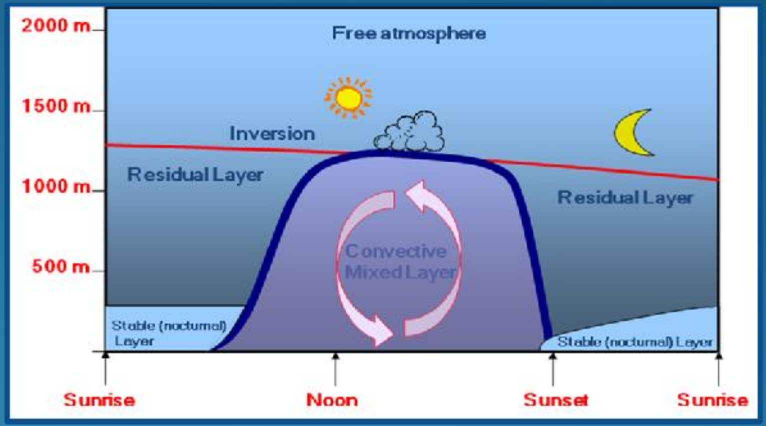
[Animation]

Turbulence measurements usually do not separate wave motions

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

PBL Processes

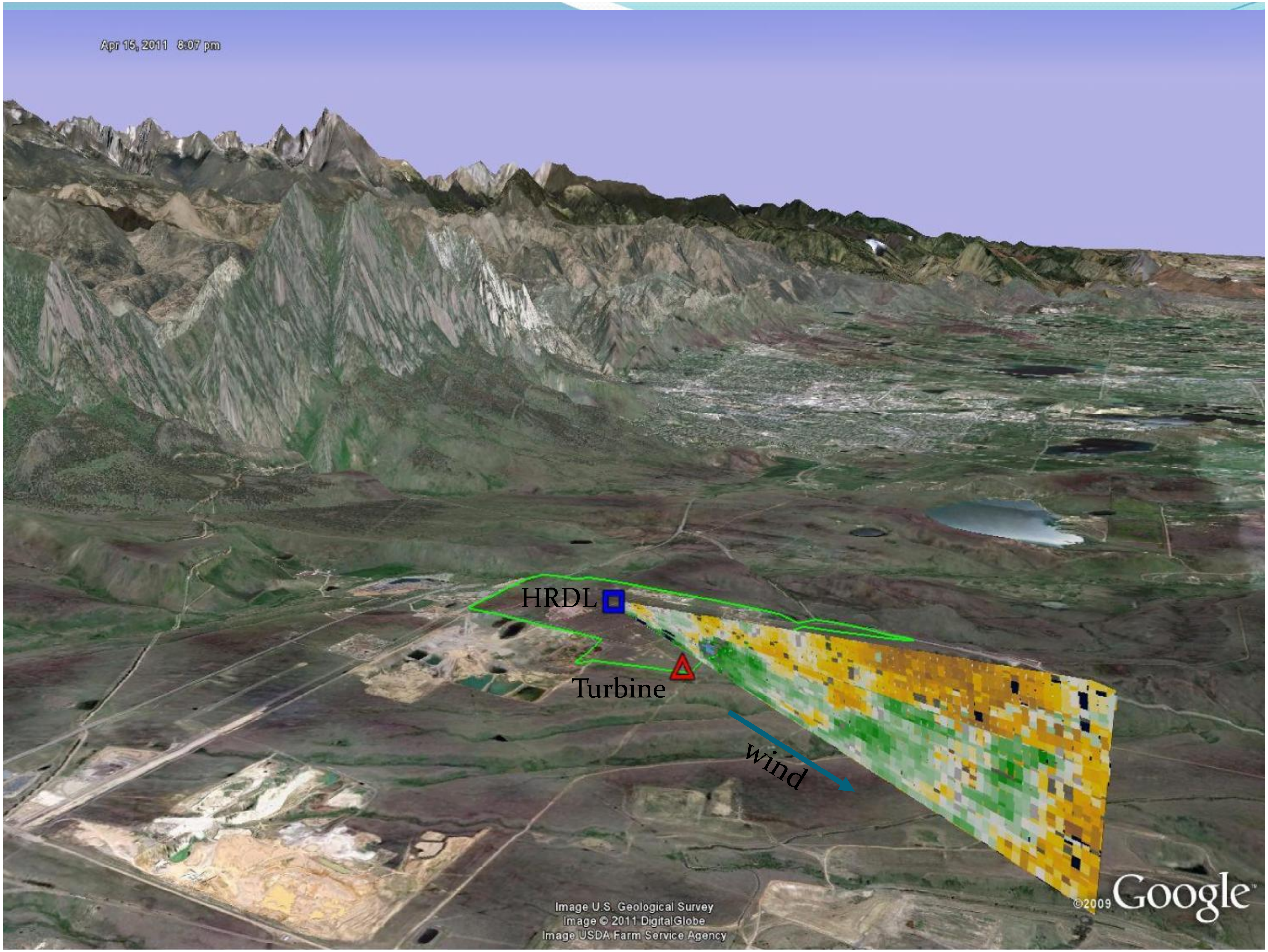
Diurnal cycle
LLJ
Shear
Stability
Waves



Key Challenges

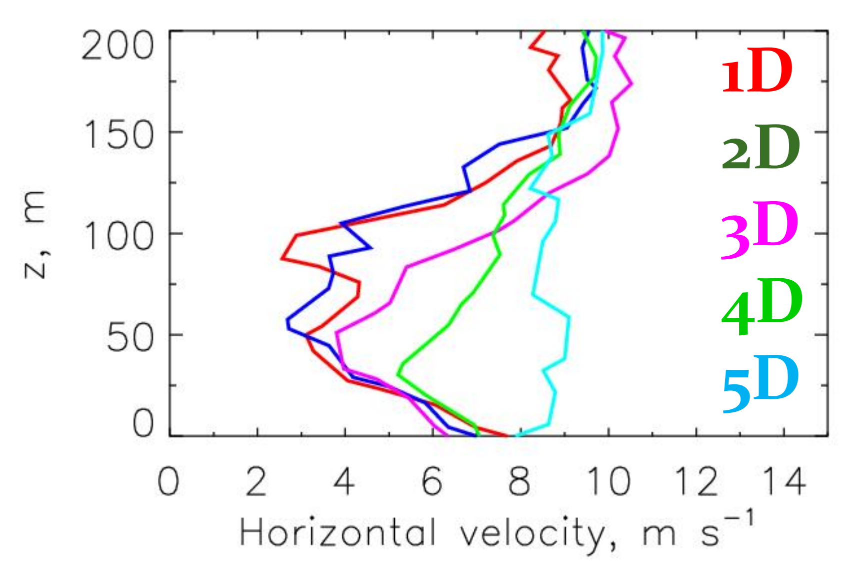
- Improve model climatology of LLJ Uj and Zj (mostly model physics)
- Improve forecast skill of LLJ's (Mostly initial conditions?)
- Understand links between stability and LLJ's
- Improve model forecast skill of stability
- Understand impacts of waves on turbines and turbine power curves

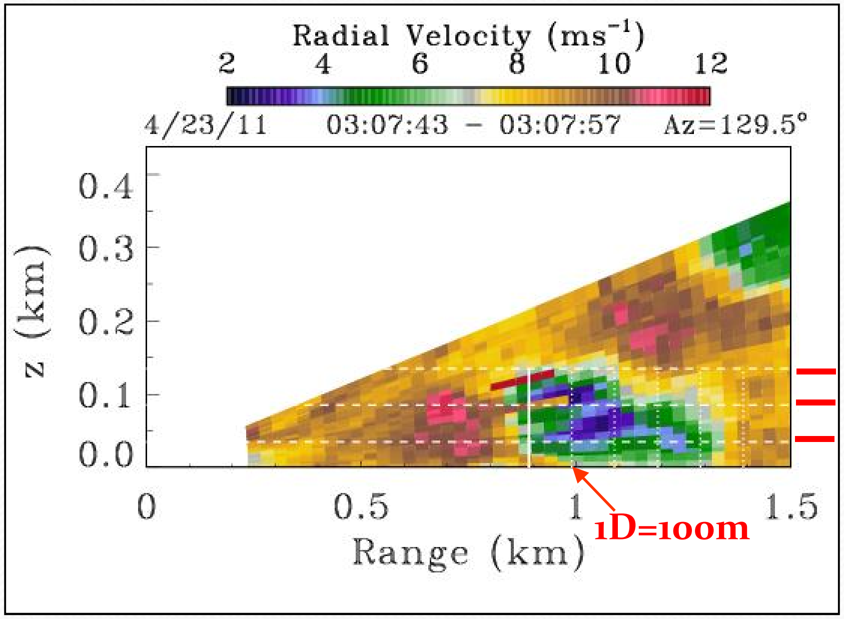
Wake effects

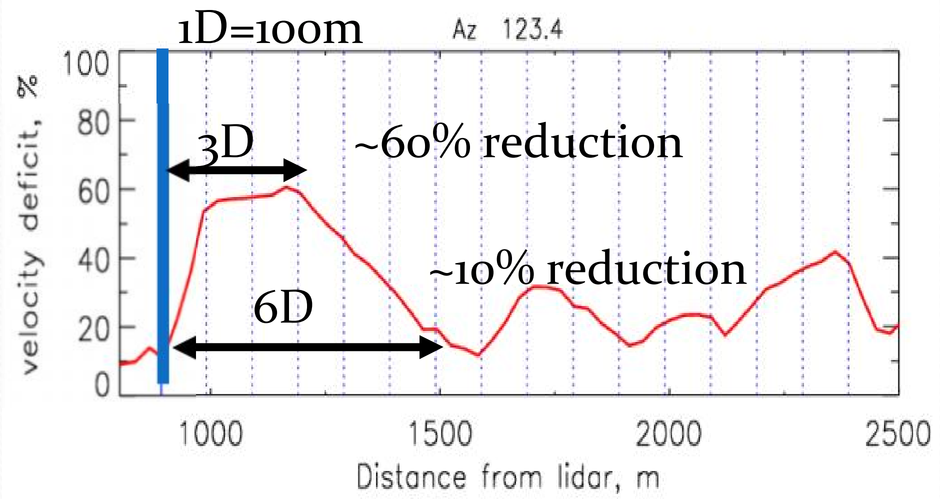


Apr 15, 2011 8:07 pm
HRDL
Turbine
wind
Image U.S. Geological Survey
Image © 2011 DigitalGlobe
Image USDA Farm Service Agency
©2009 Google

