Low Level Jet properties from lidar measurements in the Gulf of Maine

Yelena Pichugina[1, 2], Robert Banta[2] , Alan Brewer[2], Aditya Choukulkar[1, 2], Melinda Marquis[2], Mike Hardesty[1, 2], Ann Weickmann[1, 2], and Scott Sandberg[2]

[1]*Cooperative Institute for Research in Environmental Sciences, Boulder, CO*
[2]*National Oceanic and Atmospheric Administration, Boulder, CO*

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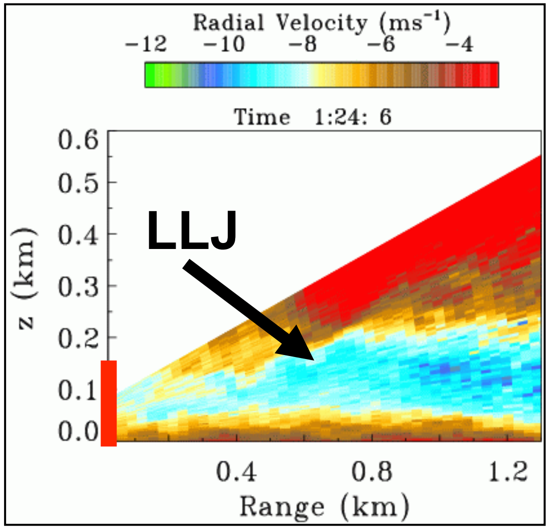
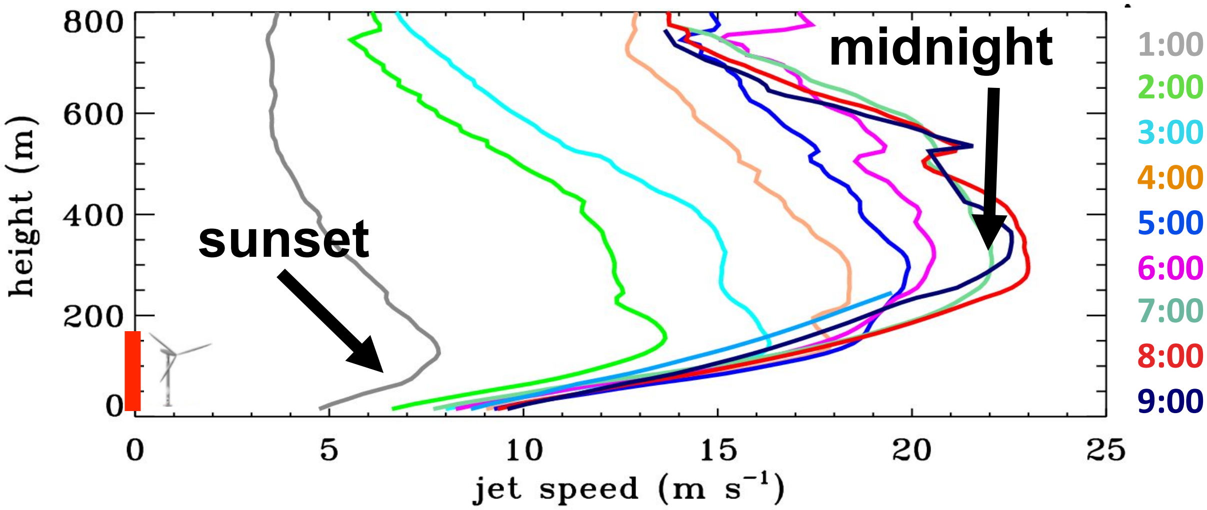
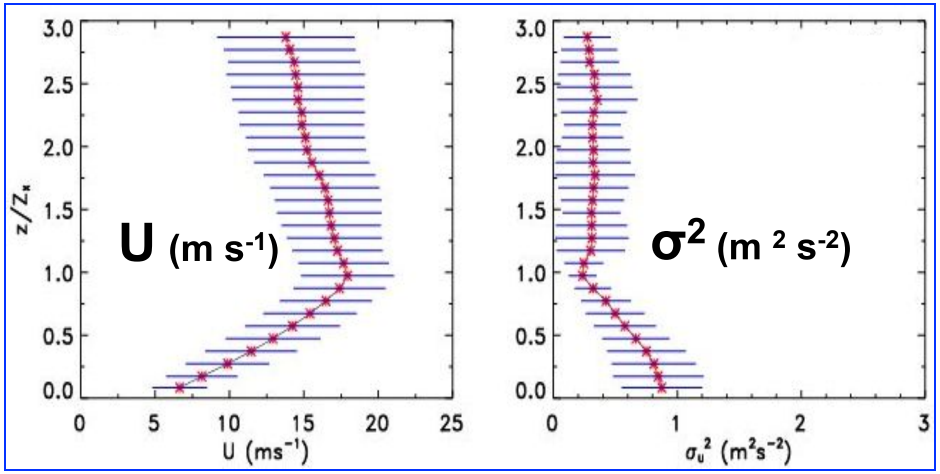
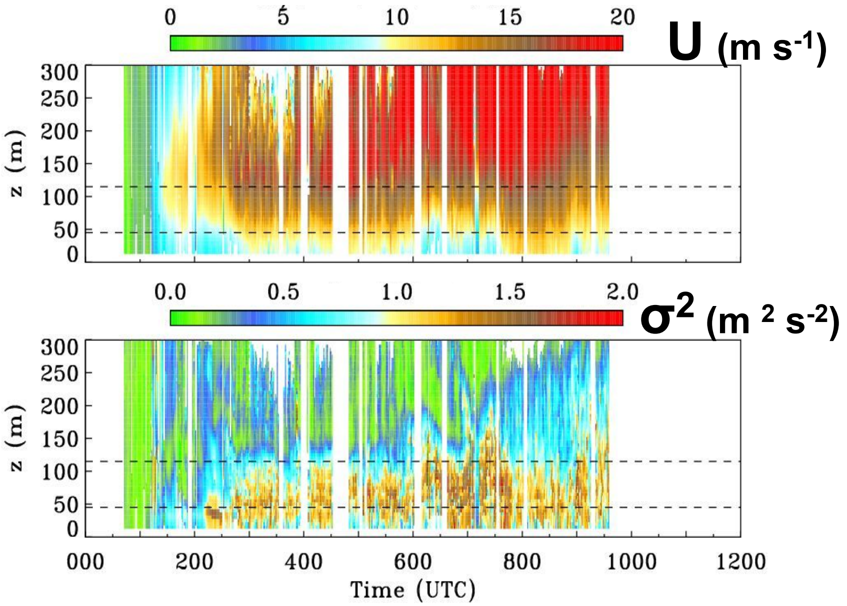
LLJ features from lidar measurements





