Investigation of Wind Plant Wake Effects at the AWAKEN Field Campaign

Aliza Abraham, Stefano Letizia, Nicola Bodini, Nicholas Hamilton, Pat Moriarty

American Physical Society Division of Fluid Dynamics

November 20, 2023

Photo by Dennis Schroeder, NREL 55200

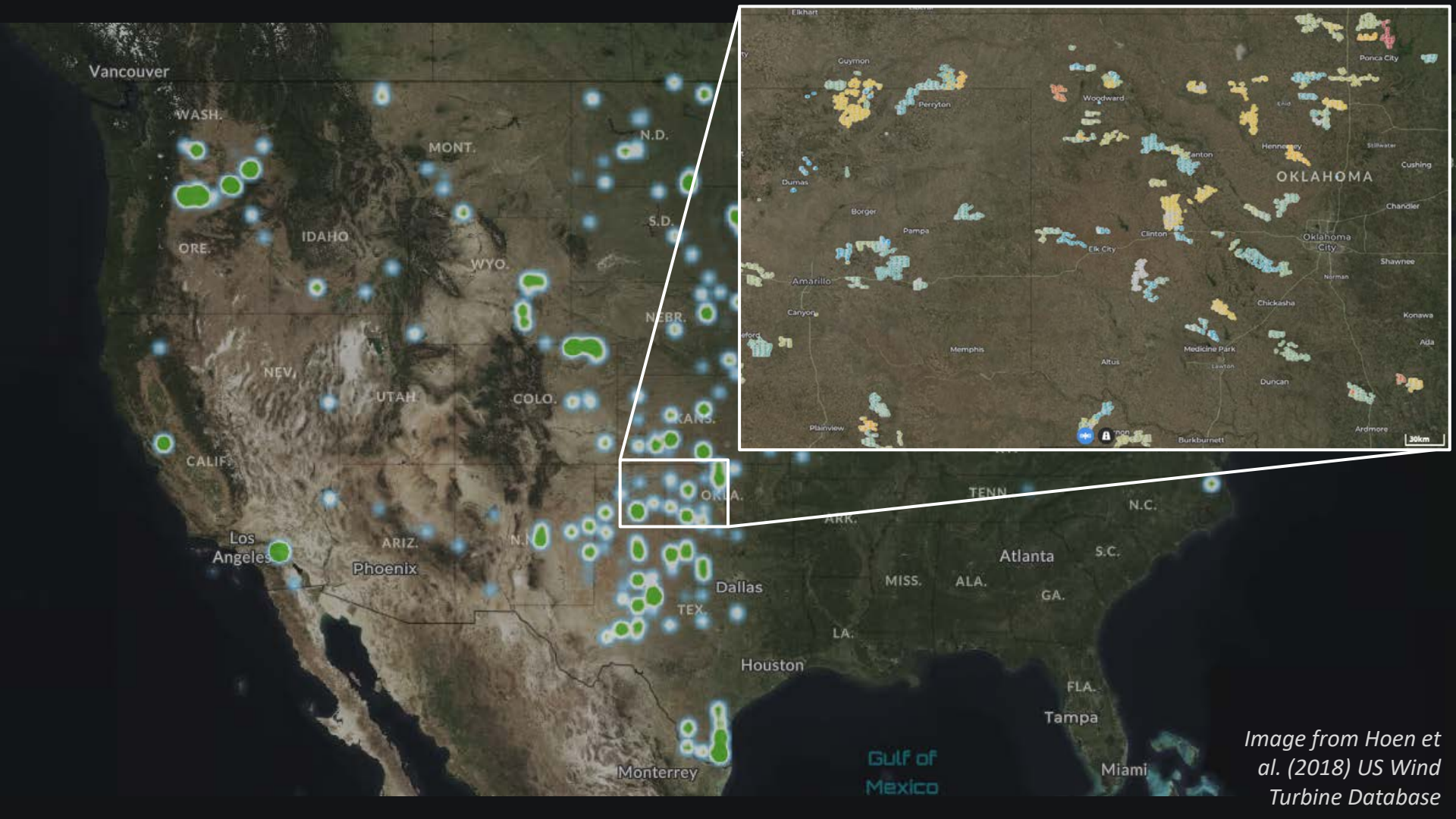
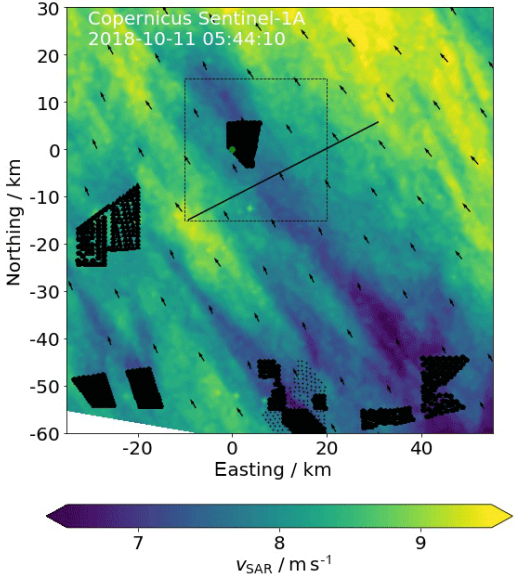


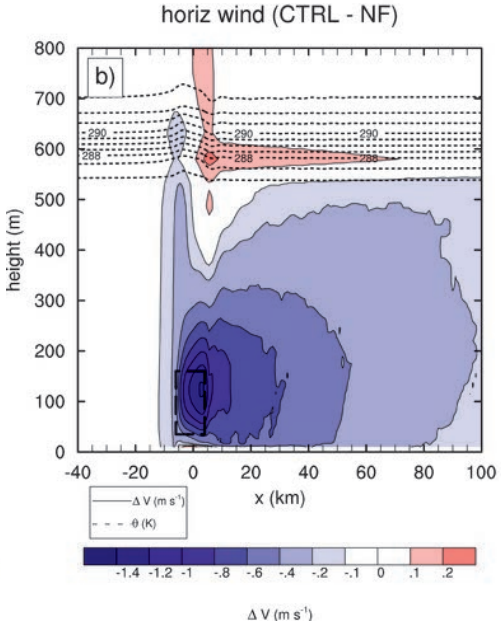
Image from Hoen et al. (2018) US Wind Turbine Database