Velocity deficit

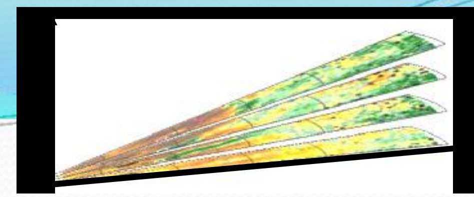


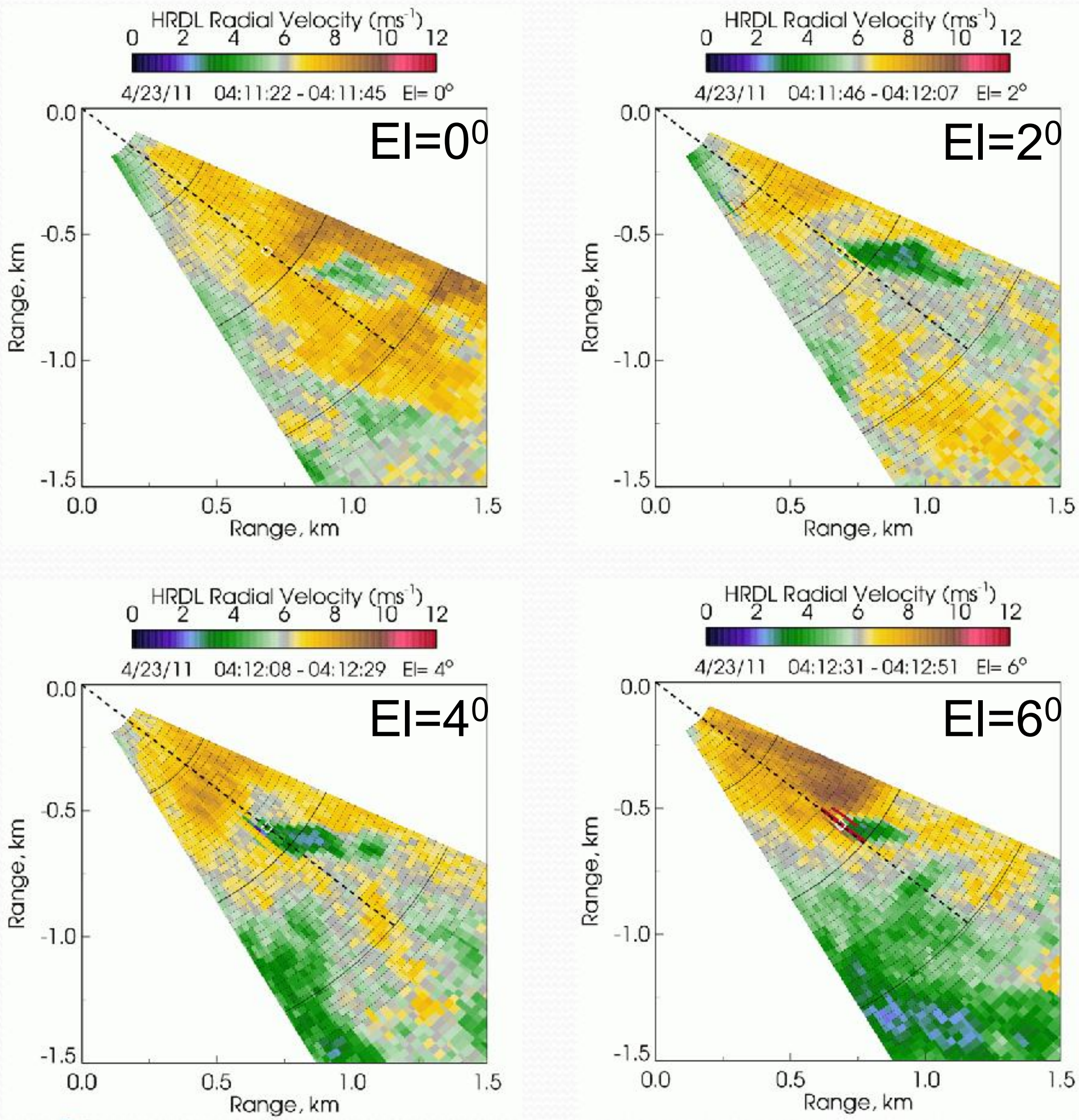


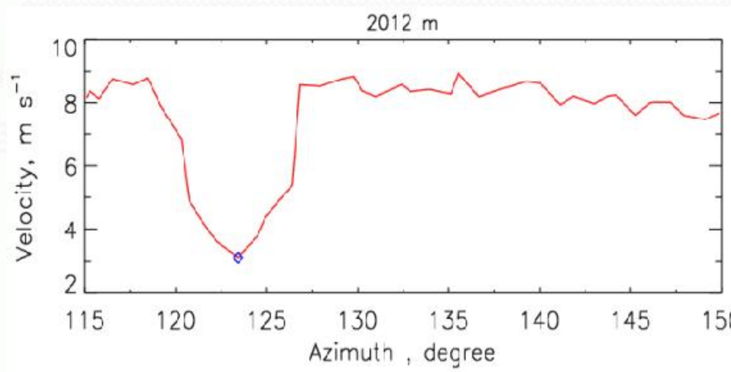


$$VD(R) = \frac{U(R) - UIN}{U_{IN}} * 100\%$$

Horizontal extend, length, and meandering of wakes







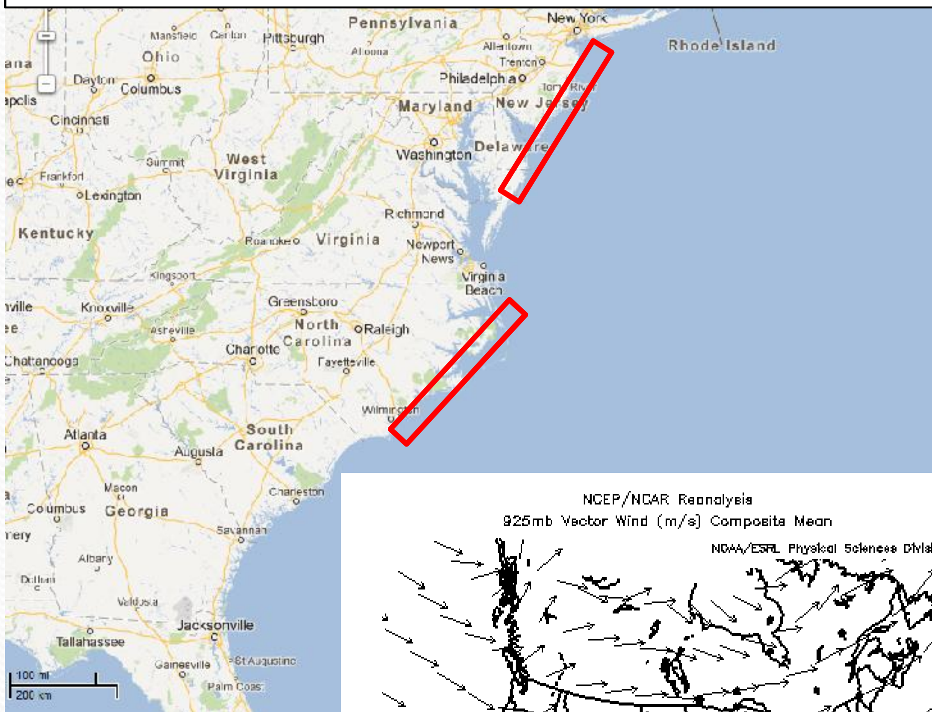
Wake effects

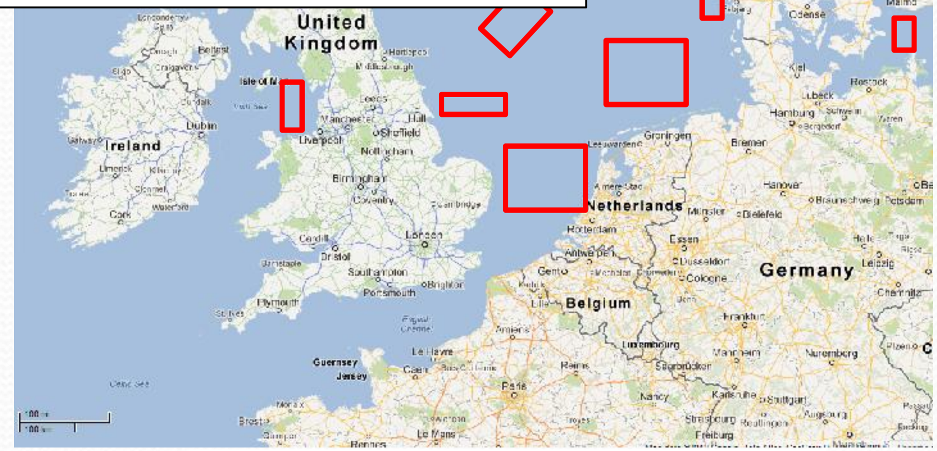
Key Challenges

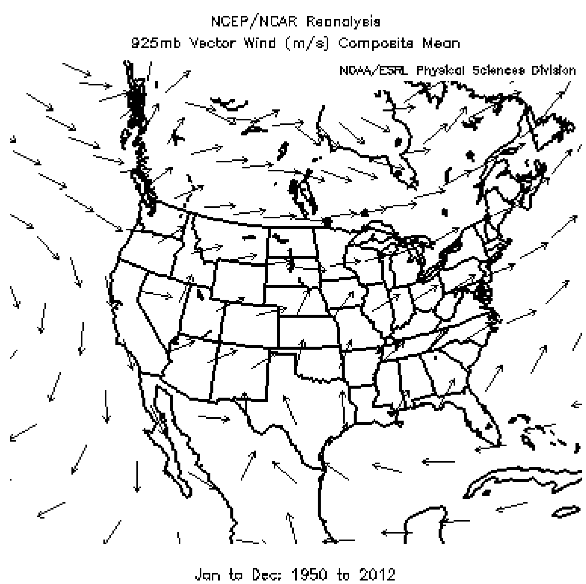
- Understand wakes dependency on atmospheric state: stability, shear, turbulence and PBL depth
- Determine optimal turbine deployment strategy

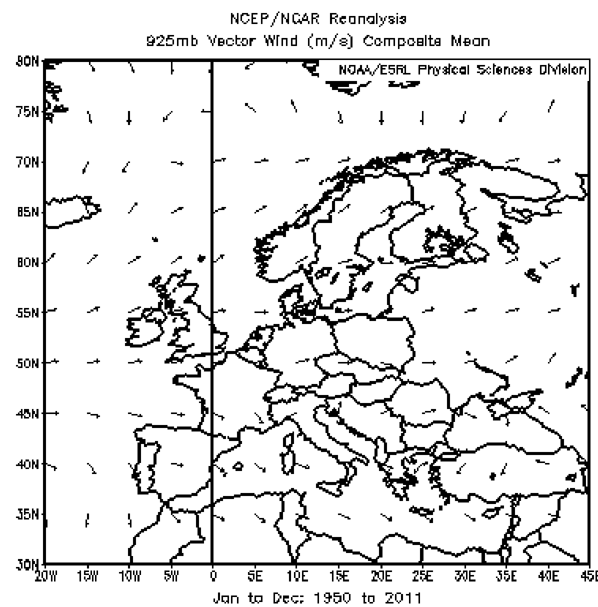
Offshore

- sea-breeze circulations
- summer strongly stable boundary layers with large shear
- winter cold-air outbreaks (icing conditions, extreme turbulence)
- coastal frontogenesis (Nor' easters)









