Wake Losses in Wind Plants – Comparing Several Methods with Measured Wakes

Bob Conzemius, Dennis Moon, Joe Eastman

WindLogics, Inc.

201 NW 4th St., Grand Rapids, MN 55744

Why?

- **Wind farm performance typically is less than what was projected during the wind resource assessment, and turbine (SCADA) data cannot fully explain underperformance.**

- **Traditional wake estimation conceptually based on single wake; large wind farms have more of an aggregate effect.**

- **Traditional wake models assume wake recovery is diffusive process only.**

Data Sources

- Meteorological towers (before and after construction)
- Wind resource assessments (gridded data)
- Gridded reanalysis data (MERRA)
- Wind Turbine (SCADA) data – wind speed, power, curtailments, turbine faults, etc.

Models

- Traditional wake models (WindFarmer, OpenWind)
- WindFarmer, OpenWind with large wind farm effects
- Weather Research and Forecast (WRF) model with turbine parameterization (Fitch et al. 2012)

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Three Sources of Wake "Truth"

- **Upwind/downwind turbine pairs (SCADA data)**
- **Pre-post build tower analysis (Met towers and MERRA)**
- **WRA minus OpA (Modeling/Towers and SCADA)**

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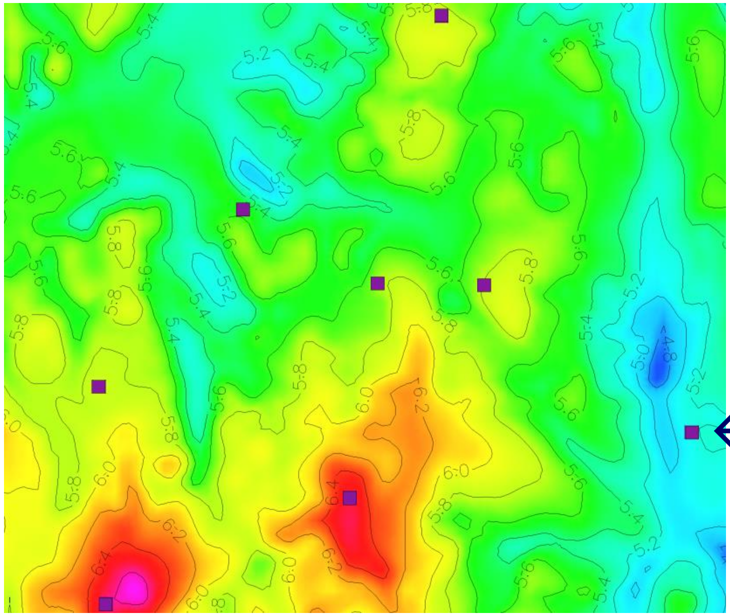
WRA minus OpA

- Inherently a full-farm estimation
- By definition, aggregated over the fleet, the right amount of “wake” (WRA-OpA wake) loss that is needed to reflect the losses incurred
- WRA-OpA wake includes actual wake, flow deviation, and power curve inefficiencies due to effects such as shear, as well as inaccuracies in WRA speed estimates
- The above factors contribute to scatter in the WRA-OpA estimates for individual sites

Wind Resource Assessments

- Conduct one year of WRF modeling
- Mass-constrained interpolation (Swift)
- Correct biases with meteorological tower data
- Long term normalization with MERRA dataset

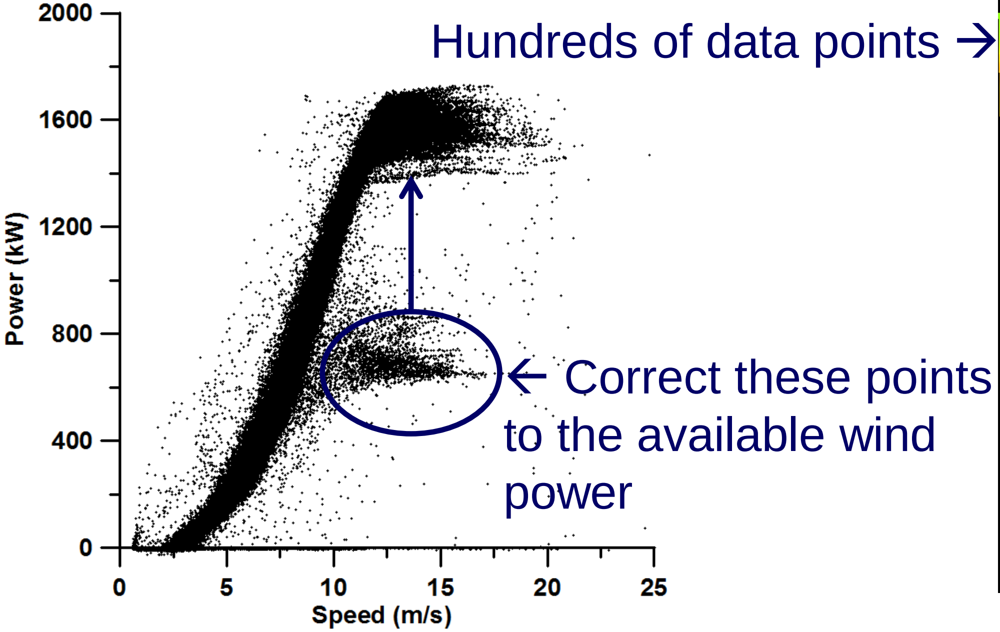


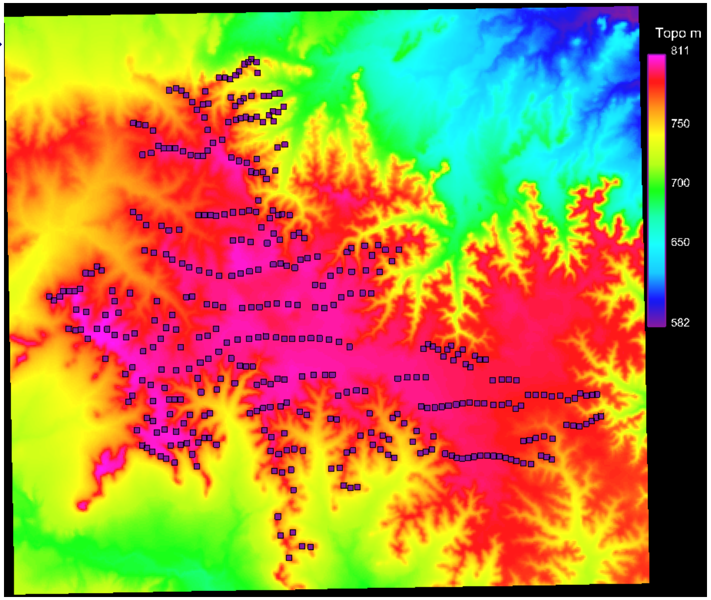
Map of wind resource without turbine waking is used as a baseline against which we compare operational data.

