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Simulating Long-Distance Wind Farm Wake Propagation Using Numerical Weather Prediction Models

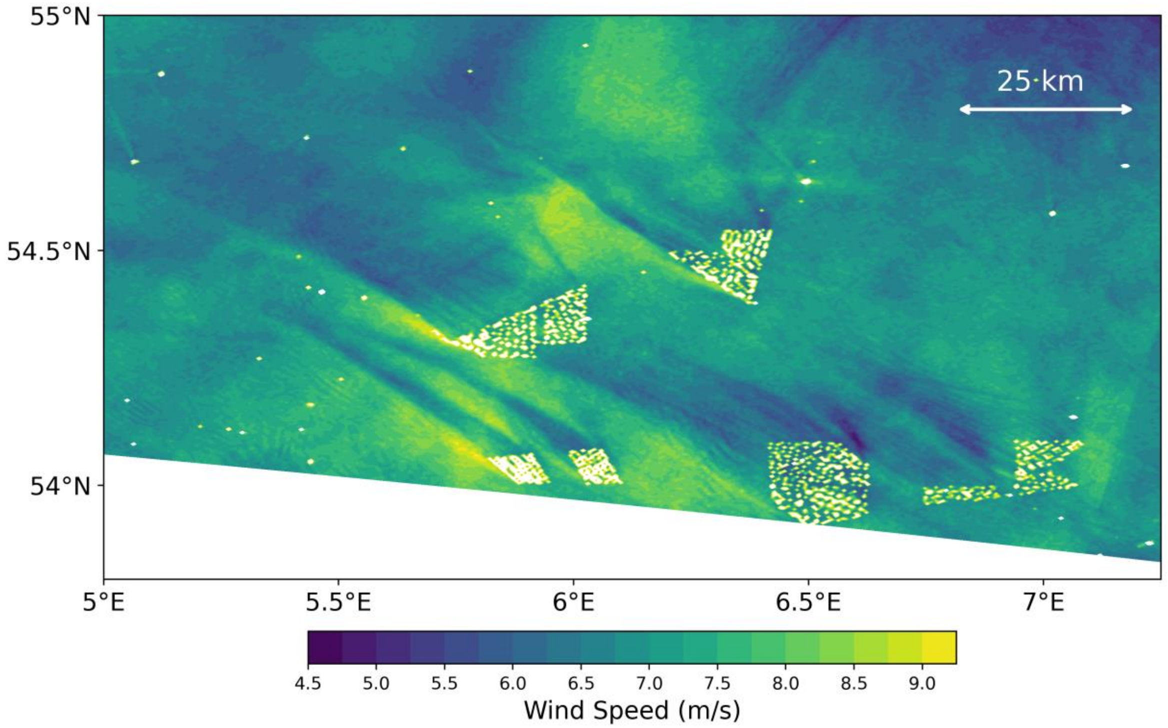
PIMS/FACTS 2023 Conference

Mike Optis

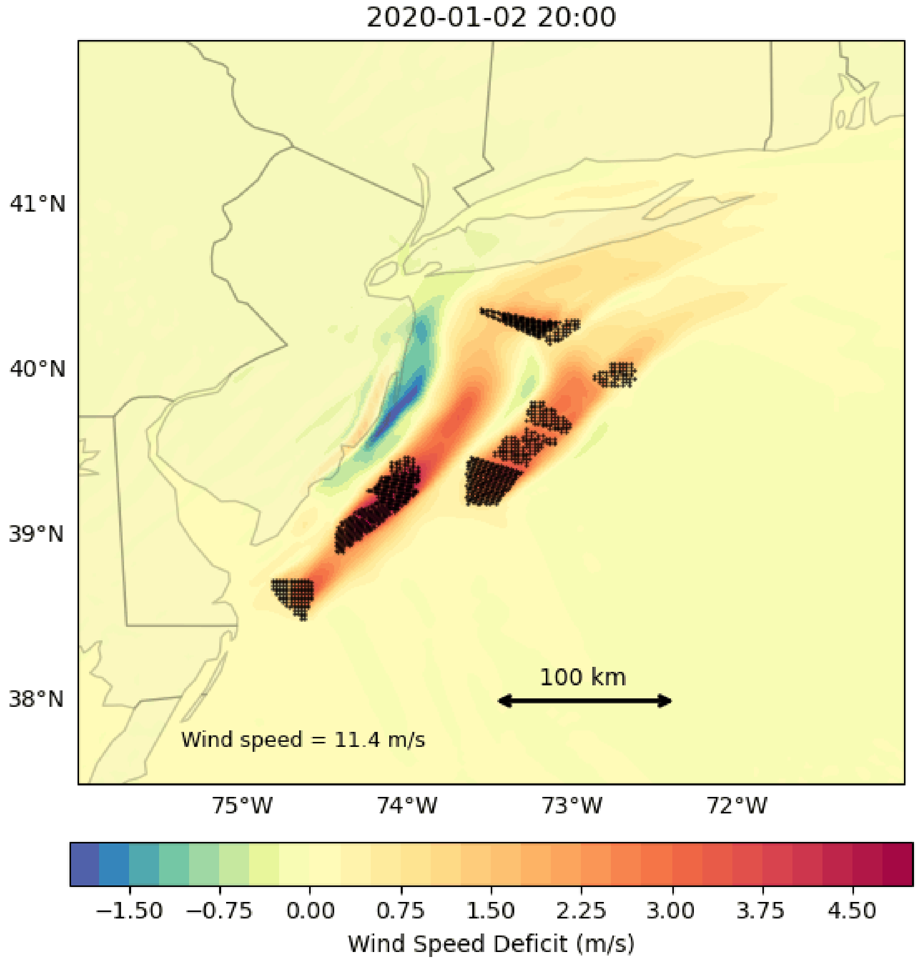
President and Founder, Veer Renewables

2023-07-28

The Scale of the Problem



Observations of ocean surface wind speed by the Sententel-1A satellite in the German Bight on April 17, 2022

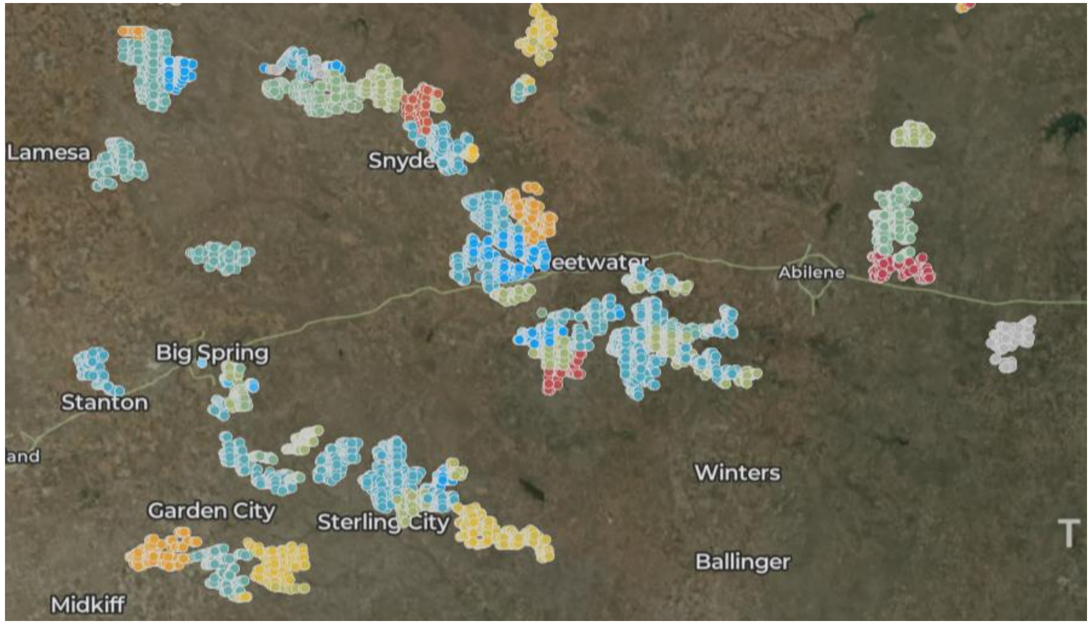


Veer Renewables WakeMap simulation in U.S. Mid-Atlantic Offshore Wind Areas

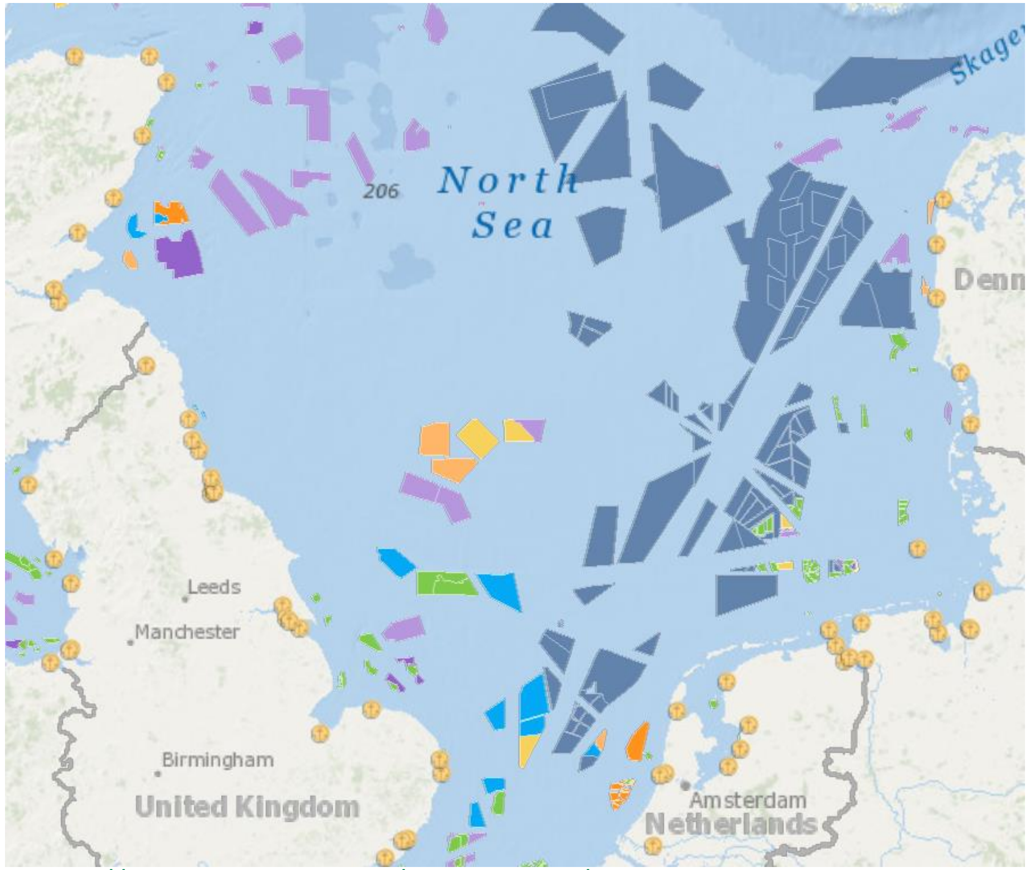
The Scale of the Problem

Conventional wake modelling tools aren't capturing these "long wakes" (nor were they intended to!)