DOE Reference Facility for Offshore Renewable Energy (RFORE)

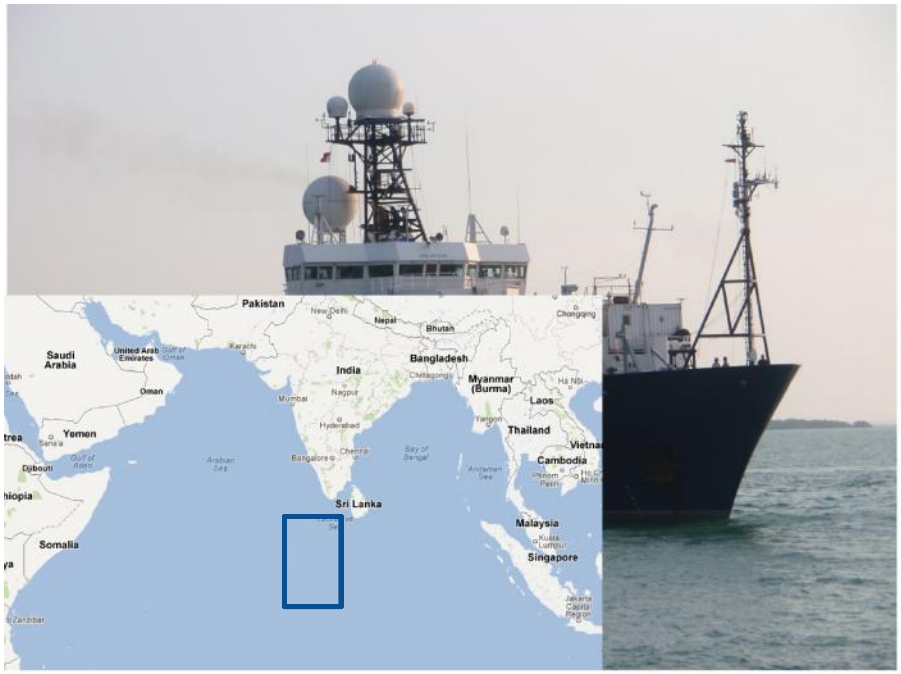
Slide courtesy of Will Shaw/DOE PNNL

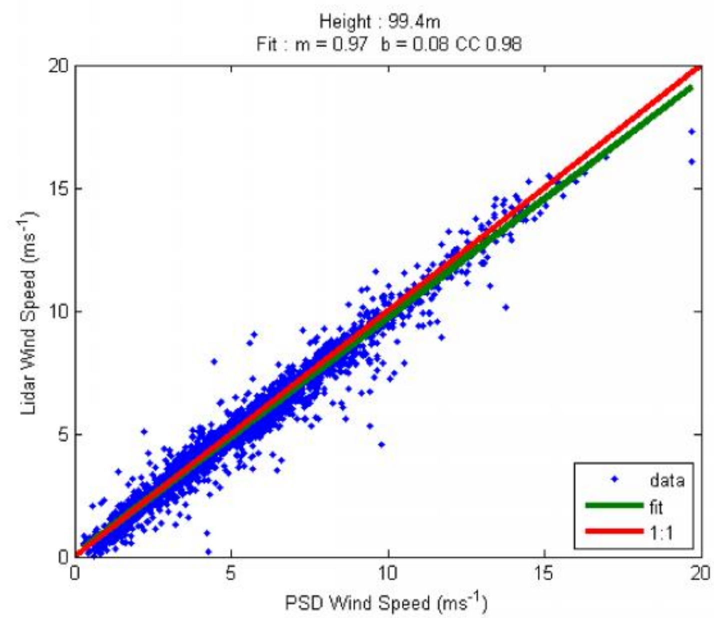
Extrapolation of offshore near surface winds to hub-height using logarithmic wind profile

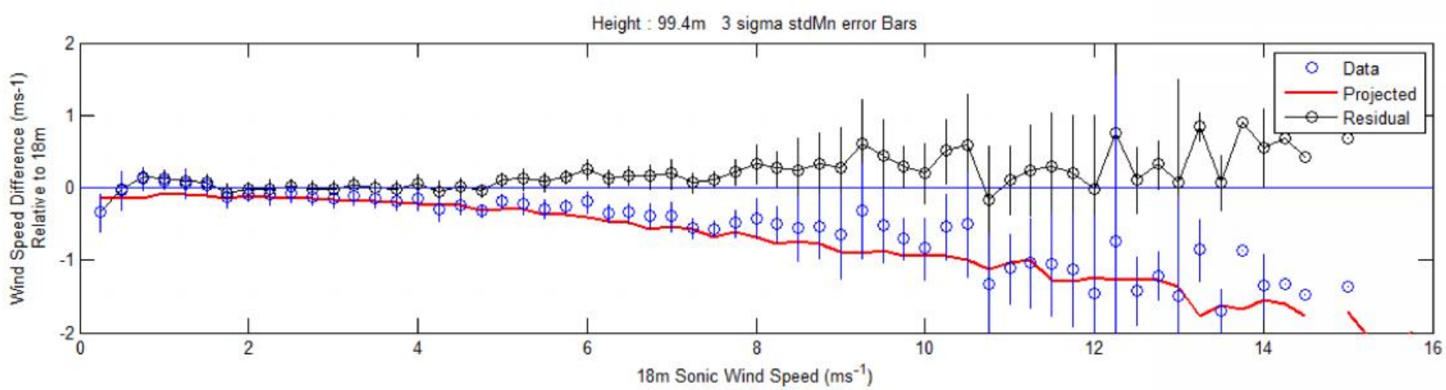
$$U(z) = \frac{u_*}{\kappa}[\log(z/z_o) - \Psi_m(z/L)]$$

u_*=friction velocity, L=Monin-Obukhov length, z_o=roughness: all 3 computed using COARE3.0 bulk flux algorithm.

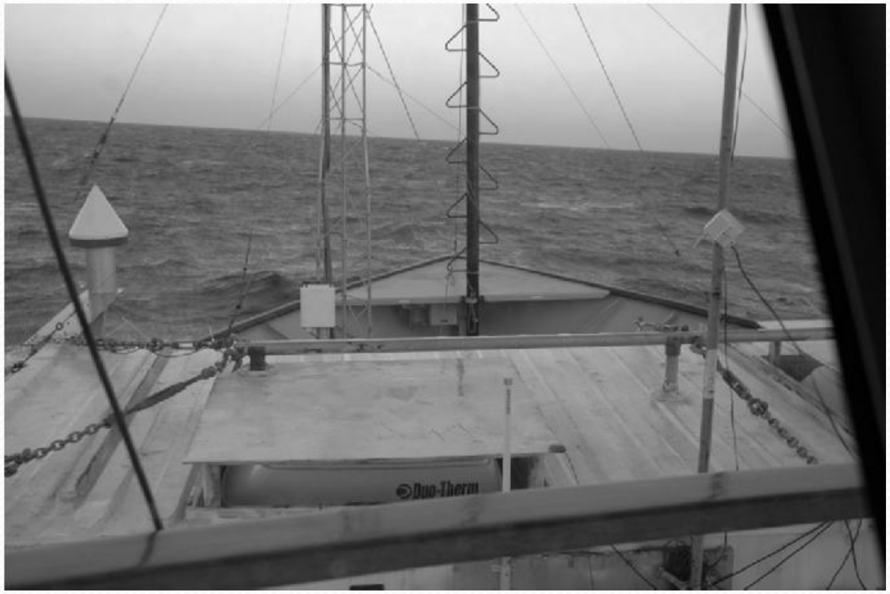
Inputs: U(18m), SST, Tair, pressure, RH, SW and LW radiative fluxes, time of day







Motion compensation



- Measure instantaneous pointing angles
- Calculate mean wind profile by averaging beams pointing at different (but known) angles

- Stabilize the pointing of the beam
- Remove platform motion from LOS velocity measurements