← Tower locations

Operational Assessments

- Use SCADA data to measure wind speed and power.
- Operational power curve specific to each turbine.
- Correct data points where power is below normal curve– accounts for curtailments, operating faults, icing, etc.
- Result is available power with curtailment and availability losses removed, so remaining loss is due to wake.
- Normalize the result with long term (MERRA) data.





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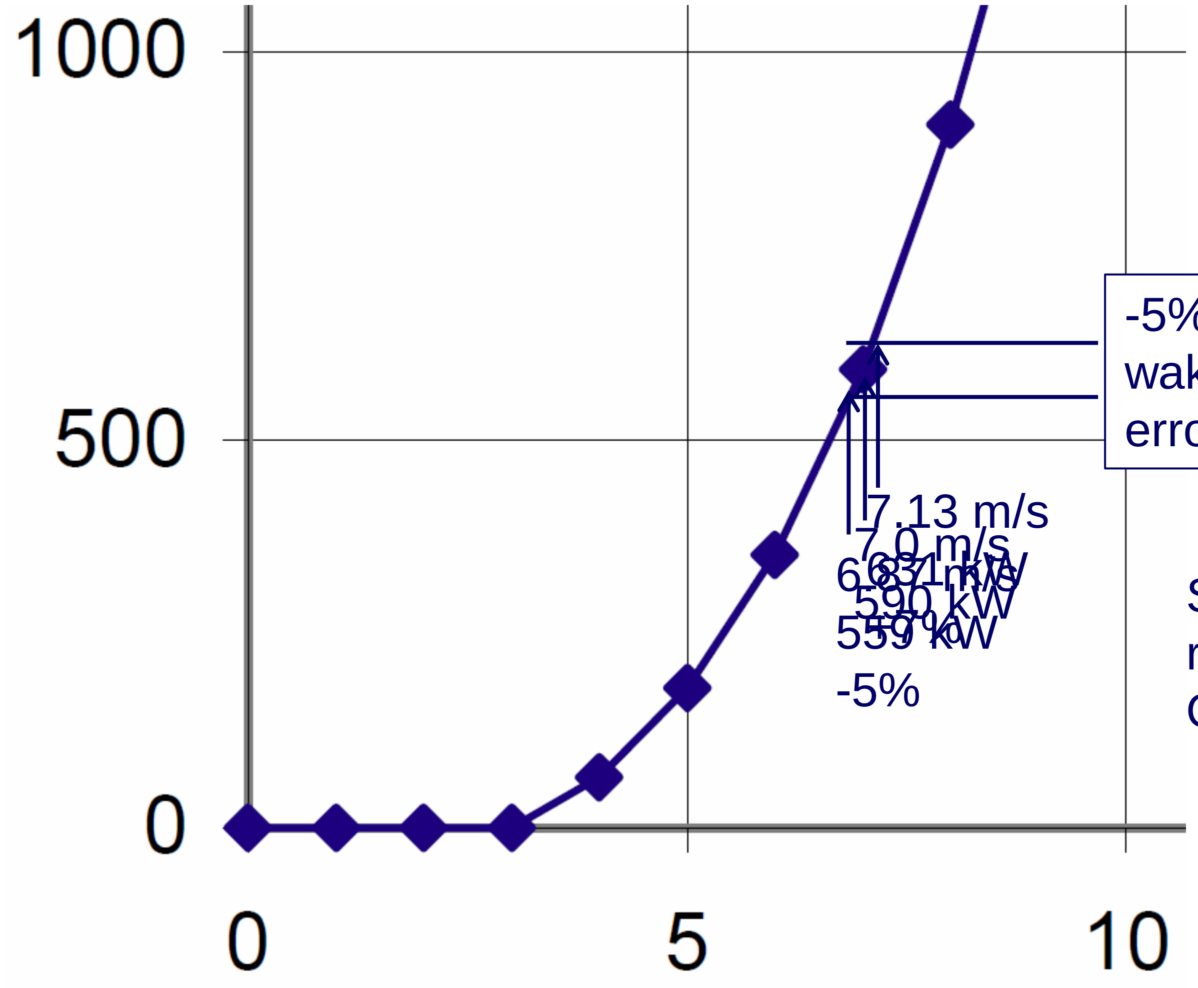
WRA GCF Speed Sensitivity



-5% to +7% swing in WRA-OpA wake due to typical speed errors

Small WRA errors can result in a significant WRA-OpA wake error.