Wind Plant Wakes

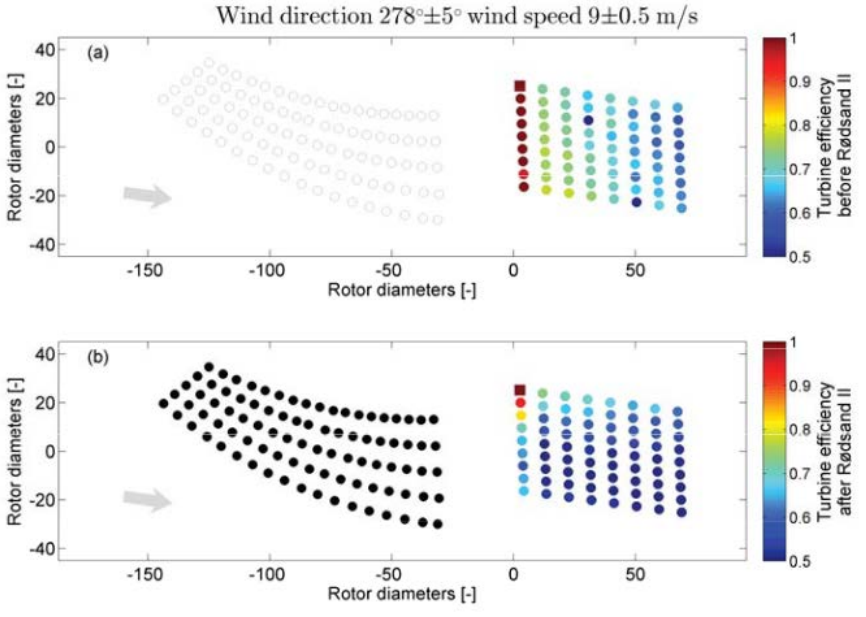
Offshore studies observe wakes persisting > 50 kilometers (km) (Schneemann et al. 2020)



Models show wakes > 100 km long (Fitch et al. 2012)



Turbine efficiency reduces substantially after neighboring plant construction (Nygaard 2014)



American WAKE experiment (AWAKEN) Field Campaign

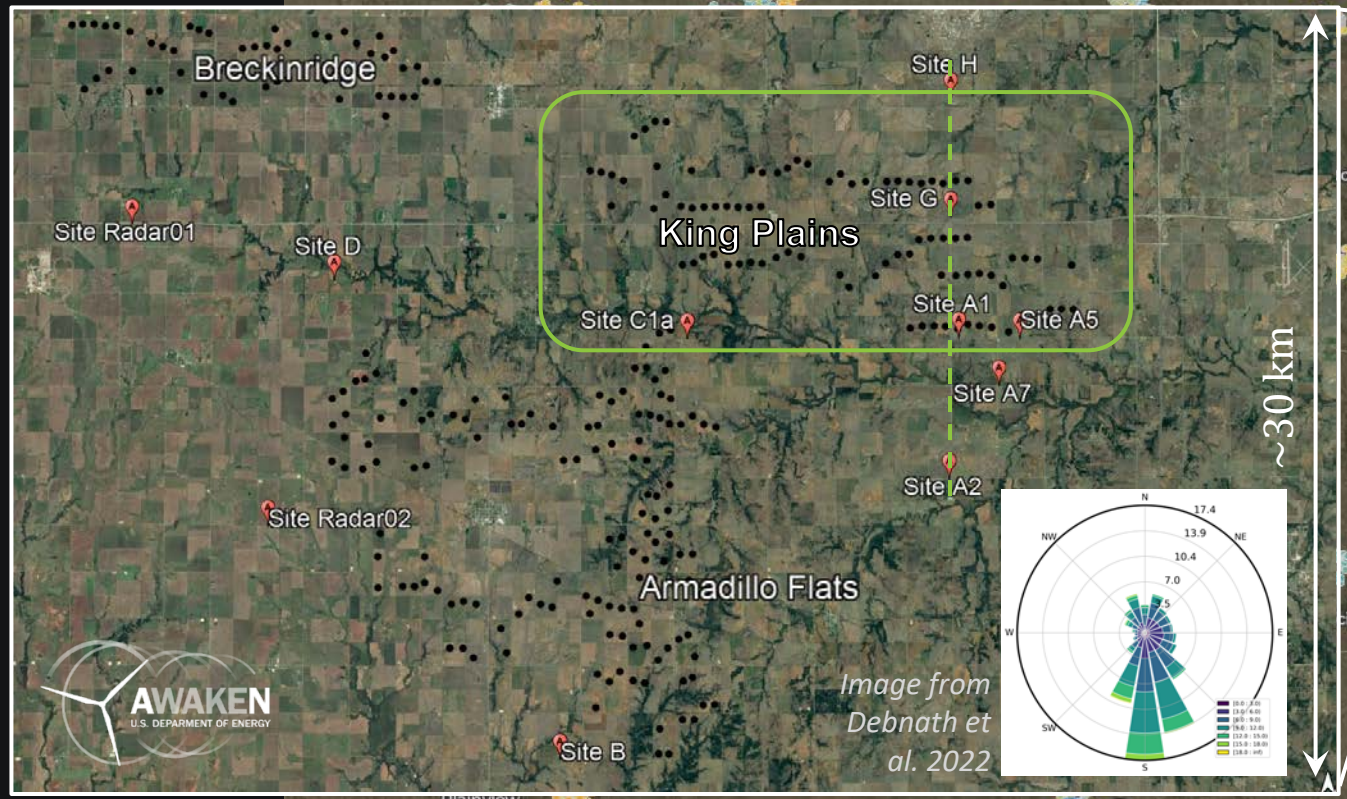
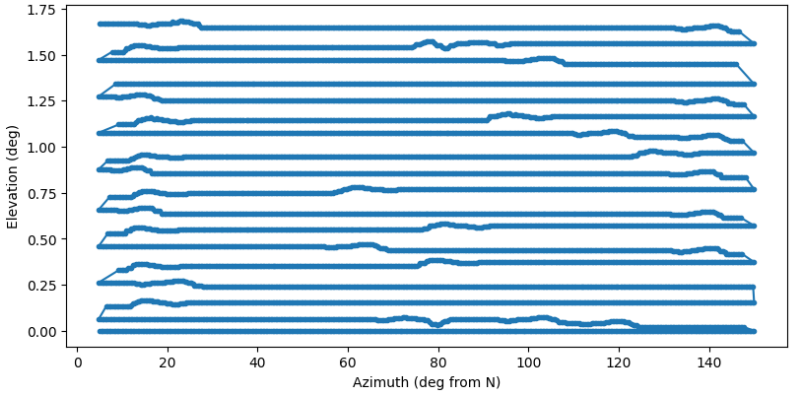