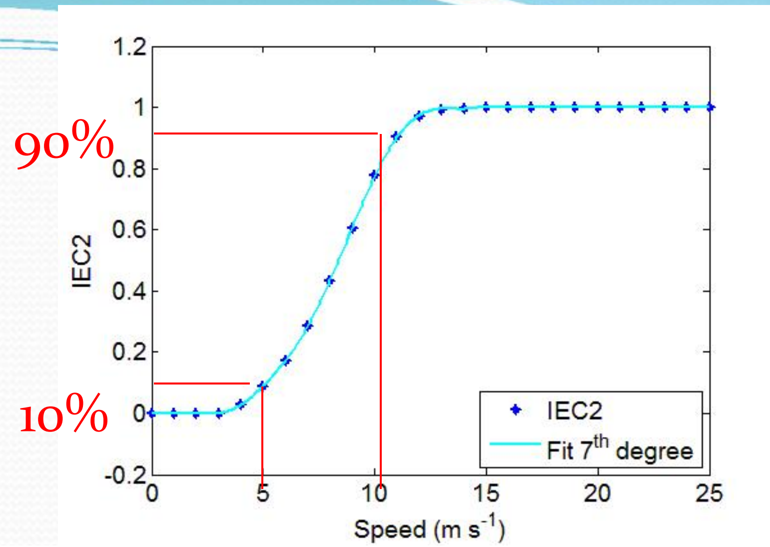
Offshore

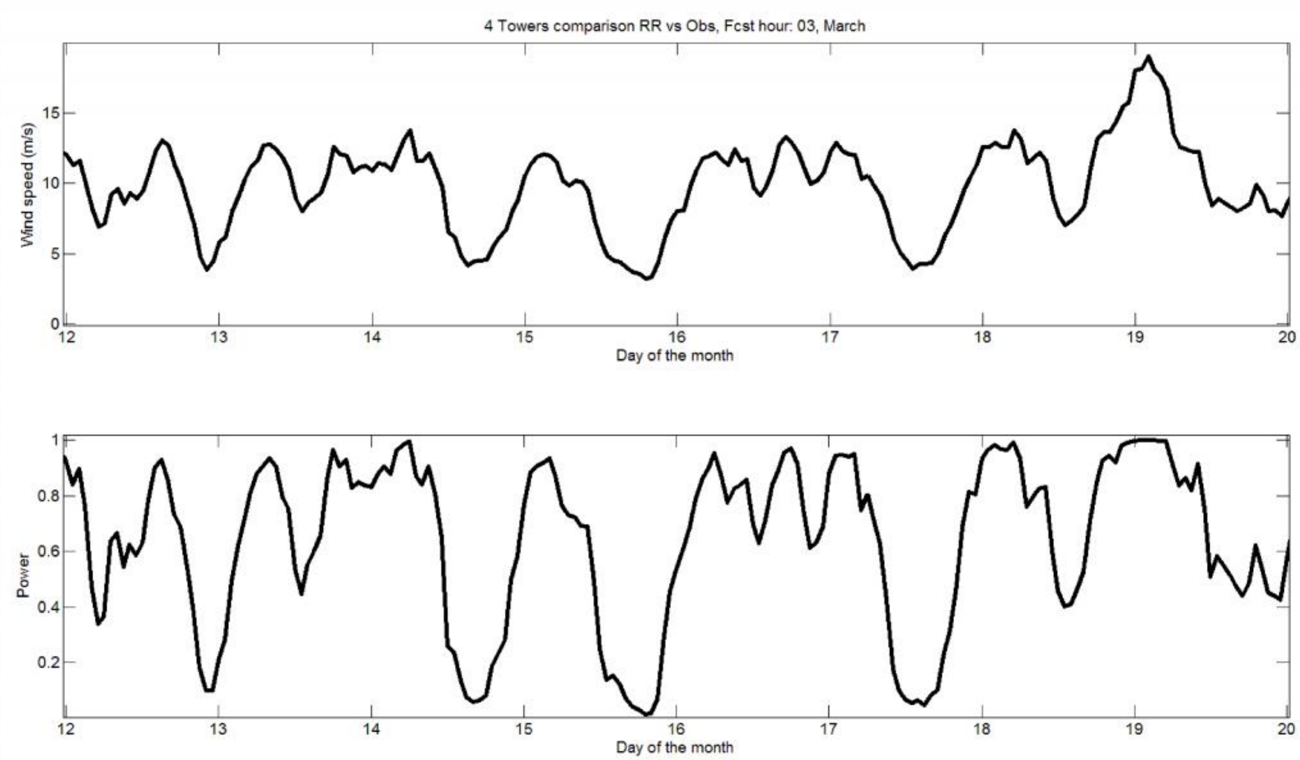
Key challenges

- Deploy hub-height wind measurements in US Atlantic waters
- Coastal boundary effects larger for Atlantic US wind farms than for Europe
- Effects include:
  - sea-breeze circulations
  - summer strongly stable boundary layers with large shear
  - winter cold-air outbreaks (icing conditions, extreme turbulence)
  - coastal frontogenesis (Nor' easters)

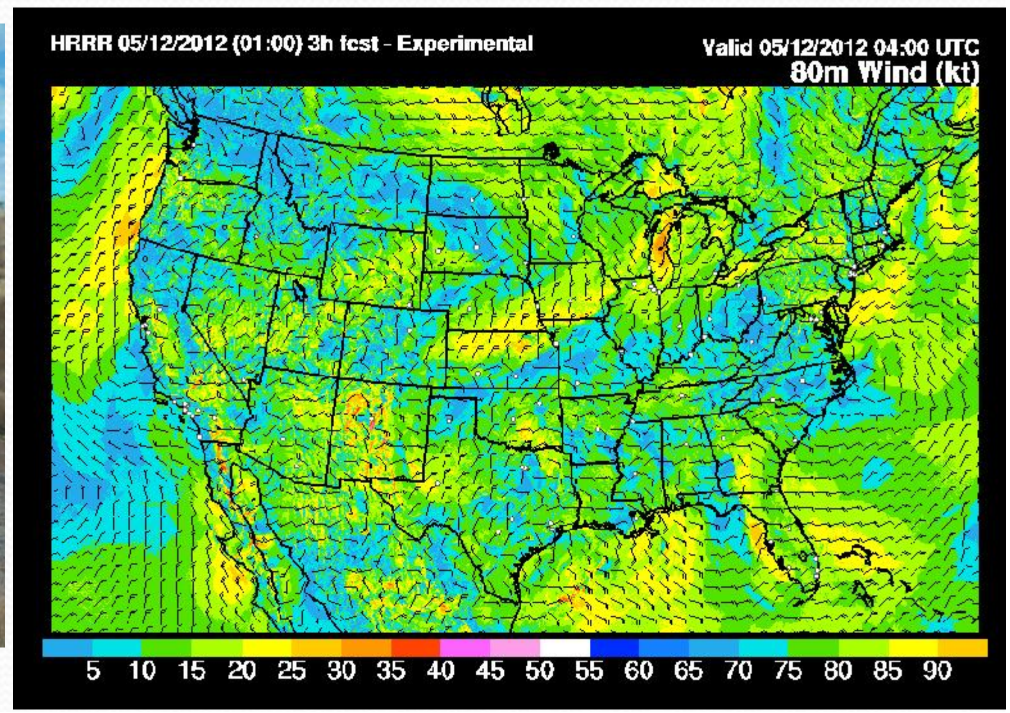
Forecasting

Wind Ramps

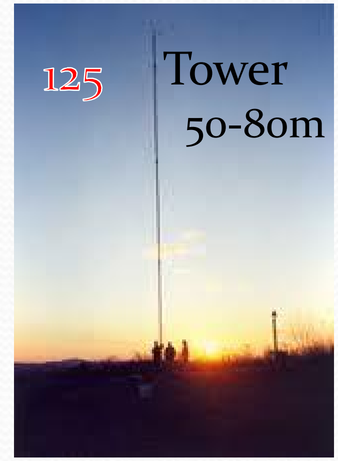

90%
10%
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
IEC2
0
5
10
15
20
25
Speed (m s^{-1})
IEC2
Fit 7th degree

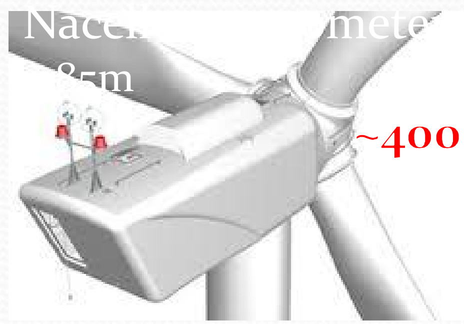

4 Towers comparison RR vs Obs, Fcst hour: 03, March
Wind speed (m/s)
Day of the month
Power
Day of the month

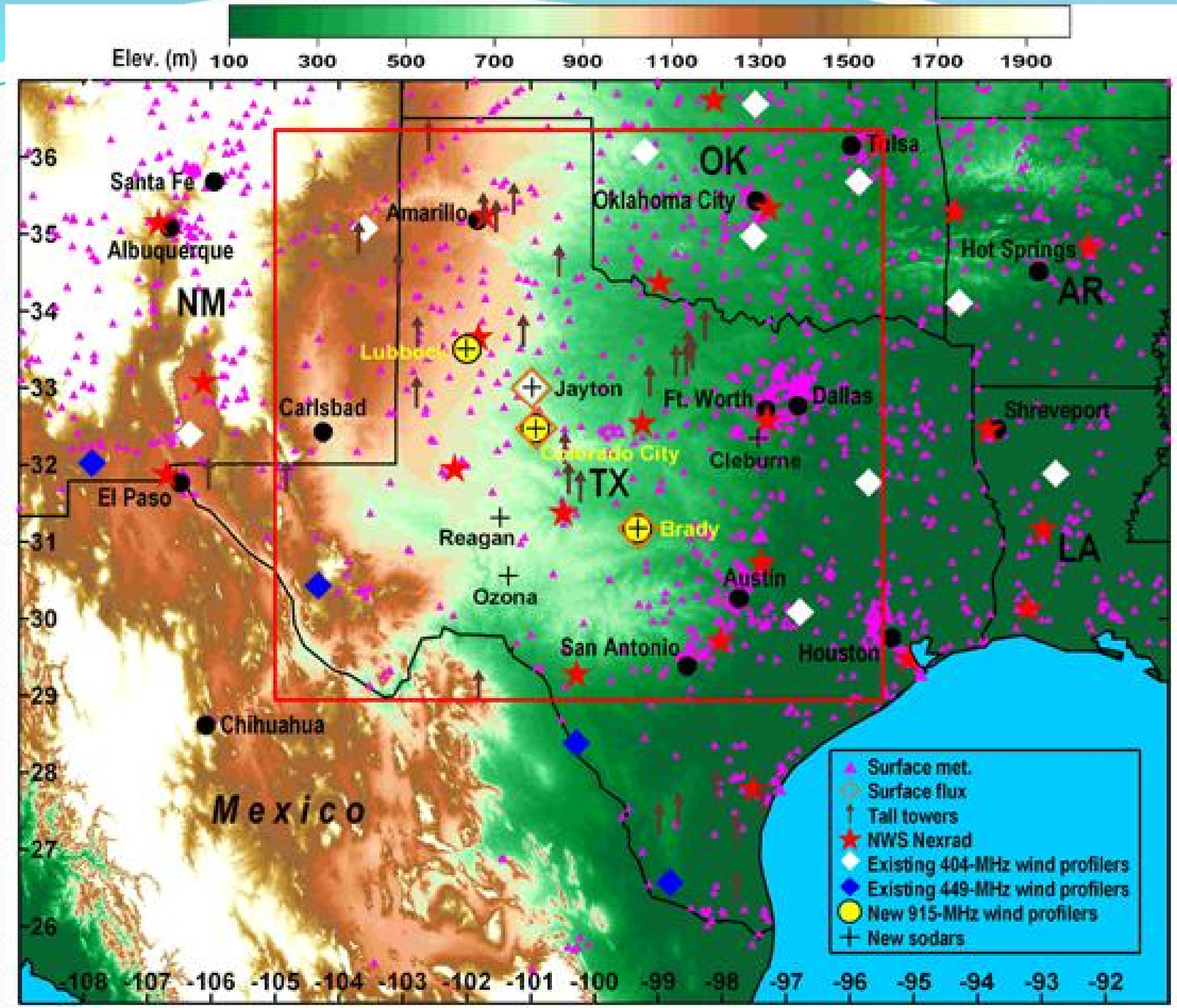
The Wind Forecast Improvement Project (WFIP)



