“Good Neighbors” or “I Drink Your Milkshake”?
Costs and Consequences of Uncoordinated Wind Energy Development

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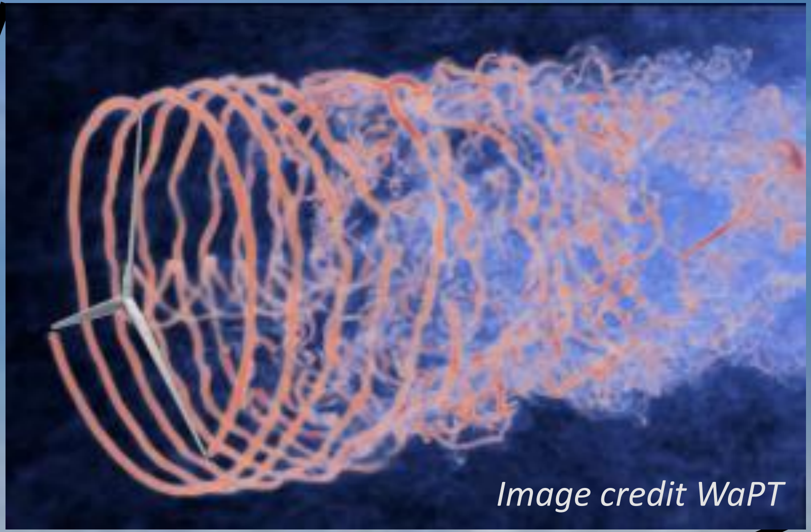
Photo By: Bel Air Aviation - Helicopter Services



Wind **turbine** wake:

Advanced controls allow us to steer wakes to reduce wake impacts (turbulence, power production) on downwind turbines

Fleming et al. 2019, *Wind Energy Science,* https://doi.org/10.5194/wes-4-273-2019

Aggregate **Wind Farm** wake:

Reduced wind speeds downwind can extend for 10s of km, visible from satellite, with surface temperature impacts

ARTICLES
nature energy
https://doi.org/10.1038/s41560-018-0281-2

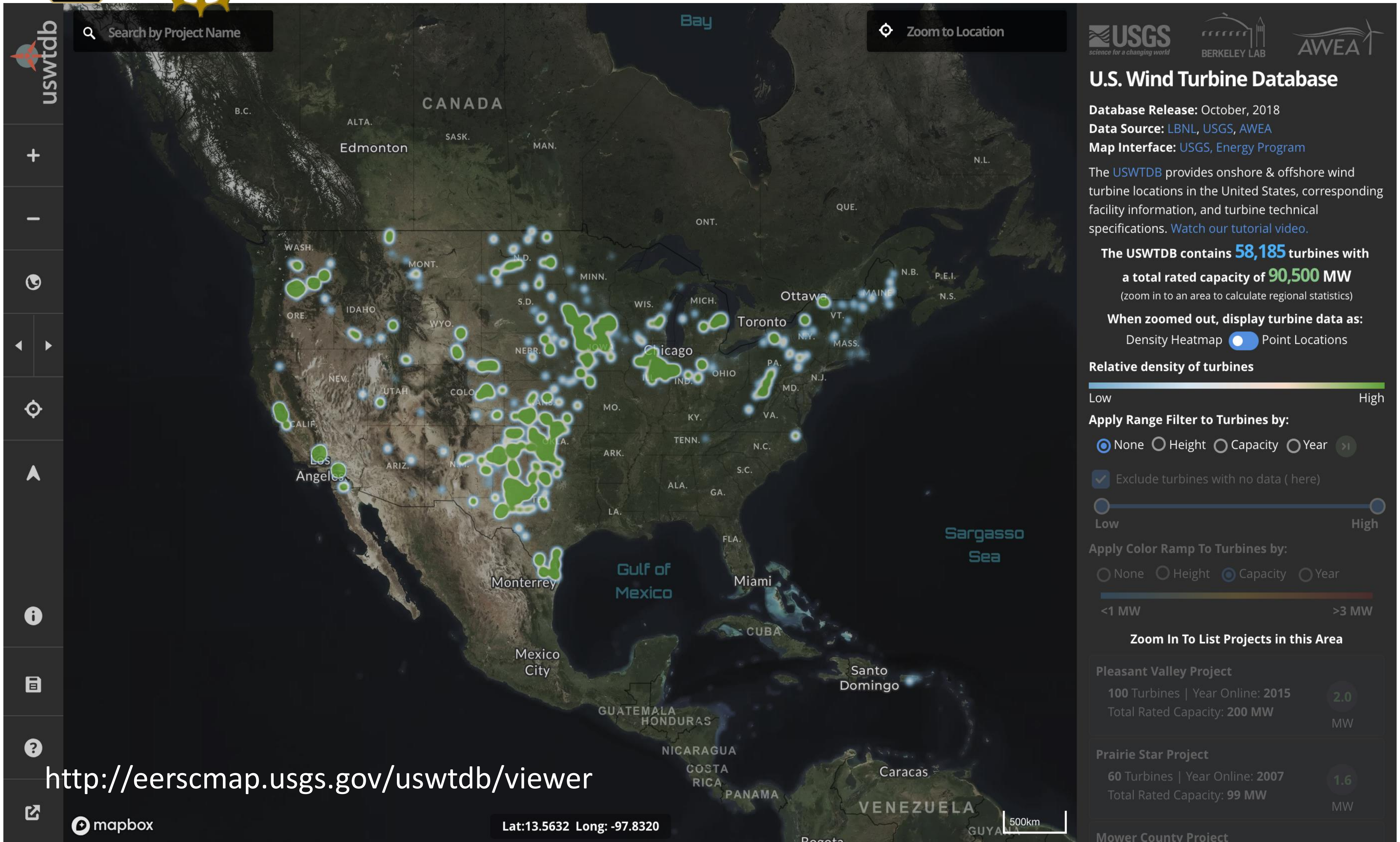
Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development