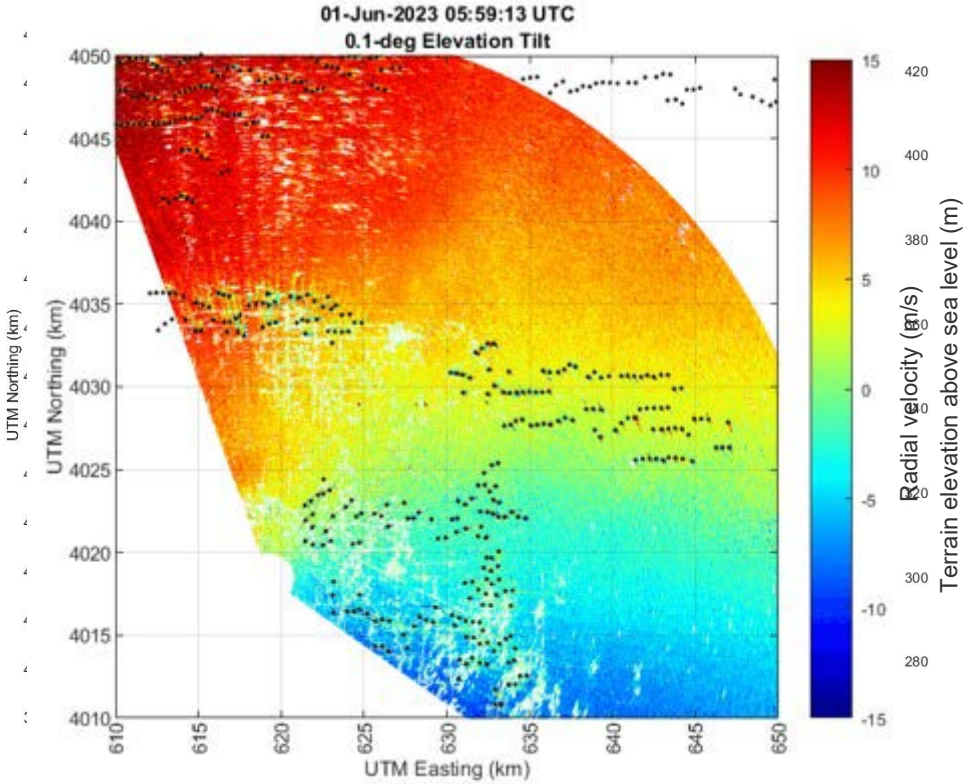
Image from Hoen et al. (2018) US Wind Turbine Database

- Multi-institutional collaboration
- Thirteen ground-based measurement sites
- Two years of data collection
- Focus on north-south transect of King Plains

X-band Dual Doppler Radar

- Two custom radars measure radial wind speeds in overlapping region
- Range > 30 km with 9-meter (m) resolution
- 145° sector scans with 0.5° resolution
- ~124 second revisit time.

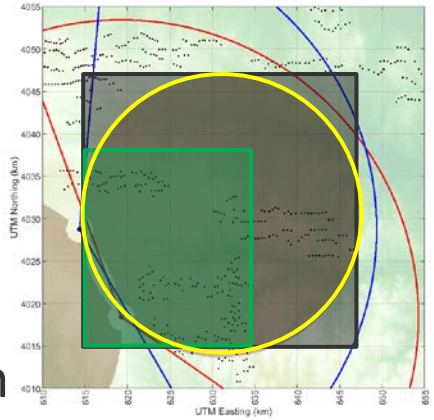


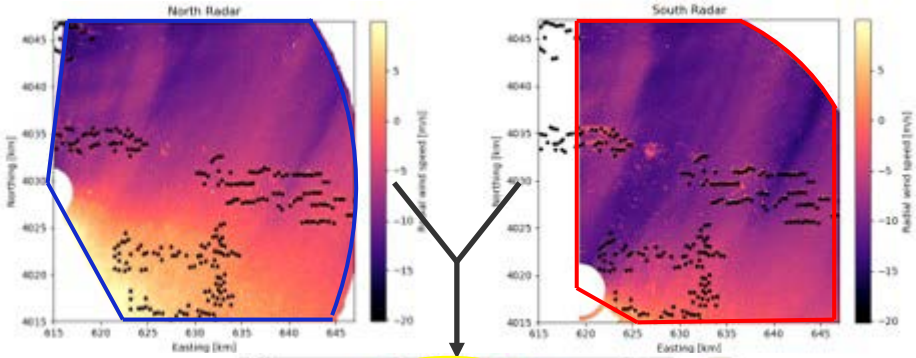


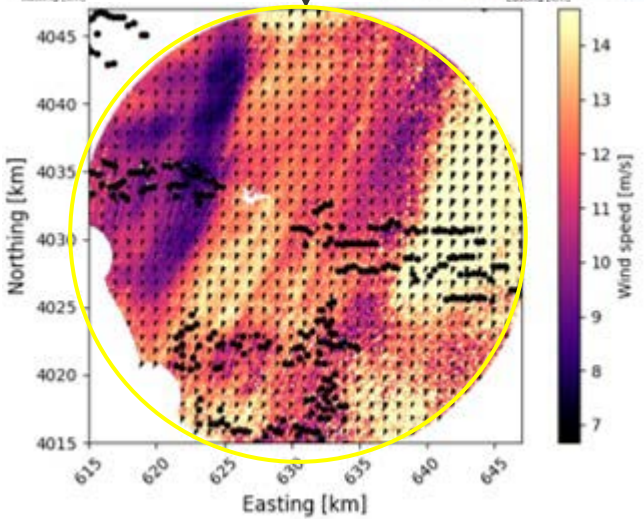
From Brian Hirth and John Schroeder, Texas Tech University

Interpolation and Reconstruction

- Radial velocities interpolated to Cartesian grids
  - **Fine grid**: 25 m
  - **Coarse grid**: 50 m
- Vertical resolution of 25 m for both grids
- Quality control procedure eliminates periods with low quality/availability
- Geometrically reconstruct radial velocities into horizontal velocity vector.