New Instrumentation

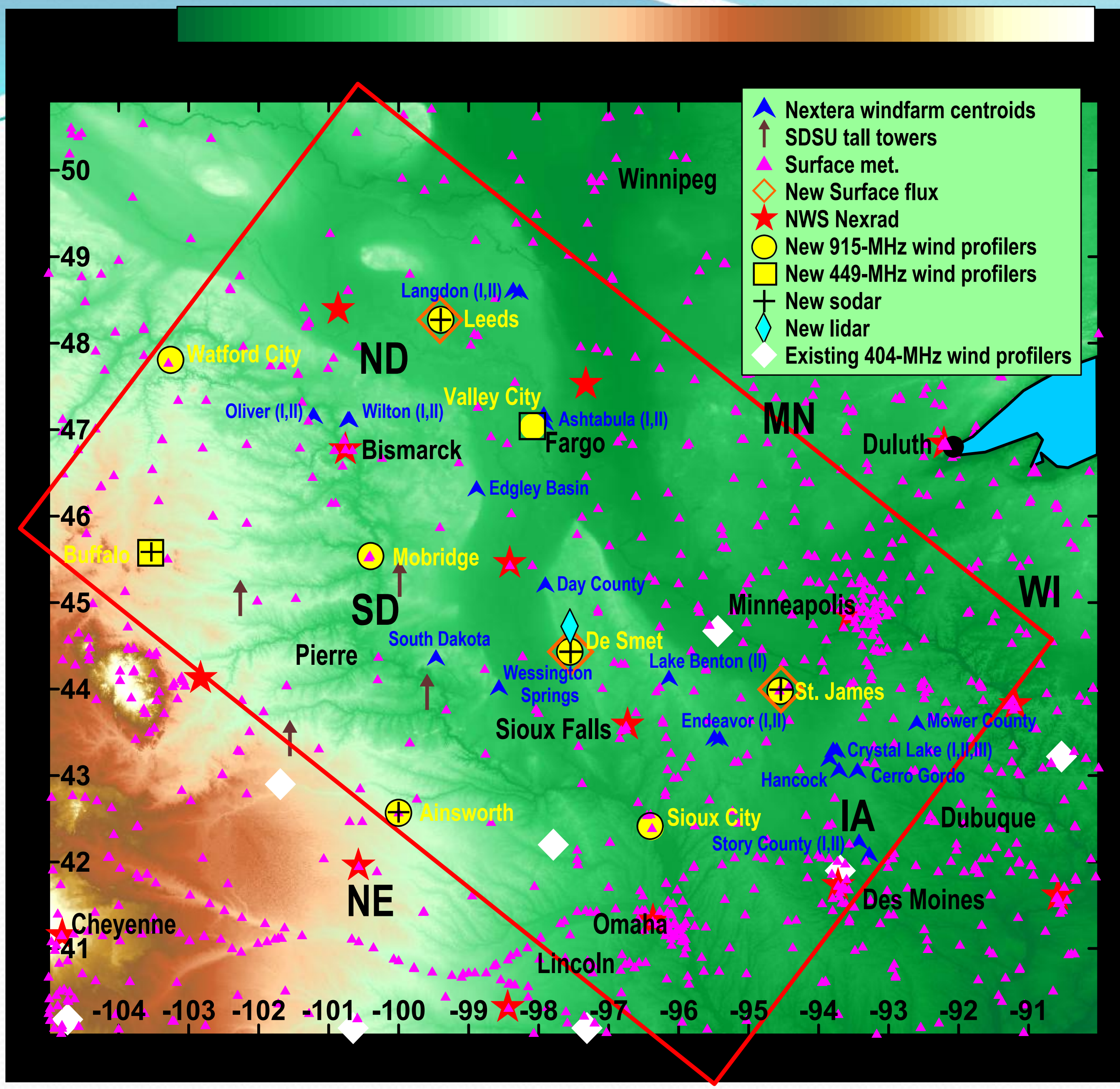






3 profilers
7 sodars

Southern Study Area



Northern Study Area

9 profilers
5 sodars
1 lidar

Hourly Updated NOAA NWP Models

RUC – older oper model - 13km

Rapid Refresh (RR)

– new WRF-based oper model in May 2012

- 13 km

HRRR - Hi-Res Rapid Refresh

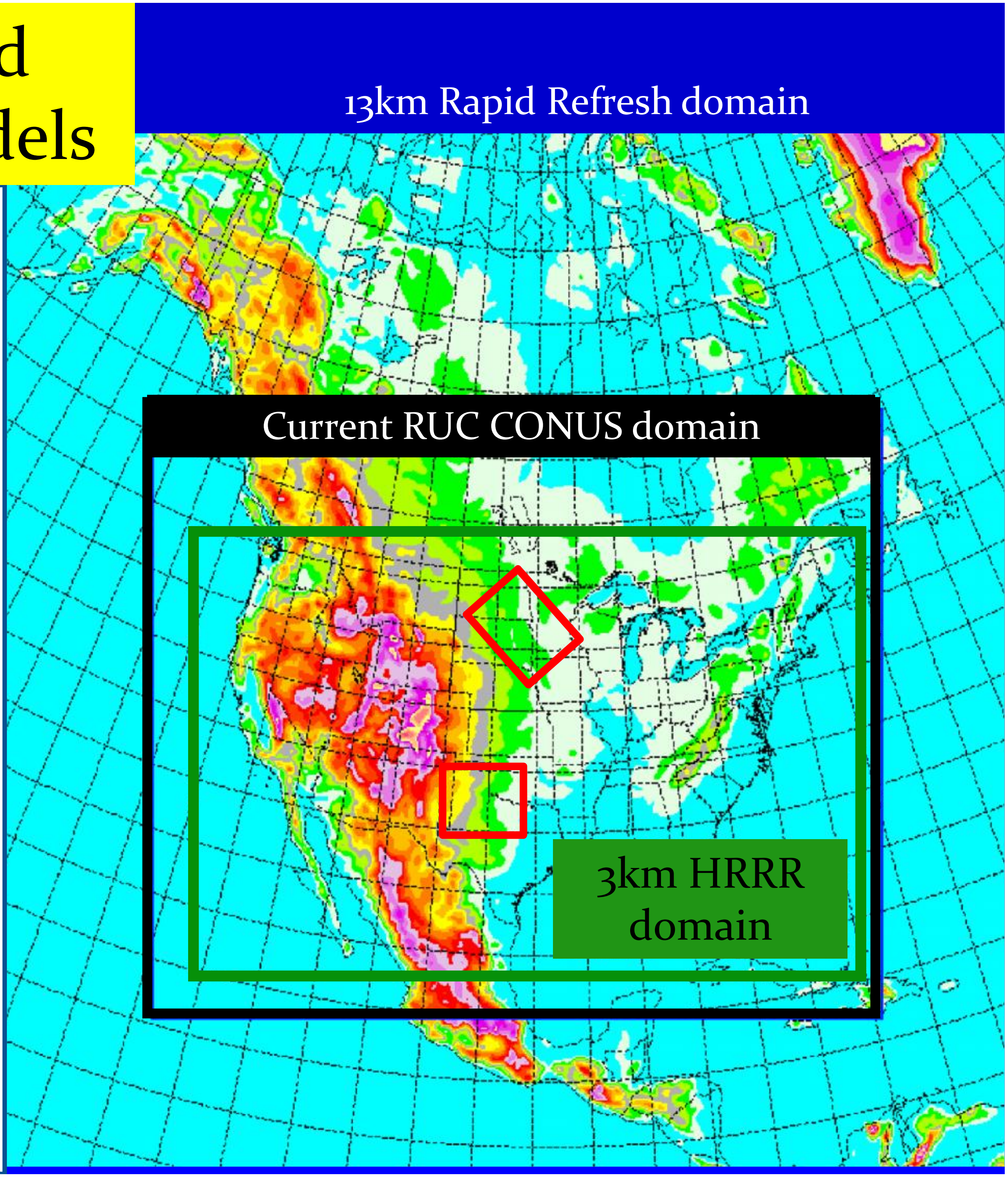
-Experimental 3km

-15h fcst updated every hour

- Initialized from RUC/RR

All models re-initialized and run every hour, run to at least 15 hs,

3D var data assimilation



Model comparisons

OPERATIONAL (NWS)	RESEARCH (ESRL)
	HRRR (w/ assimilation of WFIP obs)
Rapid Refresh (RR)	RR (w/ assimilation of WFIP obs)
Rapid Update Cycle (RUC)	RUC (w/ assimilation of WFIP obs)

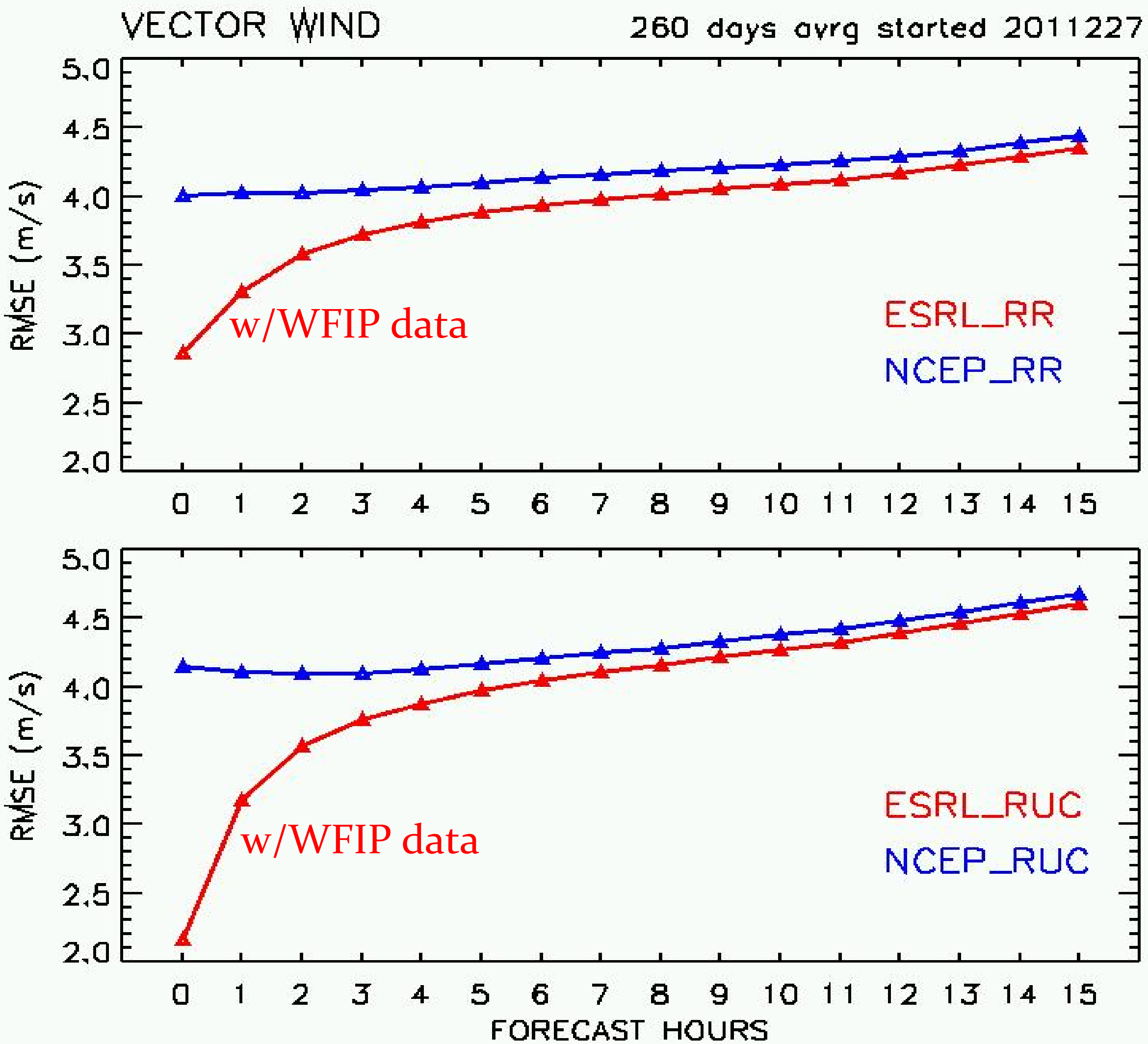
- Same grids, same dynamical core, same physical parameterizations
- Different computers, minor differences in implementation

