Accurate Measurement of Wind Properties through the Turbine-Rotor Layer for Wind Energy Using High-Resolution Doppler Lidar

Robert M. Banta,
Yelena L. Pichugina, W. Alan Brewer, and R. Michael Hardesty

NOAA/Earth System Research Laboratory,
Cooperative Institute for Research in Environmental Science (CIRES)
Boulder, Colorado

3rd International Conference: Energy & Meteorology, Boulder CO, 24 June 2015

Wind Energy – need for accurate wind information through the turbine rotor layer

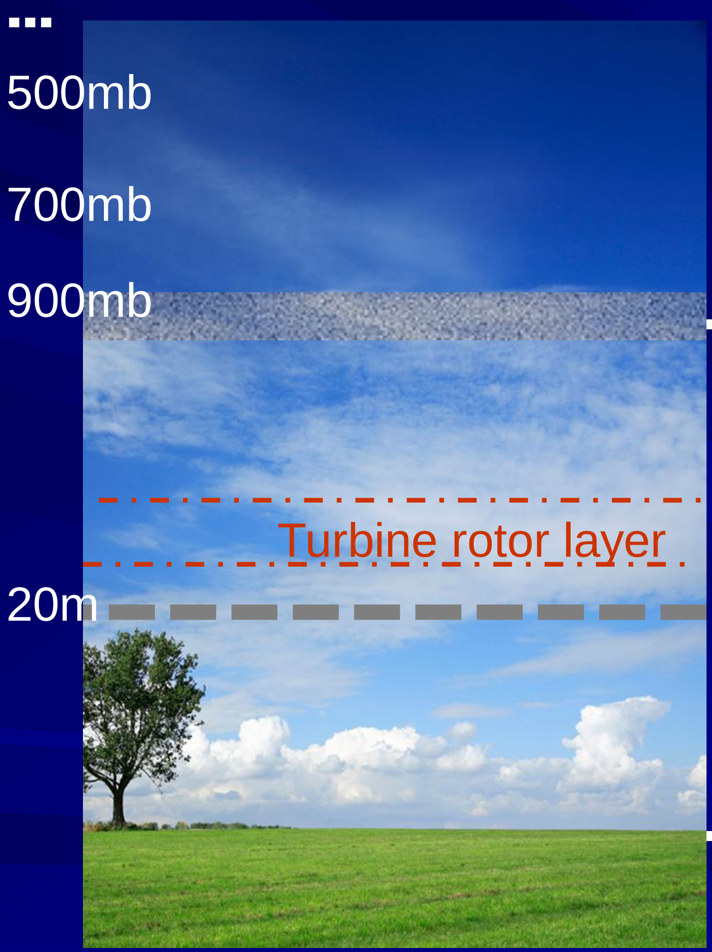
In an industry so dependent on a variable resource, such as the wind, it makes sense to understand as much as possible about that resource.

But this is not the case for wind:
characterizing and understanding the resource is a serious gap for wind energy

(Banta et al. 2013: *Bull Amer. Meteor. Soc*., 94, 883-902).

Very simply

What's different about WE ?



- **2 regions:**
  - **Slow processes**
    - Above ABL
  - **Fast** (diurnal)

- **Available measurements**
  - Slow, less precise
  - Slow, less precise
  - Fast, precise
    - near sfc

WE occupies "inverse sweet spot" in atmospheric science state of the art

Need to advance SOA to meet WE needs

Need to look at measurement capability = instrumentation

Meteorological information for wind energy:

What's different about WE ?

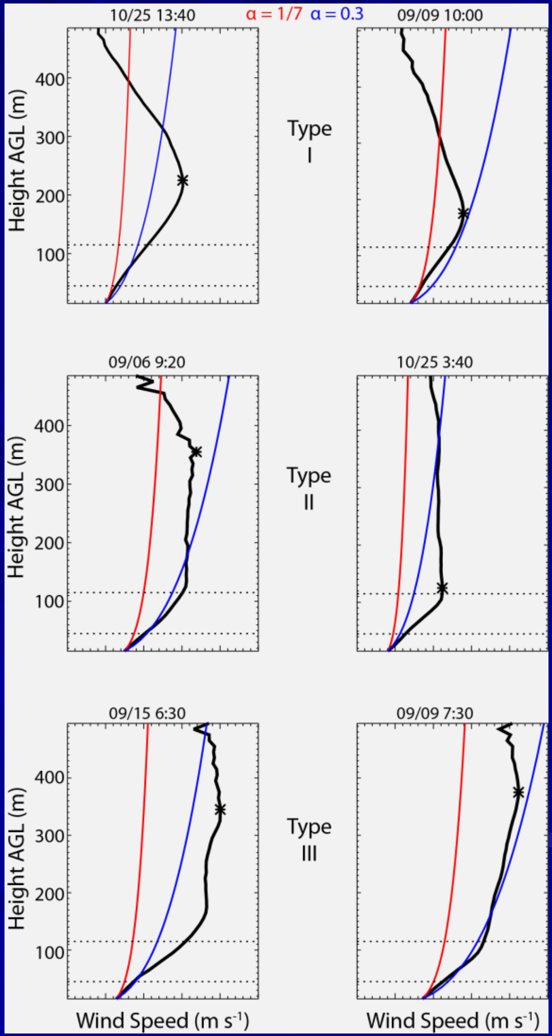
- Greater precision needed than most other meteorological applications

- Information needed aloft *[e.g., here]*

To address need for data… ?

- Surface measurements from towers
  - Extrapolate to "hub height"
  - Use standard profile shape
    - E.g., power-law profile
  - How well does that do?