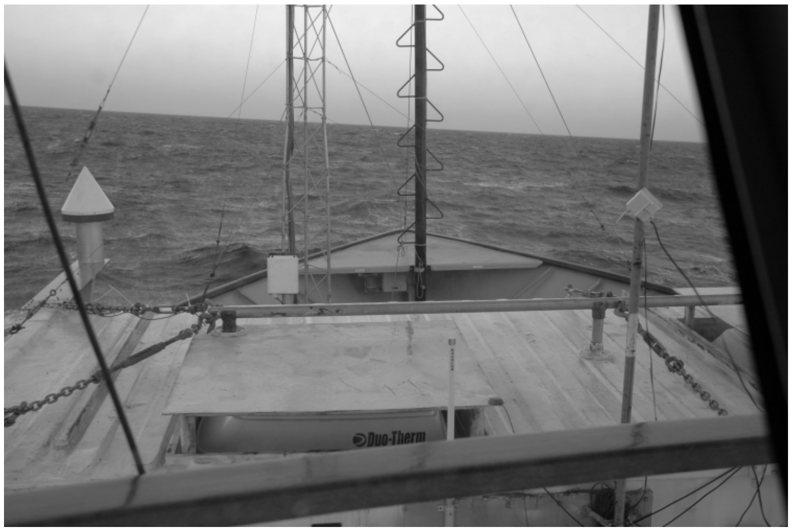


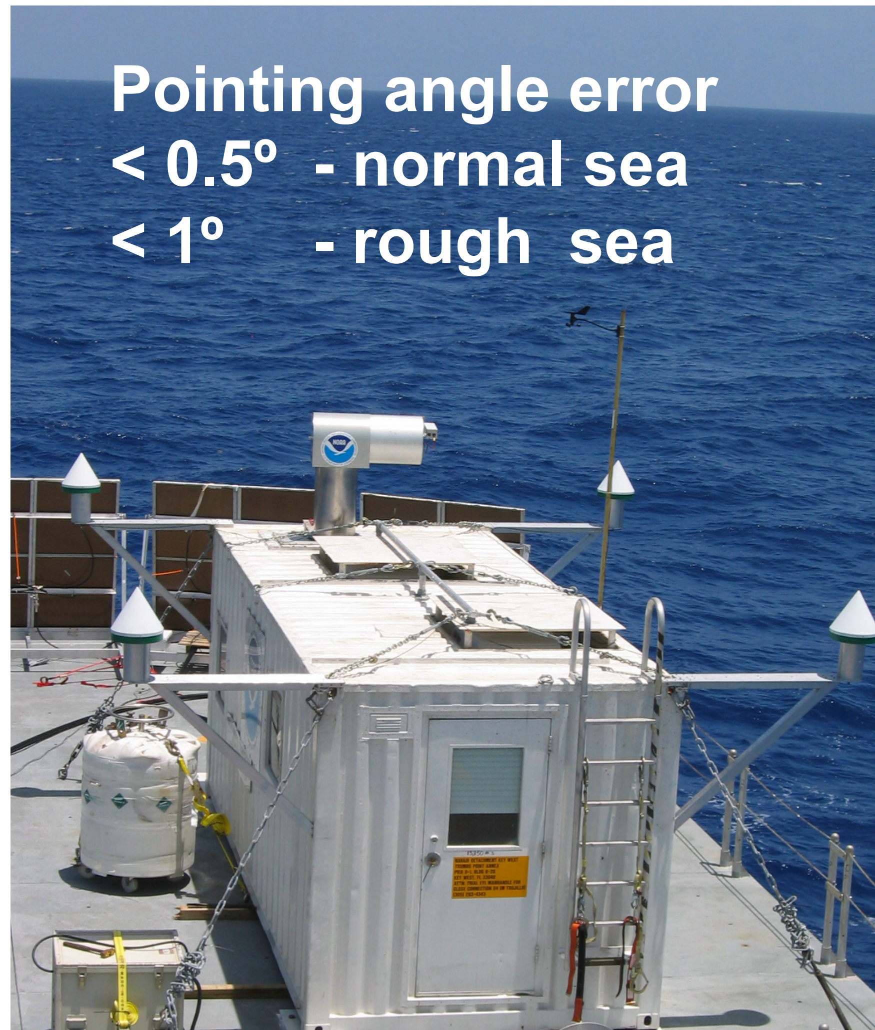


Motivation

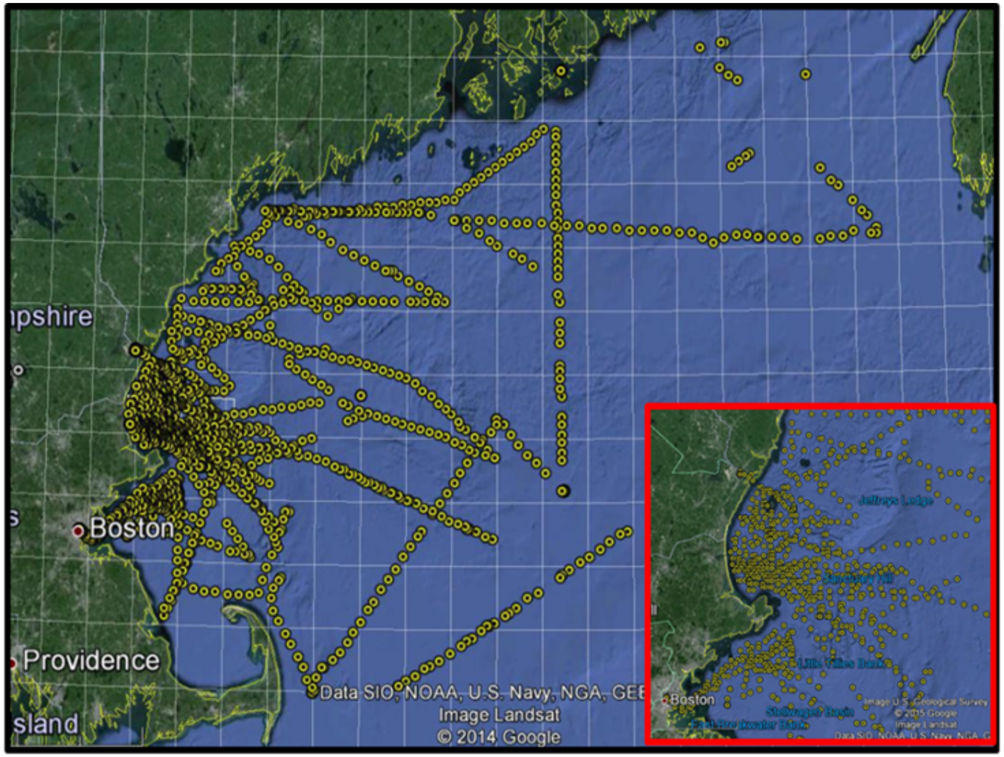
- Could LLJs be observed offshore?
  frequency, strength, height
- Magnitude of shear within rotor layer?
- How accurate are hub-height winds calculated from surface measurements?
- Power estimates based on hub-height wind speed vs rotor equivalent wind speed

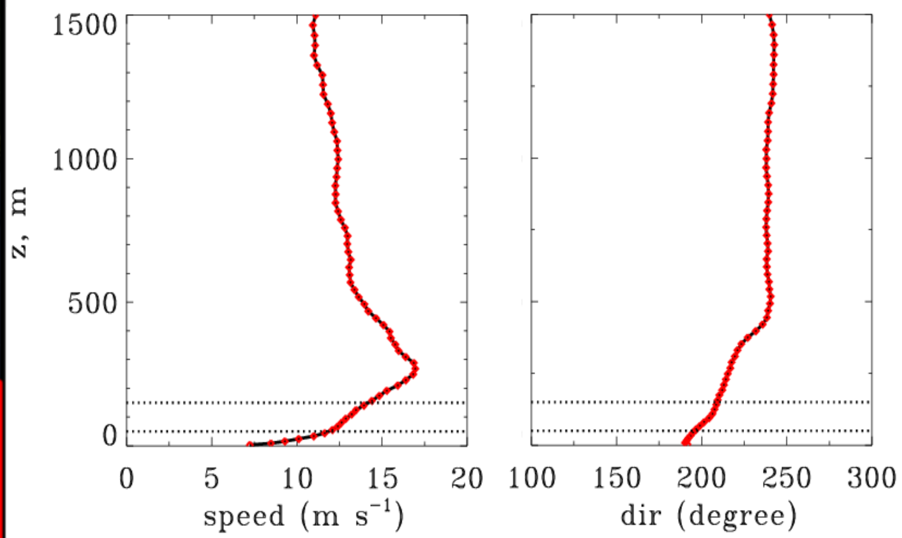
Lidar measurements from the New England Air Quality Study (NEAQS) July 09-August 12, 2004