- Exercise of opportunity – models are similar but not identical. Not ideal!
- Data Denial Experiment for 30-40 days at end of field program

New data assimilation:

- *Radar wind profilers: 27 August 2011*
- *RASS and sodars: 23 December 2011*
- *Towers and nacelles: 14 March 2012*

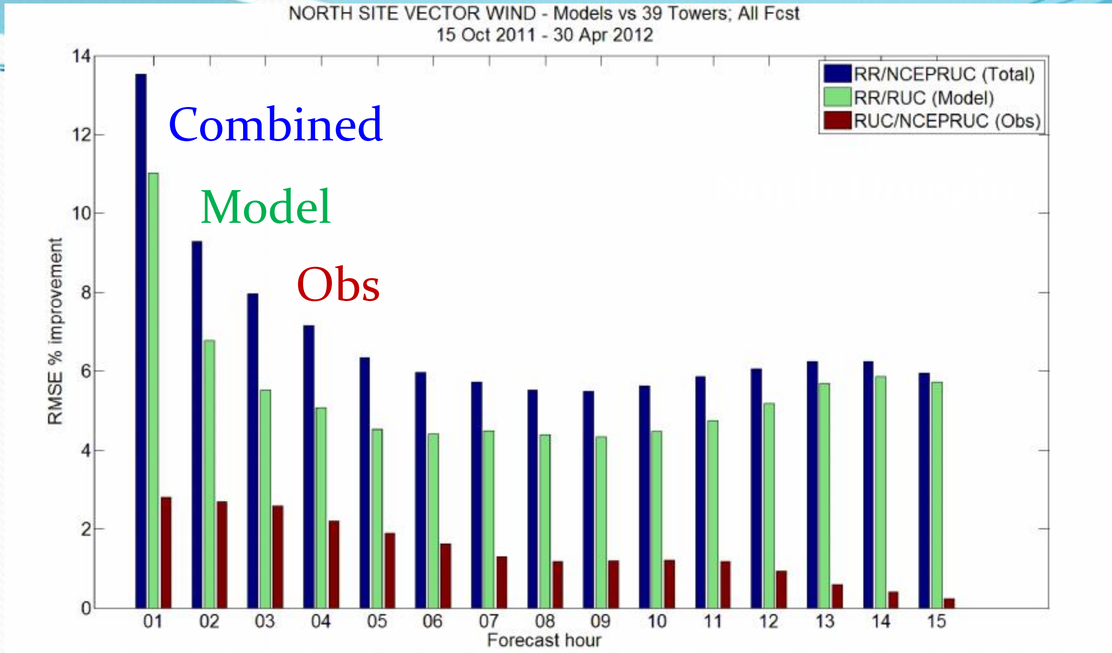
Impact of data on models: Vertically averaged radar wind profiler vector wind RMSE, w/wo WFIP data, RR and RUC models

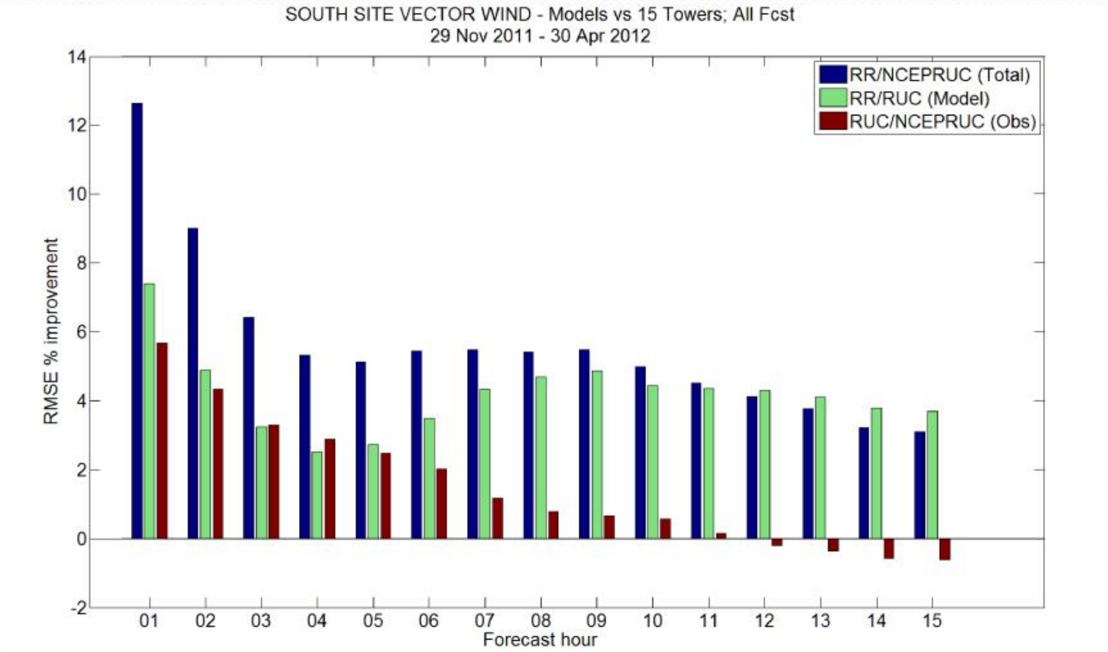


N Study Area, 9 profiler average, 500 2000m

Model evaluation using tall tower observations

RMSE
% Improvement
Vector wind

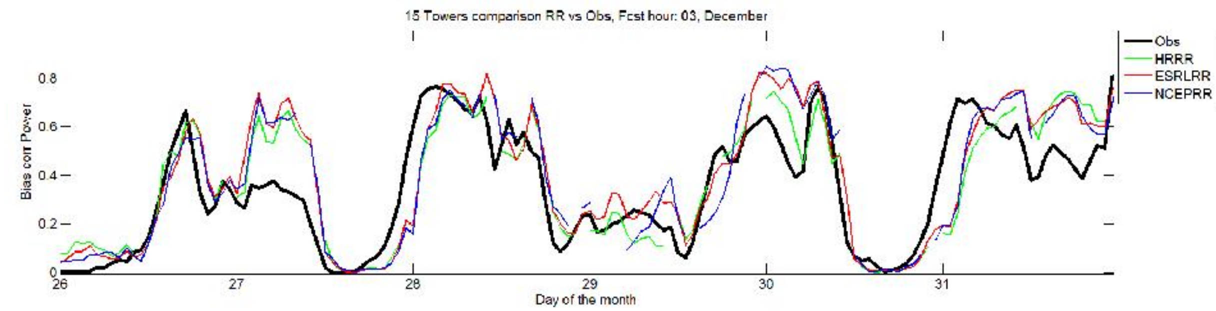




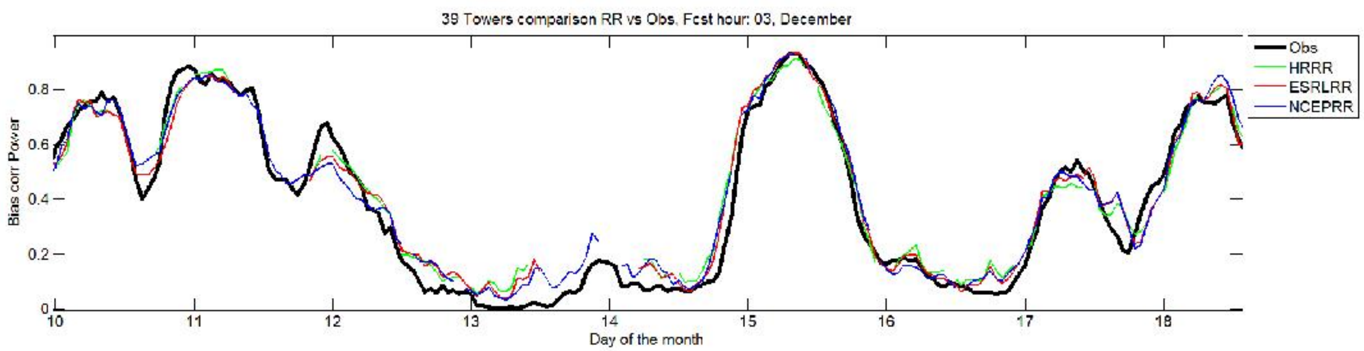
Preliminary Economic Results—Southern Region

- Analyses performed for "shoulder" month – October 2011 when load is low and wind speeds are higher
- Operational Cost Savings are dependent on natural gas prices – average actual price of 3.44 $/MMBtu used for October in Texas
- Preliminary results show both environmental and cost benefits as a result of improved forecasts

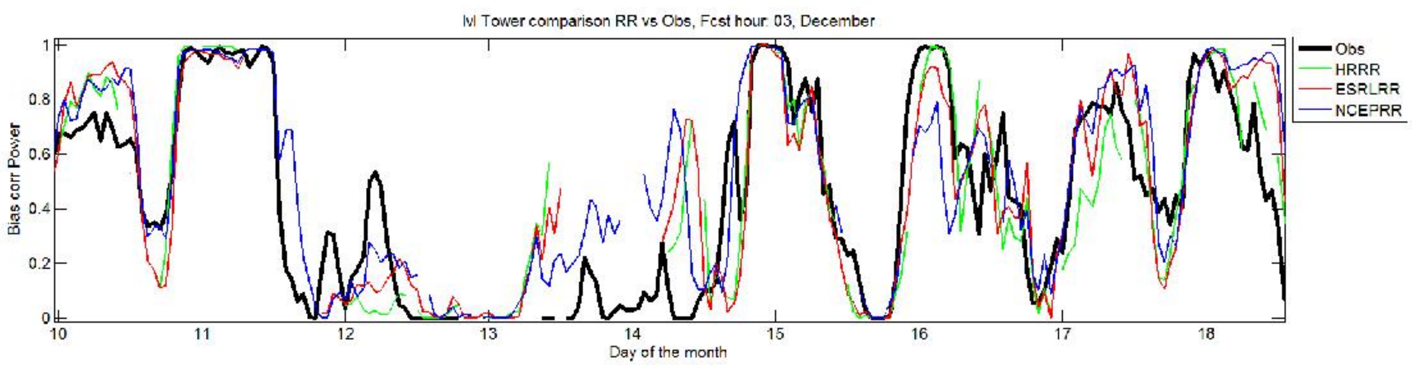
Parameter	Benefit (Savings)
Production Cost ($)	(1,086,000)
Cost to Serve Load ($)	(5,752,123)
Conventional Units - Number of Starts	(49)
Emissions (NOx Tons)	(4)
Reduction in Wind Generation Curtailment (GWh)	(22)
~ Energy Imbalance Costs paid by Wind Generators ($)	(1,500,000)