- NWP models
  - Models are not the atmosphere
    - Some output good, some not
    - Models need to be verified by reliable measurements at levels where used
    - WE users: 'we need improved models'
  - Lack of good data sets
    - Models have <u>*not*</u> been well verified for WE applications



Black = measured

Doppler Lidar

Courtesy Scott Sandberg

- Remote sensing system
  - Similar to Doppler radar
  - Transmits eyesafe infrared (IR) light
- Aerosol targets – excel. tracers of the wind
- > Hemispheric scanning
- Return signal includes aerosol backscatter in addition to frequency (Doppler velocity) data

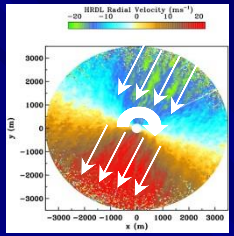
Doppler lidar

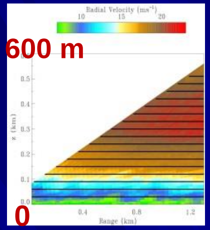
Lidar (light detection and ranging) has the necessary capabilities, e.g.,

- NOAA's High Resolution Doppler Lidar (HRDL) – research inst
- Scanning Doppler lidar: measures winds at needed resolution, precision

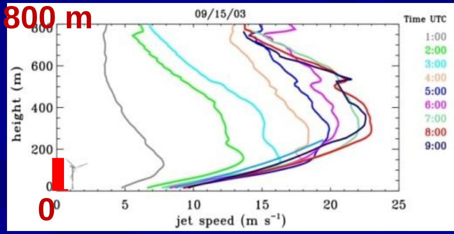
Granularity of data,
less than:
Vertical – 5 m
Time – 5 min
Precision – 5 cm s^{-1}
First data above surface – 5 m

Scan data



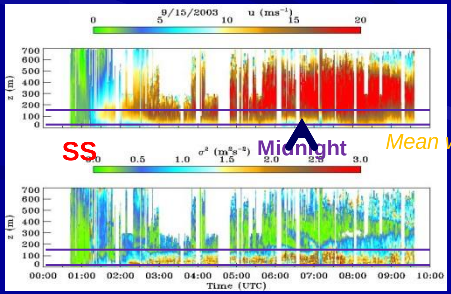


Profiles

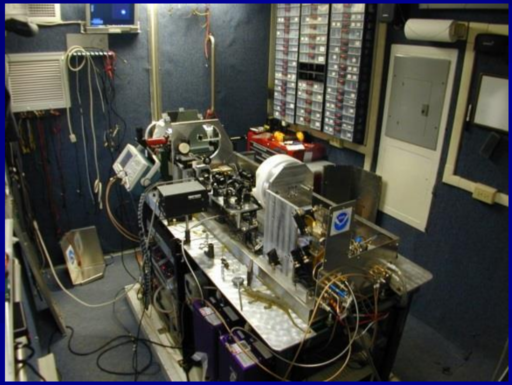


speed

Time-height cross section



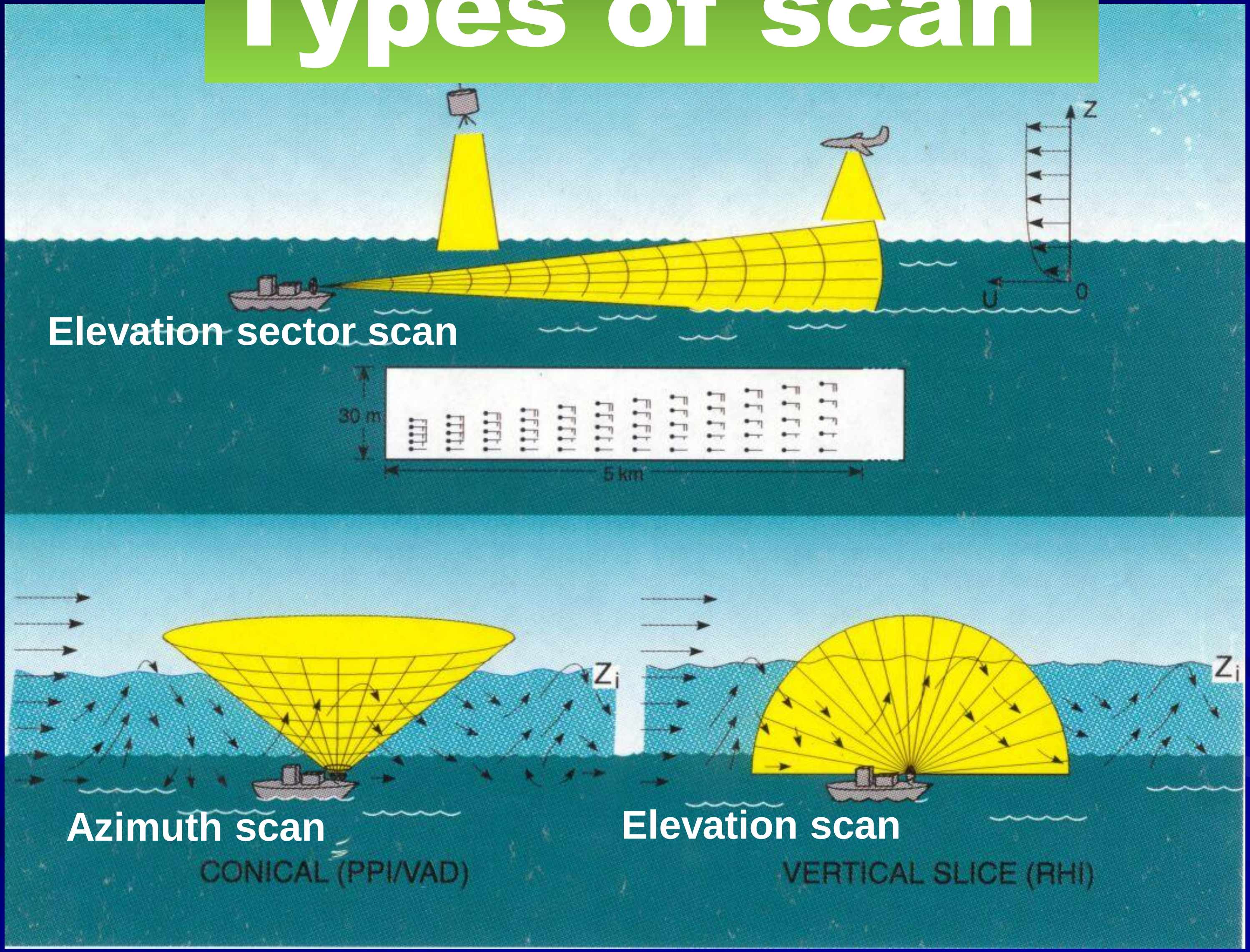
Turbulence variance (TKE)