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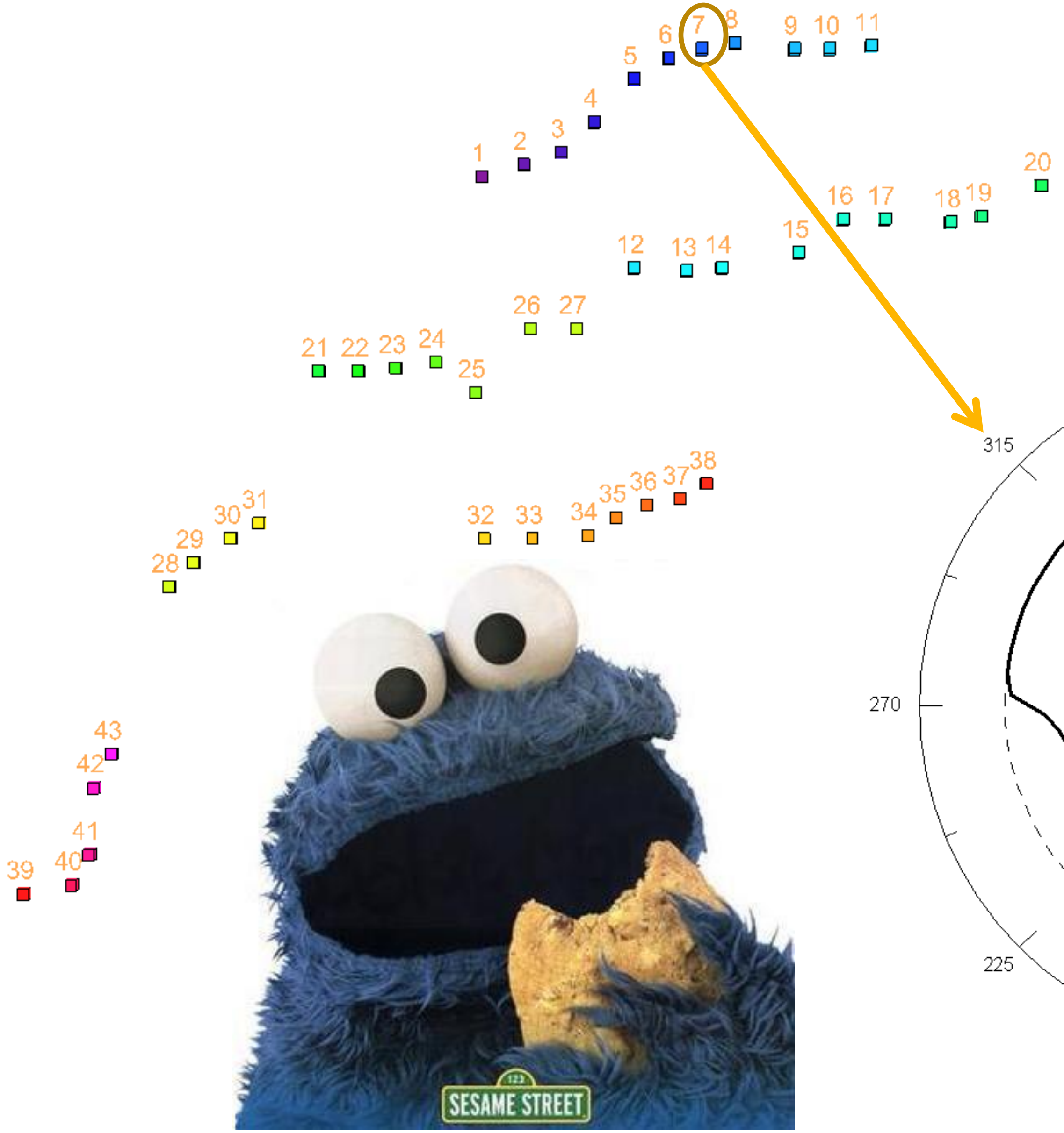
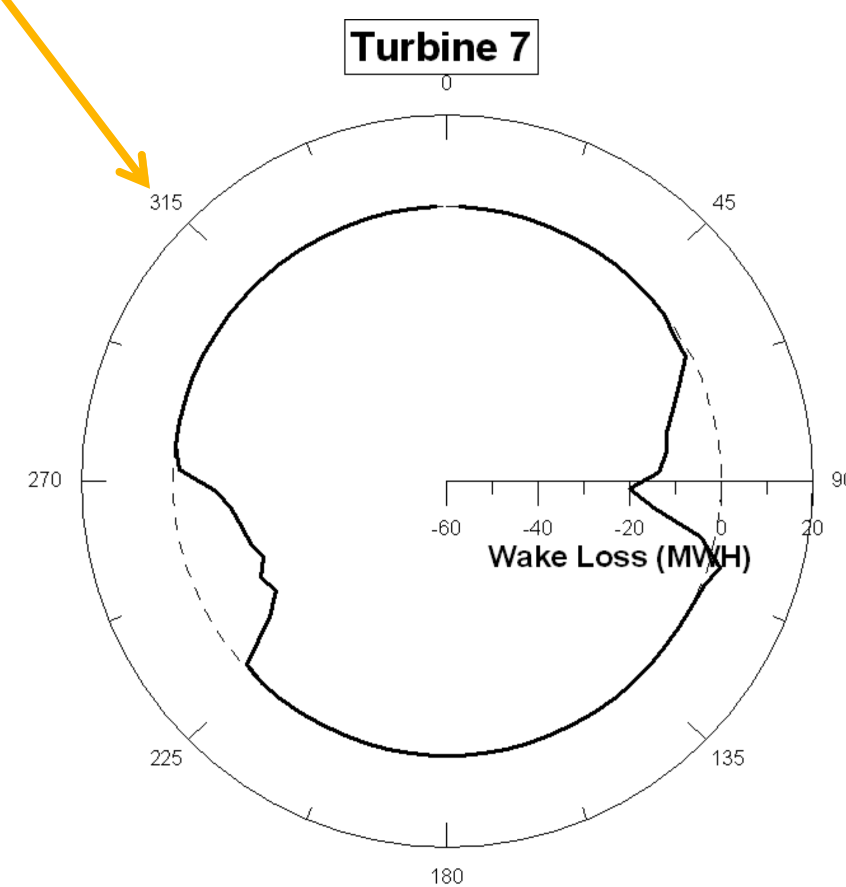
Upwind/Downwind Pairings





Upwind-Downwind Turbine Pairing

- **Works well for near-field pairings (< 10 R. D.)**
- **Cannot see far-field wakes (>= 10 R. D.), thus sees only 2% or 3% loss per site**
- **Essentially abandoned as a method (only 3 sites analyzed)**