J.K. Lundquist[1,2]*, K.K. DuVivier[3], D. Kaffine[4] and J.M. Tomaszewski[1]

Optimal wind farm locations require a strong and reliable wind resource and access to transmission lines. As onshore and off-shore wind energy grows, preferred locations become saturated with numerous wind farms. An upwind wind farm generates

Lundquist et al. 2019, *Nature Energy,* https://doi.org/10.1038/s41560-018-0281-2

Wind farms are often co-located



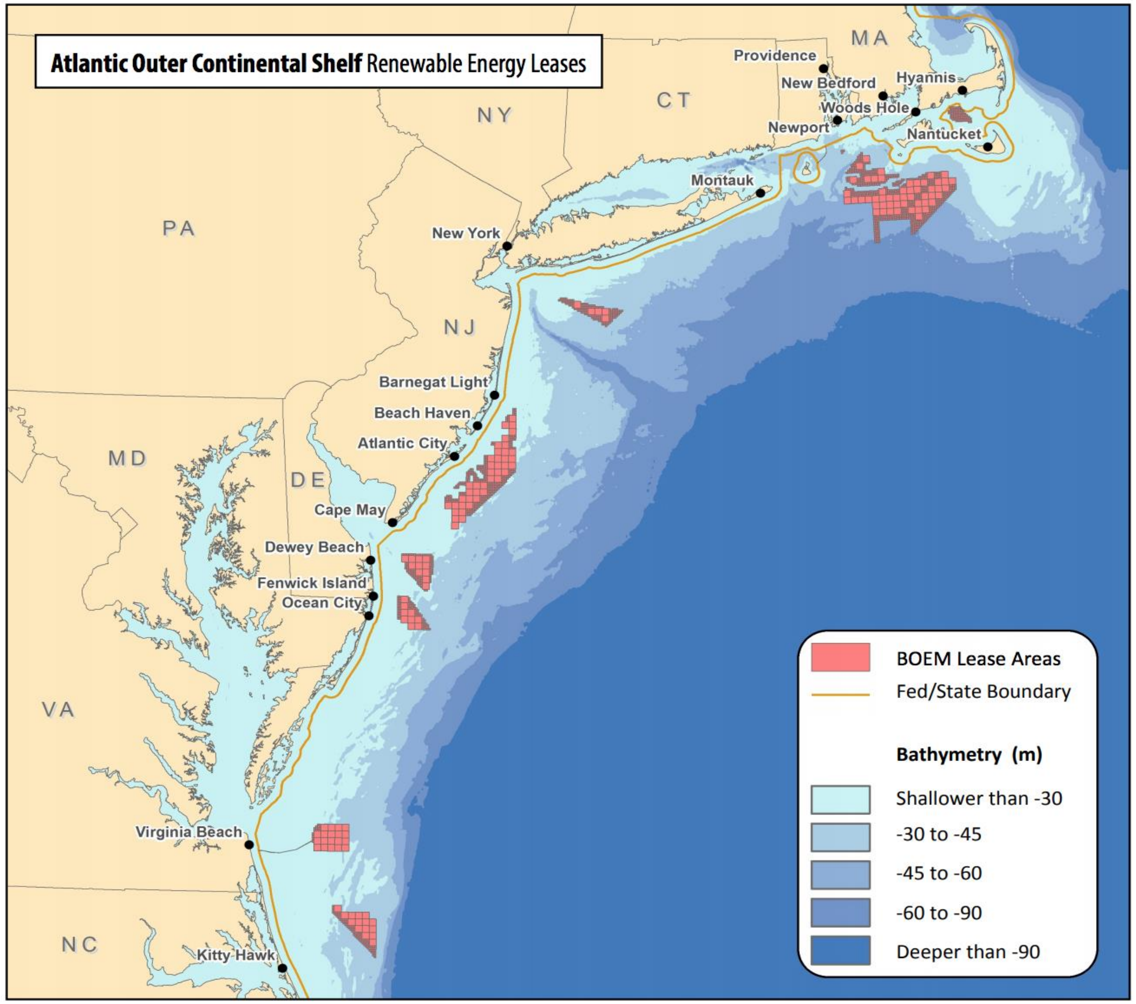
http://eerscmap.usgs.gov/uswtdb/viewer

In 2016, the US had 994 individual wind farms.