NOAA /ESRL's **High-Resolution Doppler Lidar (HRDL)**

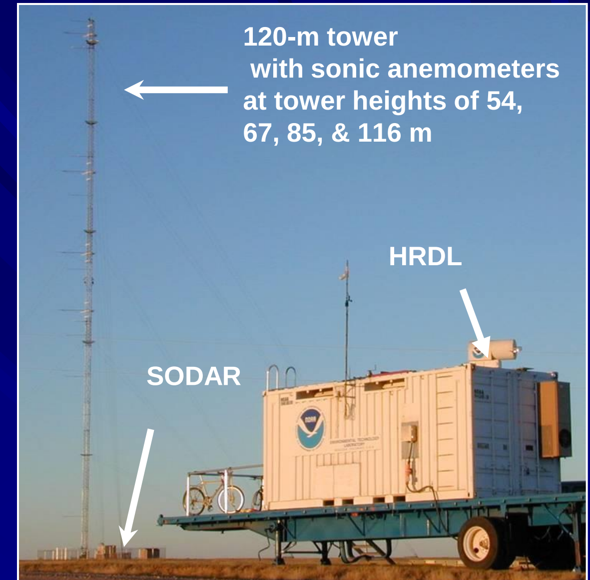
Poster 5-3

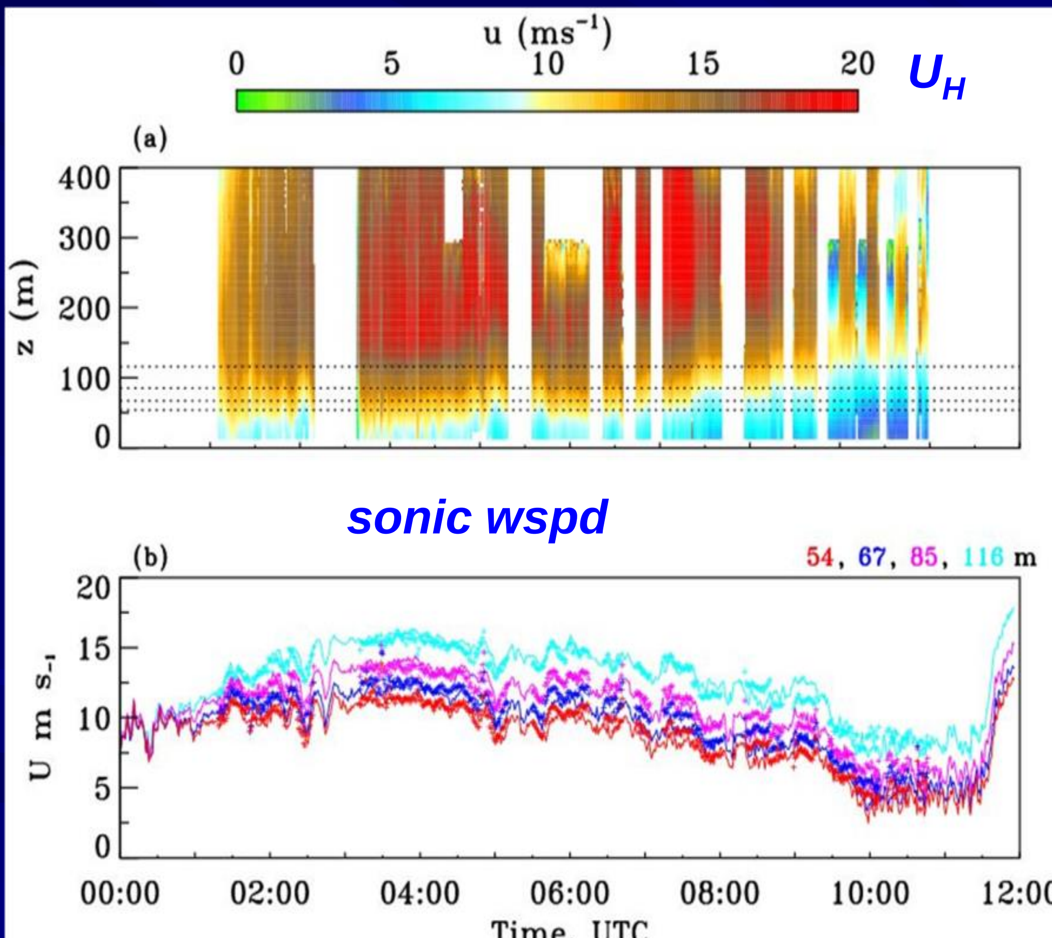
Types of scan

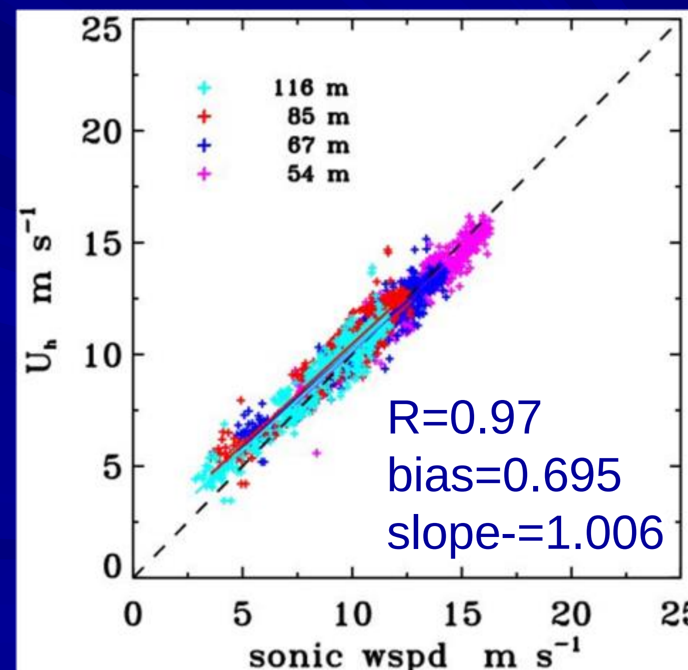


Accuracy of lidar data

Comparison to sonic anemometers
(wind speed)

