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Paradigm Shift: Wind Farm-Atmosphere Interaction (WFAI) in the Era of Large Rotors

With credits to the ArcVera team

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WINDABA 2020, Breakaway 6, Wake Effects (a misnomer)

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Key WFAI Paradigm Takeaways

- “Wake loss” is a misnomer, WFAI is the correct term
- Large rotor turbines operate mostly outside of surface layer, in more stable air, invalidating old wake model assumptions
- Role of momentum reservoir above upper blade tip is critical
- Wind farm modification of wind flow dynamics can be a critical factor in almost any case, not in current models
- Measurements to 300-m and weather modeling required
- Understanding of WFAI energy loss is the new paradigm

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What can you learn from a tweet?

Tweet

Ørsted
@Orsted

Let's just take a moment to enjoy this amazing view of the Horns Rev 2 offshore wind farm 😍 Here, the complex flow patterns formed by the wake effects behind the wind turbines are visible due to a low-hanging fog. #Offshorewind #FridayFeeling

2:17 AM · Jul 12, 2019 · Twitter Web Client

Wakes are noted and clear air approaches the wind farm. Farm changes atmosphere.

Famous Idiom

"Cannot see the forest for the trees"

This idiom applies to wakes (the trees) and WFAI (the forest).

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The big picture: WFAI, not wakes.

It is time to recognize the full challenge and complexity of energy assessment in light of the direct impacts that operating wind farms impose on the free atmosphere into which they are inserted.

Photo: Henrik Krogh

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Wind Farm-Atmosphere Interaction

WFAI Energy Loss Definition: That amount of turbine energy production lost from gross energy due to the insertion of a given wind farm into the free stream atmosphere.

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WFAI Factors

WFAI includes wind-farm-caused wakes, flow acceleration & deceleration, and modified atmospheric dynamics.

WFAI is affected by site-specific meteorological conditions up to and above blade tip including stability/inversions, wind rose/veer, and turbulence.

WFAI is affected by layout: turbine lateral and string spacing (porosity, density, depth, footprint), terrain, ground cover, tip height, other.

Note: Wind farms cannot be fully optimized without an accurate representation of WFAI. Knowledge of 3-d time-series of wind and stability above blade tips required to minimize risk.

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WFAI includes Wakes

Wakes

WFAI accounts for Acceleration

Acceleration

Flow through and around the wind farm

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WFAI Deceleration

Combined Induction Zone Deceleration Upwind of Each Row

1st row deceleration & uplift (blockage)
> 1 row width upwind

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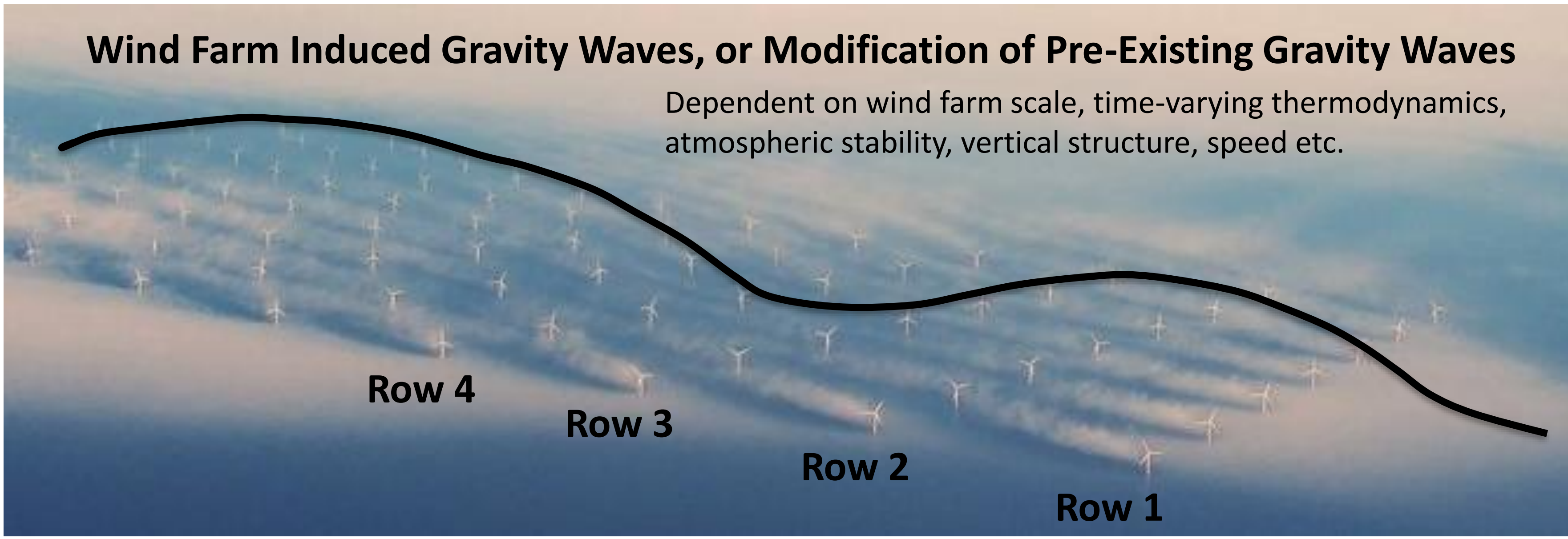
WFAI Cumulative Deceleration