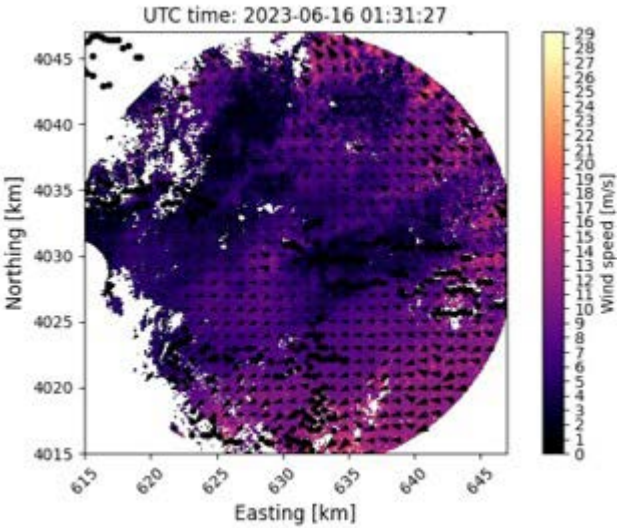




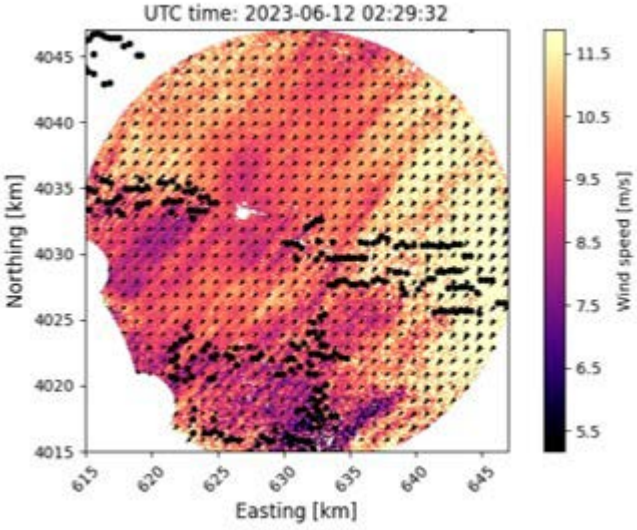


Examples of Interesting Phenomena

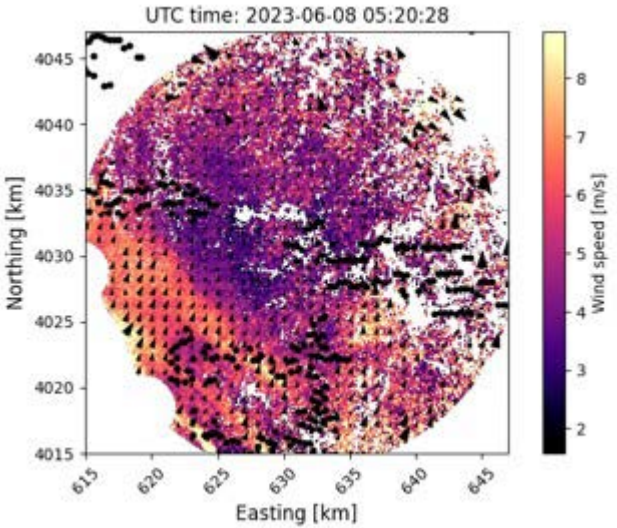
Frontal Passage



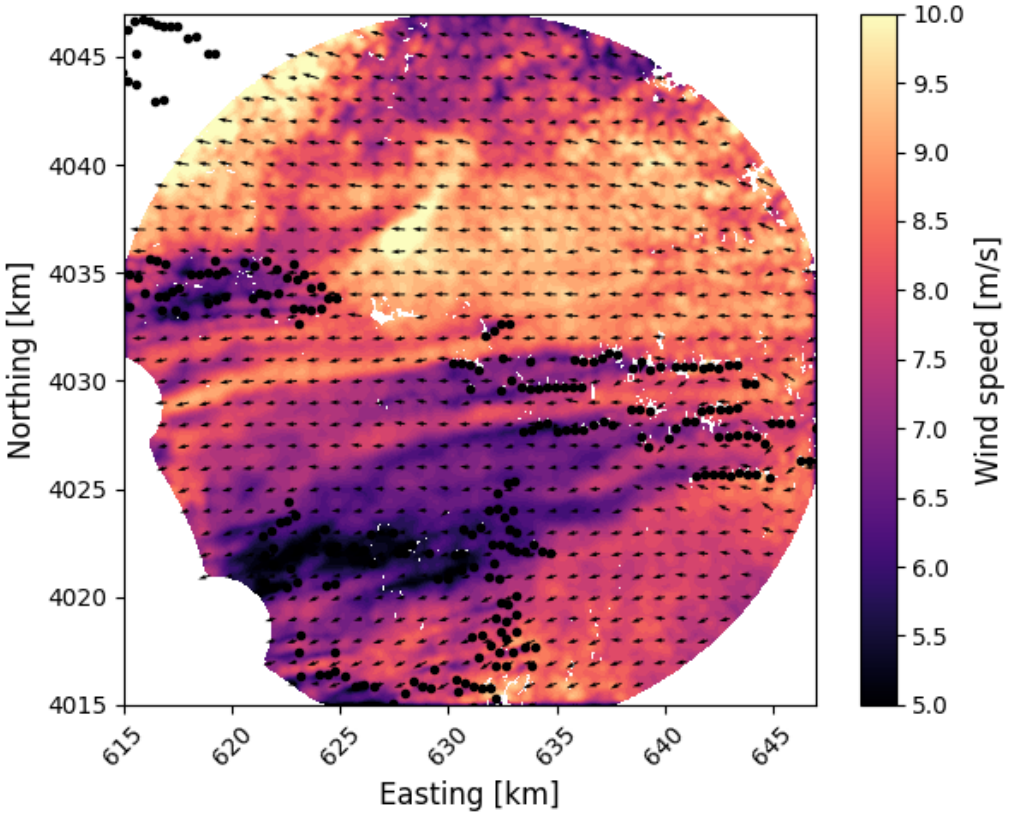
Wind Plant Interaction



Gravity Waves

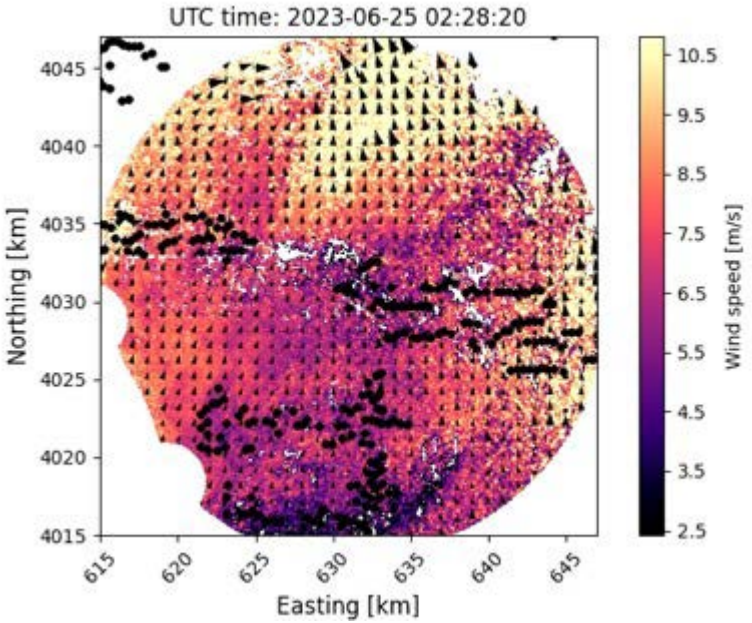


Objective: Characterize wind plant wakes to understand and predict their impacts on neighboring plants and their environment