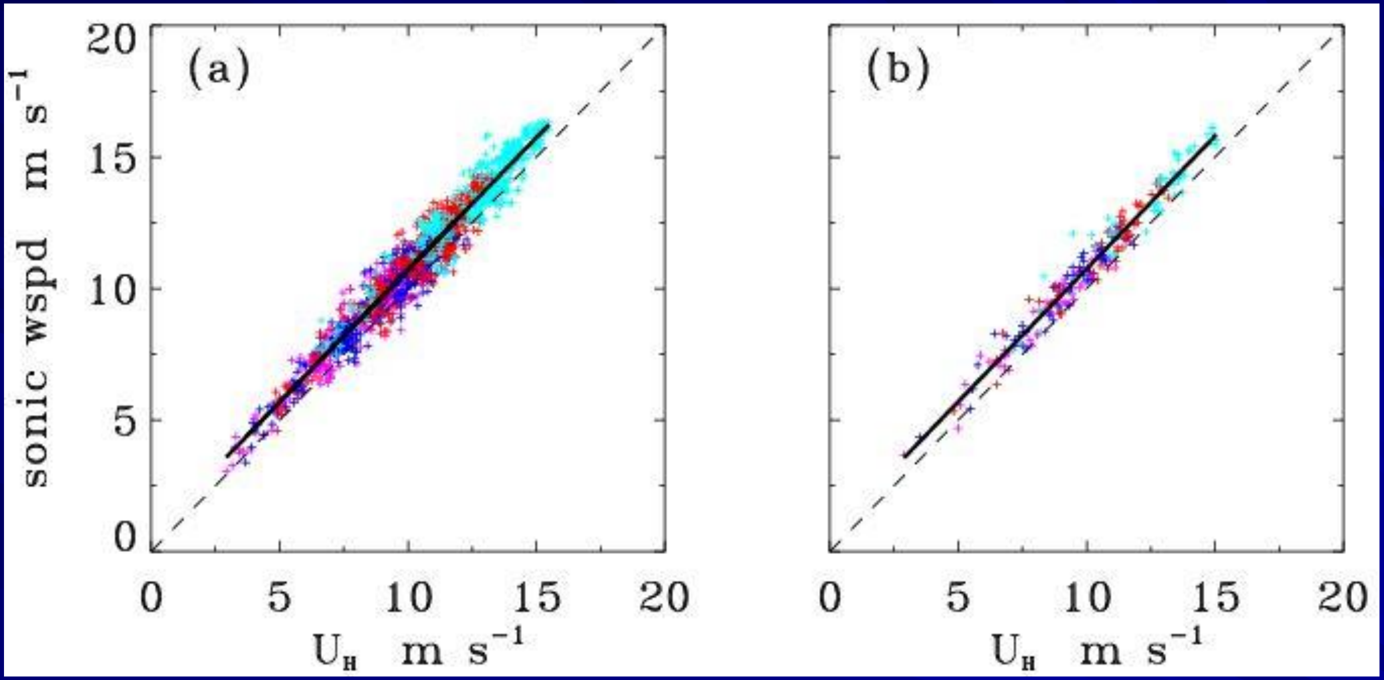






MEAN WIND:

Lidar vs. tower/sonic anemometer



1-m, 1-min → r = 0.95 **10-m, 10-min → r = 0.98**

Similar careful studies at DTU (Risoe)

***Bottom line*: Doppler lidar is a very precise way to measure the mean wind**

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.*, **25**, 1307-1327.

3 decades of lidar studies

- Sea breeze
- Complex terrain
- Windstorms
- Forest fires
- Fronts, density currents
- Low-level jets (LLJs)
- Stable boundary layer
- Air quality
- K-H-type waves

Recent emphasis: nighttime stable boundary layer
Especially vexing problem…
Important for Wind Energy – nighttime low-level jet (LLJ)

Also – wind turbine wakes

Examples: Flow Characterization

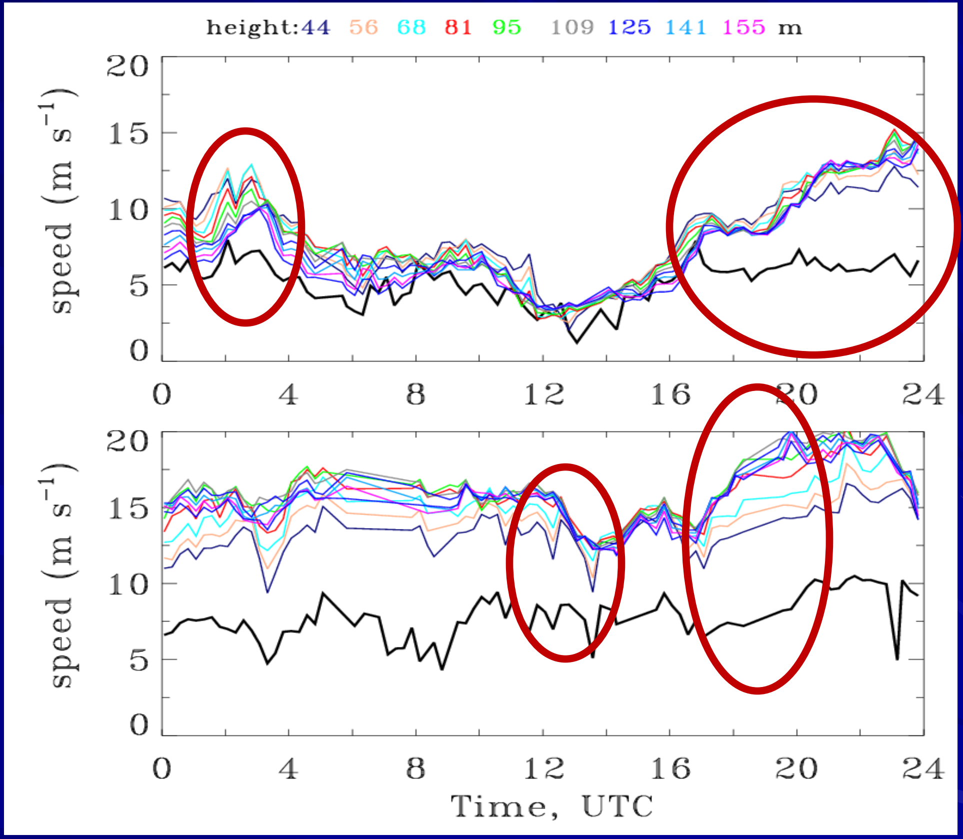
- Relationship between *near-surface flows* and *rotor-layer flows*
- Periodic flows
- Nonstationary flows
- Turbine wakes