Deceleration from Each Row
Farm Depth Matters

1st row deceleration > 1 row width upwind

WFAI Flow Modification



Wu shows upwind deceleration to 1/3 of wind farm depth in stable atmospheric conditions, with gravity waves.

References: Wu, K. L. and F. Porte-Agel, 2017: Flow adjustment inside and around large finite-size wind farms, Energies, **10**, 2164.

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The Validation Riddle

- Wake loss models and energy assessment techniques have already been tuned to get the correct P50 net energy (within uncertainty) for all phenomena, including wakes, behind the first row.
- Riddle: Adding more losses from gross energy calls into question prior validation, does it not? Other losses must drop if WFAI loss increases.
- Riddle: How could we suddenly discover that whole wind farm effects on the atmosphere are now material to wakes/WERA accuracy?

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So What Changed?

- Most significant change over time is in the height of wind turbines (tips +50-100 m in 10-15 years), implicit rotor diameter increase
- 50% of blade sweep above the atmospheric surface layer challenging assumptions in common wake loss models and obviating improved need to understand the momentum reservoir above blade tip
- Critical offshore due to common stable marine inversion.
- Bottom Line: Industry should move beyond common wake loss modeling.
- The new WFAI paradigm is all encompassing with regard to the effects of a wind farm on the pre-construction free atmosphere.