Of these, 884 (or 88.8%) are located within 40 km of another wind farm, potentially impacted by wakes.

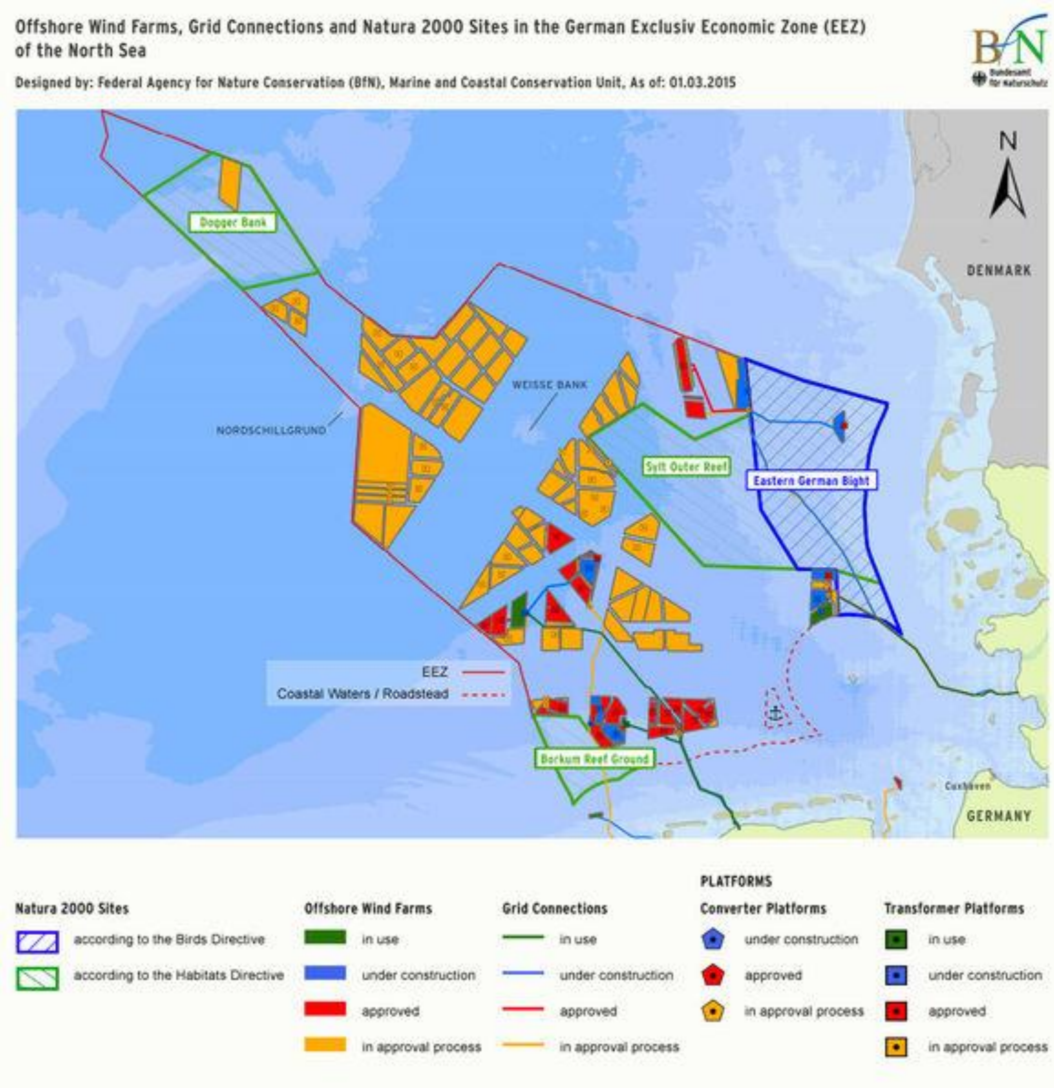
Wind farm interactions will only increase in the future