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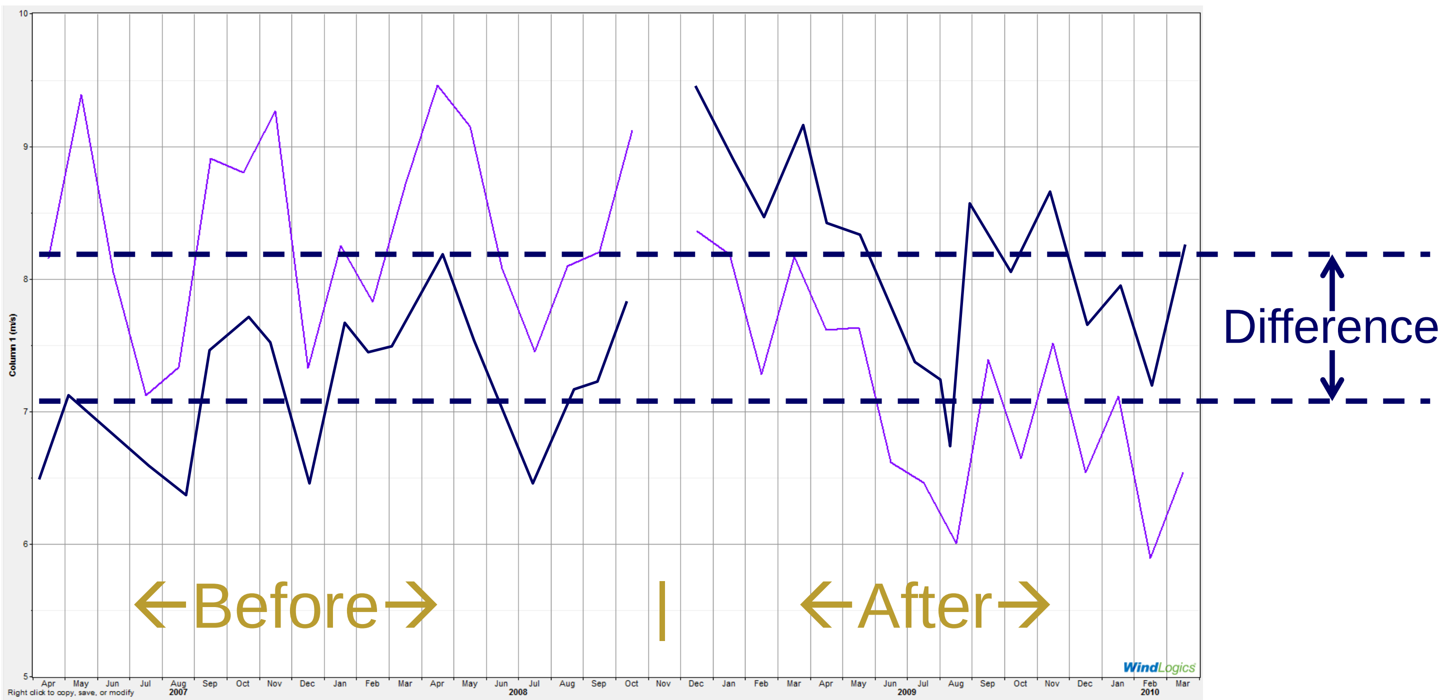
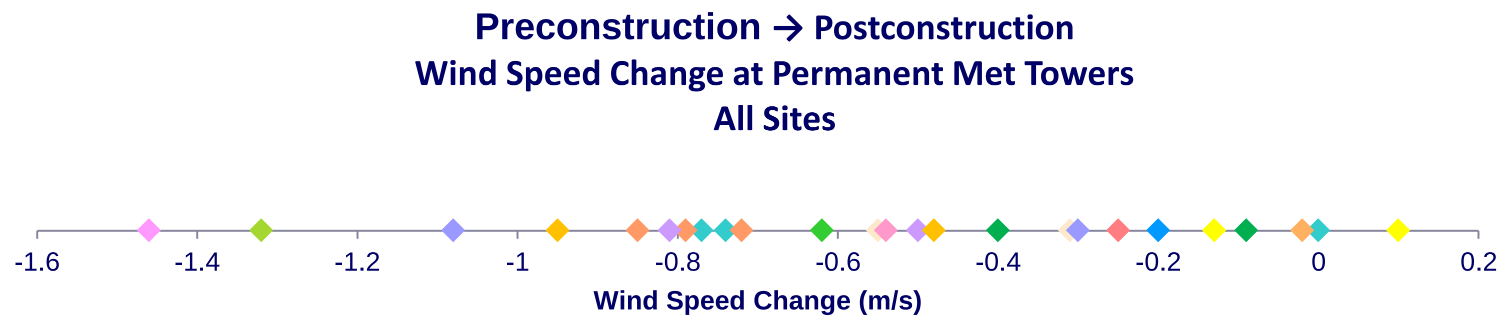
Pre-Post Build Tower Analysis

- **Use data from towers located onsite one year before and after wind farm.**
- **Use machine learning and MERRA to overlap datasets and calculate difference.**
- **Limited number of sites (23) and towers (typically one or two per site).**



Pre-Post Build Tower Analysis Results

- The impact of turbine wakes on the analyzed met speeds is substantial
- Speed reductions at the towers range from 0.04 m/s to almost 1.5 m/s
- Impacts were much larger at tower locations in the middle of the farms



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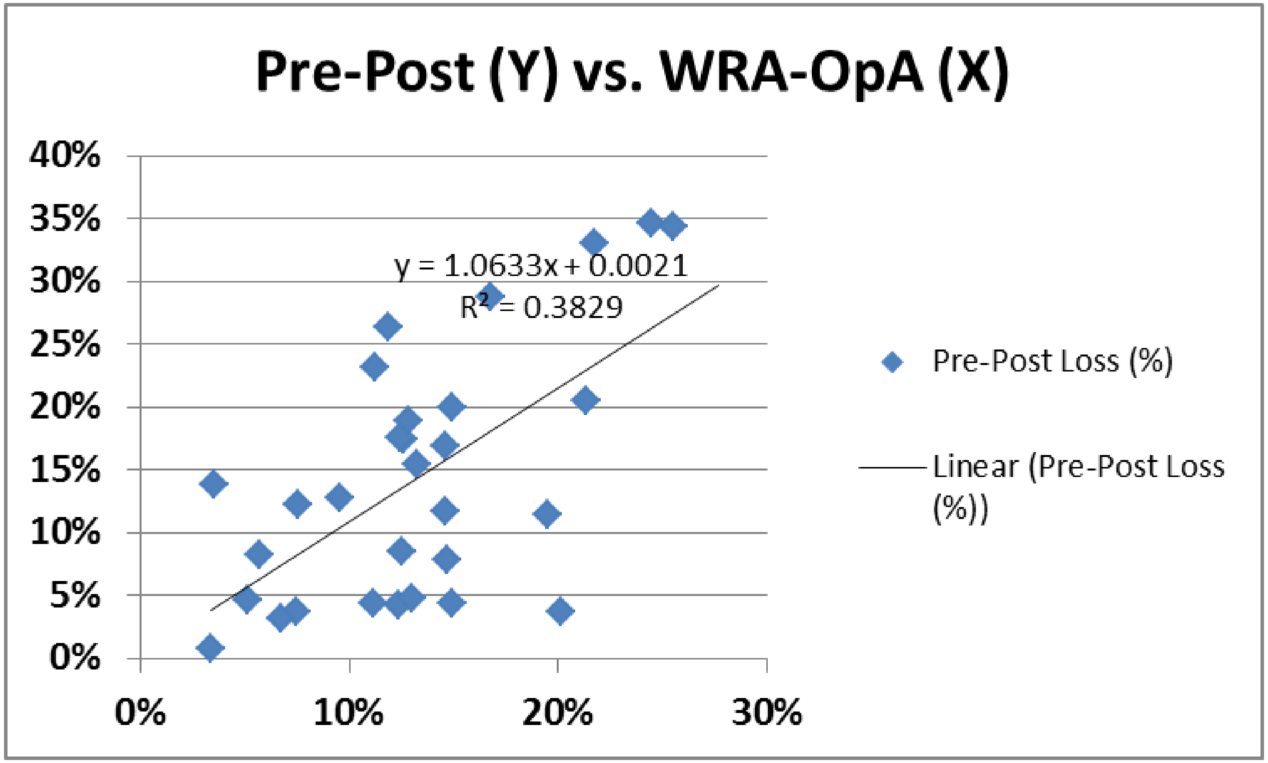
WRA Errors and Resulting WRA-OpA Wake Errors