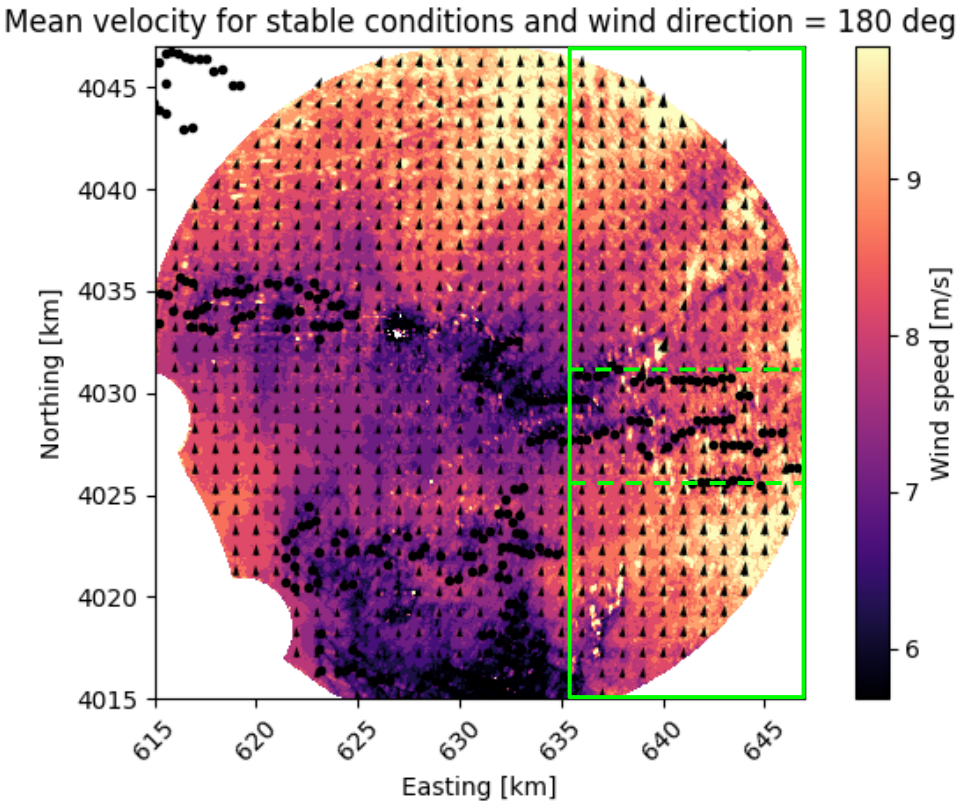


Data Binning

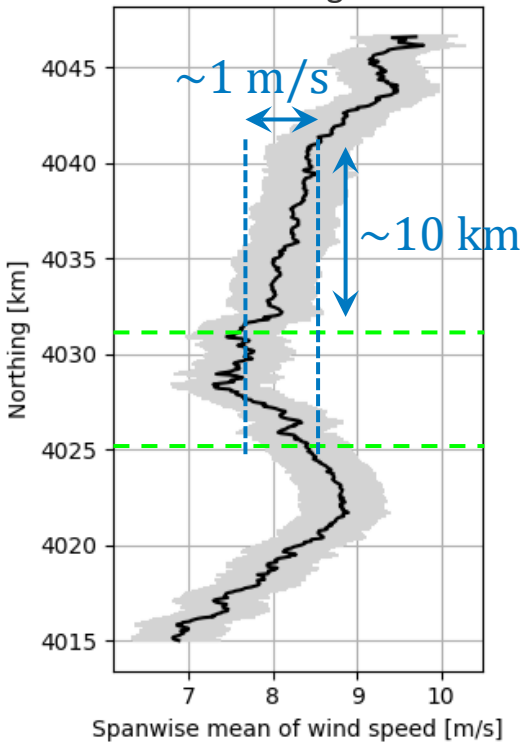
- Identify periods with available dual-Doppler radar data and:
  - Wind from south ($180° \pm 10°$) based on upstream profiling lidar
  - Stable atmospheric boundary layer ($0\ \mathrm{m} < L_{\mathrm{Obukhov}} < 600\ \mathrm{m}$)
  - Minimum contiguous duration of 30 minutes
  - ≥ 80% of King Plains operating normally
  - No extreme variations within domain
- Eight periods totaling 513 minutes selected.



Ensemble Average

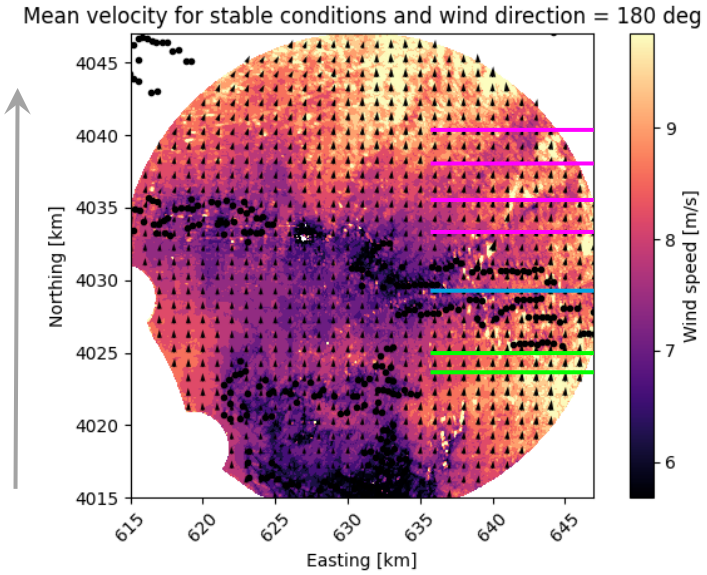


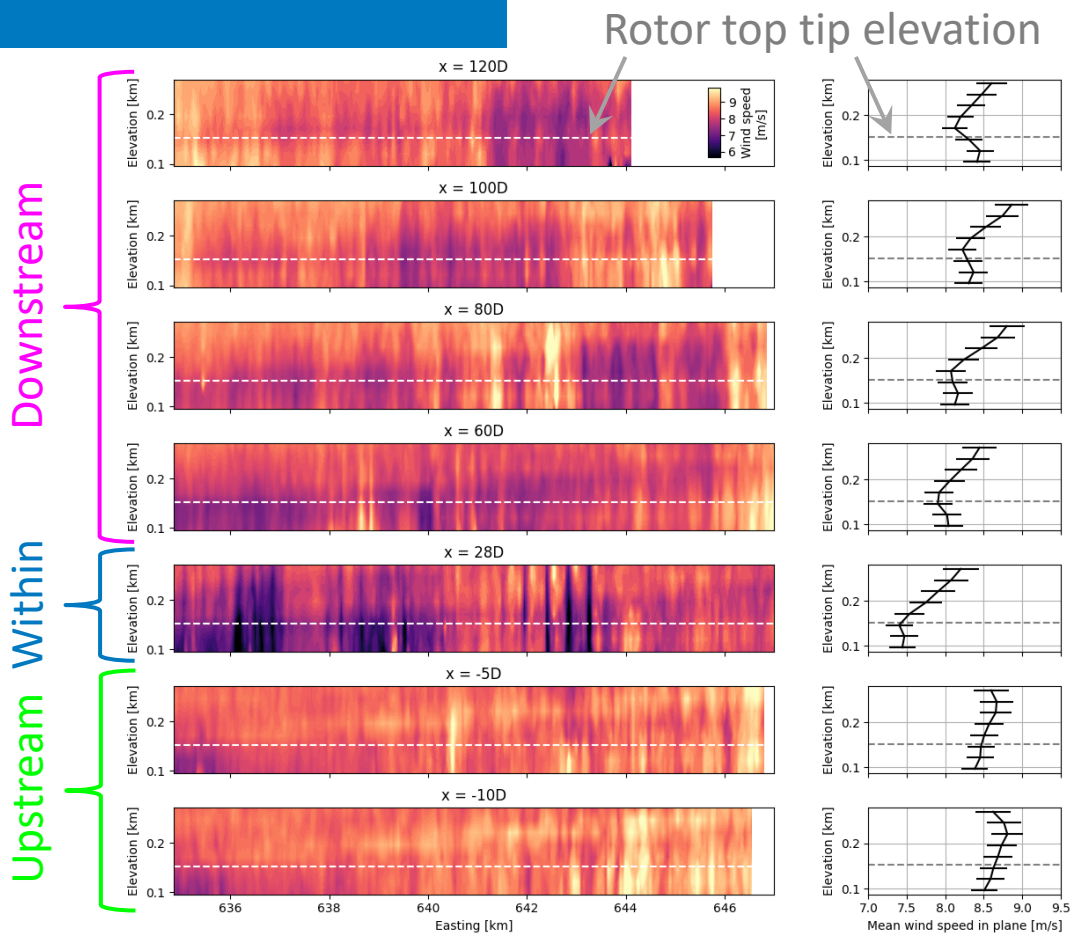
East-west average over eastern King Plains



Vertical Distribution

Velocity profiles show deficit persisting farther above rotor top tip





Conclusions

- X-band radar captures velocity volume containing three wind plants in AWAKEN field campaign
- Enables wind plant wake quantification
  - Velocity deficit ~ 1 meter per second (m/s)
  - Extent $\gtrsim 10$ km, especially at elevations above the plant
- Results will be used for model validation and benchmarking.