As wind farms become more crowded, we need better tools to account for this phenomenon



https://eerscmap.usgs.gov/uswtdb/viewer

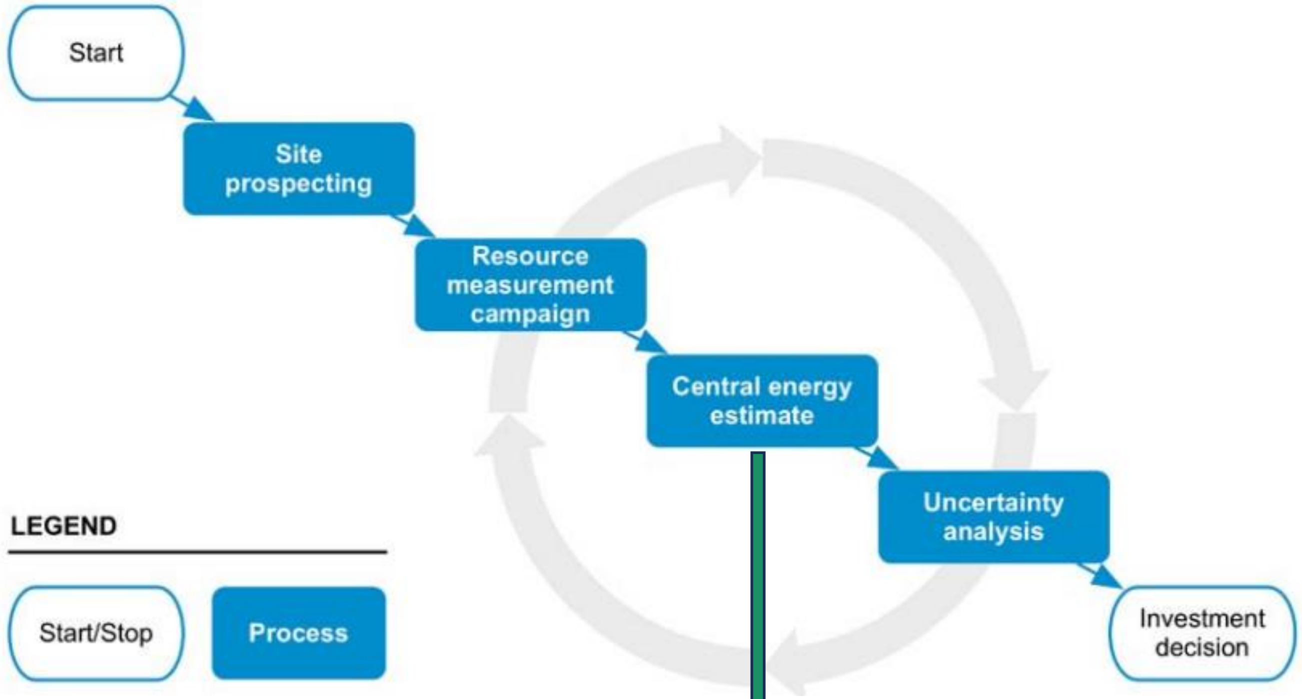


https://map.4coffshore.com/offshorewind/

Overview of Talk

- Importance of wake modelling in pre-construction energy estimates
- Scientific basis for wake modelling
- Idealized wake models and their limitations
- Wake modelling using numerical weather prediction models
- Validation results

Energy Production Estimates (EPEs)



Source: https://www.nrel.gov/docs/fy16osti/64735.pdf

- Long-term Resource Correction
- Horizontal/Vertical Extrapolation
- Turbine Selection
- Layout optimization
- **Loss Estimation**

The bedrock for wind farm financials

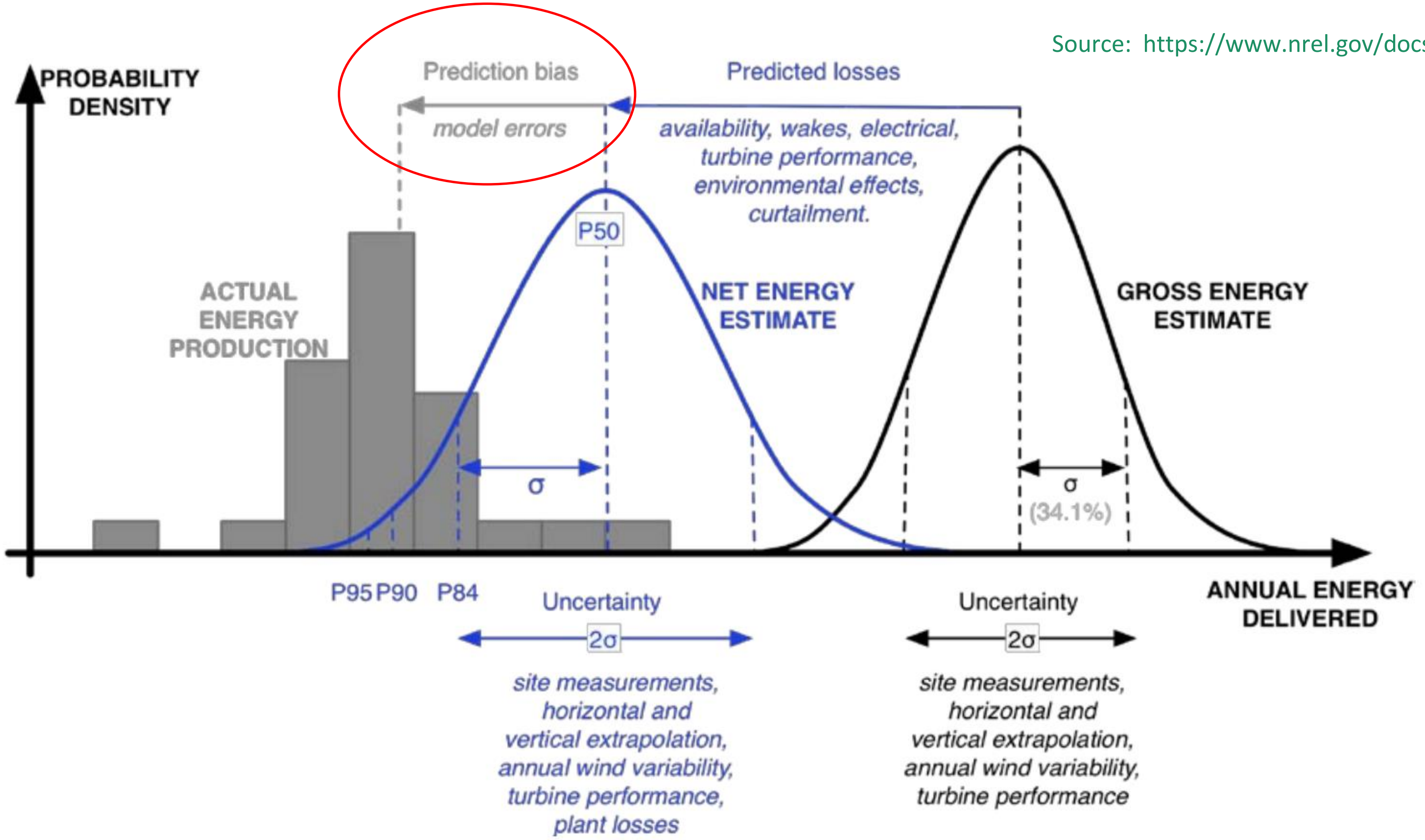
- Revenue projections
- Securing investments/loans
- Setting power purchase agreements

Accuracy is paramount

- Financials are tight and a 3% error in energy production can drastically impact project profitability

We have a Bias Problem

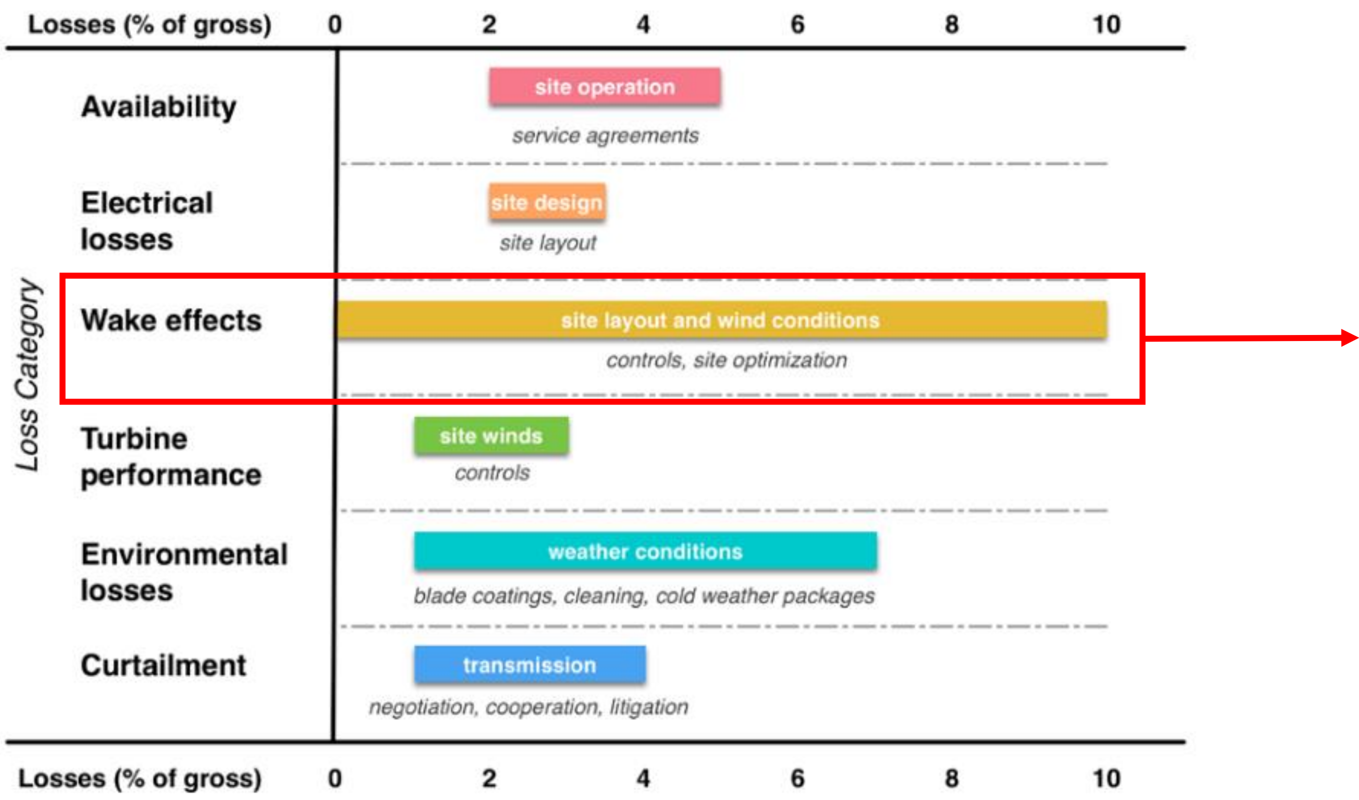
Source: https://www.nrel.gov/docs/fy16osti/64735.pdf