15 Towers comparison RR vs Obs, Fcst hour: 03, December
Bias corr Power
Day of the month
Obs
HRRR
ESRLRR
NCEPRR

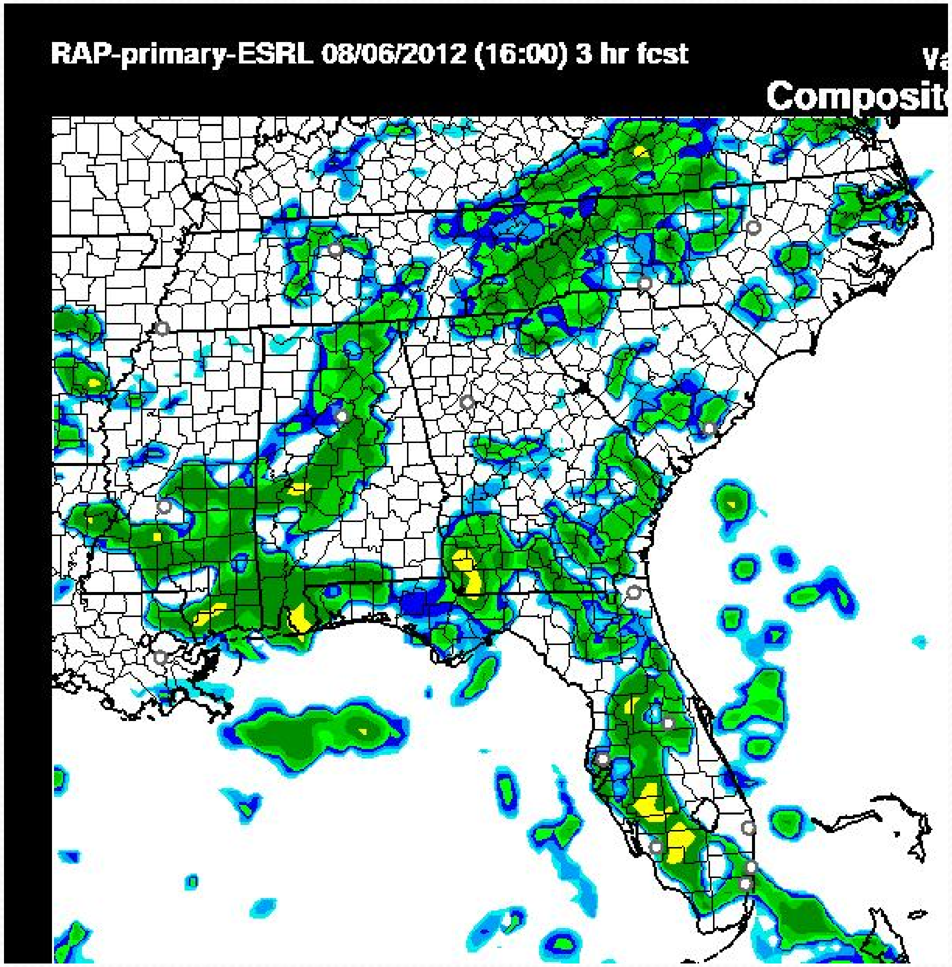


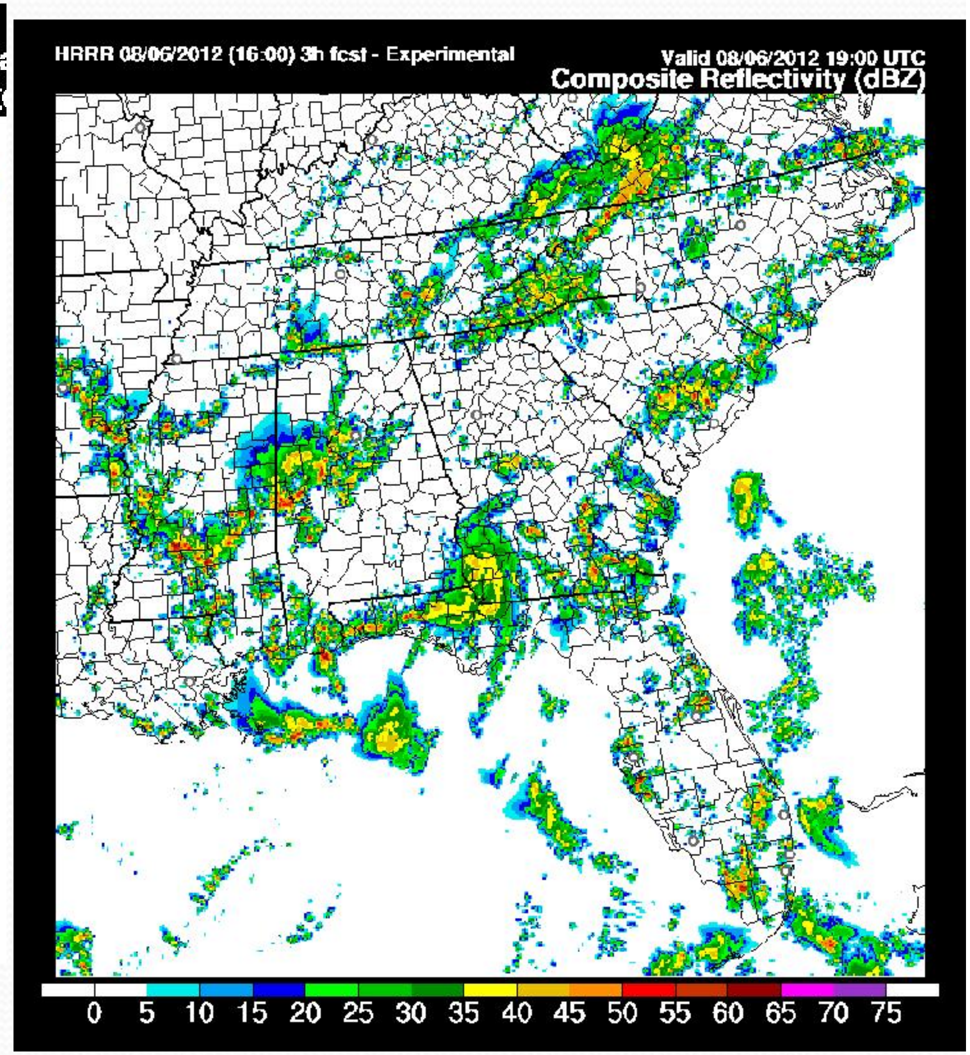
39 Towers comparison RR vs Obs, Fcst hour: 03, December
Bias corr Power
Day of the month
Obs
HRRR
ESRLRR
NCEPRR



lvl Tower comparison RR vs Obs, Fcst hour: 03, December
Bias corr Power
Day of the month
Obs
HRRR
ESRLRR
NCEPRR

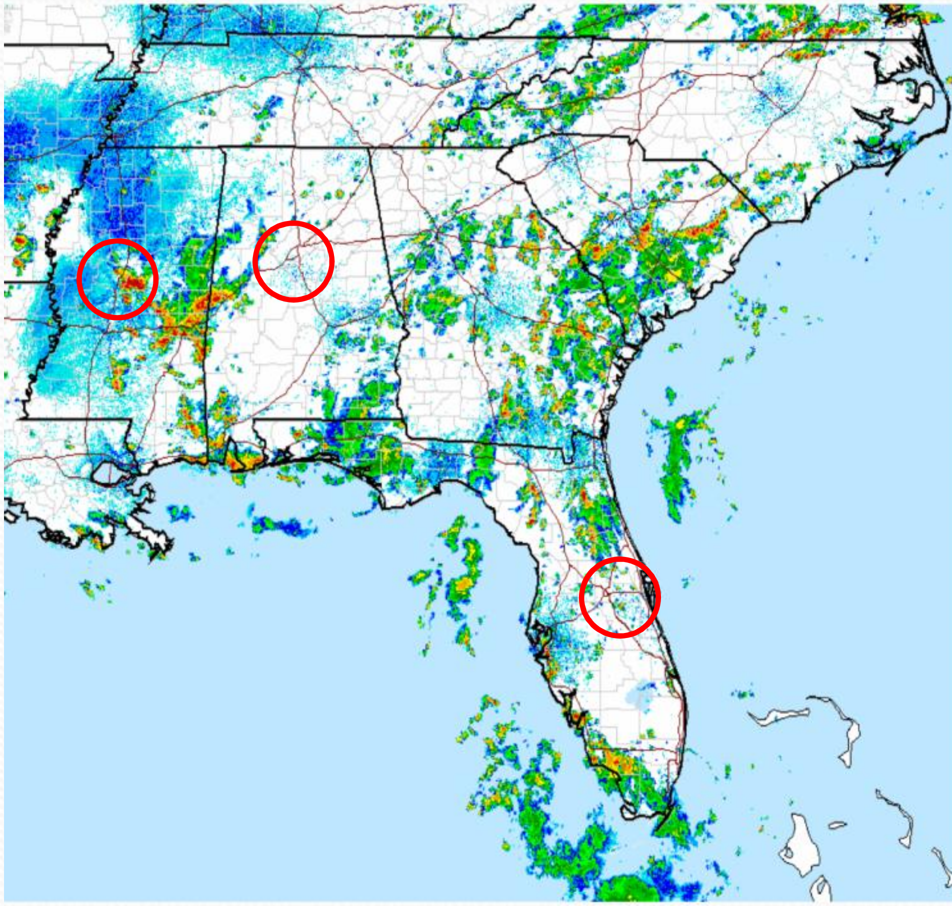
3 hour cloud reflectivity forecasts, valid 19 UTC 06 August 2012