US Offshore Plans



https://www.boem.gov/Renewable-Energy-Lease-Map-Book/

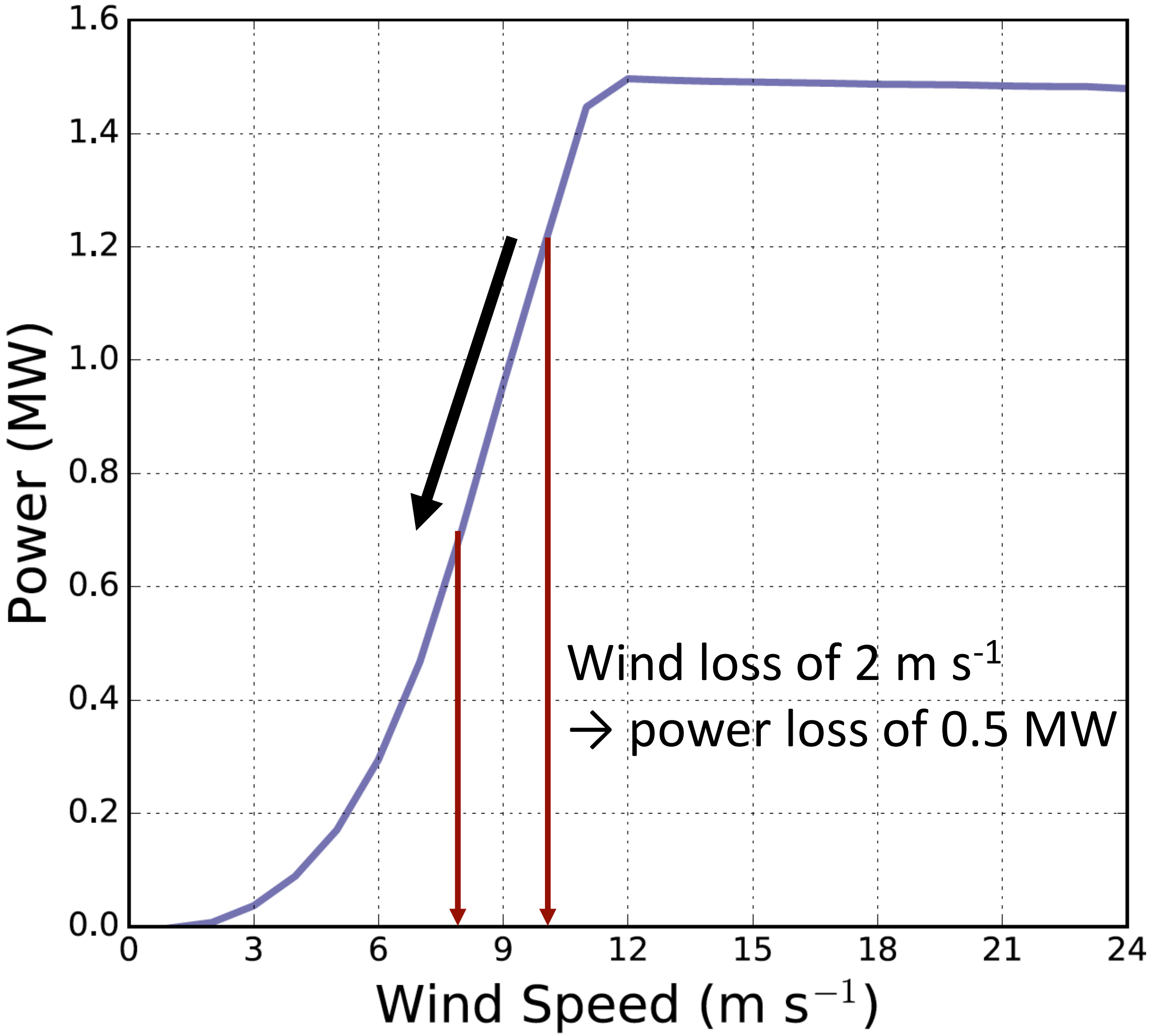
German Offshore Plans



Wind turbines affect their ambient environment

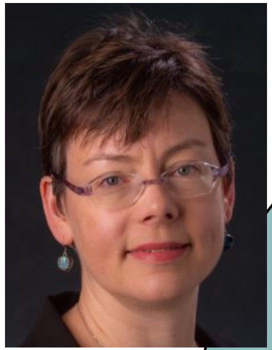
Turbines reduce wind speeds and increase turbulence downwind (i.e. “wake effects”)

Consequence: downwind, waked wind farms generate less power[1]



[1]Nygaard, N. G., 2014: Wakes in very large wind farms and the effect of neighbouring wind farms. *J. Phys. Conf. Ser.*, **524**, 012162, doi:10.1088/1742-6596/524/1/012162

We considered wakes from three perspectives



J. Tomaszewski

D. Kaffine

KK DuVivier

Atmospheric Science:

How do wakes vary with atmospheric conditions; can we predict them?