  – *Last 3: Animations of scan data*

Decoupling of flow:

surface vs. rotor layer

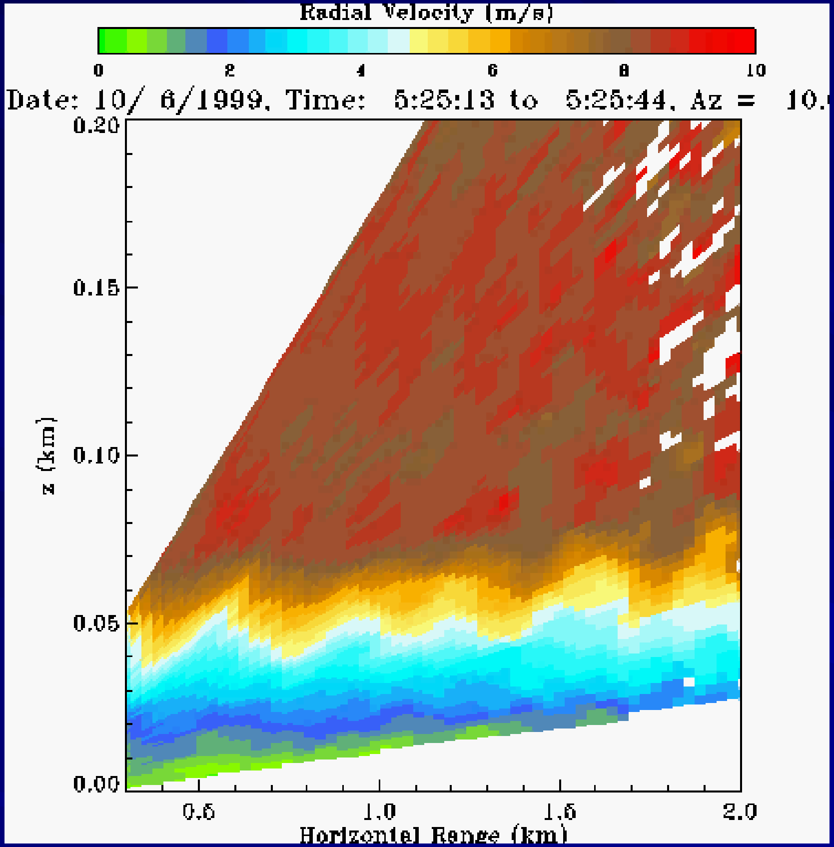
Height lines: 44-155 m
Solid black lines: 8 m



Wind speed (0-20 m/s) vs. hour of the day

- Abrupt increases / decreases (***ramps***)
- Near-surface flow often decoupled from surface
  - Near-surface wind measurements often unrepresentative of wind behavior aloft
  - Extrapolation techniques can yield large errors

Periodic flow



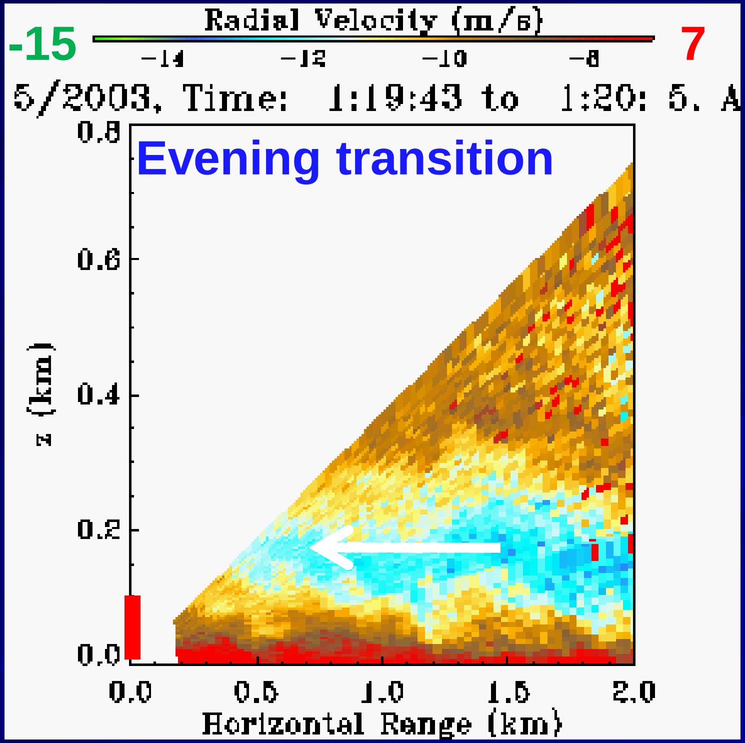
LLJ impact: strong shear produces turbulence, wave activity