Normal to apply a 2-5% “haircut” to EPE estimates to cover this unexplained bias

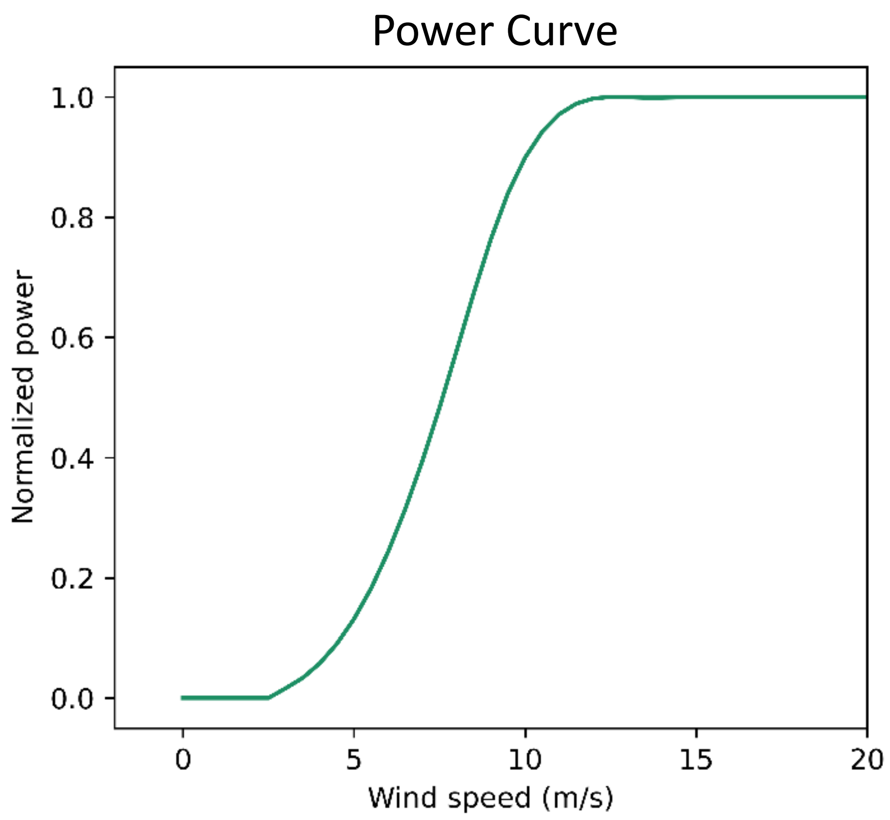
EPE Loss Accounting

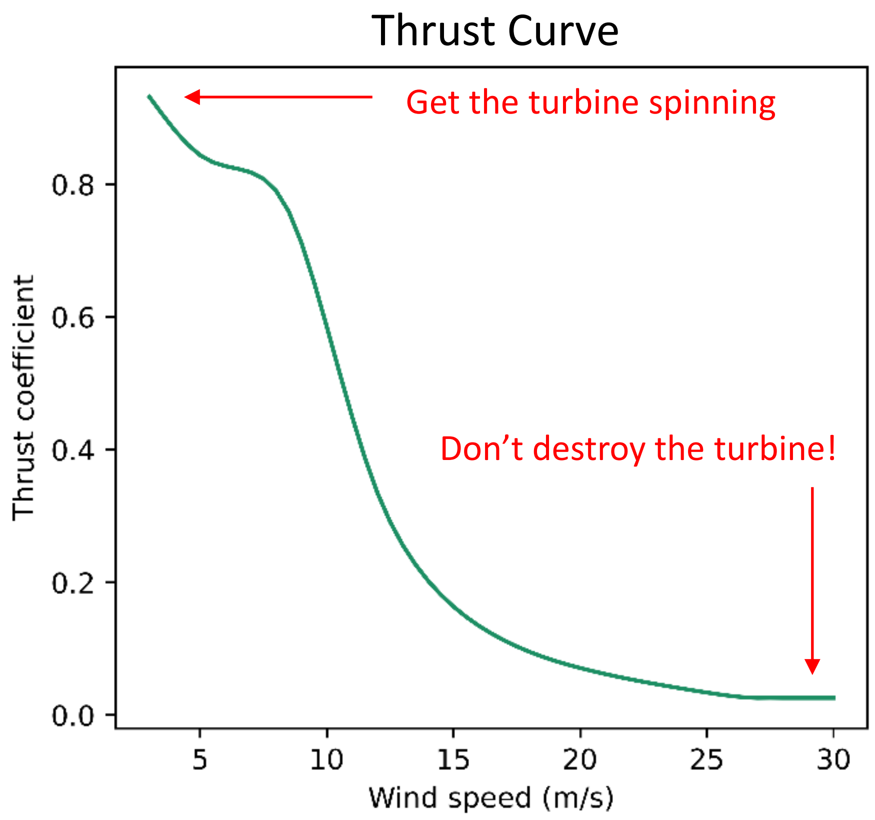
Wide range in potential wake losses, depending on turbine layout, turbine characteristics, local terrain, and **atmospheric stability**



Source: https://www.nrel.gov/docs/fy16osti/64735.pdf

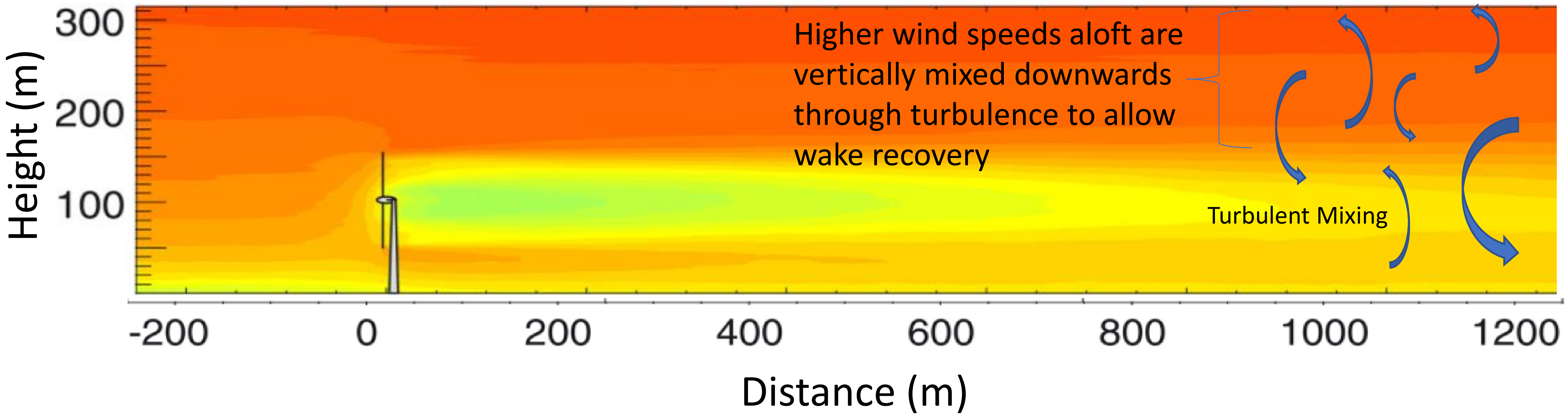
How do We Estimate Wake Losses?





- Thrust coefficient (C_T): The ratio of the thrust exerted by the wind on the turbine blades to the total wind power
- At each wind speed, there is an optimum thrust coefficient where balance between energy extraction and flow through rotor is maintained
- Exit wind speed determined based on drag equation: $$\mathbf{F}_{\text{drag}} = \frac{1}{2} C_T(|\mathbf{V}|)\rho|\mathbf{V}|\mathbf{V}A,$$