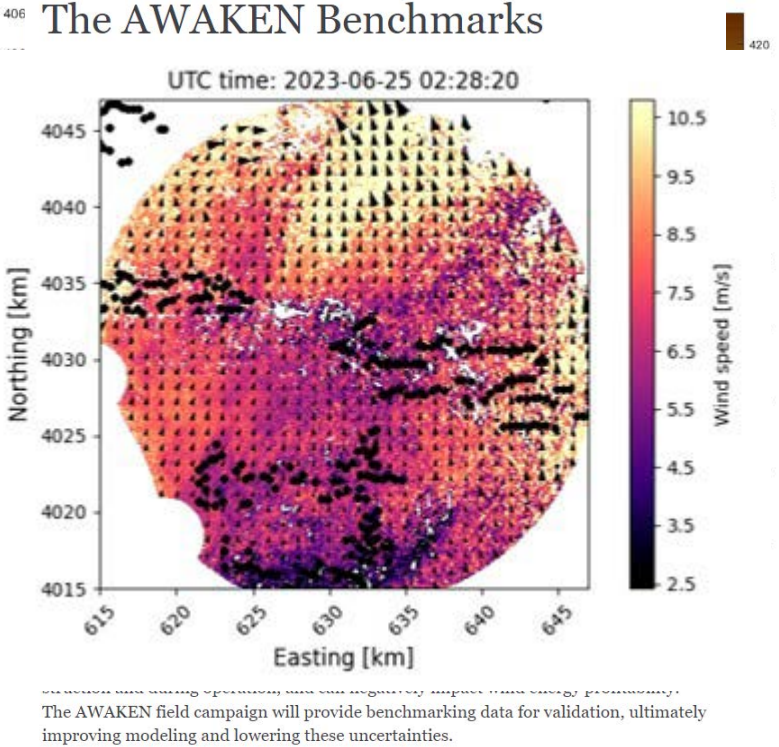
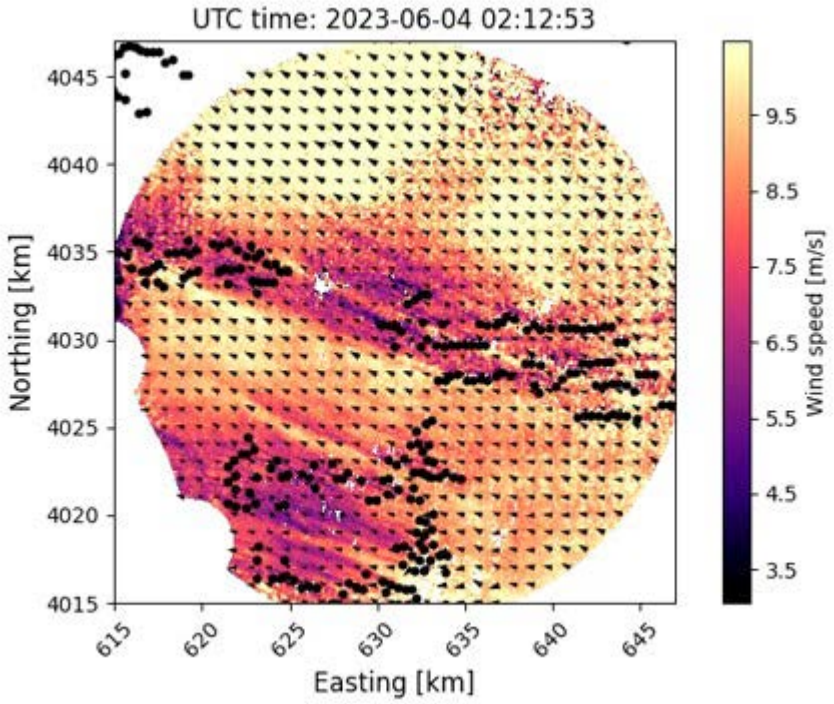


Image from https://awaken-benchmark.readthedocs.io/

Other Scientific Questions

- Interaction with atmospheric dynamics
  - Low-level jets
  - Gusts and wind direction changes
  - Frontal passages
  - Gravity waves
- Plant blockage and speed-ups
- Neighboring plant losses
- Comparison between radar and other instruments.



Acknowledgements

Brian Hirth, Texas Tech University

John Schroeder, Texas Tech University

Photo by Bryan Bechtold, National Renewable Energy Laboratory

References

Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database v6.0 (May 31, 2023): U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.

Schneemann, Jörge, Andreas Rott, Martin Dörenkämper, Gerald Steinfeld, and Martin Kühn. "Cluster Wakes Impact on a Far-Distant Offshore Wind Farm's Power." *Wind Energy Science* 5, no. 1 (January 2020): 29–49. https://doi.org/10.5194/wes-5-29-2020.

Fitch, Anna C., Joseph B. Olson, Julie K. Lundquist, Jimy Dudhia, Alok K. Gupta, John Michalakes, and Idar Barstad. "Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model." *Monthly Weather Review* 140, no. 9 (2012): 3017–38. https://doi.org/10.1175/MWR-D-11-00352.1.

Nygaard, Nicolai Gayle. "Wakes in Very Large Wind Farms and the Effect of Neighbouring Wind Farms." *Journal of Physics: Conference Series* 524 (June 16, 2014): 012162. https://doi.org/10.1088/1742-6596/524/1/012162.

Thank you!