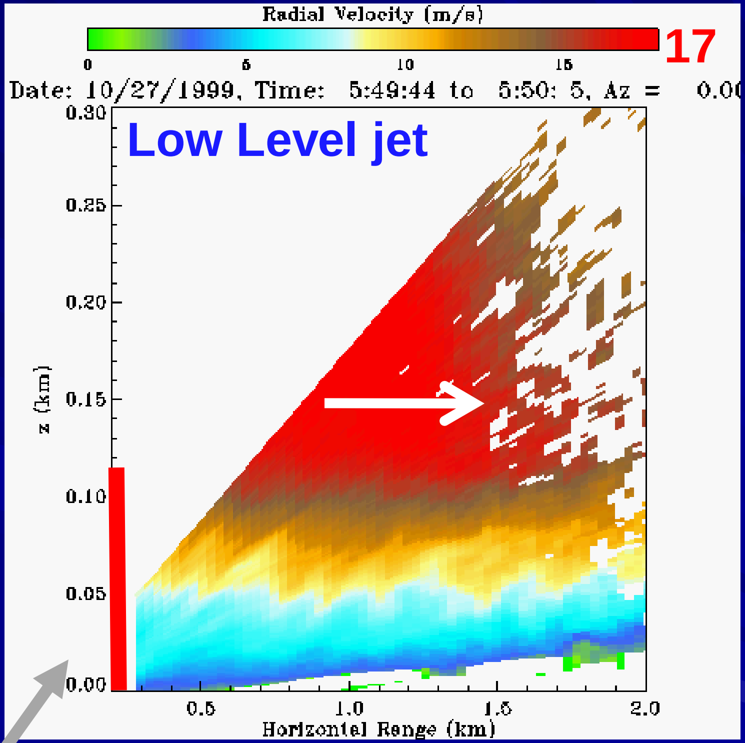
*Newsom and Banta 2003: <u>J. Atmos. Sci</u>, **60**,16-33.*

If at right (wrong?) frequency – potential for resonance effects with rotor blades

Time dependence and evolution:

Nonstationary effects





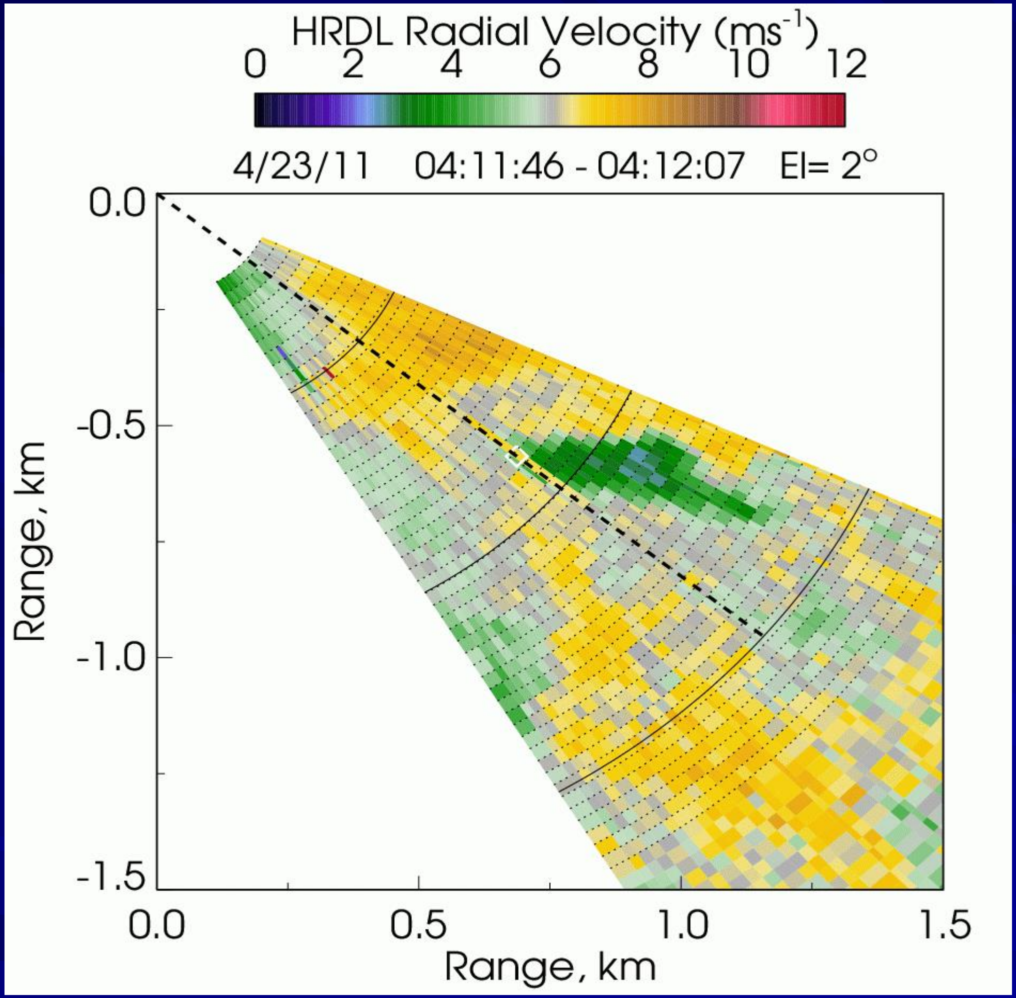
LLJ forms in ‘fits and starts’ from 0119 to 0201 UTC (1819 to 1901 MST) *[42 min total]*

Turbine height (115 m)

LLJ speed pulsates, turbulence quantities vary in time (2249-2300 MST) *[11 min total]*

Even hourly profile data -- not good enough.

Wake animation



6 min of animation – 0411-0417 UTC

*Banta, R.M., Y.L. Pichugina, et al., 2015: 3-D volumetric analysis of wind-turbine wake properties in the atmosphere using high-resolution Doppler lidar. J. Atmos. Oceanic Technol., **32**, 904-914.*

These are fun, but …

- Images and animations give important insight into how flow systems work
  - But… *quantitative* information needed to advance characterization, understanding … and modeling

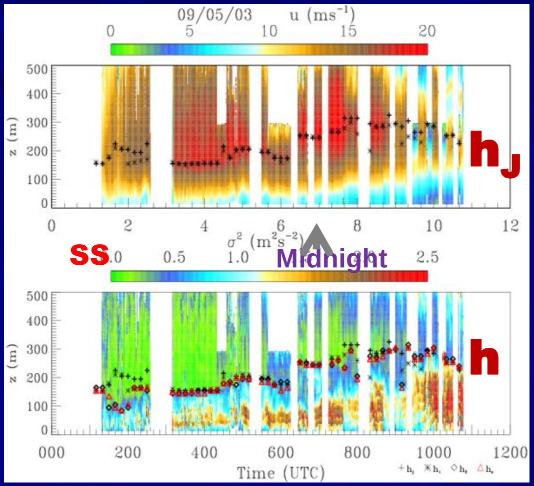
- Doppler lidar also provides this kind of (*quantitative*) data where needed for WE
  - *Each pixel represents a number*
- Analysis products, such as profiles, make use of such data

Nighttime, Stable Boundary Layer (SBL)

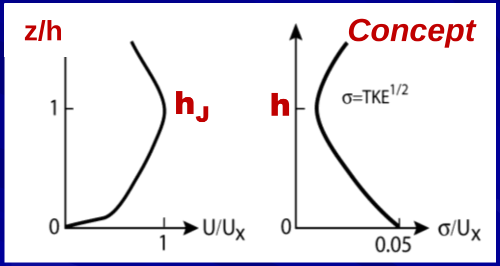
Atmospheric stability, lack of mixing → SBL described as "chaotic"

Q: can *any* generalizations be found to help understand the nocturnal SBL ?