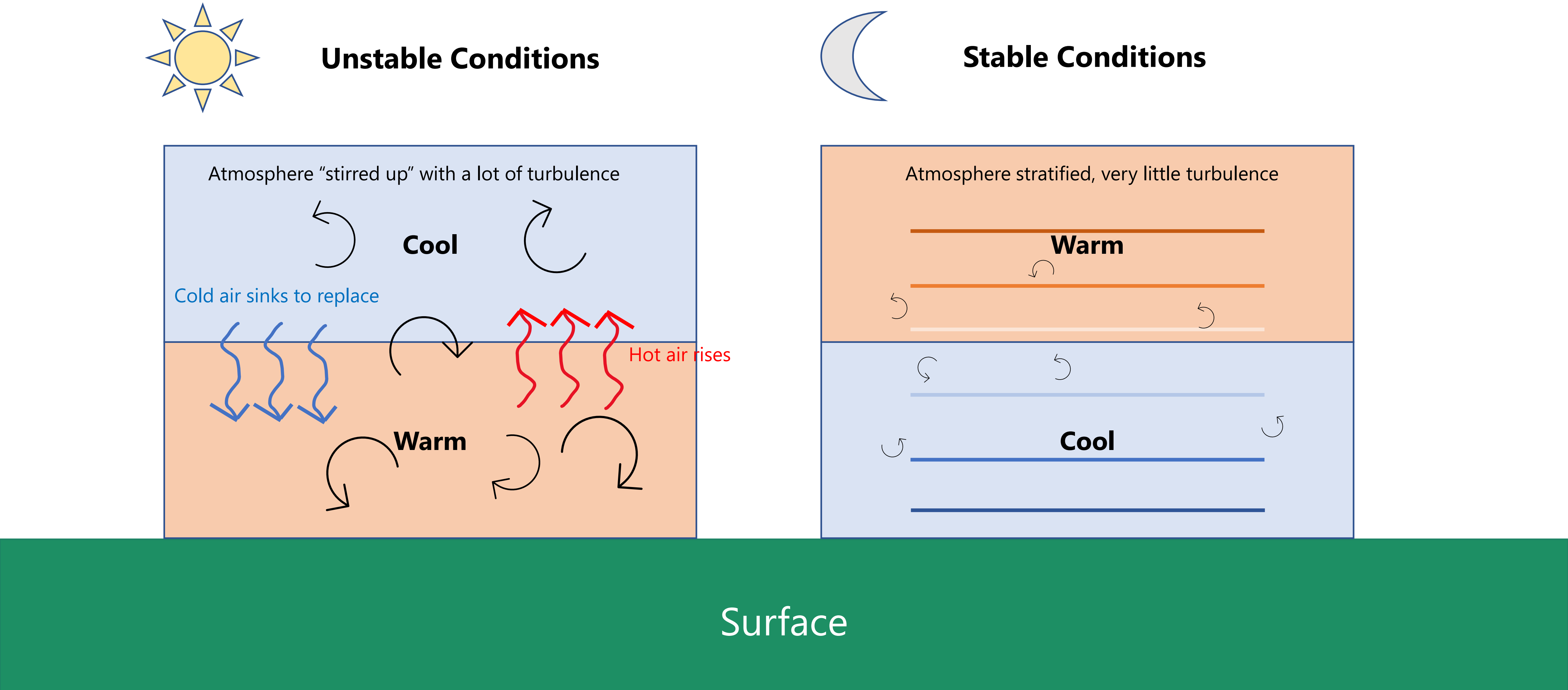
How Far Do Wakes Propagate?



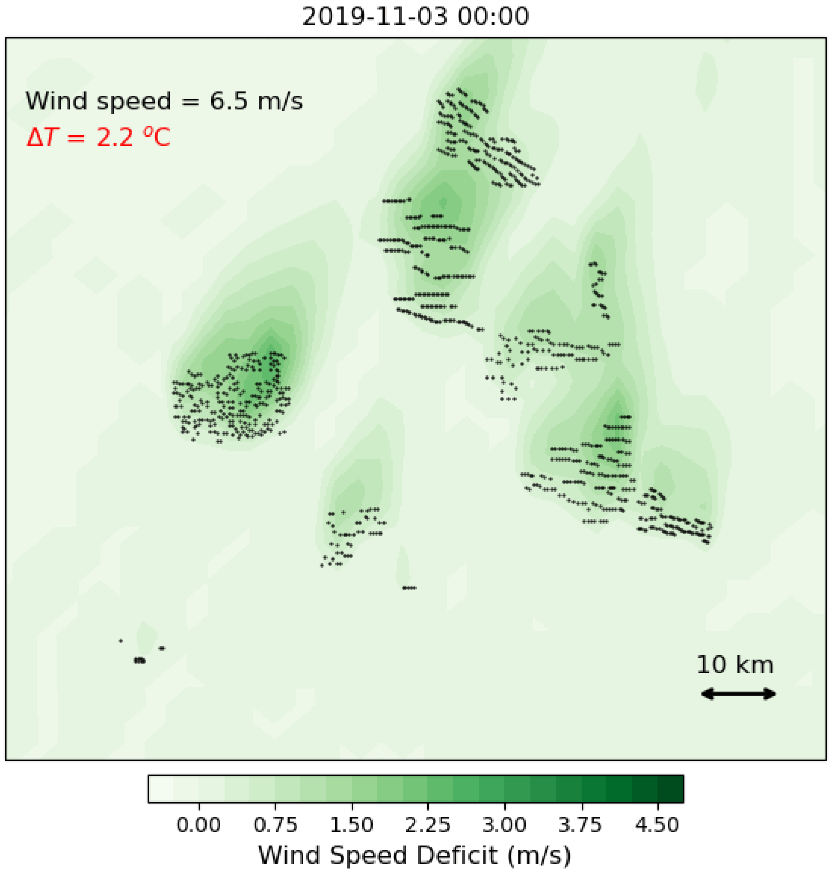
Moderate to high turbulence is vital for rapid wake recovery

Low turbulence can lead to “long wake” propagation

Turbulence and Atmospheric Stability

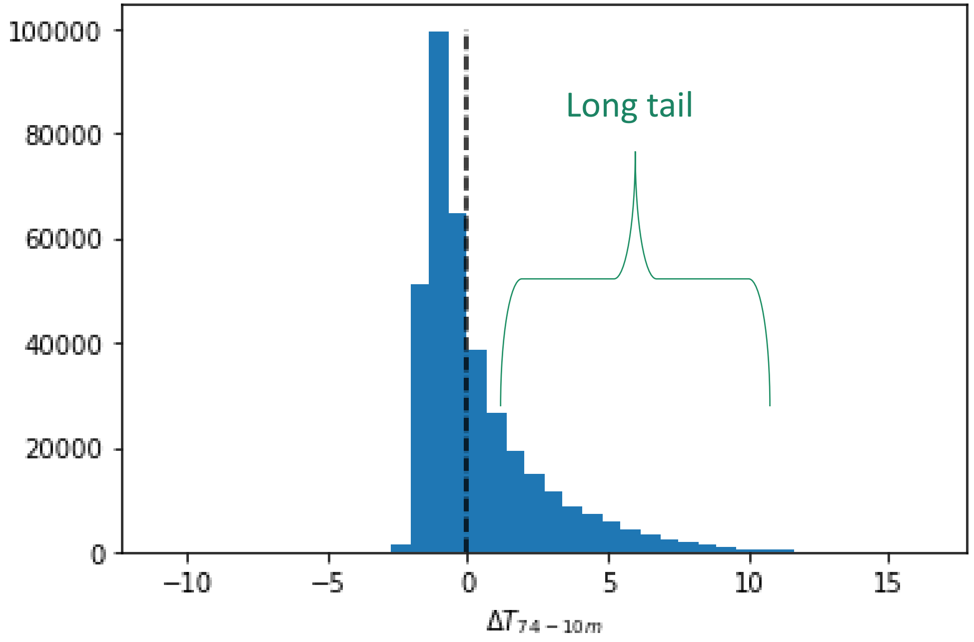


Stable Conditions are Paramount

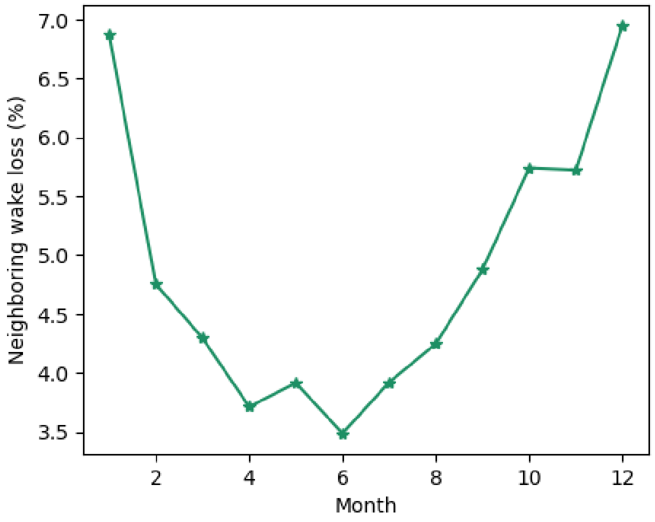


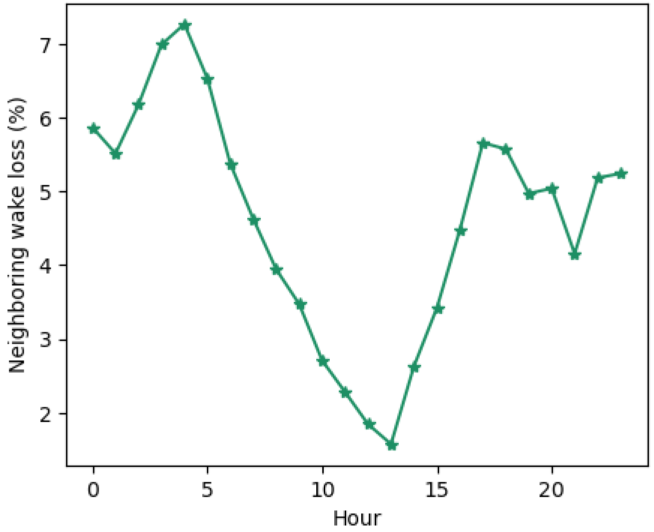
WakeMap simulation in North Texas

Things get very stable in Texas



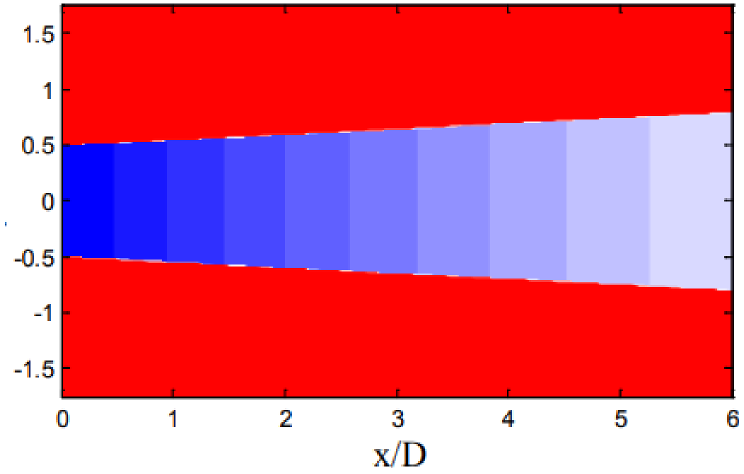
Seasonal and Diurnal Trends in External Wake Losses





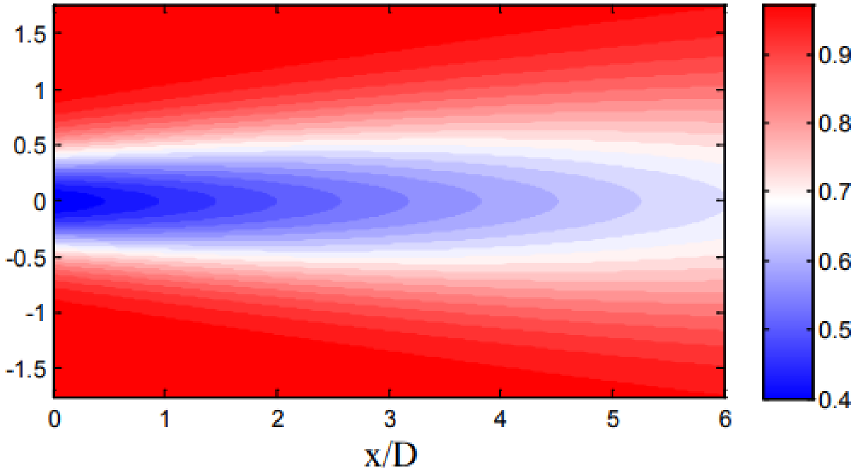
Do Conventional Wake Models Capture this Complexity?

https://www.nrel.gov/docs/fy14osti/60208.pdf



Park

$$u_w = U_0 \left[1 - \frac{1 - \sqrt{(1 - C_T)}}{(1 + 2ks)^2} \right]$$



Eddy-Viscosity

$$U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial r} = \frac{-1}{r} \frac{\partial (r \overline{\mathrm{uv}})}{\partial r}$$

$$-\overline{\mathrm{uv}} = \varepsilon \frac{\partial U}{\partial r}$$

Typically model no wake losses after ~50 rotor diameters (5 km onshore, 10 km offshore)

Within a wind farm, they can work quite well!