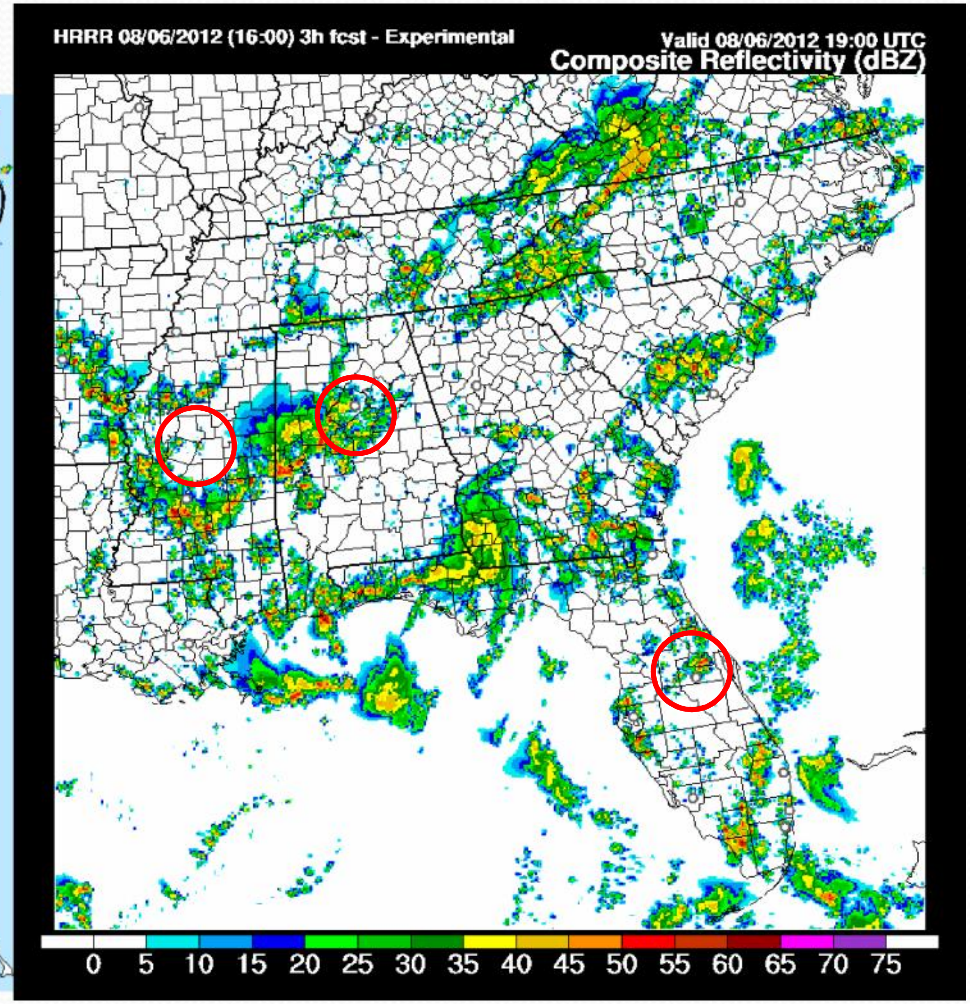




NWS operational RAP model
13km resolution, parameterized convection

ESRL experimental HRRR model
3km resolution, explicit convection





Observed radar reflectivity
19 UTC 6 Aug 2012

HRRR radar reflectivity, 3hr forecast
19 UTC 6 Aug 2012

Forecasting

Key Challenges

- Relatively minor changes in wind speed result in large changes in power (ramps)
- Insufficient obs to capture relevant atmospheric scales
- Assimilation of current obs needs to be improved
- Operational models need to be run at storm resolving scales
- Thunderstorm initiation is a major problem

Summary

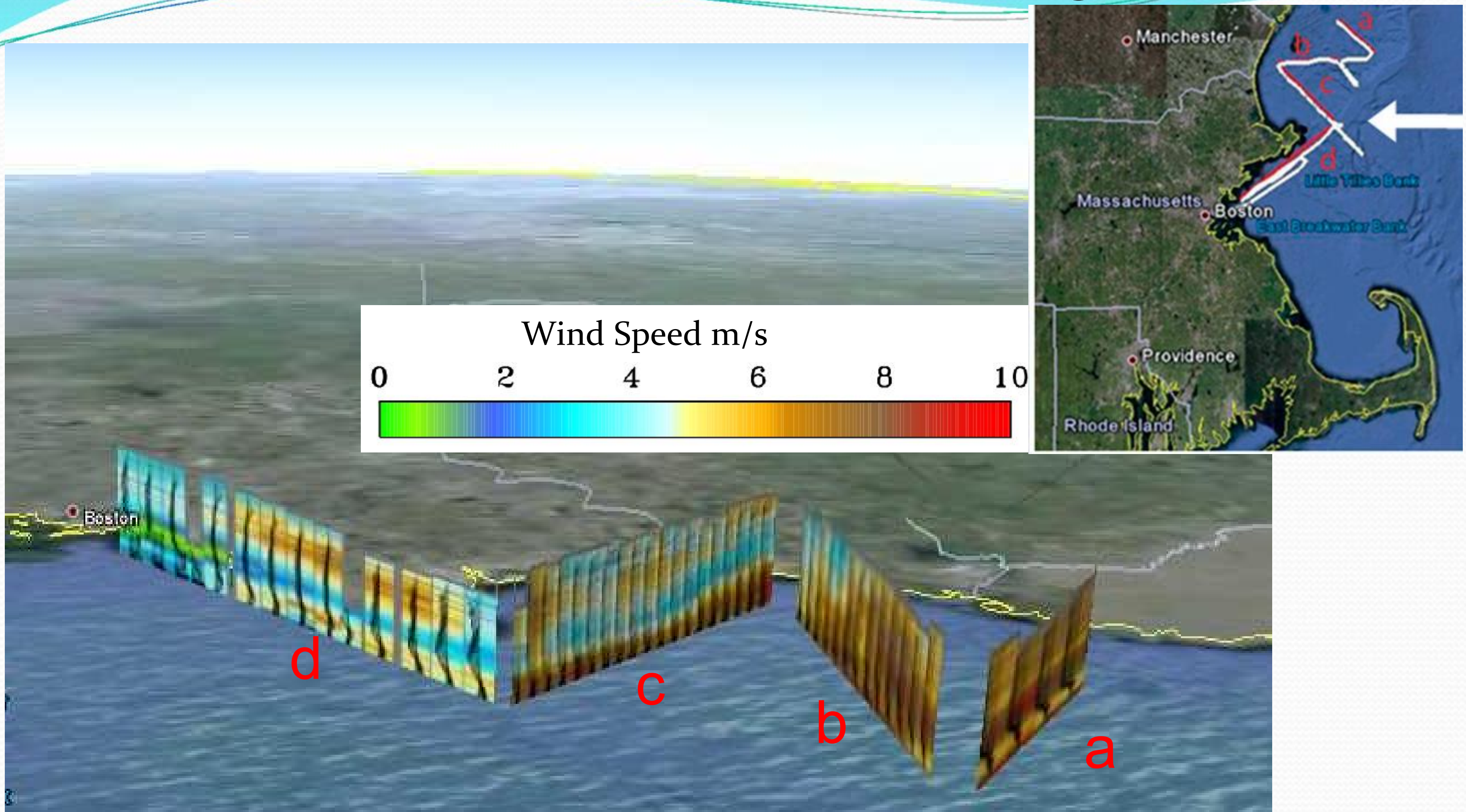
Part I:

- Economics
- Instrumentation
- PBL processes
  - diurnal cycle, LLJ, shear, stability, waves
- Wake effects
- Offshore
- Forecasting/data assimilation
  - Ramp events
  - Thunderstorms

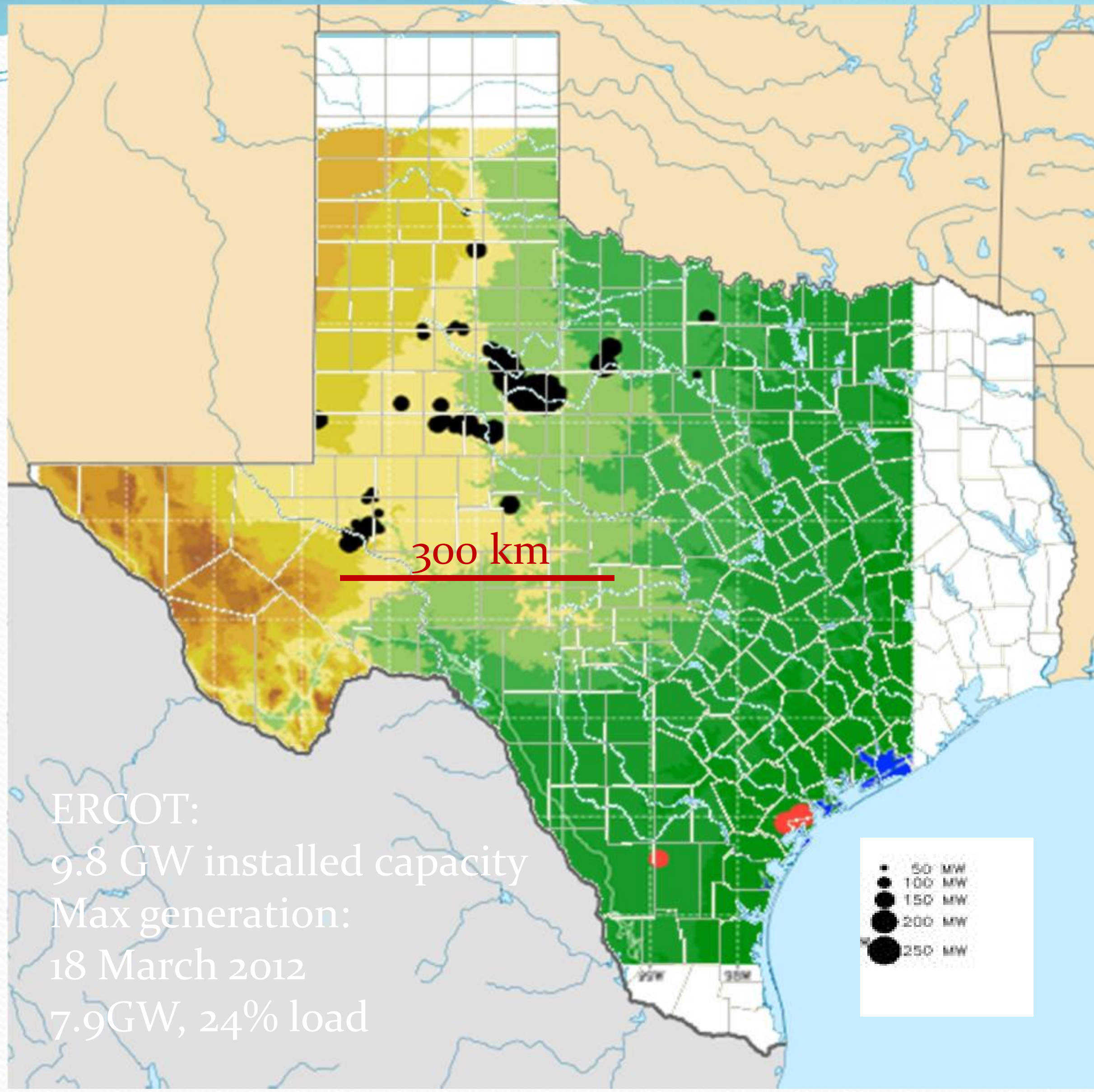
Contributions from

Laura Bianco
Irina Djalalova
Katja Freidrich
Julie Lundquist
Bob Banta
Yelena Pichugina
Stan Benjamin

Spatial and temporal variability of winds



Pichugina Y. L., R. M. Banta, W. A. Brewer, S. P. Sandberg, and R. M. Hardesty, 2012: Doppler-lidar-based wind-profile measurement system for offshore wind-energy and other marine-boundary-layer applications, JAMC, **51**, pp. 327-349



300 km
ERCOT:
9.8 GW installed capacity
Max generation:
18 March 2012
7.9GW, 24% load
50 MW
100 MW
150 MW
200 MW
250 MW