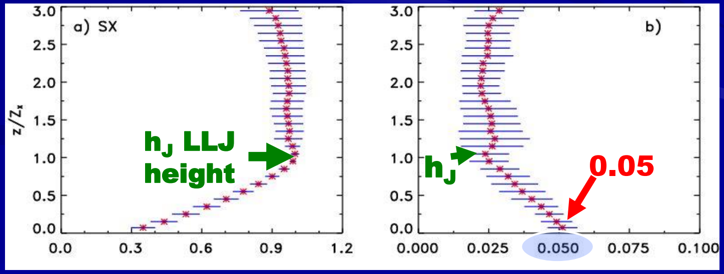
- Using Doppler lidar, we have found:
  - Key to understanding the SBL is the low-level jet (LLJ) – US Great Plains
  - U_J, Z_J important scales in wSBL, mSBL
    - Speed, height of LLJ
  - Shear ~ 0.1 s^{-1}
  - Streamwise $\sigma_u^2 \approx$ TKE in stable conditions
  - Peak σ_u ~ 5% of U_J
  - Quantitative relationships between mean LLJ properties and turbulence in the SBL
    - Necessary for NWP model verification (mesoscale, LES, DNS)



Banta 2008: Acta Geophys.



Composite from lidar profile data



Horizontal profile variability

- Vertical structure important, *BUT…*
  - – How does that structure vary horizontally ?
- Flow dynamics driven by horizontal gradients – pressure, T, …
- How well do NWP models capture that horizontal variability ?