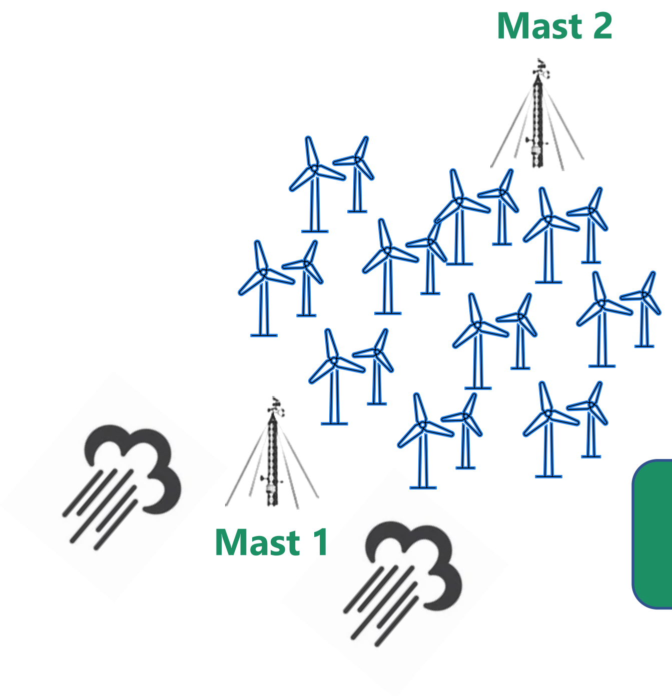
Failure of Conventional Wake Models

- Designed for (and tuned by) wake losses within a wind farm

- Conditions inside and outside a wind farm can be very different

- Engineering wake models work well in relatively turbulent conditions where wakes recover quickly

- Long wakes operate in a parameter space outside the range of engineering wake models



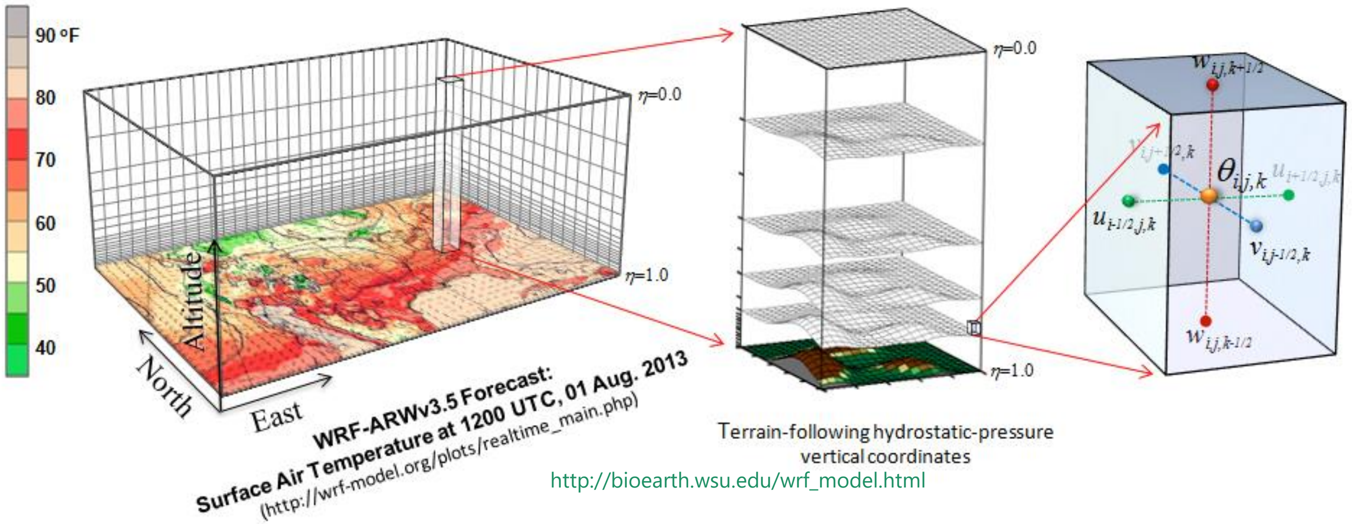
Wind speed > 3 m/s
Wind direction from SW
ΔT > 0

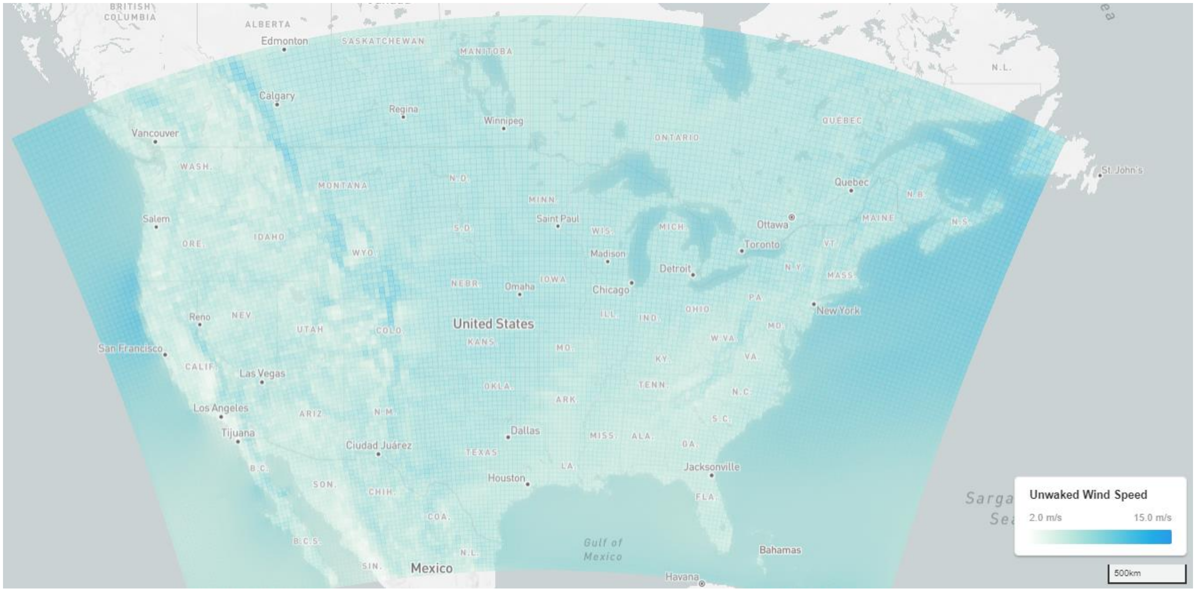
	Mast 1	Mast 2
Mean wind speed	10.0 m/s	8.3 m/s
Mean TI	**5.0%**	**11.2%**
Mean ΔT	**2.6°C**	**1.6°C**

TI = Turbulence Intensity

So how do we best model long wakes?

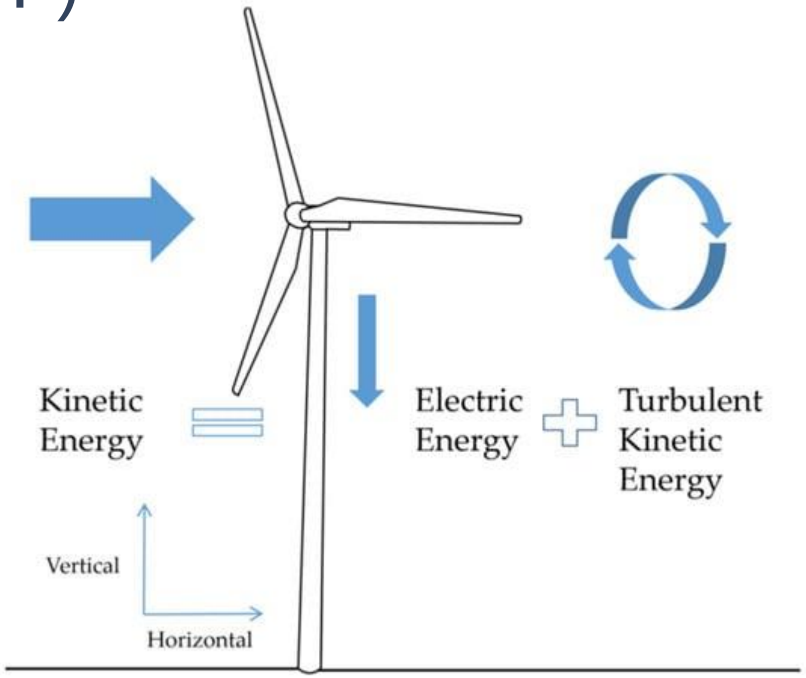
- Numerical weather prediction models
- 3D representations of the atmosphere in real environmental conditions
- Capture the full diurnal and monthly variations in wind resource and relevant atmospheric variables
- Weather Research and Forecasting (WRF) is the industry standard