Reach out with questions or ideas:

Aliza.Abraham@nrel.gov

NREL/PR-5000-88104

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Photo by Bryan Bechtold, National Renewable Energy Laboratory

Backup Slides

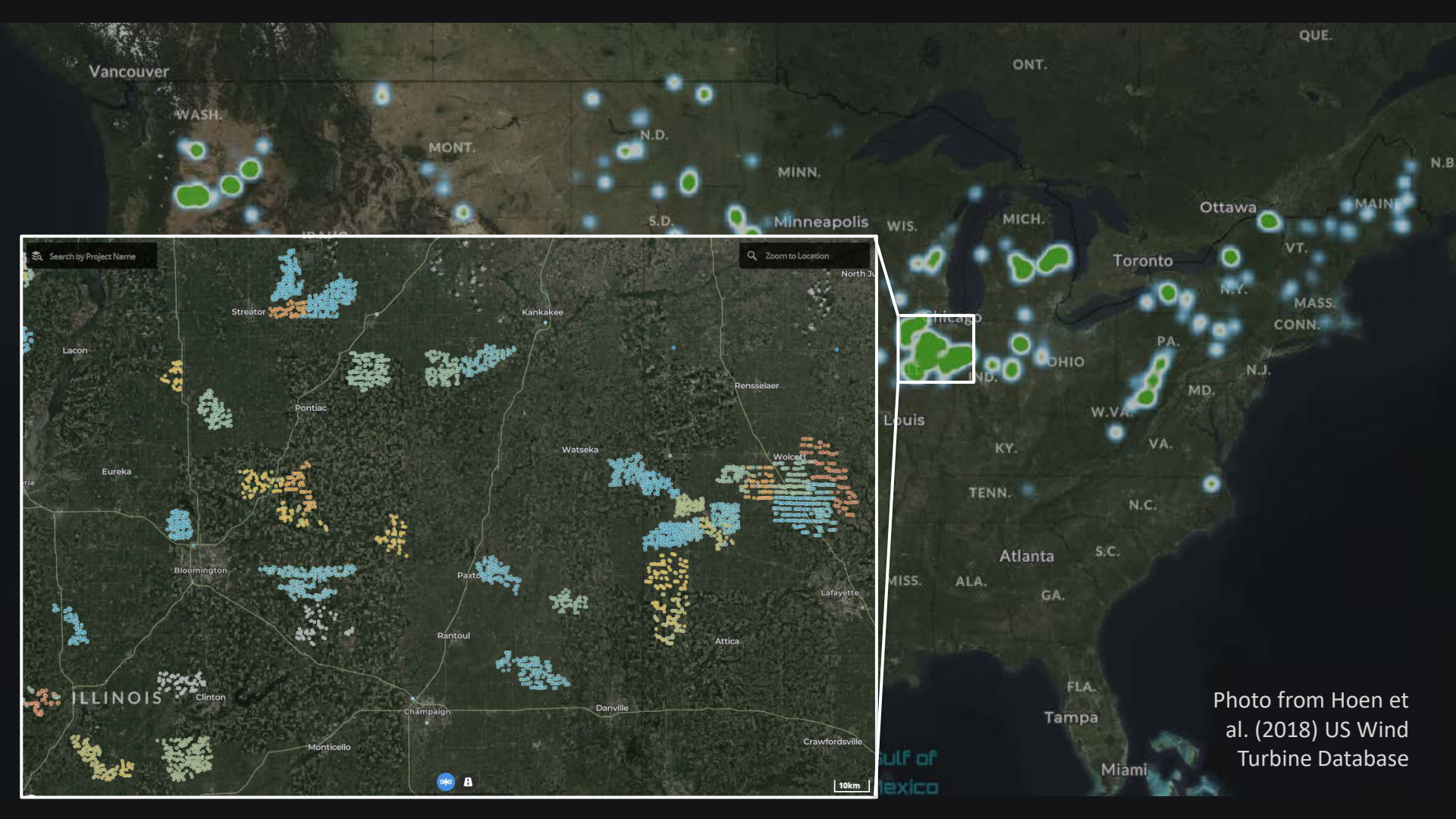
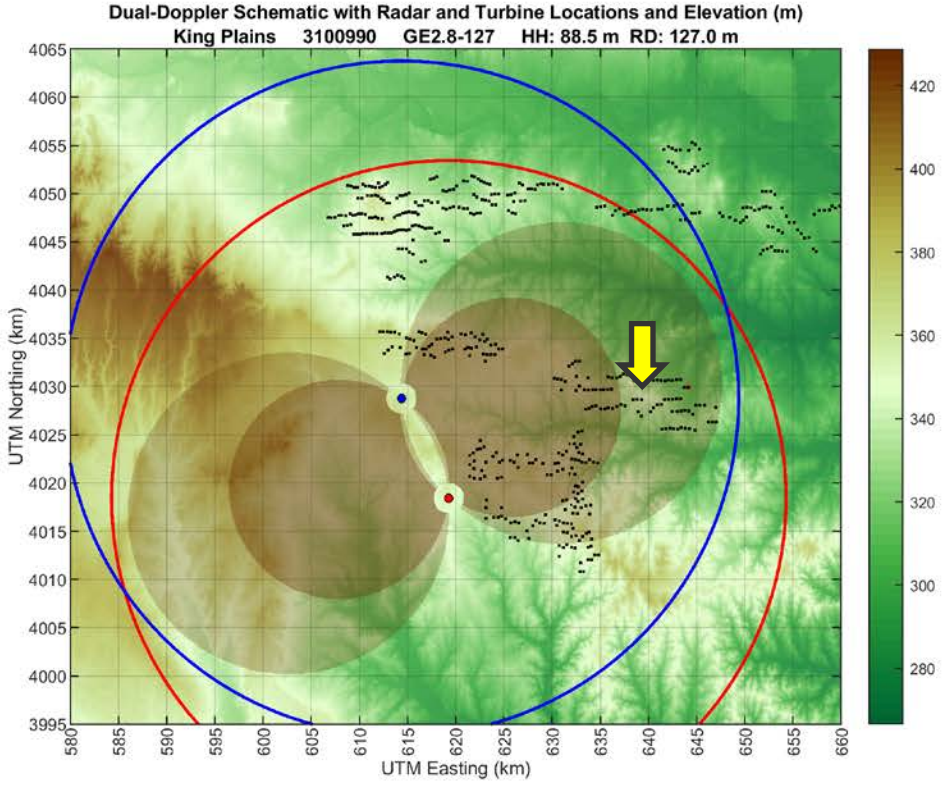
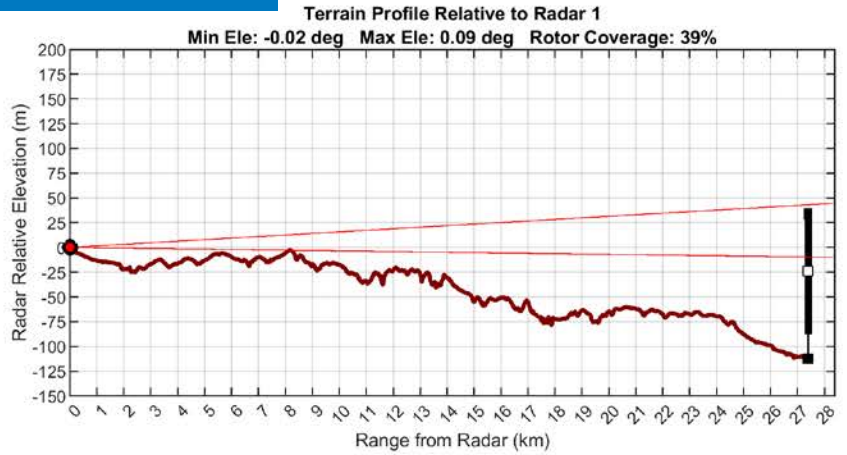
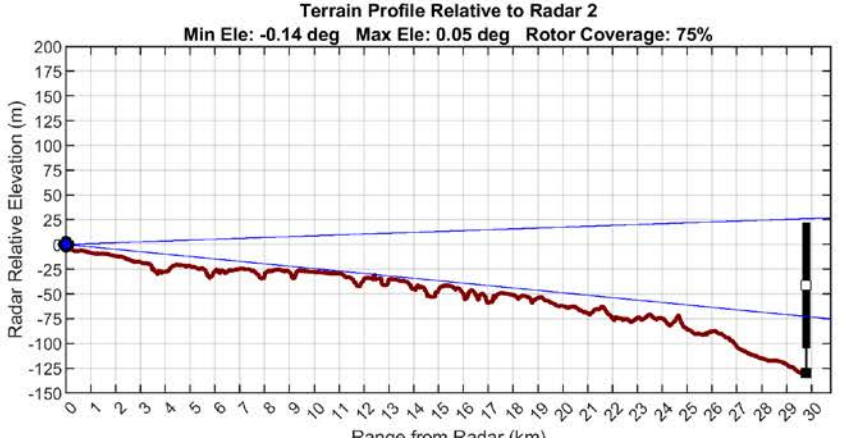