- Mischaracterization of wake of at least several percent is likely within any single farm
- Over the whole fleet, these errors average to near zero
- Our two sources of wake truth show only a tenuous relationship due to both WRA GCF sensitivity and spatial sampling effects of the pre-post towers



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Two Sources of Pre-Build Wake Estimates

- **Wake models (OpenWind and WindFarmer)**
  - Simplified physics
  - Fast run time

- **Weather Research and Forecast model (WRF)**
  - Complex physics representation
  - Long run time

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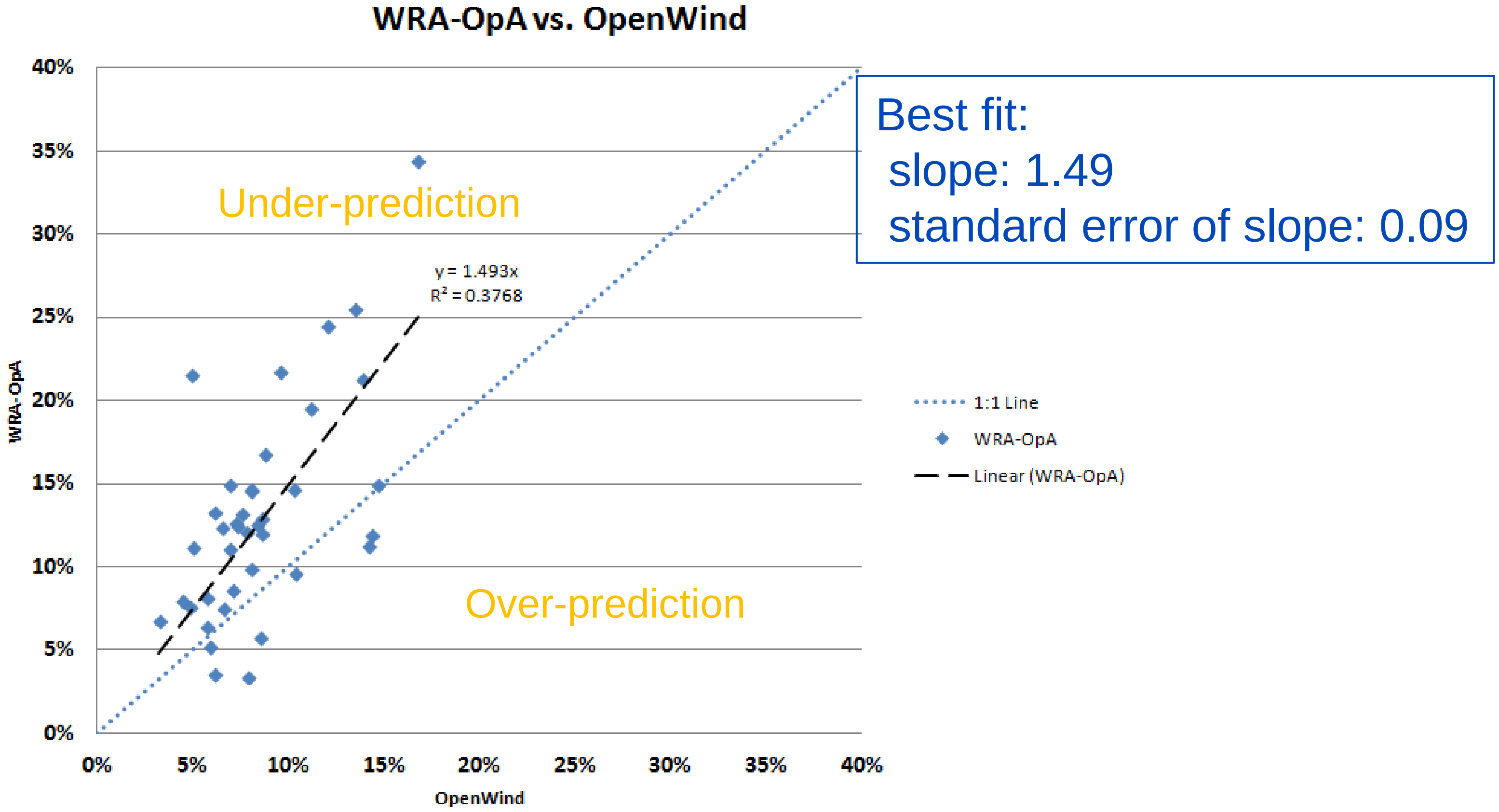
OpenWind/Wind Farmer

- **Legacy versions of these programs were confirmed (from recent literature) to under-predict wakes for large farms**
- **New versions of both include large wind farm correction (Deep Array), which in acts as an increase in surface roughness.**
- **Our tests show that these new versions also under-predict wake by ~33% for both small and large farms**



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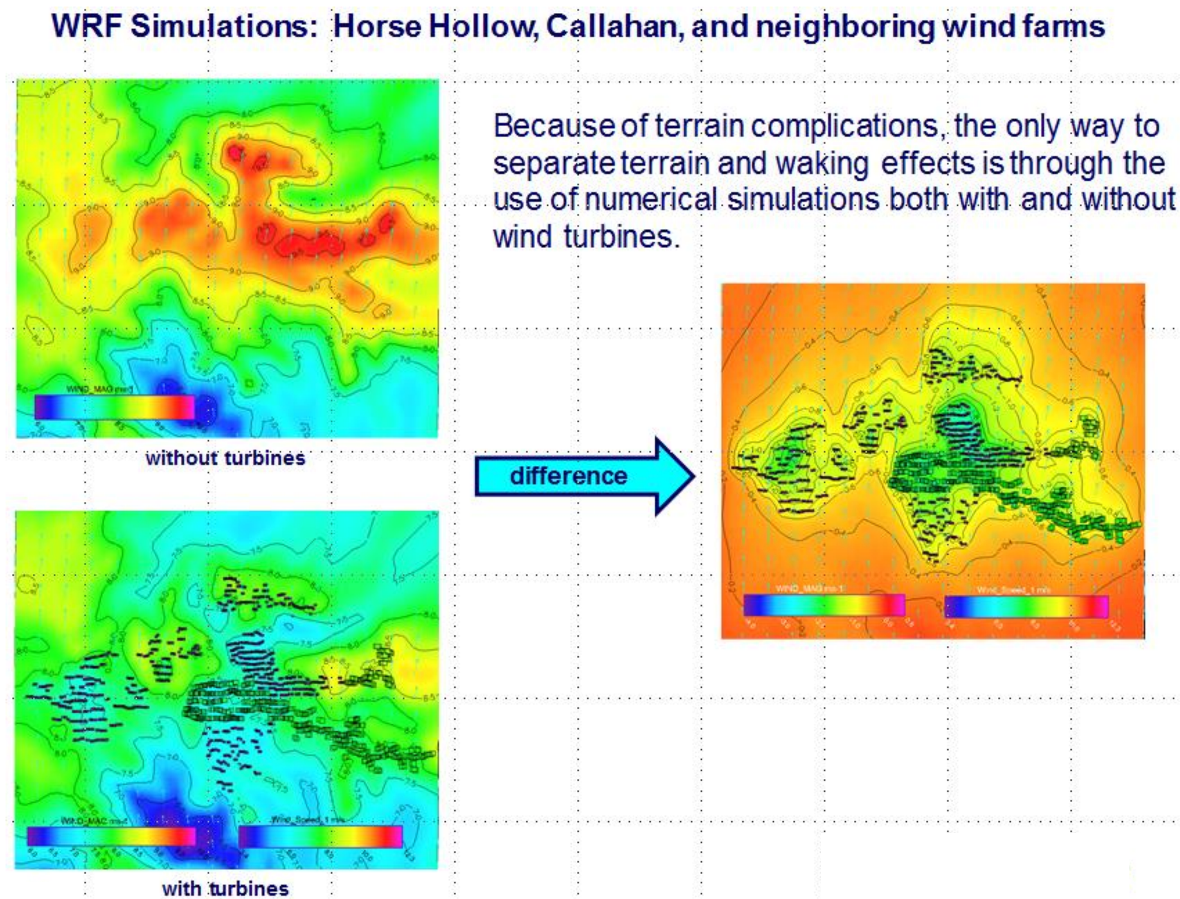
WRF Wake Simulations