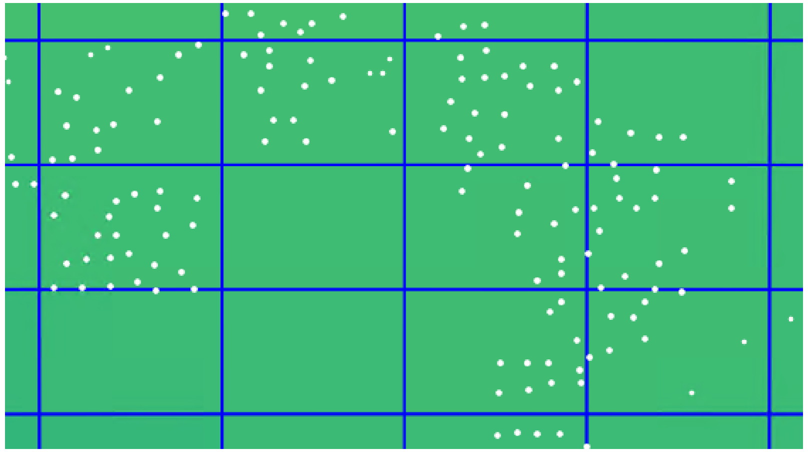


WRF Wind Farm Parameterization (WFP)

- Wind turbines act as a elevated momentum “sink” and turbulence “source”
- Additional terms added to Navier-Stokes fluid dynamics equations in WRF
- Power and thrust curves define amount of momentum extraction and turbulence generation
- Typically multiple wind turbines per grid cell



https://www.mdpi.com/1996-1073/15/12/4223



~1-6km

$$\frac{\partial u_k}{\partial t} = -\frac{1}{2}\frac{N_t}{A_{cell}}\frac{A_k C_T U_k u_k}{(z_{k+1} - z_k)},$$

$$\frac{\partial v_k}{\partial t} = -\frac{1}{2}\frac{N_t}{A_{cell}}\frac{A_k C_T U_k v_k}{(z_{k+1} - z_k)},$$

$$\frac{\partial TKE_k}{\partial t} = \frac{1}{2}\frac{N_t}{A_{cell}}\frac{A_k C_{TKE} U_k^3}{(z_{k+1} - z_k)}.$$

https://wes.copernicus.org/preprints/wes-2022-19/wes-2022-19.pdf

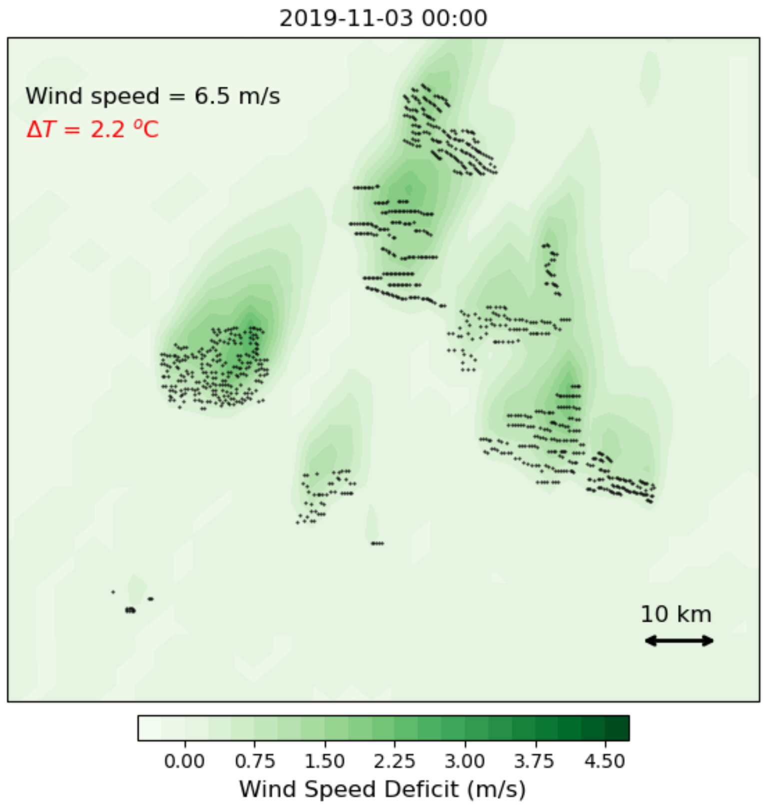
WRF Wind Farm Parameterization (WFP)

WRF WFP is not a wake model.

Wakes are determined by running two NWP simulations – one with and one without wind farms – and comparing the differences

How wakes propagate and dissipate depends on evolving atmospheric conditions

Onshore Impact

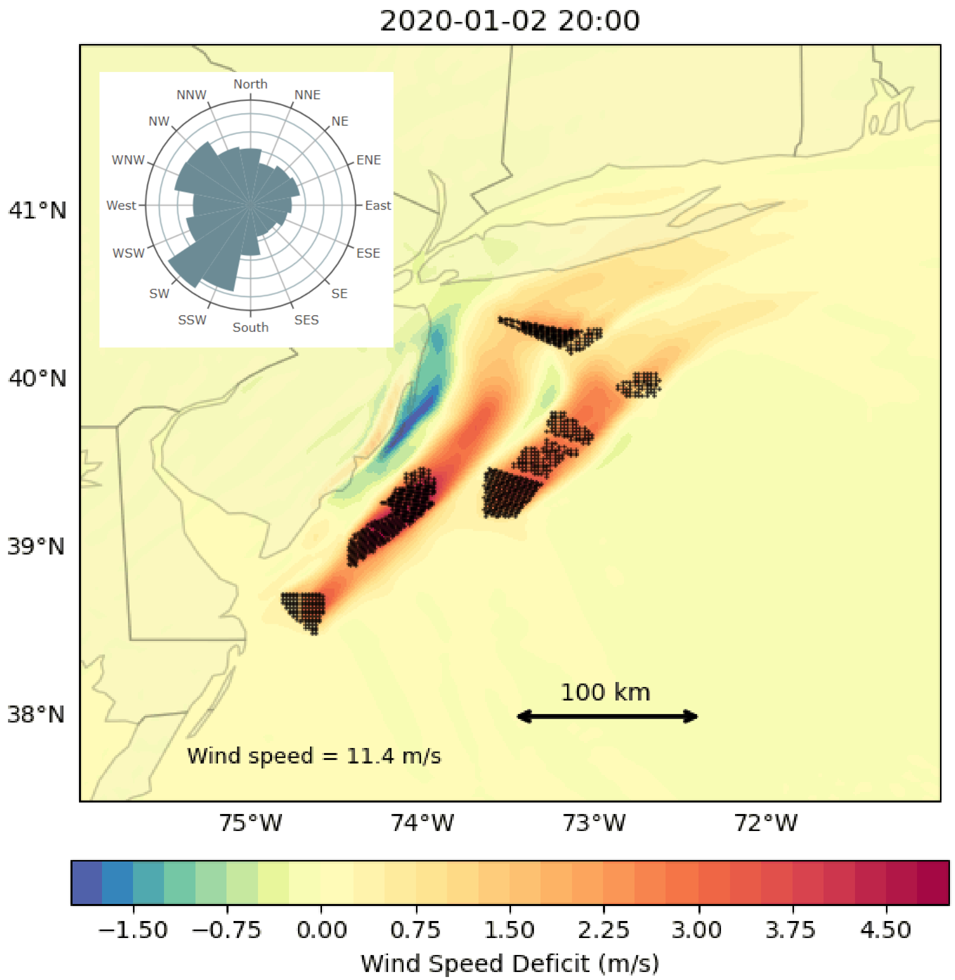


Modeled neighboring wake loss impacts at EDF wind farms

Wind Farm	AEP Impact All Neighbors	AEP Impact Neighbors > 10 km
A	4.20%	0.40%
B	4.30%	0.50%
C	1.90%	0.50%
D	4.10%	0.80%
E	5.10%	1.10%
F	3.20%	1.30%
G	5.40%	2.50%
H	3.30%	2.60%
I	5.20%	2.70%
J	3.80%	3.60%
K	3.70%	3.70%
L	4.90%	3.80%
M	8.00%	4.90%

AEP = Annual Energy Production

Offshore Impact



Veer Renewables WakeMap simulation in U.S. Mid-Atlantic Offshore Wind Areas

- U.S. Offshore Atlantic subject to frequent and strong stable stratification
  - Warmer inland air (Delaware/Virginia) flowing over a colder sea
  - Long fetch in dominant wind direction

- WRF WFP finding staggering wake losses in this region
  - Lundquist et al 2023[1] – 35.9% at Massachusetts lease area
  - Barthelmie and Pryor[2] – 35.3% at Massachusetts lease area
  - Veer Renewables finding similar losses

- These wake losses are DOUBLE what industry standard wake models are predicting

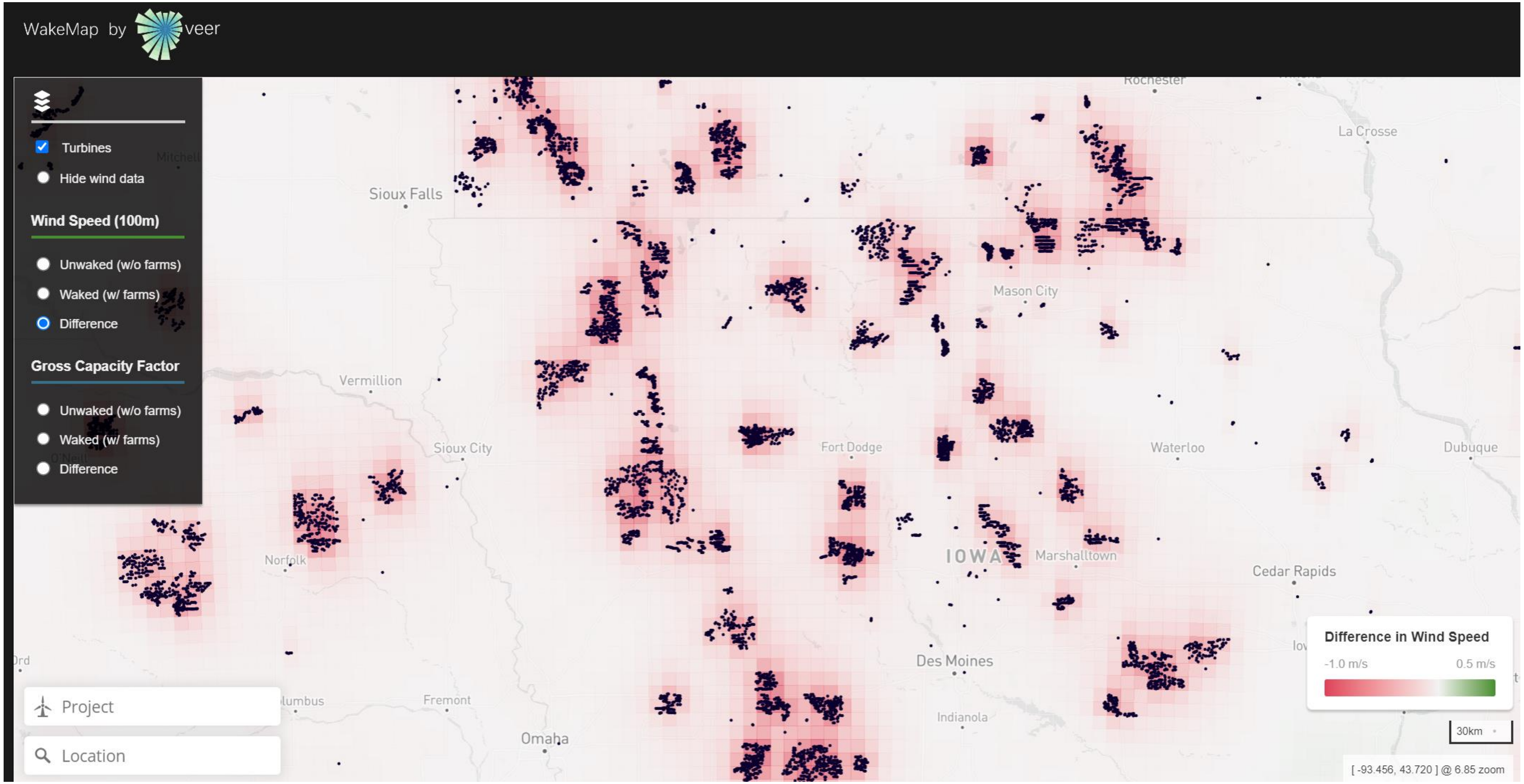
- Enough to collapse the financial viability of these projects