Lidar dataset:
15-min averaged profiles of wind speed and direction



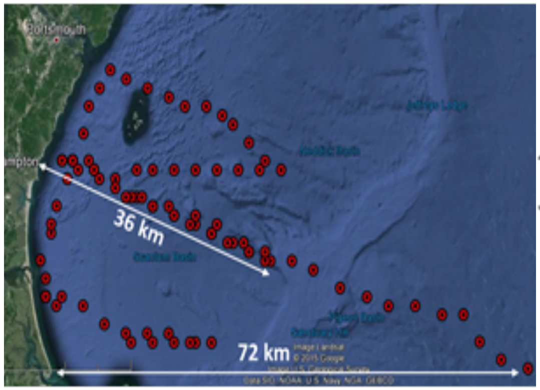


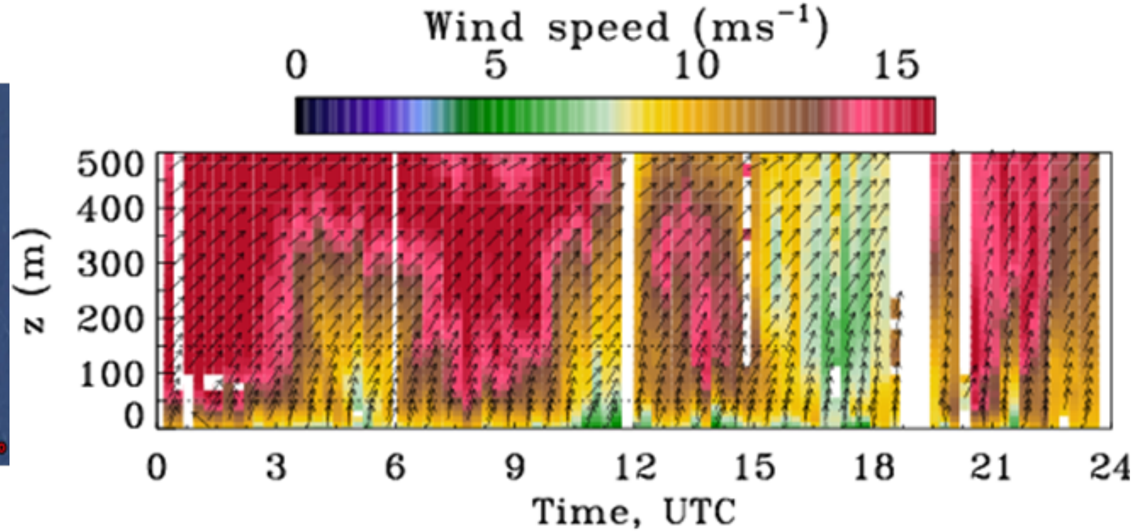
Profiles of wind speed and direction

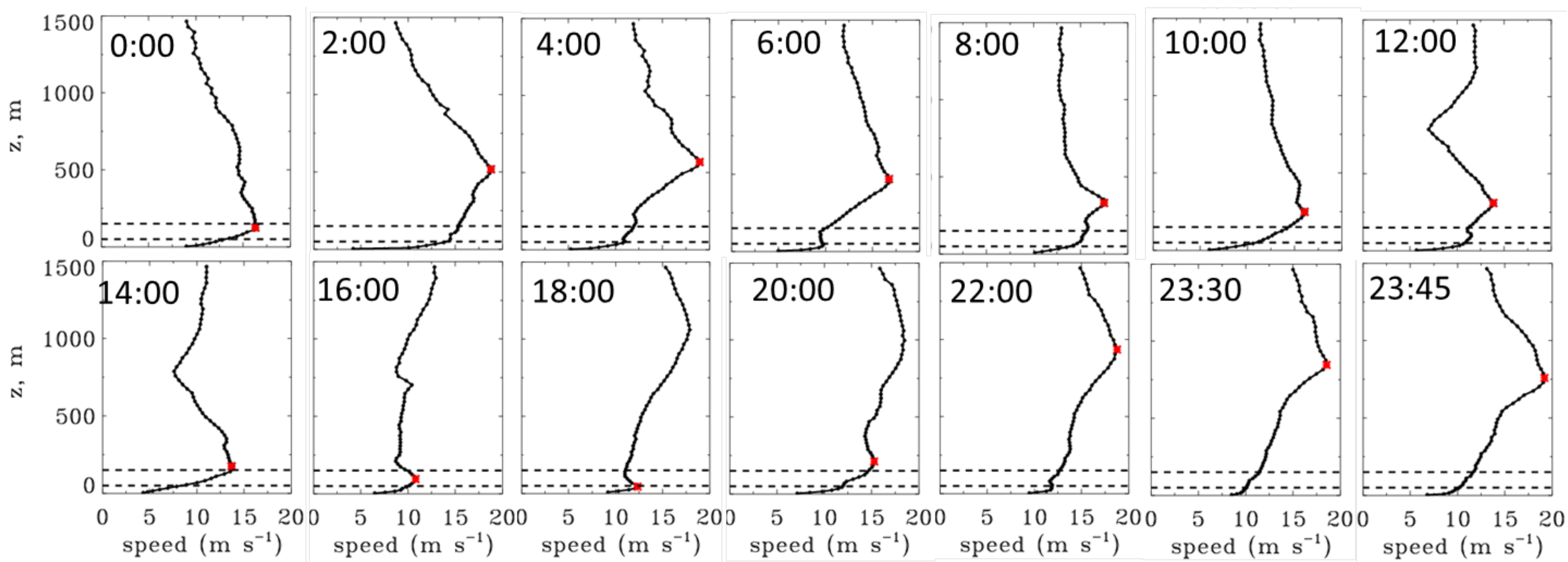
About 2000 profiles of wind speed were analyzed to indicate LLJ properties (frequency, strength, height of jet maxima), and wind shear through the layer of 50-150 m

LLJs along ship tracks

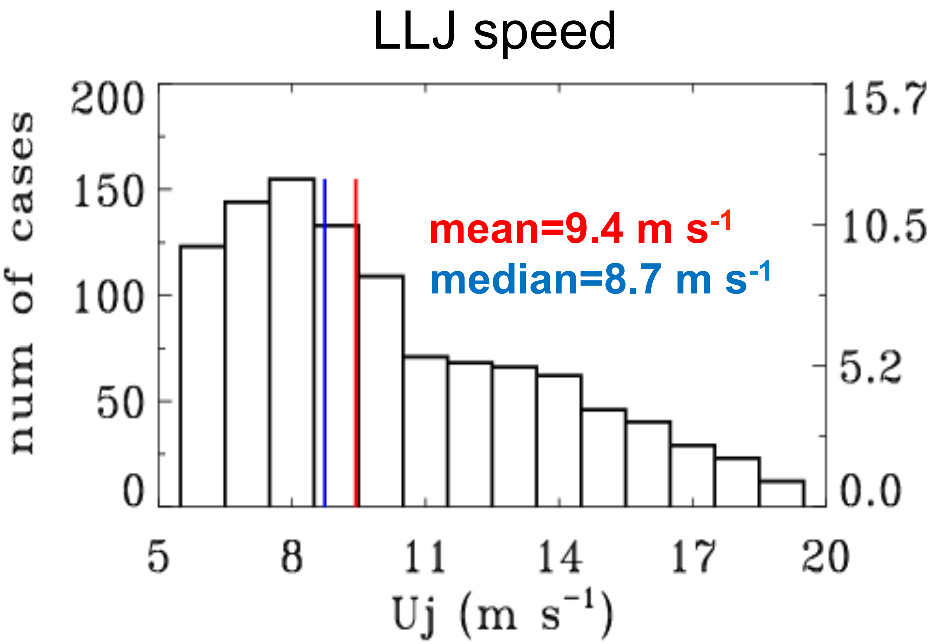
August 11

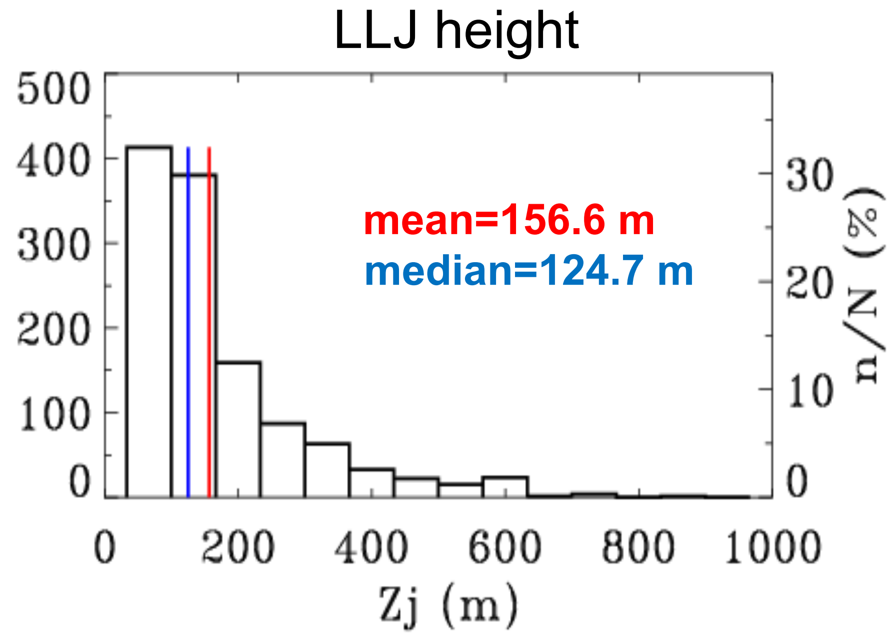




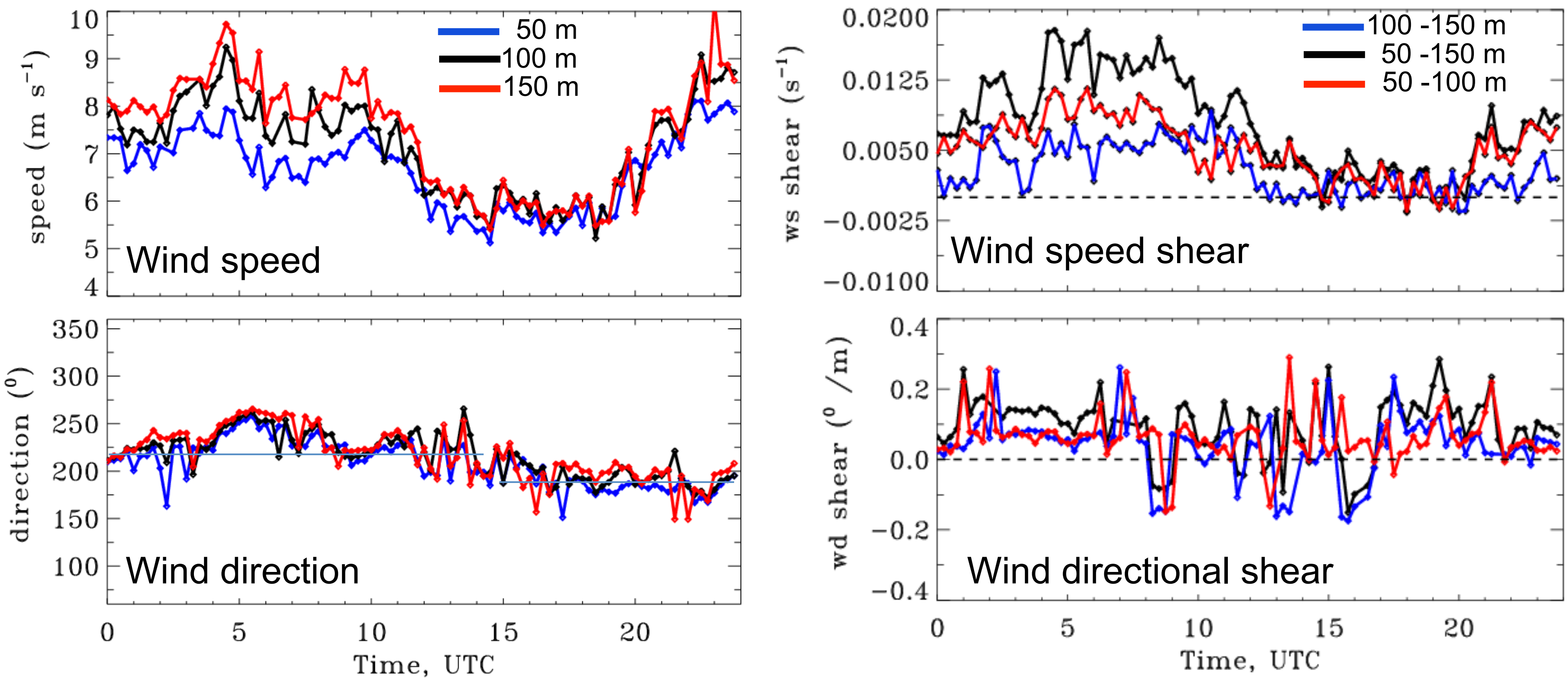


72% of 15-min wind speed profiles show LLJs





Mean shear through the rotor layer
(July 9 - August 12)