Economic:

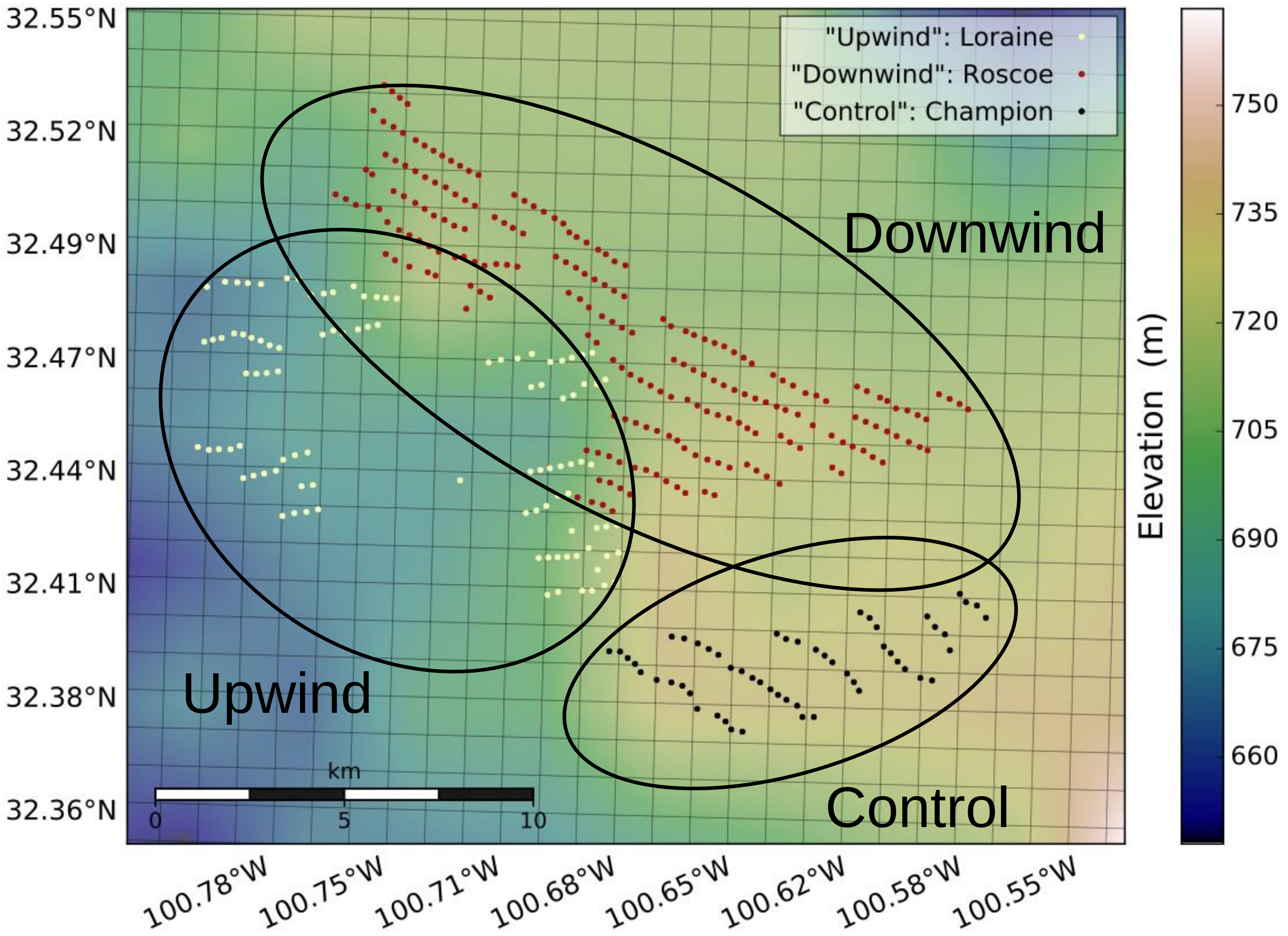
How do wind farm wakes impact power production for downwind wind farms?

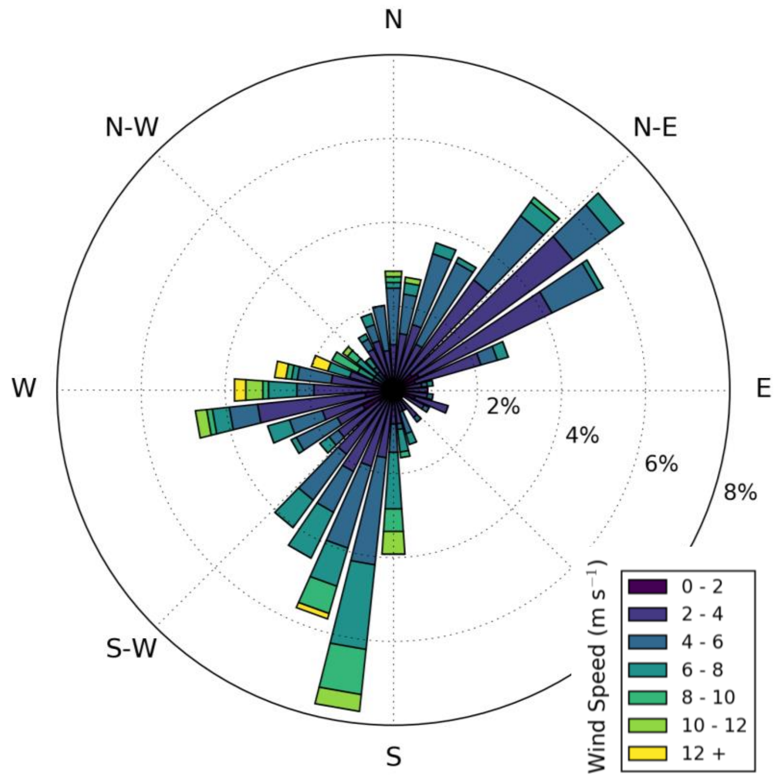
Legal:

How do state and local laws address wind farm wake concerns?