- Gridded model simulation to cover the same year for waked and unwaked runs
- Subtract “turbines” run from “no turbines” run to find wake impacts.
- 28 wind farms have been simulated using WRF



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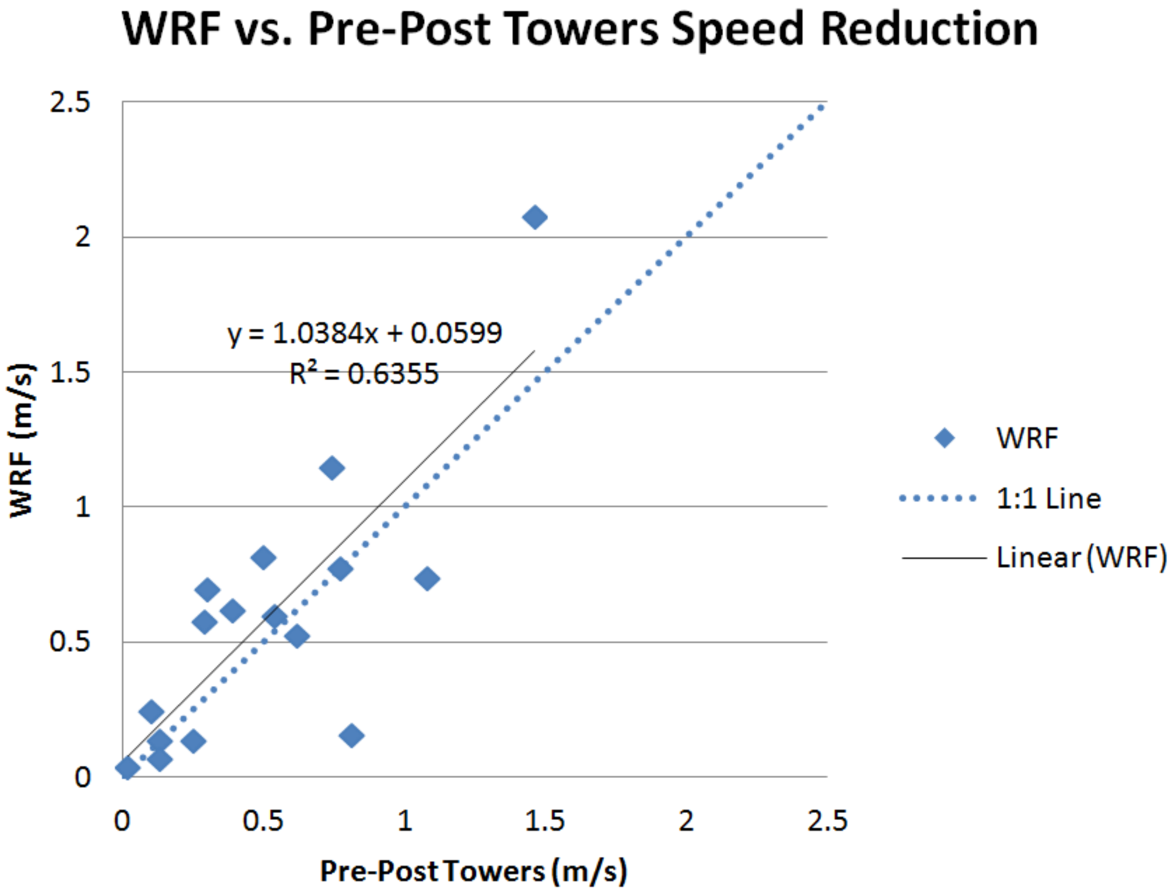
Intercomparison: WRF and Pre-Post Towers

- Continuous spatial coverage of wake speed deficit from WRF allows us to sample at the Pre-Post tower locations for direct comparison against our best wake observations, showing good agreement