1- https://wes.copernicus.org/preprints/wes-2023-38/

2-https://www.cell.com/joule/pdf/S2542-4351(21)00430-X.pdf

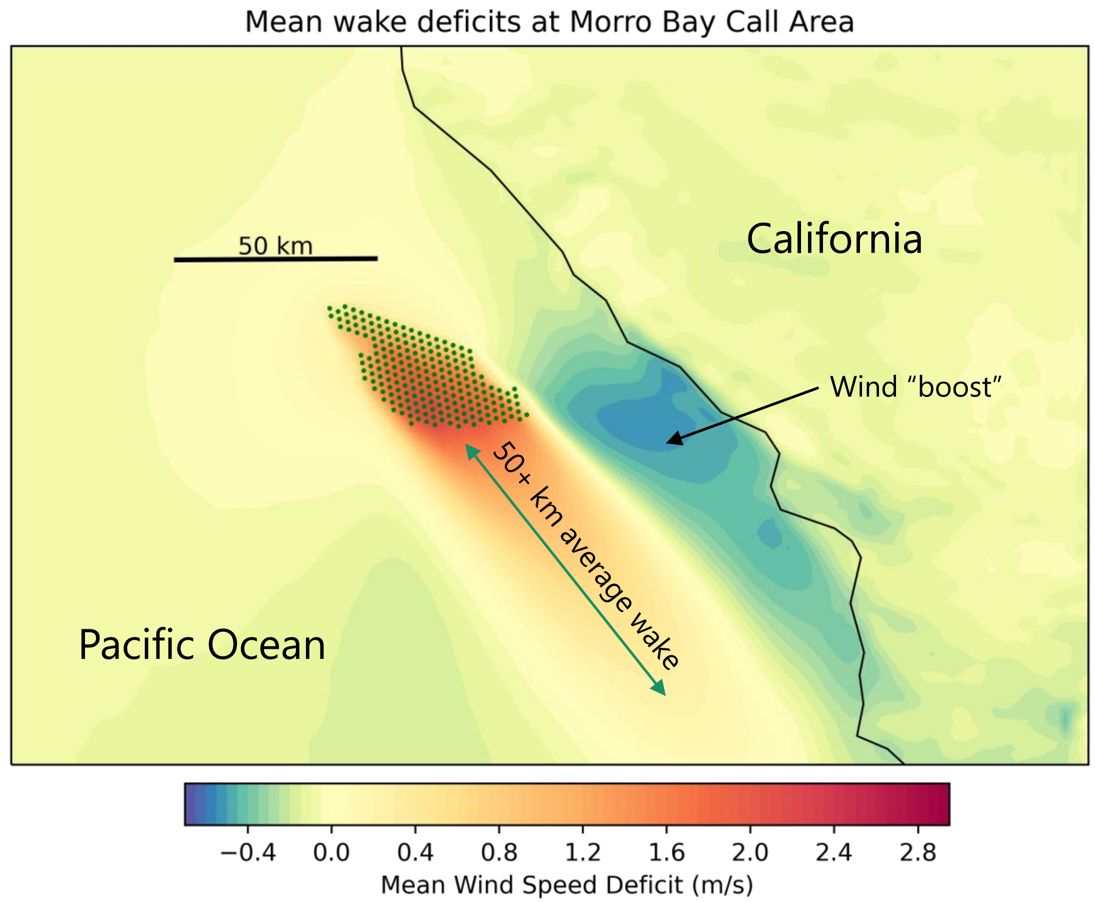
Explore for yourself!

wakemap.veer.eco



It’s not all losses!

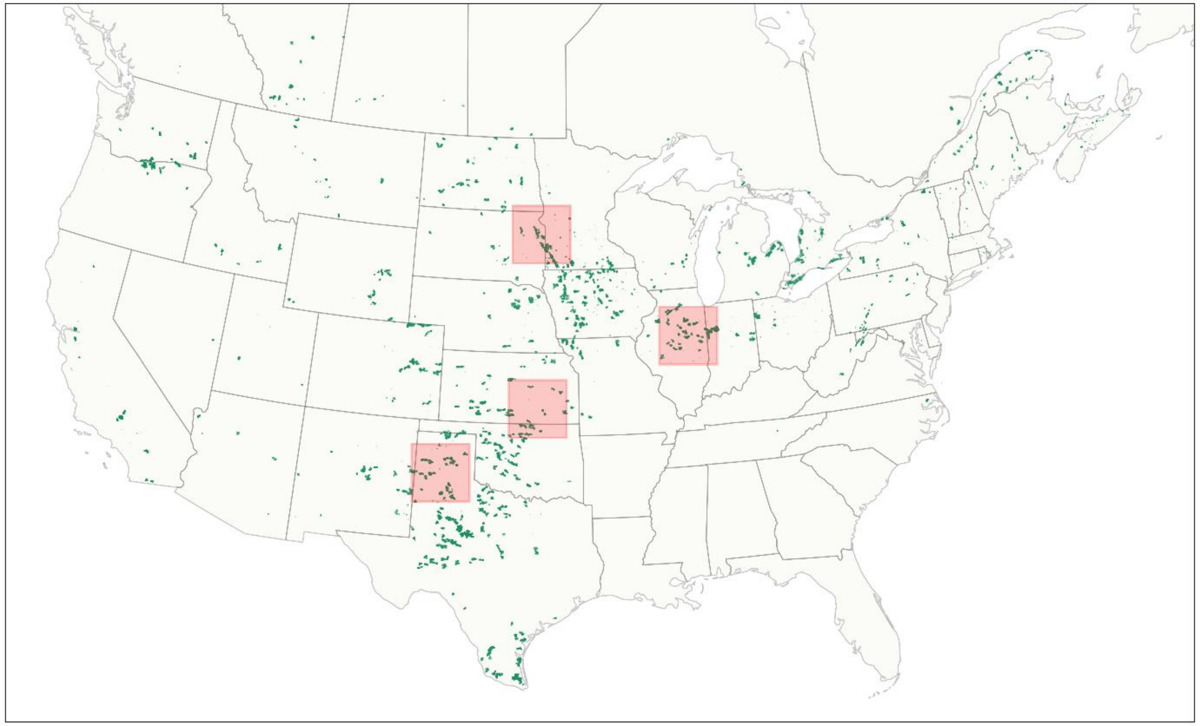
- These momentum “sinks” in WRF effectively act as an obstacle
- Flow will slow as it approaches the wind farm (i.e., blockage) and accelerate around, especially in stable conditions
- In rare cases, the mean wind resource nearby can be higher than if the wind farm wasn’t present.
- Standard wake models would never account for this

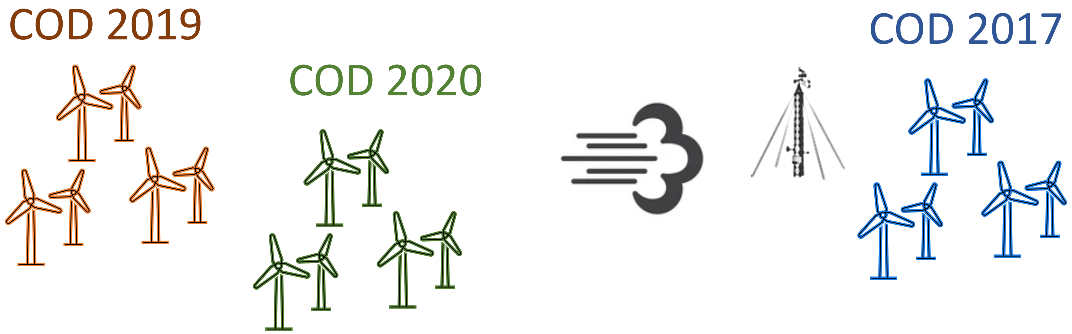


Veer Renewables WakeMap simulation in U.S. Offshore California Wind Area

Validation (and onshore long-wake evidence!)