What are the costs and consequences of wake effects arising from uncoordinated wind energy development?

Wind farm cluster in TX presents interesting case





Jan 2013 Wind Rose from San Angelo ASOS

Wake effects can be simulated with WRF WFP

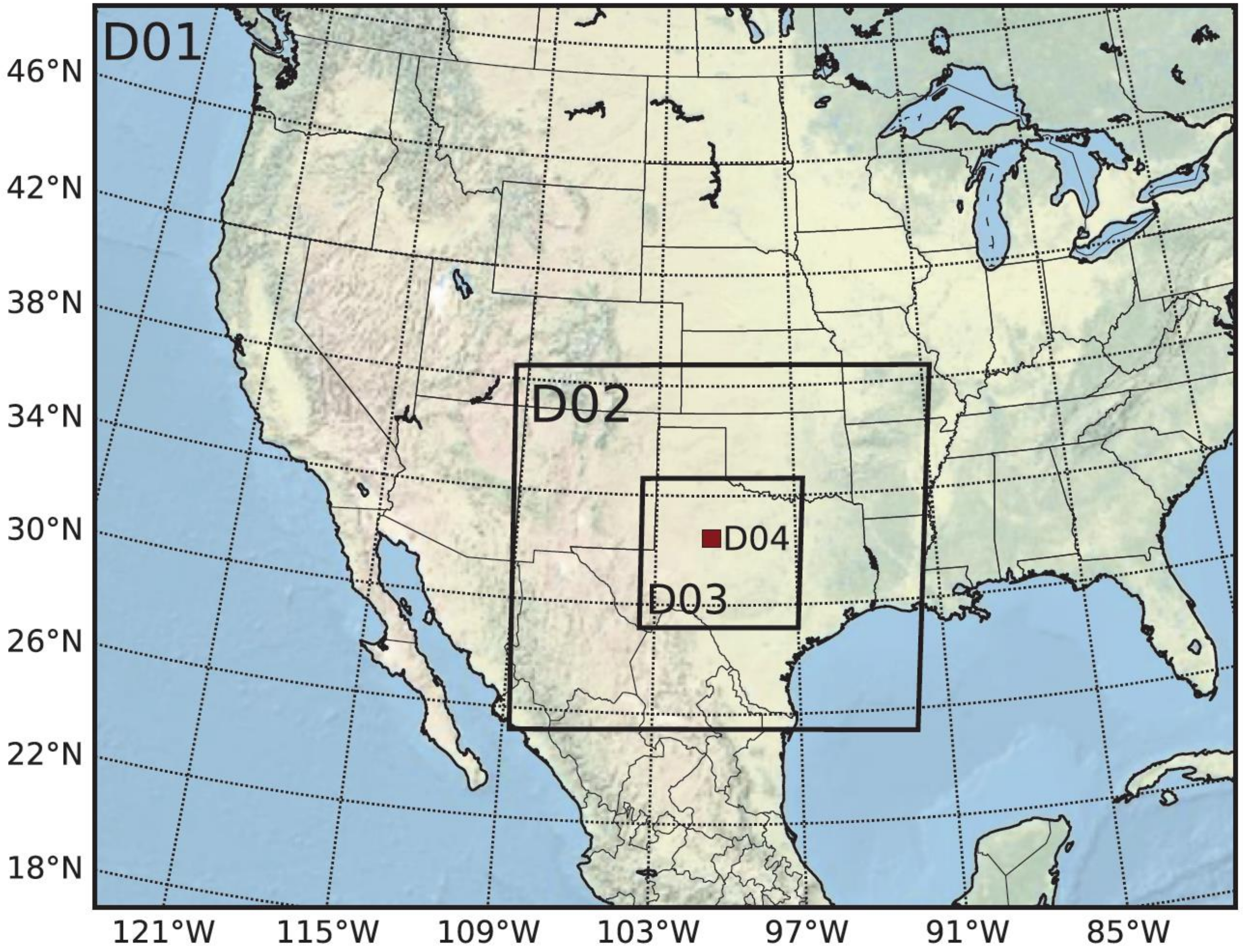
Weather Research and Forecasting (WRF) with Wind Farm Parameterization (WFP)[1]

Two effects:

- Increased drag at rotor height
- Added TKE at rotor height (IMPORTANT[2])

Three cases simulated:

Upwind + Downwind + Control (UDC)
Downwind + Control (DC)
No wind farms

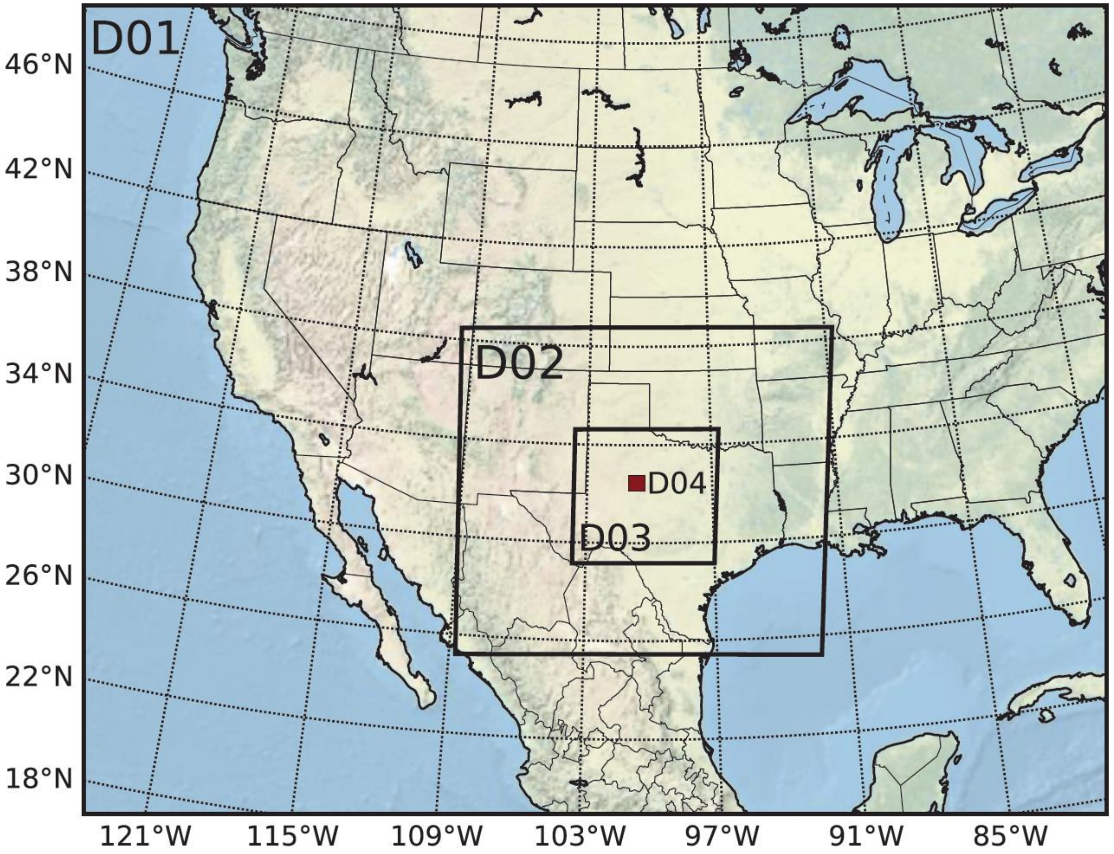


[1]Fitch et al., 2012: Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model. Mon. Wea. Rev., **141**, 1395–1395, doi: 10.1175/MWR-D-12-00341.1

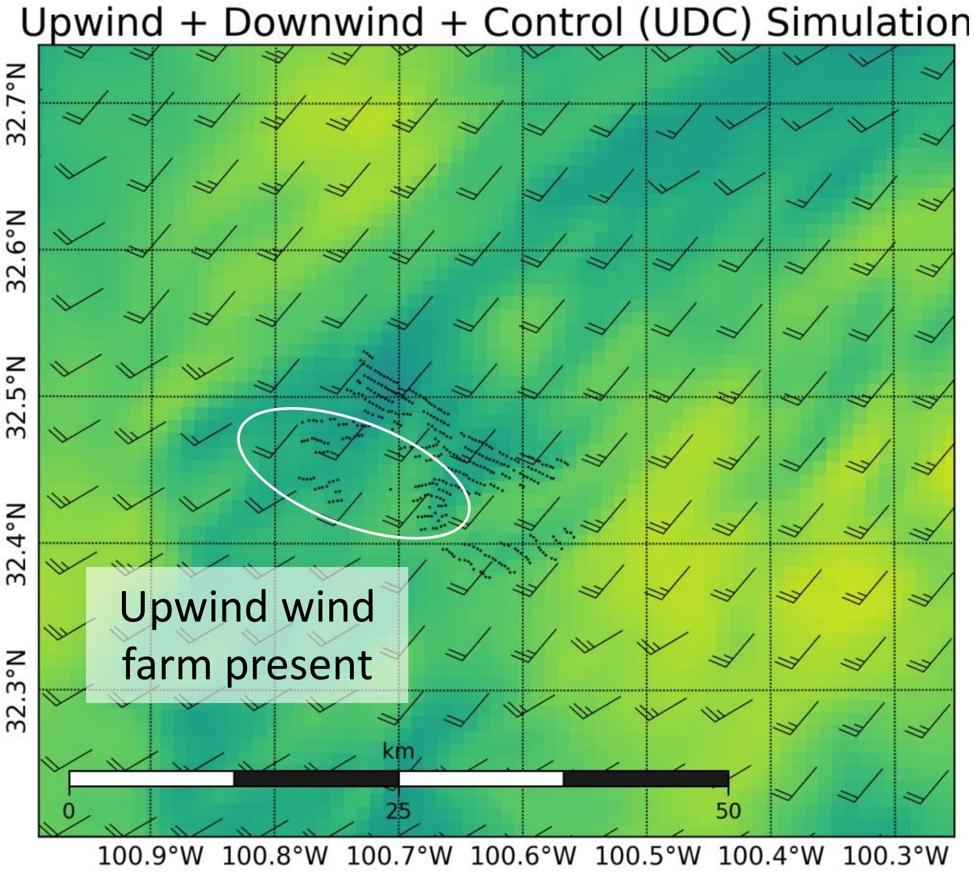
[2] Vanderwende et al., 2016: Simulating effects of a wind turbine array using LES and RANS. It Journal of Advances in Modeling Earth Systems, 8, 1376–1390, doi:10.1002/2016MS000652