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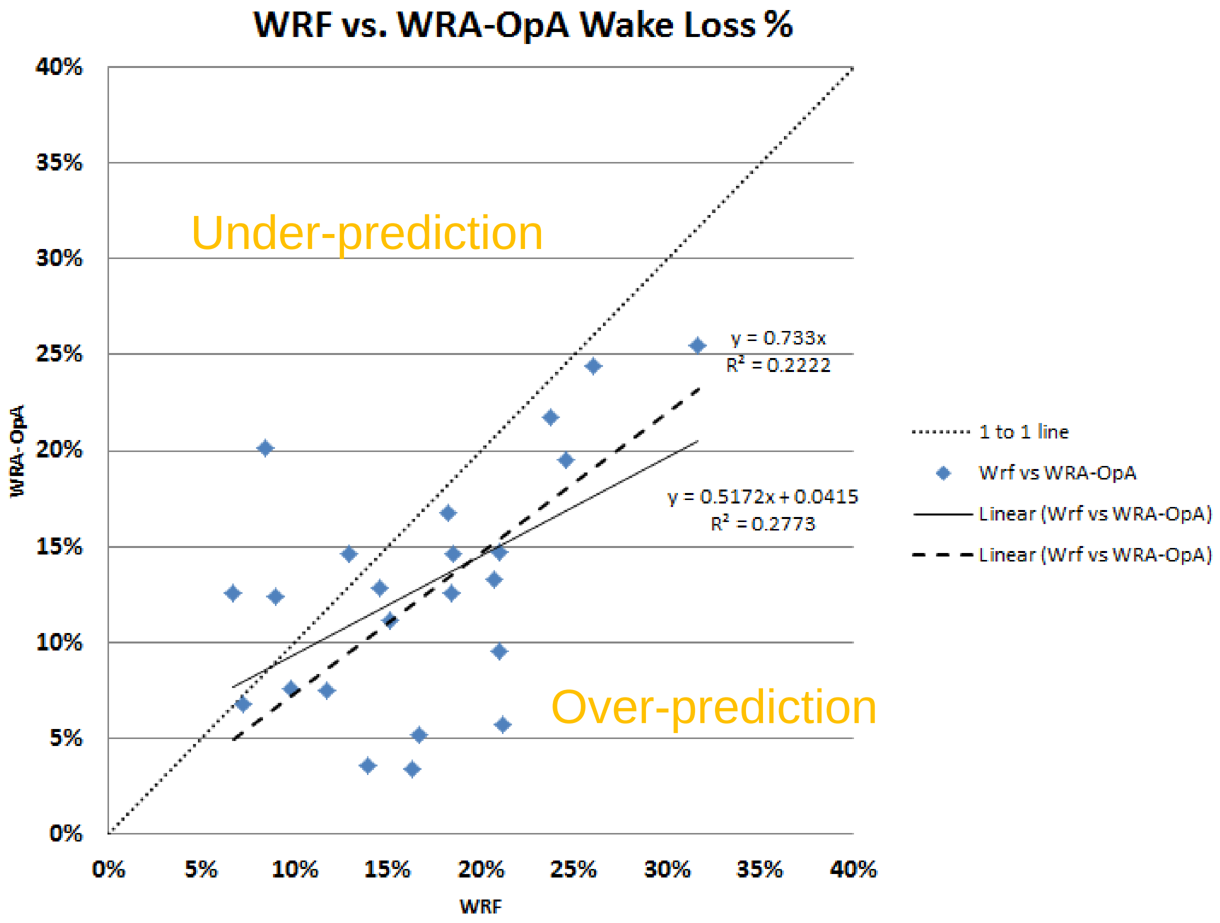
Intercomparison: WRF and WRA-OpA

- Our tests indicate actual wake 27% less than predicted by WRF
- Because of thrust coefficient curve and WRF high speed bias, WRF over-predicts wake while accurately predicting speed difference.



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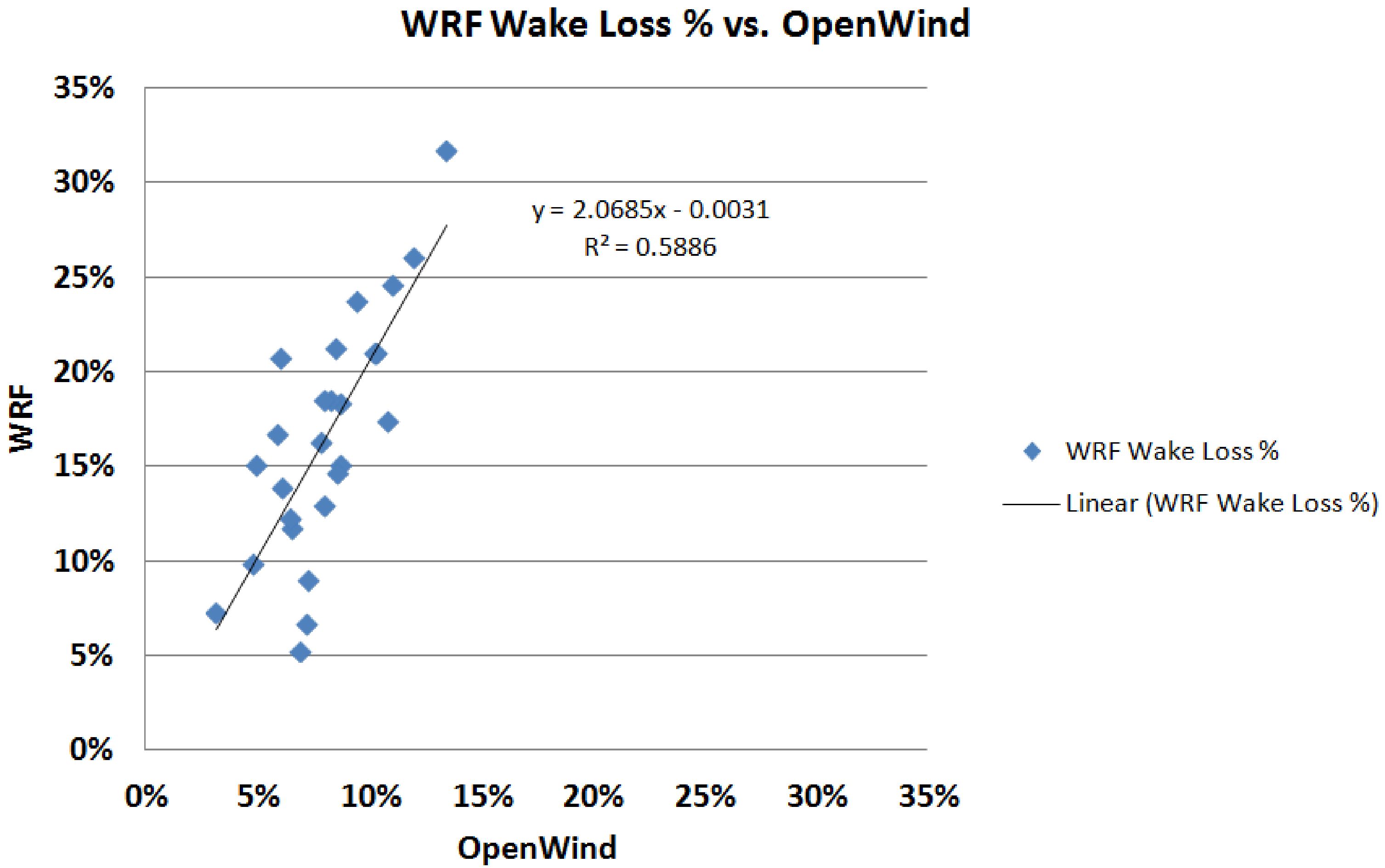
Intercomparison: WRF and OpenWind

- OpenWind and WRF correlate well, indicating that the two physics-based approaches are responding to the same relevant site features



Conclusions

- **Scatter inherent in the WRA-OpA method limits its usefulness as a direct regression target**