Photo from Hoen et al. (2018) US Wind Turbine Database

Terrain Effects



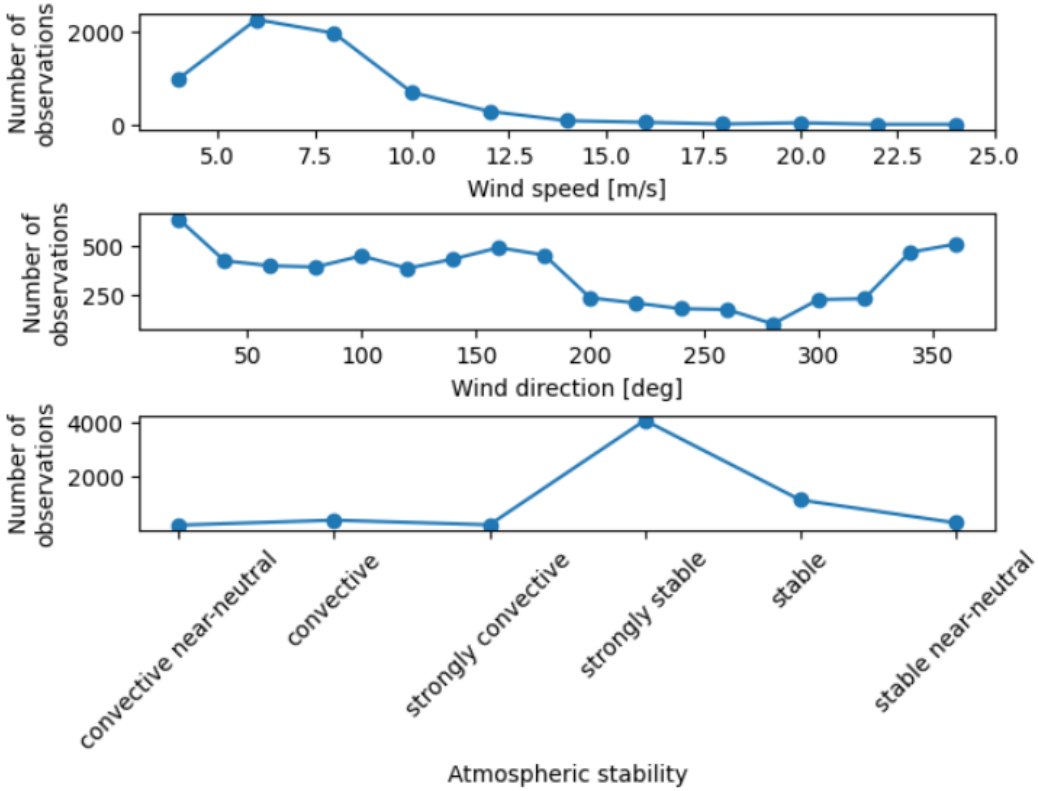




Figures from Brian Hirth and John Schroeder, Texas Tech University

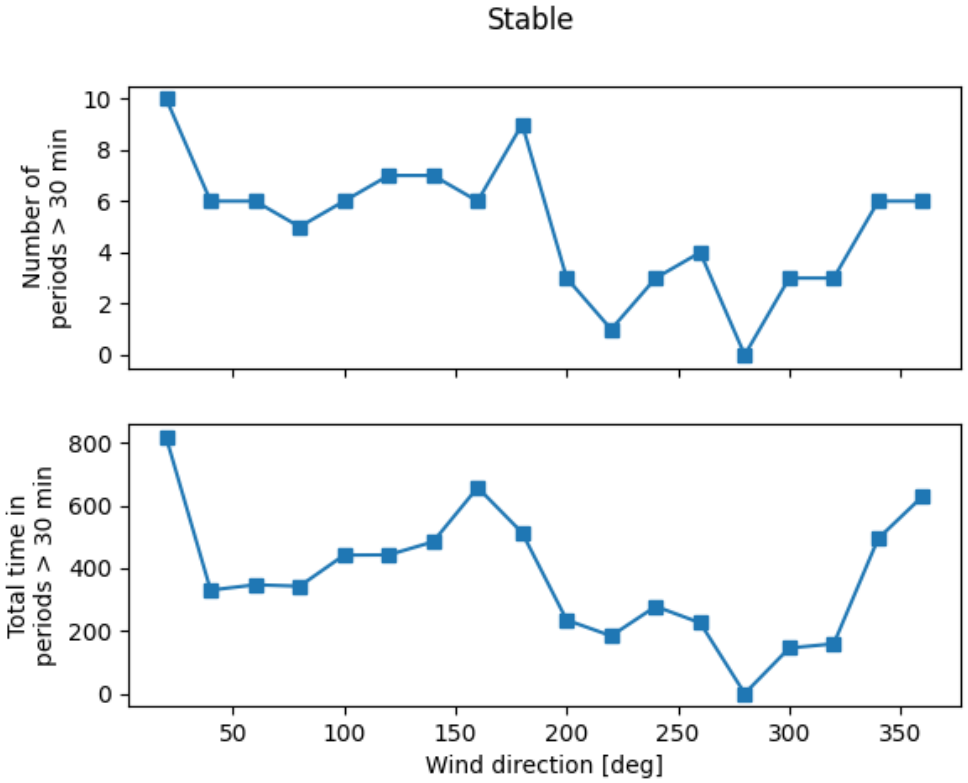
Data Binning

- Bin dual-Doppler velocity fields based on:
  - Hub-height wind speed and direction (profiling lidars)
  - Atmospheric stability (sonic anemometers)
- ≥ 80% of King Plains turbines operating normally



Data Binning

- Minimum averaging interval of 30 minutes (min) (20 km ÷ 10 m/s ÷ 60 s)
- Identify periods where wind stays in the same direction bin (20 degree [deg] width) and atmosphere is stable for at least 30 contiguous minutes
  - Allow gaps up to 10 min.



Time Series

- Period with consistent wind speed and direction
- Characterize velocity deficit at downstream planes.