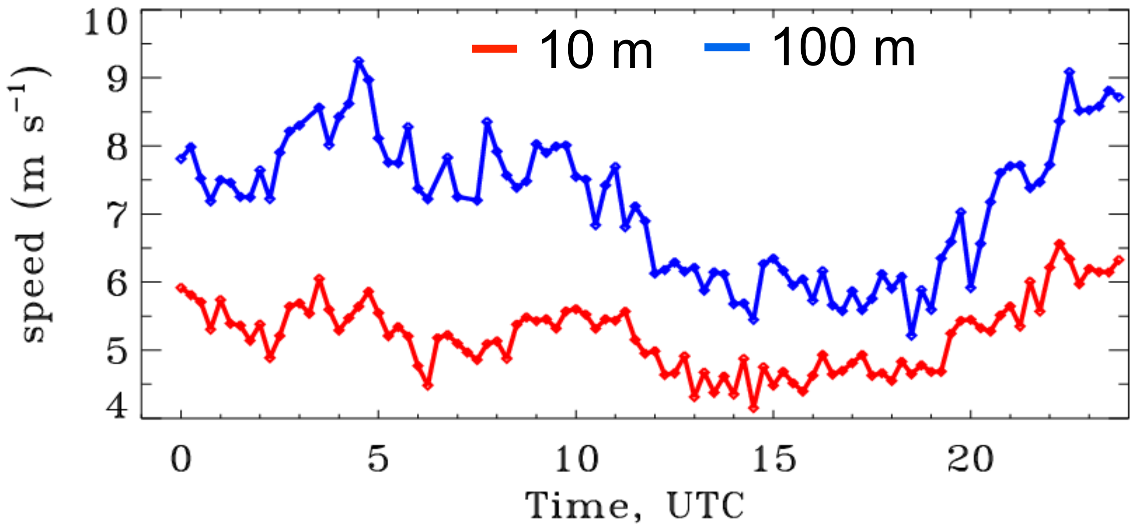


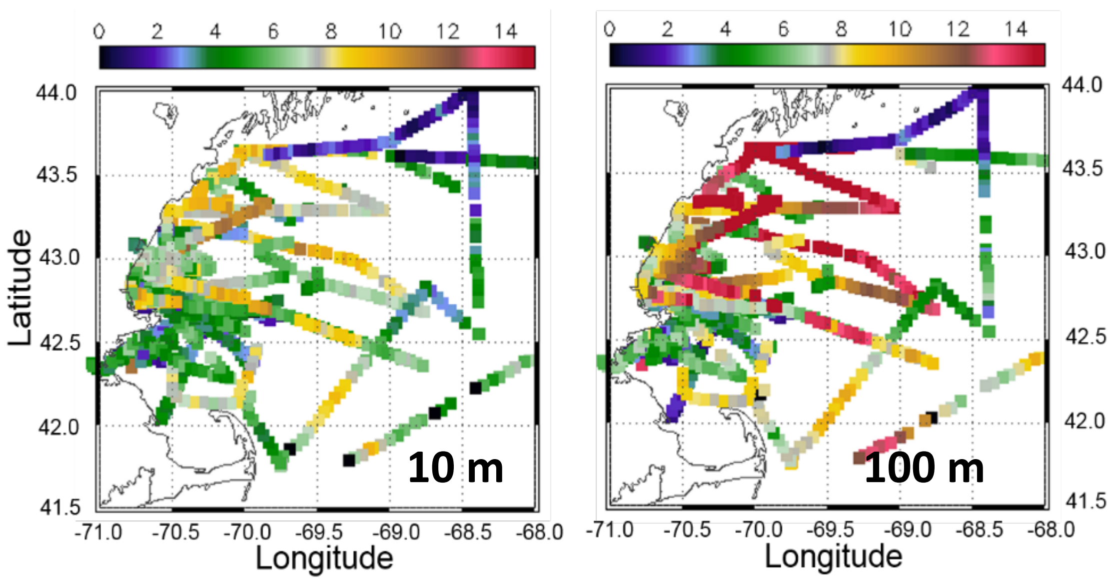
Wind shear stronger:
- at night hours
- below hub-height