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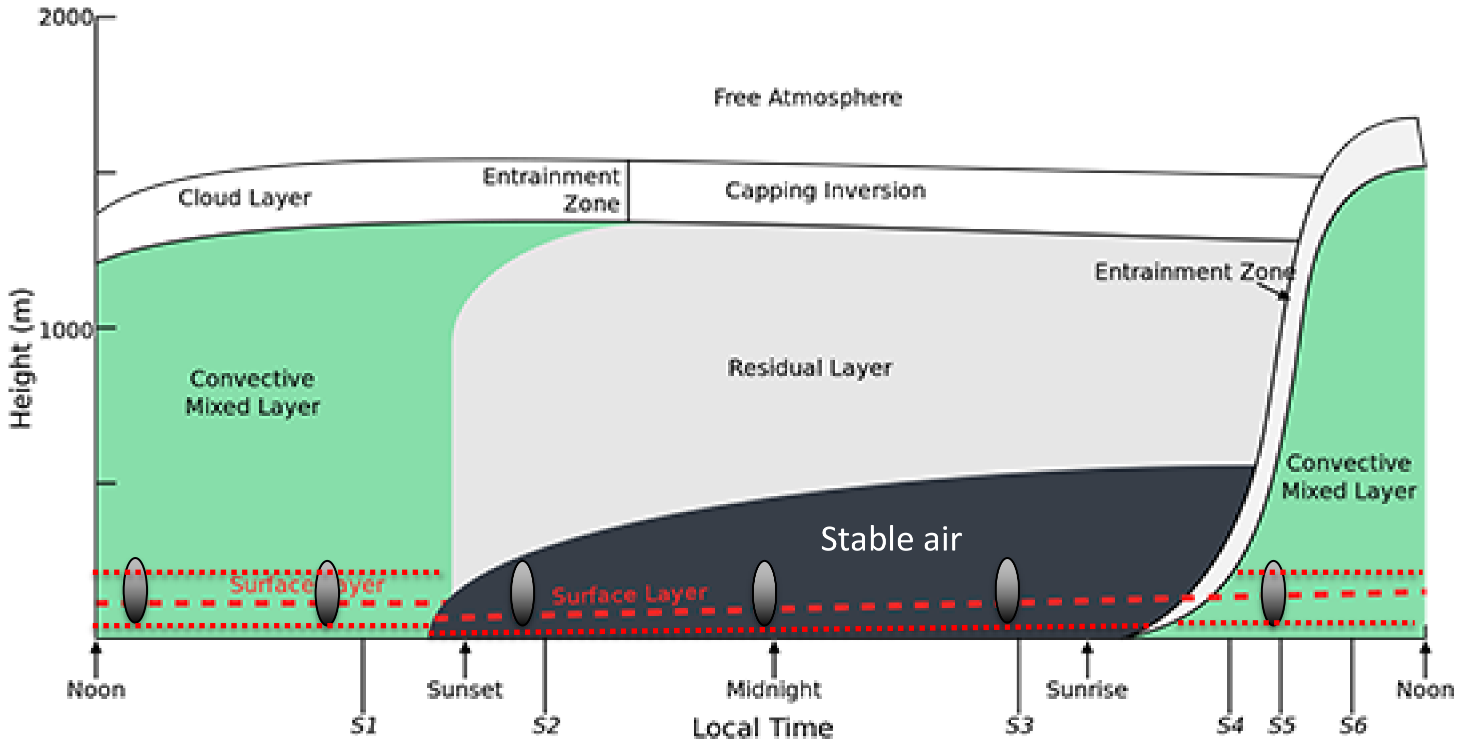
Large Rotor Turbines: Sweep Well Above Surface Layer

Atmospheric surface layer depth varies: 50-200 m days, 10-100 m nights



Adapted from Stull (1988)

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WFAI &Wake Misnomer

- Tuned so-called wake loss models include much more than wake losses, including acceleration, deceleration, and other effects.
- If validated with 1st row as 100% production no first-row blockage and already include downwind-row blockage, gravity waves/freestream flow modification, and acceleration – more than wakes
- If validated with free stream meteorological tower as a proxy for 100% production, then you have a WFAI model –more than wakes
- Conclusion: “wake loss” is a misnomer WFAI is more accurate.

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Study Method for WFAI: 4 Cases

- Based on data from operational wind farms
- Pre-construction meteorological data from permanent met masts, and post-COD met & operational data (3)
  - Before/after wind speed ratios
- Operational data from wind farm before and after a nearby wind farm was constructed (1)

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Summary of Operational WFAI Studies

- **Case 1, ~220-MW:** Brazil, four strings, 2.3-2.7 RD in-string spacing
- Unidirectional ESE wind rose
- WFAI energy loss 54% > ArcVera GTAP wakes

- **Case 2 ~150-MW:** Brazil, three strings, 1.6-2.0 RD in-string, ESE winds
- WFAI energy loss 50% > ArcVera GTAP and EV DAWM wakes

- **Case 3, ~250-MW:** Brazil, five strings with 1.5-1.7 RD in-string, ESE winds
- WFAI energy loss 56% > ArcVera GTAP and EV DAWM wakes

- **Case 4:** US wind farm with large wind farm built within 50 RD to north, 5 years later
- Wind rose: South and NW
- In south winds AEP reduced 0.4%
- **Long-distance blockage evidence**

Cases 1-3: WFAI energy loss found to be 4-7% more than wake models.
First-row blockage alone found to be 2-4% of gross energy.