Commercially-Available Lidars for Wind Energy Applications

Examples

QinetiQ Zephyr

Continuous Wave (CW) Lidar

Scanning Lidars

Leosphere 200-S

Lockheed-Martin WindTracer

Wind Profiling Lidar

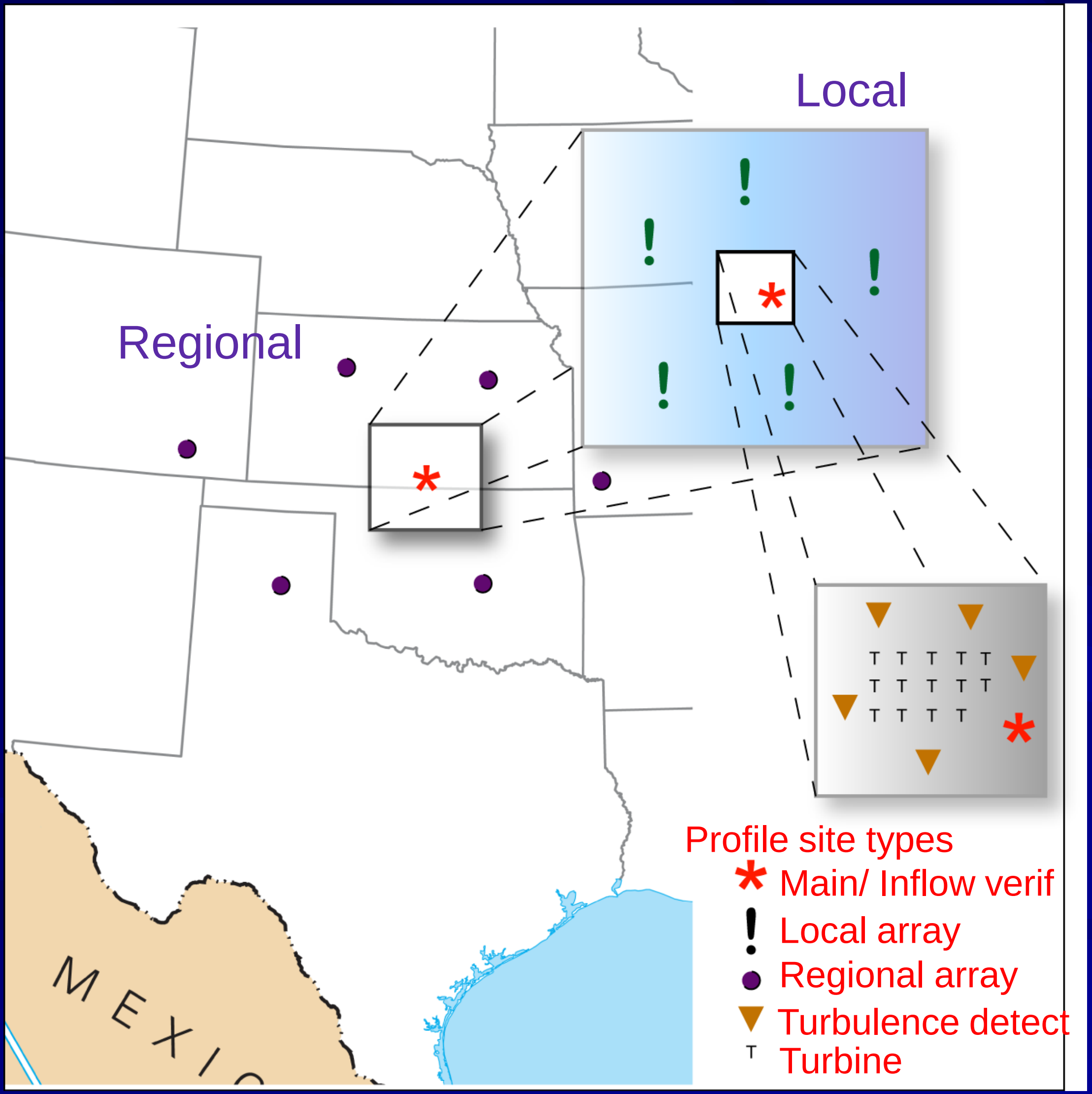
NRG/Leosphere WindCube

Pulsed Coherent Lidars

HALO Photonics

Nested-array example

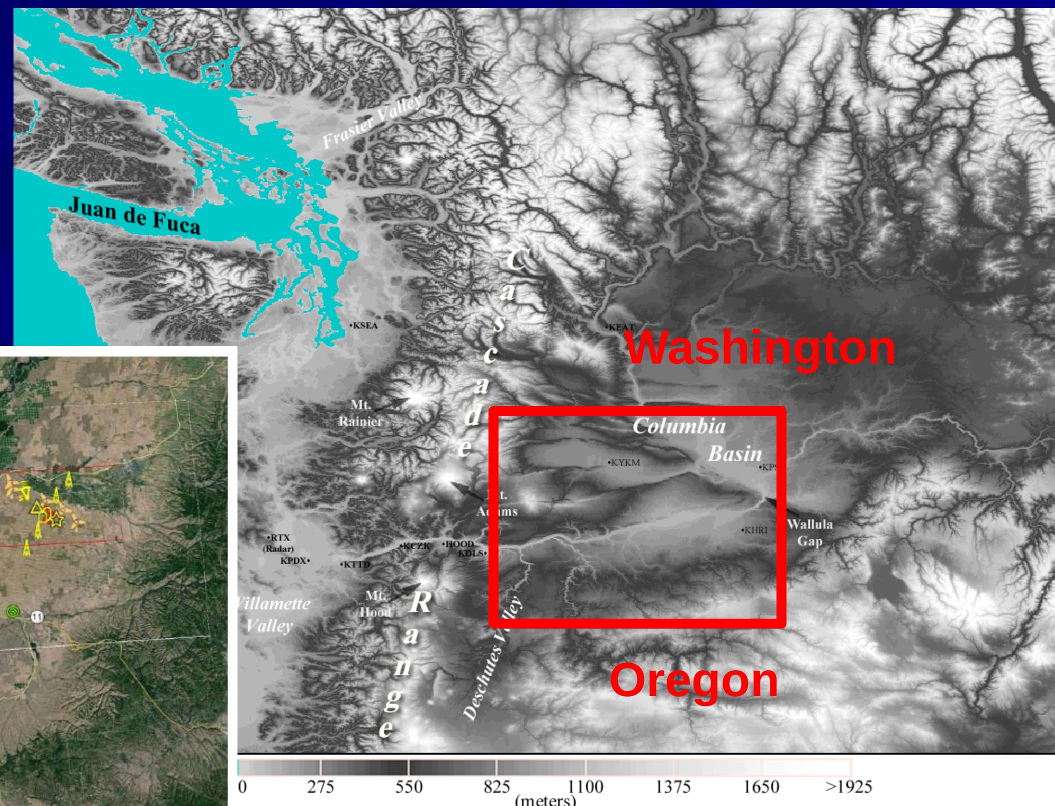
Multi-scale arrays of profiling sites

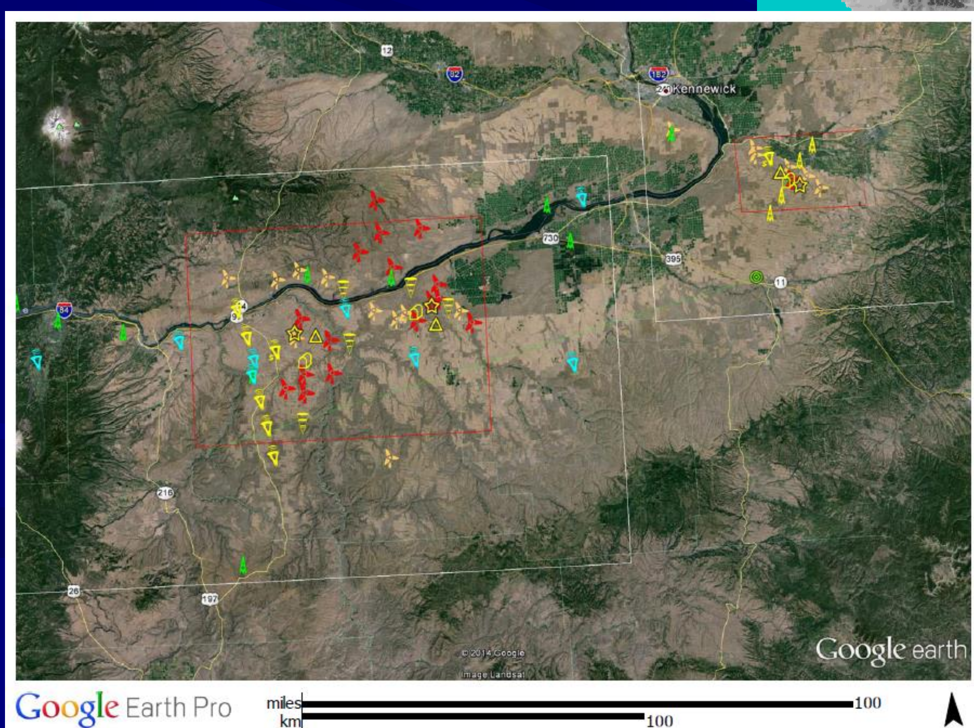


- Main site for verif. *(close-in array, turbc)*
- Local array 1-h+ circumference
  - Next larger scales
- Regional array ~ mesoscale gradients
- Regional arrays will overlap
- Tracking flow features– from outer to inner arrays

Wind Forecast Improvement Project – 2
(DOE, NOAA sponsored)

18-month forecasting project will start Sept 2015





Several Doppler lidars deployed as part of multiscale arrays of sensors

Summary

- Doppler lidar provides high-quality wind data in the previously undersampled region of the atmosphere
- Scan, image data – cool, revealing
- Profile data → important quantitative information
- Arrays of lidars → profiles, data over a region
  - Where real advances in understanding, modeling of atmospheric flows for wind energy (and solar) will come

Thank you!