Wind directional shear is not significant

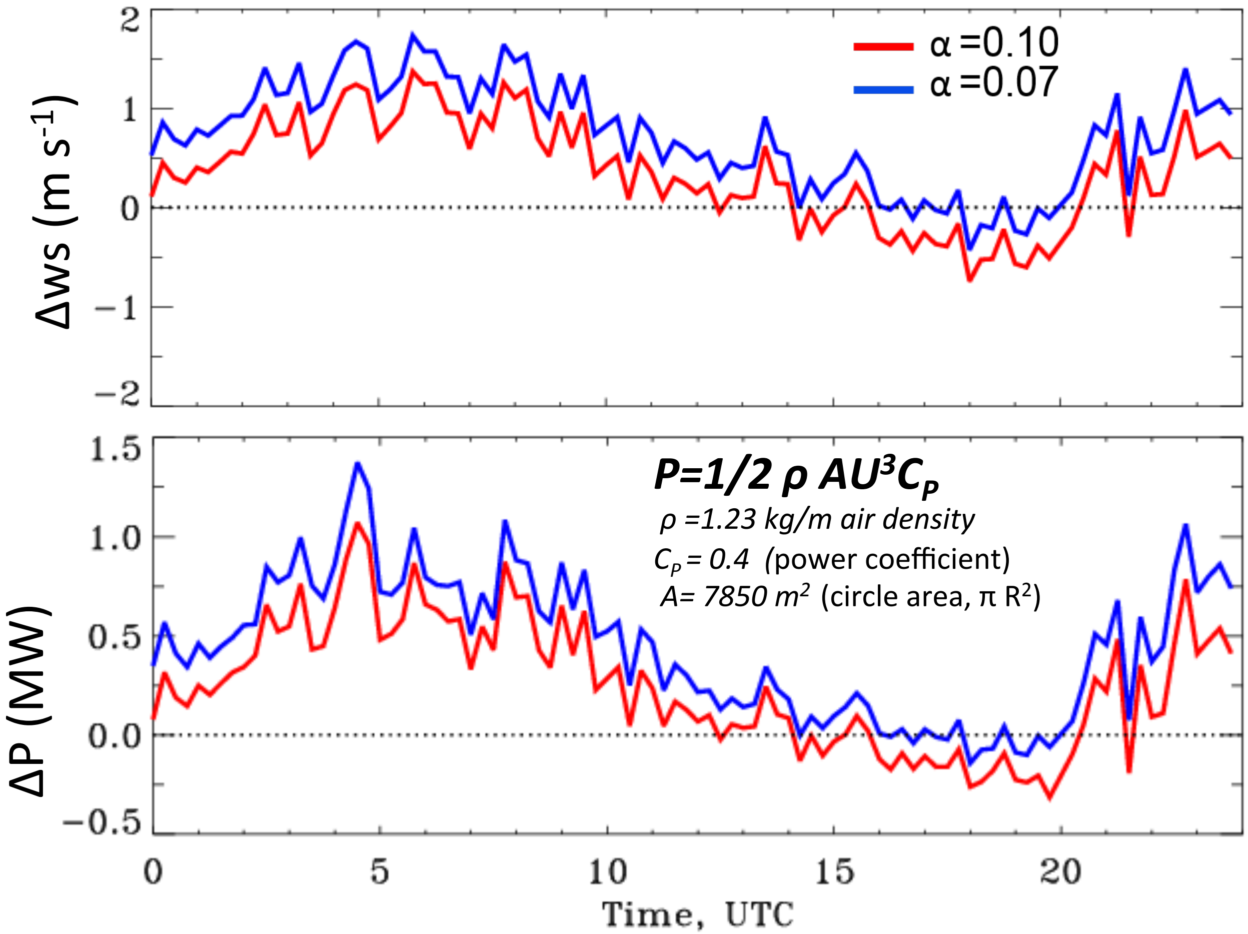
Surface and hub-height winds

$U = U_{REF}(Z/Z_{REF})^{\alpha}$





Measured and computed winds at 100 m

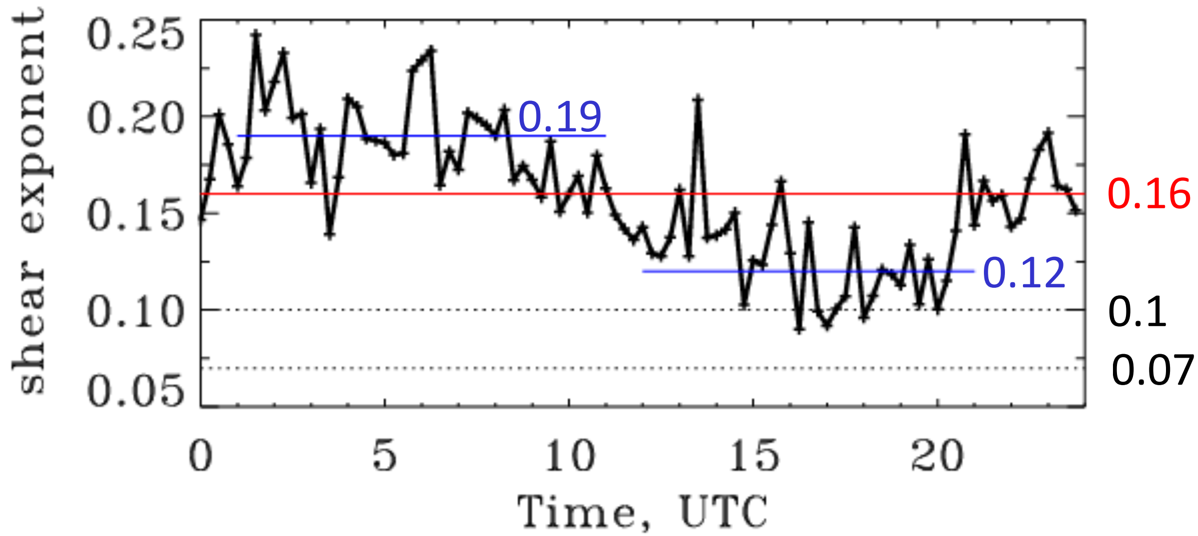


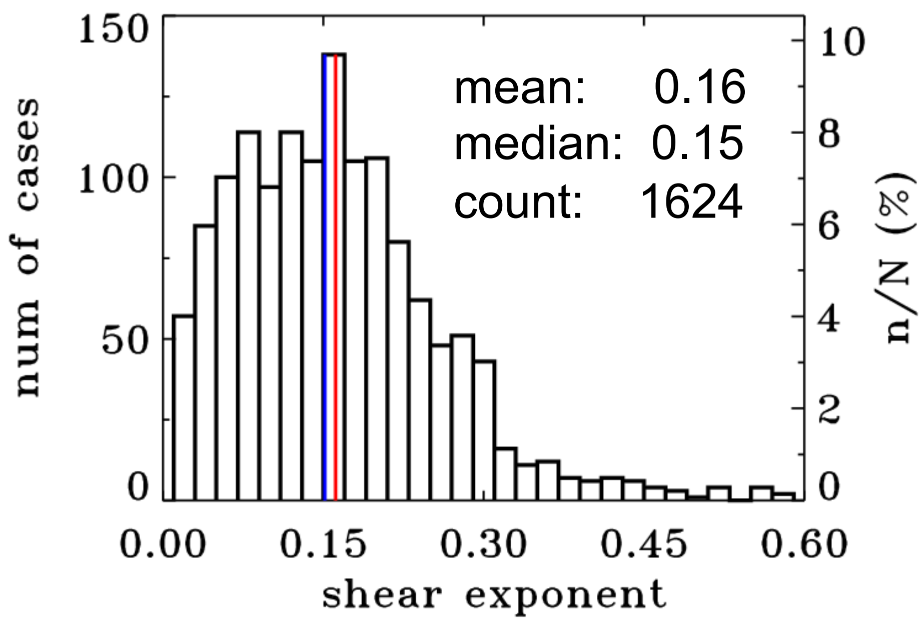
Experiment- mean power bias:

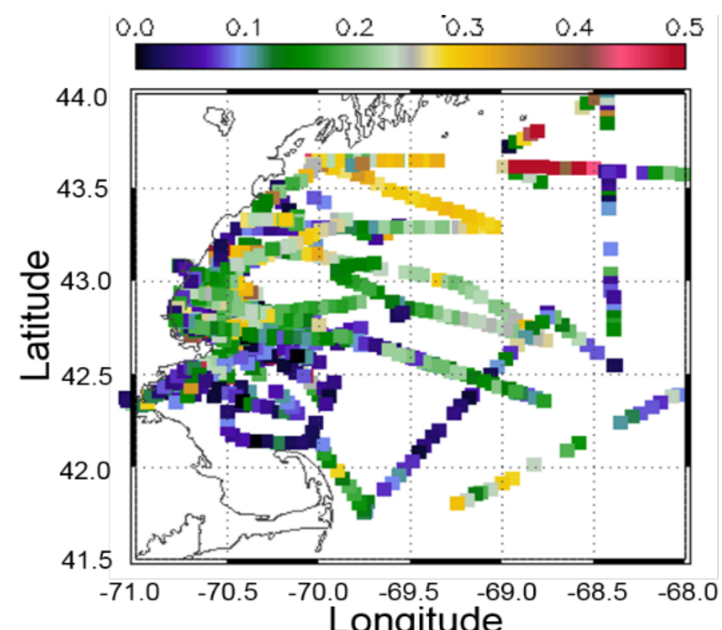
0.23 MW (α =0.10)

0.42 MW (α =0.07

Can a value of the shear exponent (**α**) be found from measurements?





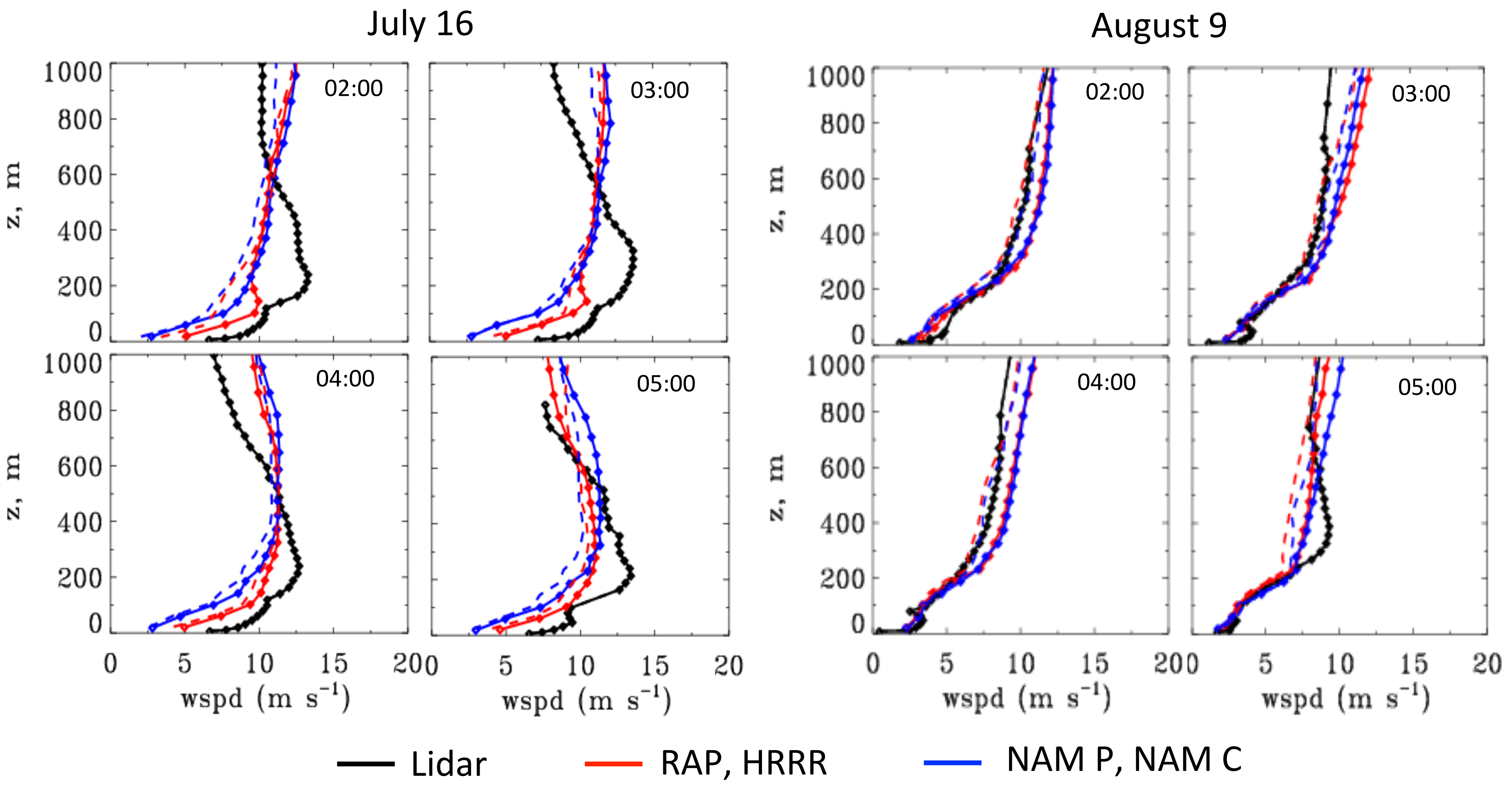


Prediction of Offshore Wind Energy Resources (POWER)