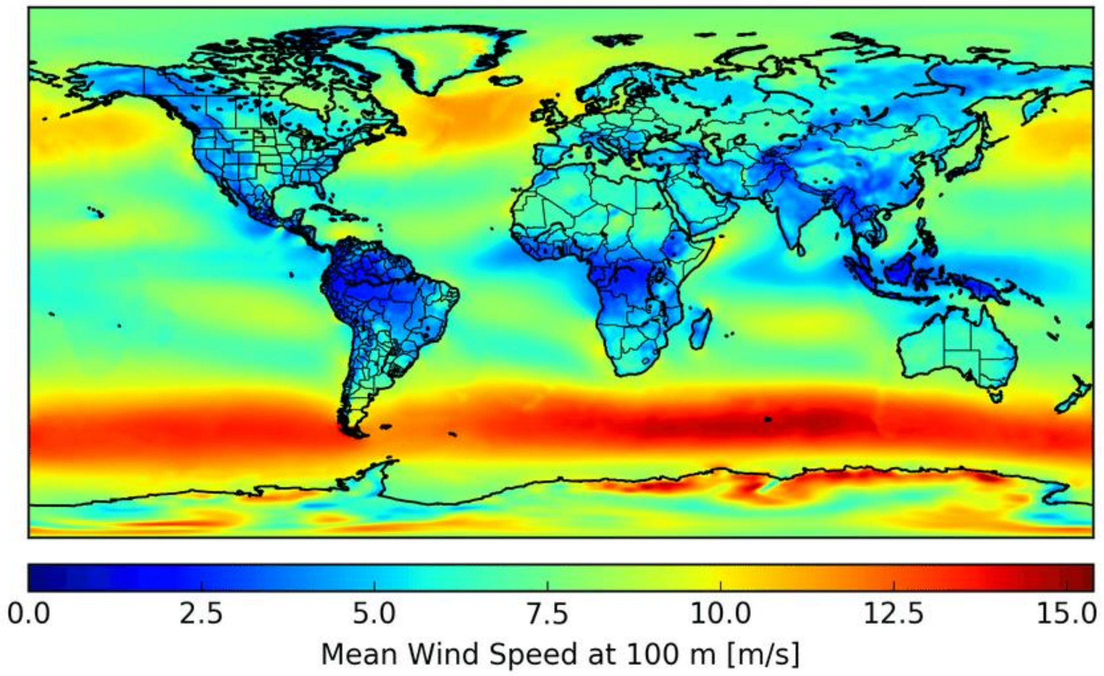
- 5 wind farms selected, which had the following characteristics:
  1. Operating for at least a year before and after neighboring farms were commissioned
  2. Free-stream permanent met mast (PMM) in same sector as neighboring farms
  3. Ideally, PMM had vertical temperature gradient measurements for atmospheric stability calculations





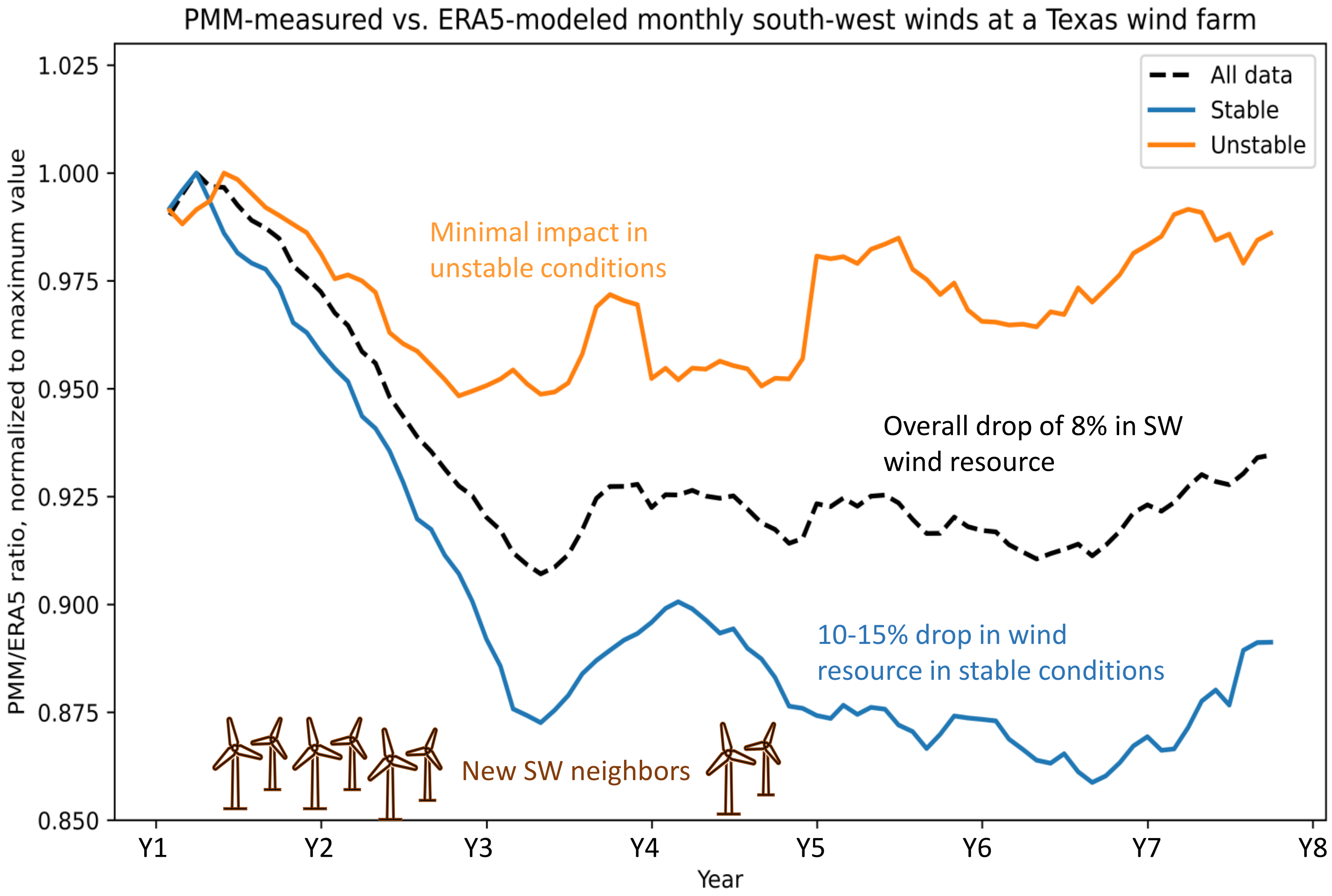
PMMs show evidence of long wakes

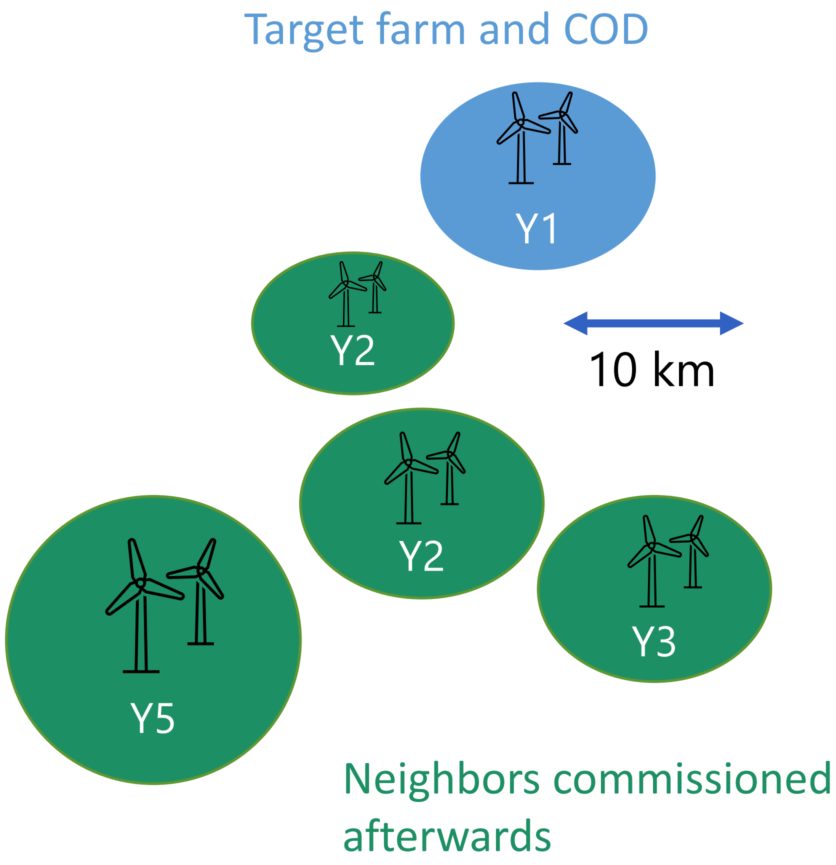
- You just have to know how to look!
- Compare wind resource trends in the PMM vs. ERA5 reanalysis
- Crucially, ERA5 simulations are not informed by surface wind measurements, but rather upper altitude measurements (radiosondes, aircraft, etc.)
- I.e., ERA5 does not see wind farm impact on the wind resource
- If we compare PMM vs. ERA5 over time, we can reveal the impact of long wakes



https://www.researchgate.net/publication/320686586_Global_available_wind_energy_with_physical_and_energy_return_on_investment_constraints

Example


PMM-measured vs. ERA5-modeled monthly south-west winds at a Texas wind farm
All data
Stable
Unstable
Minimal impact in unstable conditions
Overall drop of 8% in SW wind resource
10-15% drop in wind resource in stable conditions
New SW neighbors
PMM/ERA5 ratio, normalized to maximum value
1.025
1.000
0.975
0.950
0.925
0.900
0.875
0.850
Y1
Y2
Y3
Y4
Y5
Y6
Y7
Y8
Year


Target farm and COD
Y1
Y2
10 km
Y2
Y5
Y3
Neighbors commissioned afterwards

Validation Results

Validation Site	Neighbor Capacity (MW)	Neighbor distance (km)	Wind Resource Deficits					
			All Data		Stable		Unstable	
			Observed	Modeled	Observed	Modeled	Observed	Modeled
Texas 1	700	10-25	7-9%	9.6%	10-13%	11.9%	2-5%	6.5%
Texas 2	350	5-20	10-12%	8.7%	N/A	N/A	N/A	N/A
Minnesota	200	5-15	1-3%	4.2%	5-6%	5.2%	±1%	3.1%
Illinois	450	30-40	3-4%	2.4%	N/A	N/A	N/A	N/A
Oklahoma	800	10-40	6-8%	5.4%	9-11%	7.8%	3-5%	2.7%
		Average	**6.3%**	**6.1%**	**9%**	**8.3%**	**2.5%**	**4.1%**

Caveats

WRF should not be run at resolutions lower than 0.75-1.0 km

WRF WFP may not accurately assess wake losses within a wind farm

WRF WFP best coupled with an internal wake model, large-eddy simulation, etc.

Concluding Remarks

- Wake propagation and dissipation are fundamentally weather-dependent with strong seasonal and diurnal trends
- Conventional wake modeling approaches generally ignore this dependence
- As bigger and taller wind farms are constructed, and at higher density, we need better wake modeling tools like WRF WFP
- Critical we consider long wake impact before building a new wind farm, designating new offshore lease areas, etc.
- Should consider implementing WFP into weather forecast models

Questions?

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