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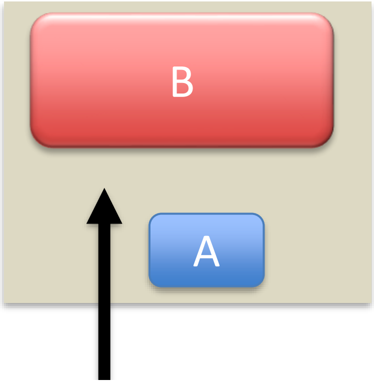
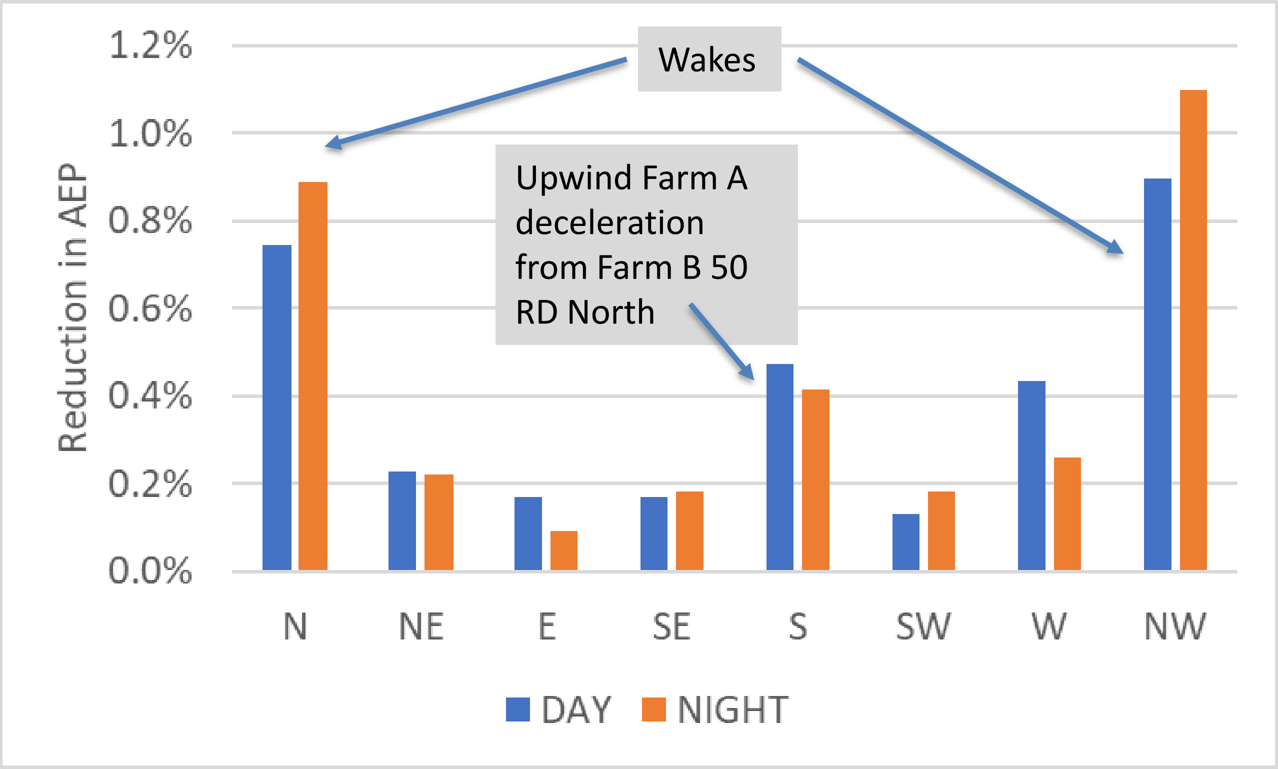
Case 4: Long-Distance Farm Deceleration

Cartoon picture



South winds found to reduce production at Farm A



Unexpected: Farm A production impact from Farm B in south winds is slightly greater during daytime.