NOAA models used in the study

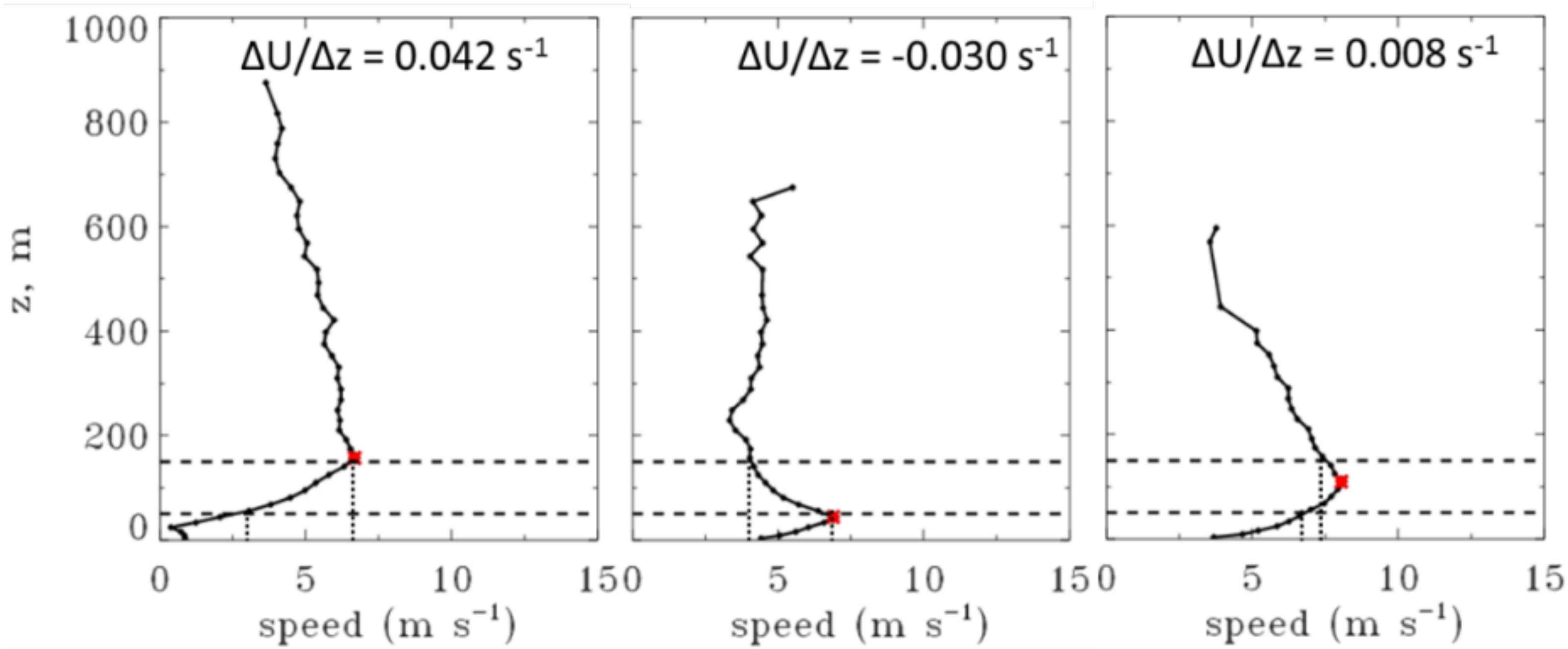
Rapid Refresh	**RAP**	13 km
High Resolution Rapid Refresh	**HRRR**	3 km
North American Mesoscale RR	**NAMRR**	12 km
NAMRR Contiguous United States	**NAMRR Conus**	4 km

Examples of lidar-measured and modeled wind profiles



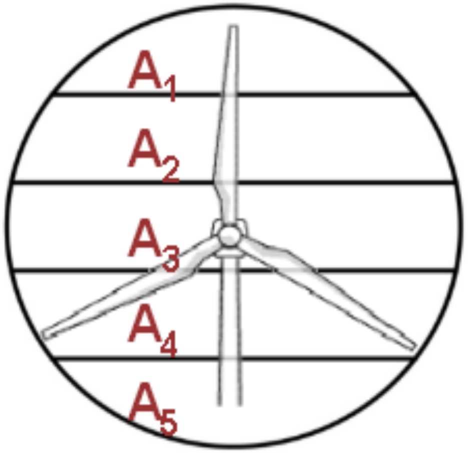
Greater discrepancies - for LLJ-like profiles

Shear through the rotor layer



In all cases power estimates using hub-height winds can produce significant errors

Techniques to compute the rotor equivalent wind speed



(1) $$U_{eqT3} = \sqrt[3]{\frac{1}{A}\left(\sum_i \overline{U_i^3} \cdot A_i\right)}$$

Wagner et al., 2009

(2) $$U_{eq} = \sqrt[3]{\frac{1}{A}\sum_{i=1}^{N} U_{Ti}^3 A_i} = \sqrt[3]{\frac{1}{A}\sum_{i=1}^{N} \overline{U}_i^3 \left[1 + 3\left(\frac{\sigma_{ui}}{\overline{U}_i}\right)^2\right]\left[1 - \frac{\overline{\theta}_i^2}{2} - \frac{\sigma_{\theta i}^2}{2}\right]^3 A_i}$$

σ_{ui}^2 is the variance of velocity fluctuations at *i*-th level

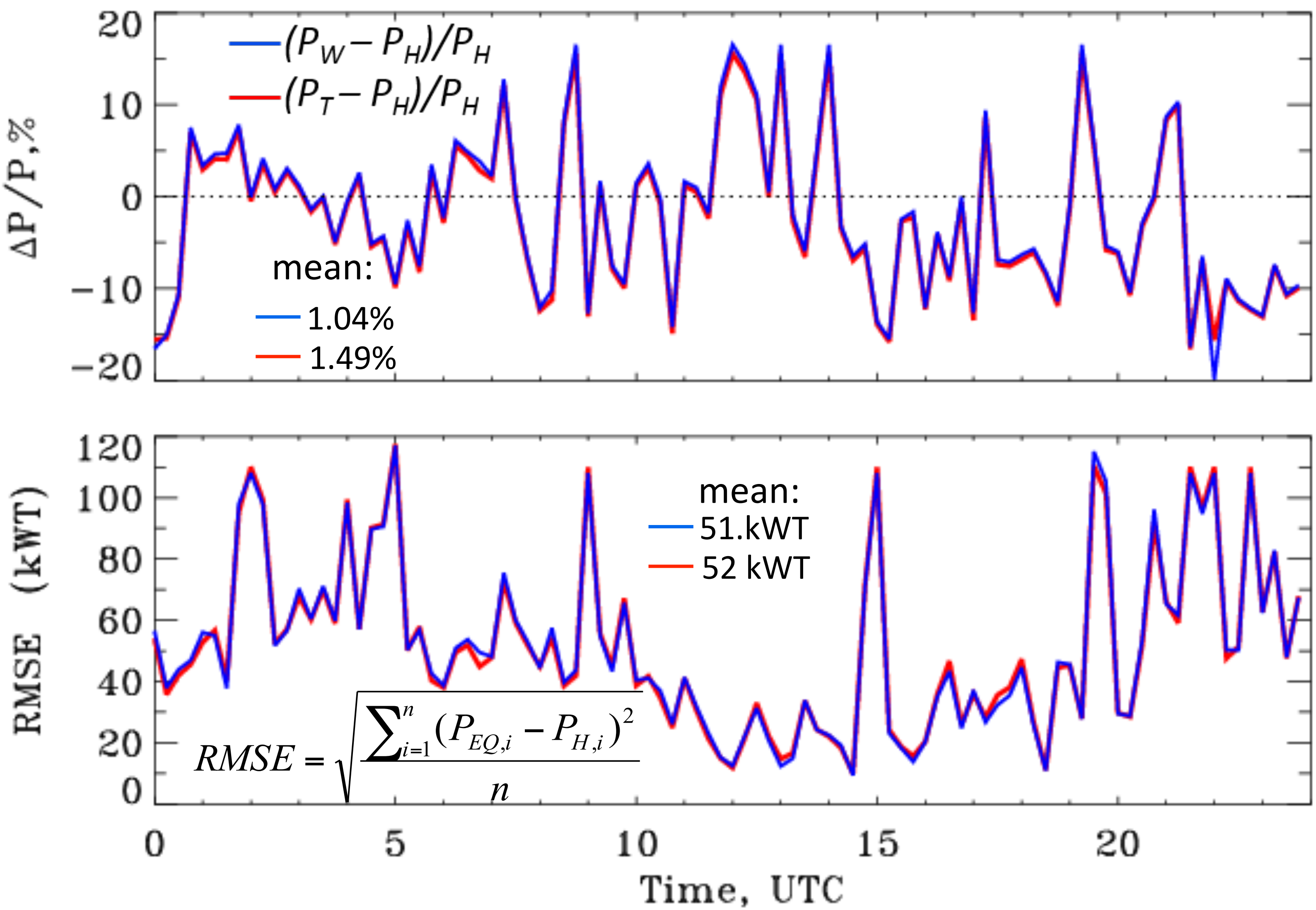
θ_i is the angle of the wind with respect to the rotor axis at *i*-th level