- **Best use of the WRA-OpA results is to scale the physics-based results**

- **Given the good correlation between WRF and OpenWind, we can use these deep array wind models and apply a correction factor to use in most projects**
  - WRF represents the reference solution for research and refinement

Future Work

- Continue to research options for running WRF-with-turbines sufficiently fast to support operational use in the future (MIC cards, Cloud, time sub-sampling)
- Implement more detailed data management campaign that covers pre and post construction time periods
- At existing wind farms, exploit novel situations, such as the farm tripping off, with continuity of wind observations, to further infer wake impacts
- Continue to participate in wind community-wide wake research efforts

Appendix

References

- *The OpenWind Deep-Array Wake Model: Development and Validation*. Brower and Robinson, AWS Truepower. 2011.
- *Modelling and Measuring Flow and Wind Turbine Wakes in Large Wind Farms Offshore.* Barthelmie et al., Wind Energy. 2009; **12:**431-444.
- *OpenWind Theoretical Basis and Validation.* AWS Truepower. 2010.
- *Wake effects within and between large wind projects: the challenge of scale, density, and neighbours- onshore and offshore.* Phillips et al., Garrad Hassan, Presented at EWEC 2010.
- *Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms. Barthelmie et al., Journal of Atmospheric and Oceanic Technology*, **27** (2010), 1302-1317.
- *Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind farm*. Barthelmie and Jensen, Wind Energy, **13** (2010): 573-586.

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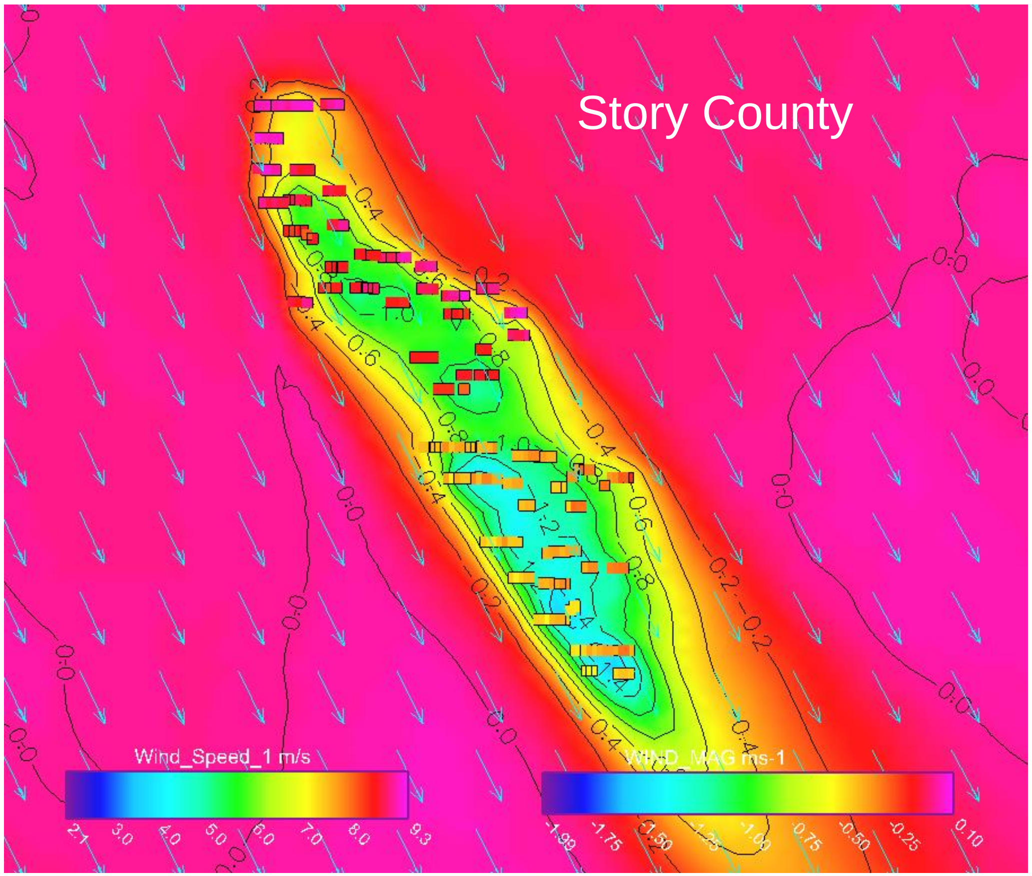
Active Wake Research Programs

- Iowa State University
- University of Colorado
- WakeBench (IEA Subtask)
- Los Alamos National Laboratory
- University of Wyoming
- Texas Tech University

WRF Sector Analysis

- **Directional sector analysis at the simulated farms confirmed that the pattern of WRF speed difference (turbines minus no turbines) was reasonably accurate**



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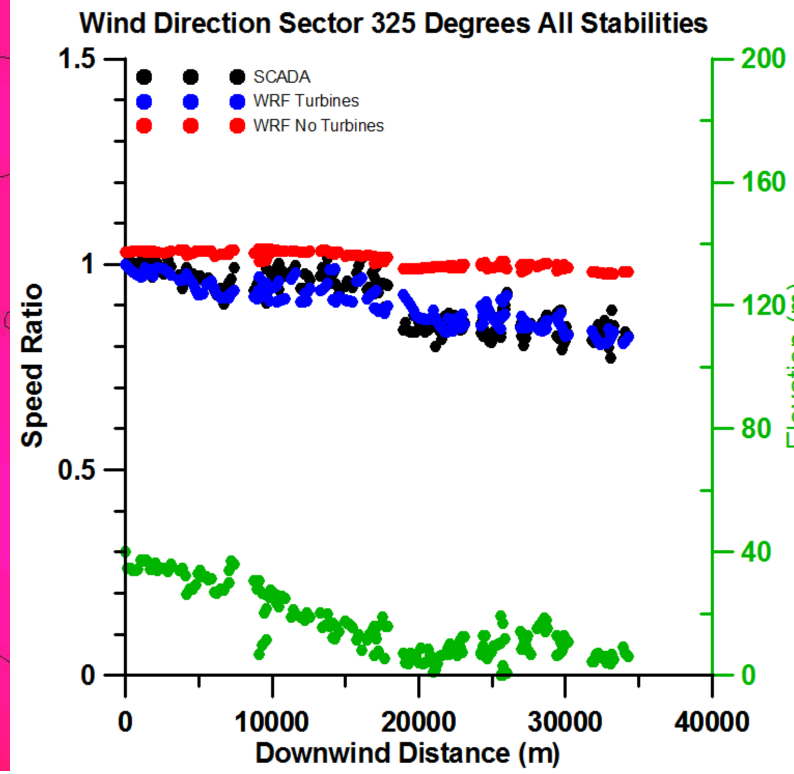

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