The Future

- WFAI modifications made to wake loss models starting in 2016 based on case studies
- Refinement over time to more accurate WFAI loss per research and publications
- Routine use of full weather physics high-resolution modeling with/without embedded turbines*

**already possible with numerical weather prediction models we now run; expensive but worth effort in high risk cases due to demonstrated energy error in current wake loss models, and consideration of long-distance wakes/blockage*

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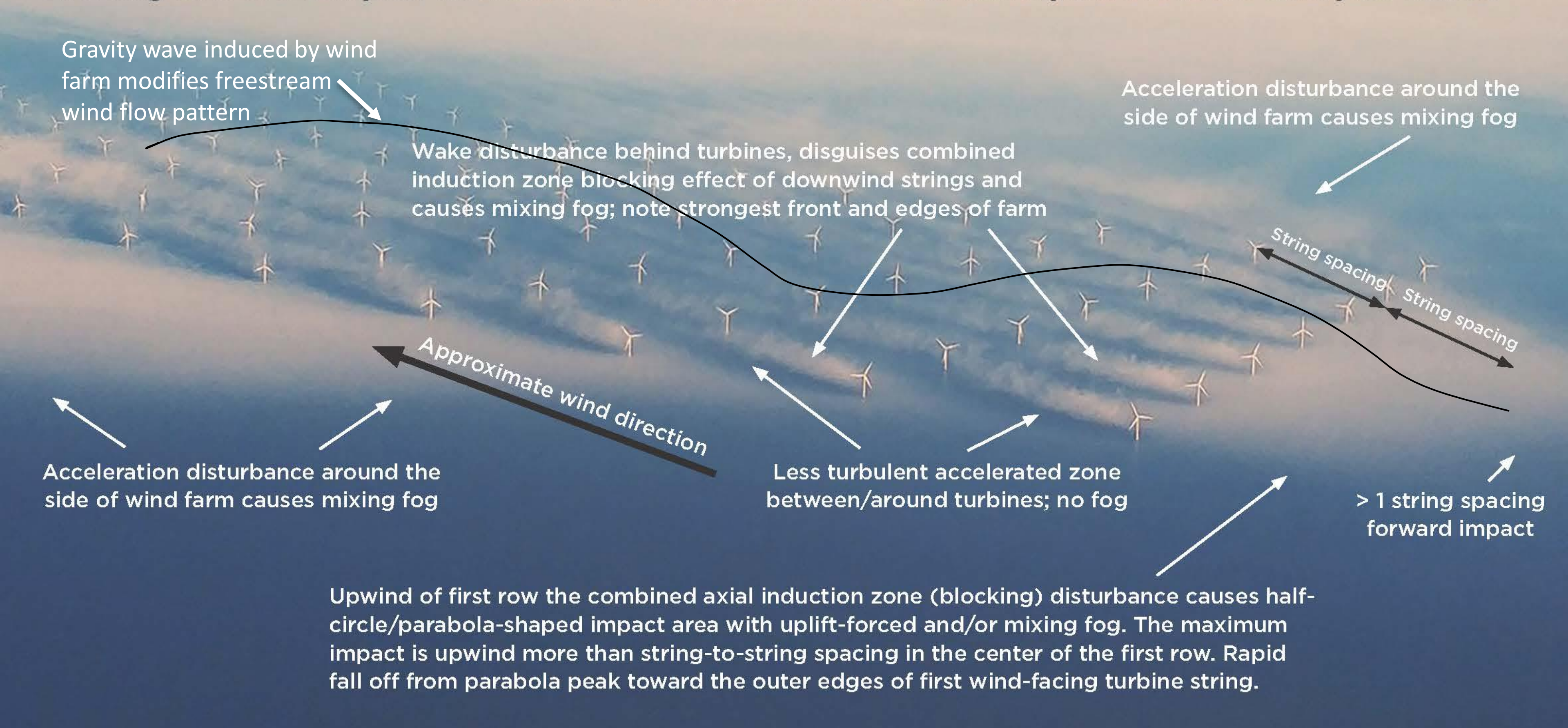
A picture tells a thousand words:
Wind Farm Atmosphere Interaction (WFAI Losses)

Photograph of Horns Rev:
Showing that the complex interaction of a wind farm with the atmosphere is more than just wakes.



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Based on ArcVera Renewables R&D
Prepared by G. Poulos, May 2020

Photo credit: Henrik Krogh

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