$\overline{U}_i$ is the wind speed at the *i*-th level

$\sigma_{\theta i}^2$ is the direction fluctuations at the *i*-th level

Choukulkar et al., 2015

Normalized bias of wind power computed by the hub-height and the rotor equivalent wind speed



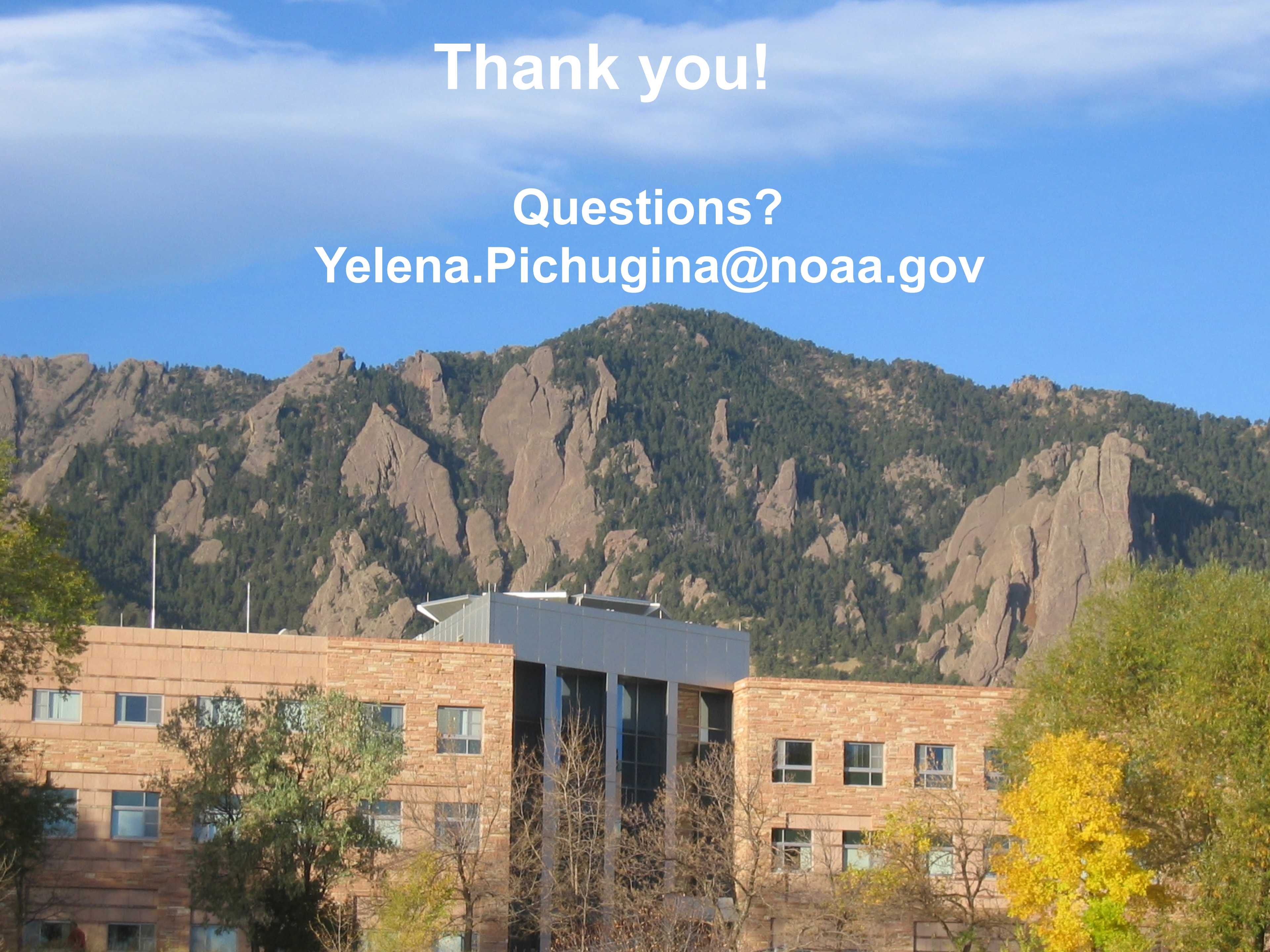
Conclusions

- Wind profiles obtained from ship-borne Doppler lidar measurements often show LLJs within turbine rotor heights
  - more frequently during nighttime hours
- The maximum of jet speed varies from 5 to 20 ms^{-1}, with the mean value of 9.4 ms^{-1}
- Jet heights are spread up to 600 m, with the mean value of 156.6 m
- LLJs can significantly modify wind profiles producing vertical wind-shear of 0.03 s^{-1} or more across the rotor layer of 50-150 m
- Extrapolation of near-surface winds to hub height power-law relation show biases of 0.25 s^{-1}
- The shear exponent (α), found from lidar data, show diurnal variations from 0.1 to 0. 25, with the mean value of 0.16 for the entire experiment
- A two techniques for calculating rotor layer equivalent wind were tested and show 1-1.5% less power compare to the power estimated by hub-height wind.

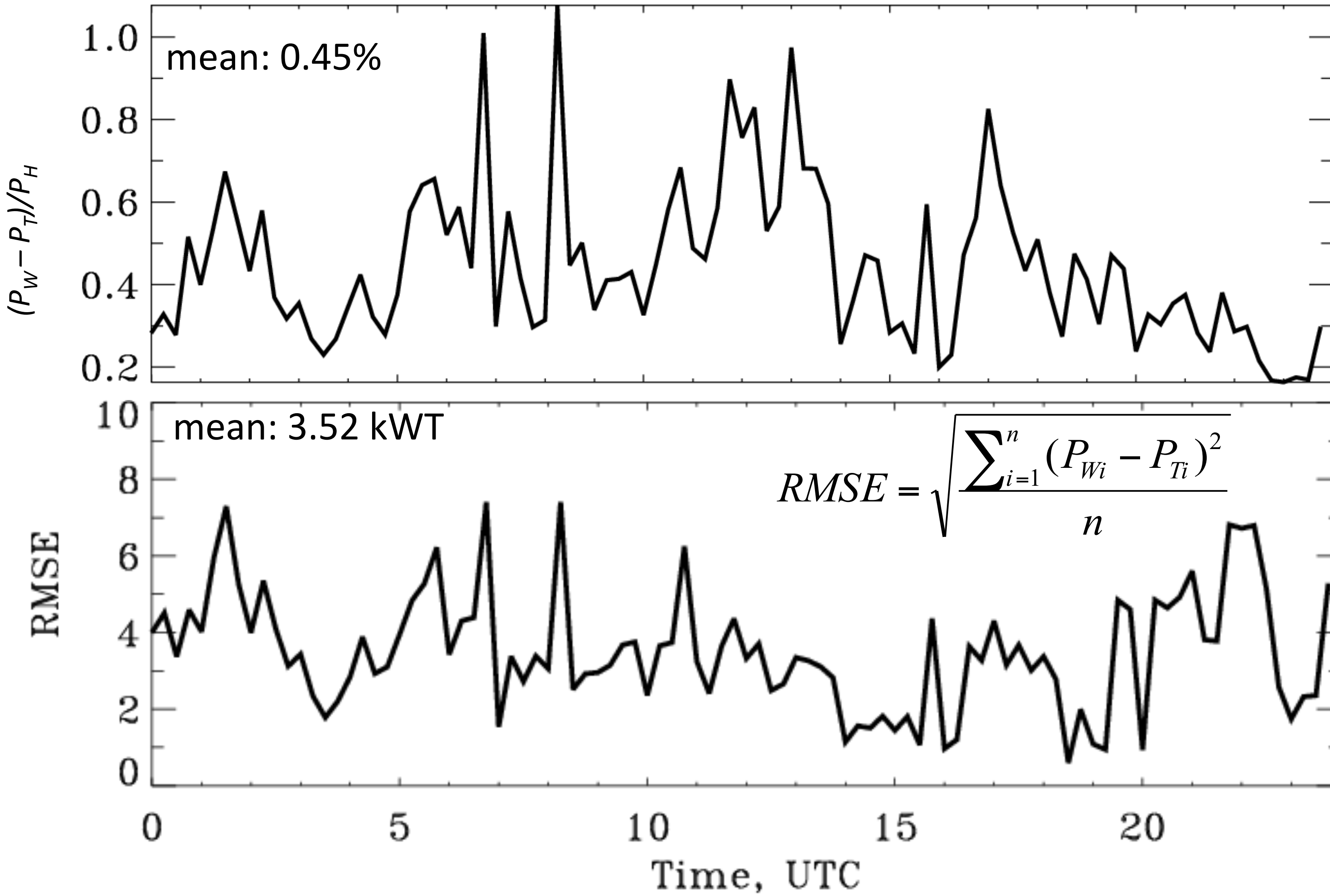
Thank you!

Questions?

Yelena.Pichugina@noaa.gov



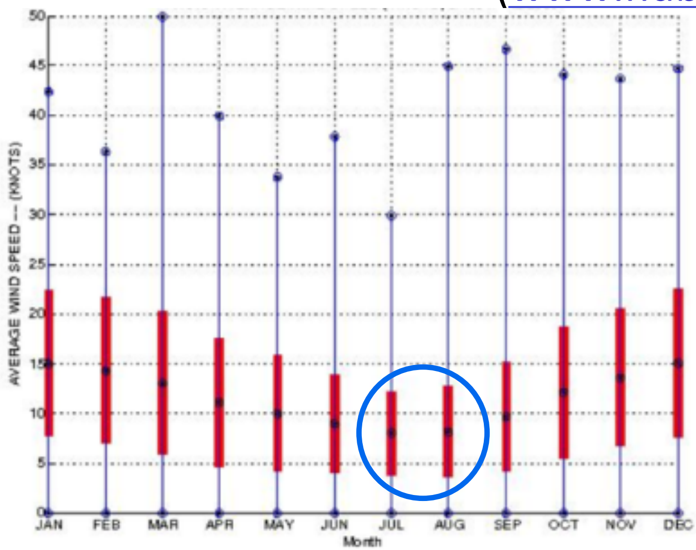
Normalized bias of the power based on the rotor equivalent wind computed by using 2 techniques

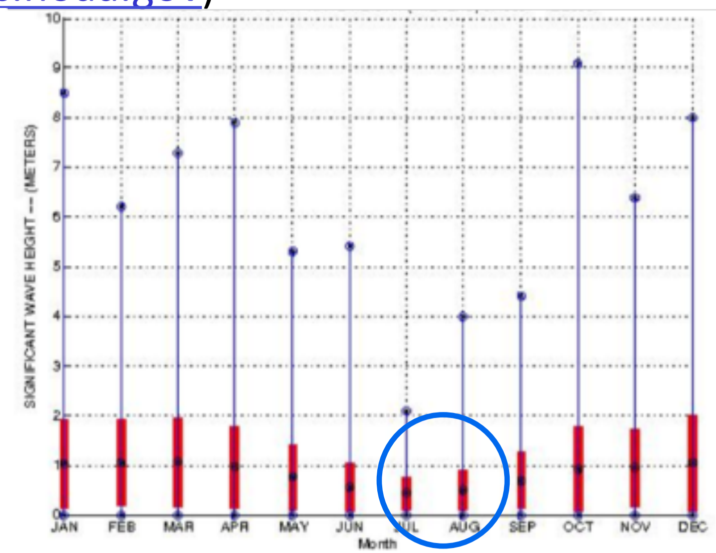


$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_{Wi} - P_{Ti})^2}{n}}$$

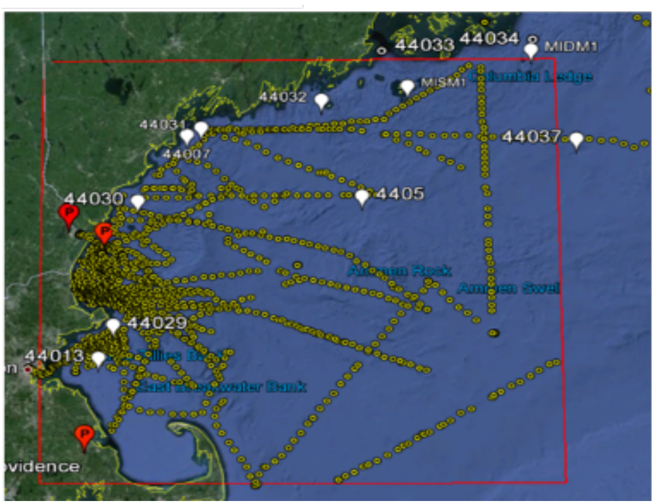
The NCBD buoy's data

Data from the Lighted Buoy BF NOAA 44013, located 16 n miles east of Boston (www.ndbc.noaa.gov)



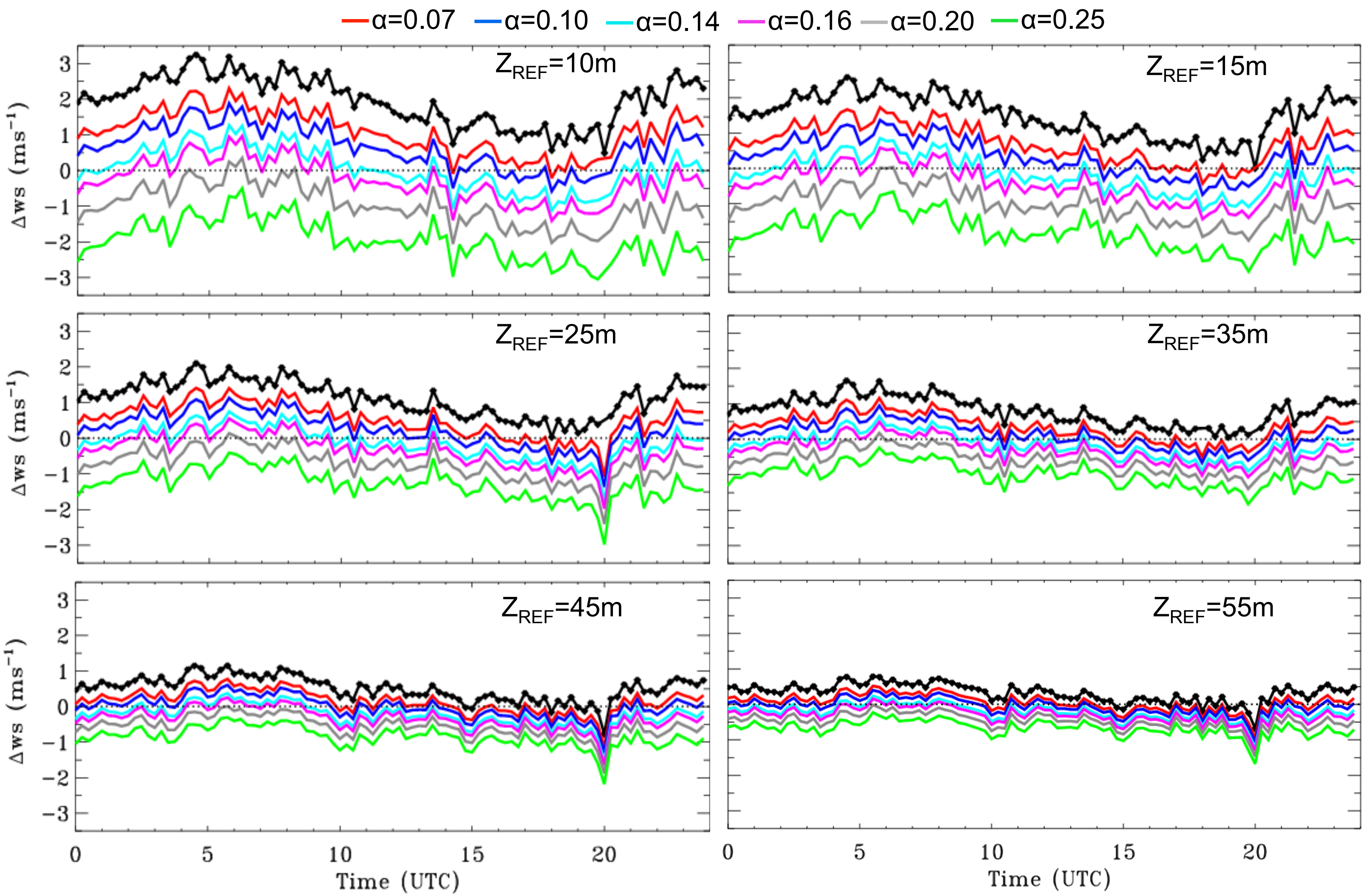


The summer period during the experiment was characterized by the low winds and the wave height averaged over 10 years



Buoy-based sonic anemometer measurements are not representative of the higher elevation winds due to the unknown shear/stability profiles [Sienkiewicz, 2014]

The bias between measured hub-height wind and computed by the power-law by using different values of shear exponent and referenced heights



Time series of the bias between measured hub-height wind and computed by the power-law by using six different values of shear exponent (α) as indicated by the color bar at the top of the figure. The referenced wind used in the computations are also lidar measured wind at the referenced height (Z_{REF}) as indicated on the each panel. Black lines and black diamond symbols in each panel show difference between winds measured at hub-height and referenced height.