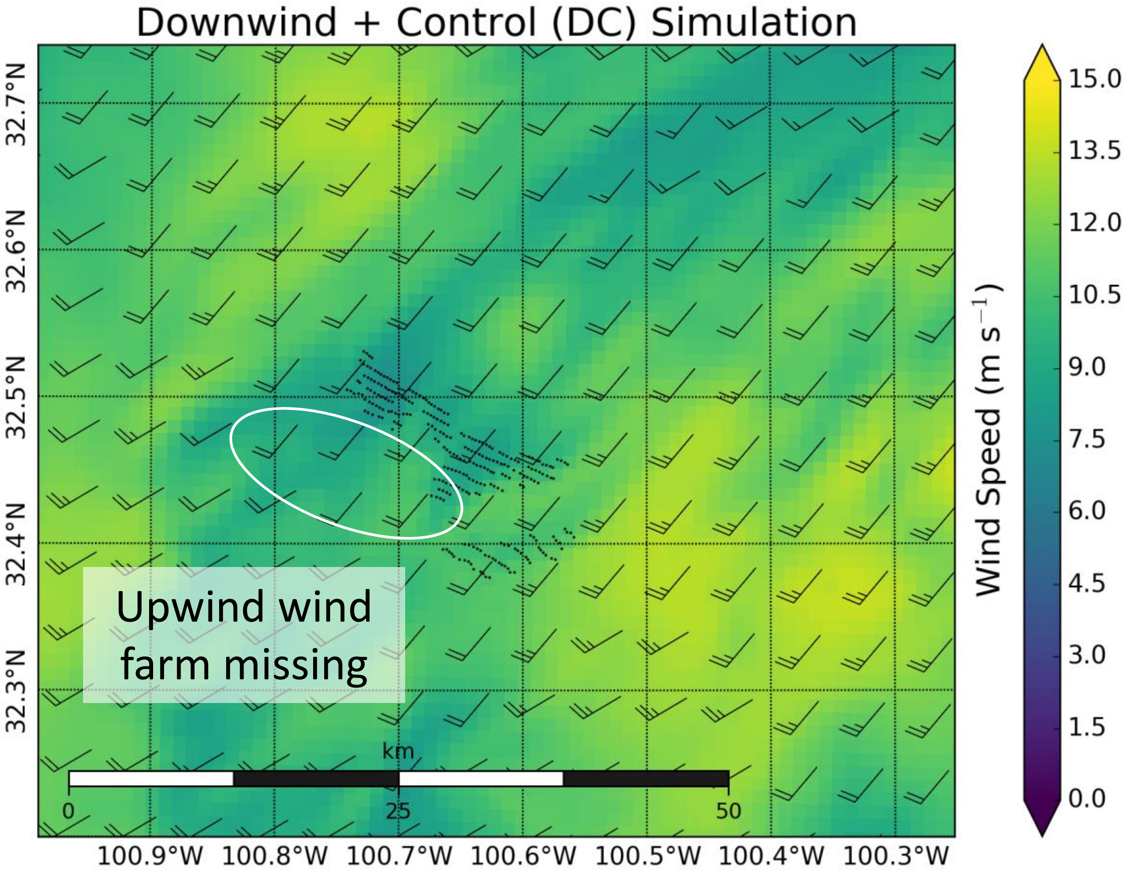
Wake effects can be simulated with WRF WFP

Horizontal resolution	27 > 9 > 3 > 1 km
Vertical resolution	12 m in lowest 200 m
Initial & boundary conditions	ERA-Interim
PBL	MYNN
Time step	30 sec
Output resolution	10 min
Period simulated	Jan 2013, in 24-hr analysis periods
Spin-up time	12 hr
Turbine parameterized	GE 1.5 MW SLE (80 m hub height & rotor diameter)



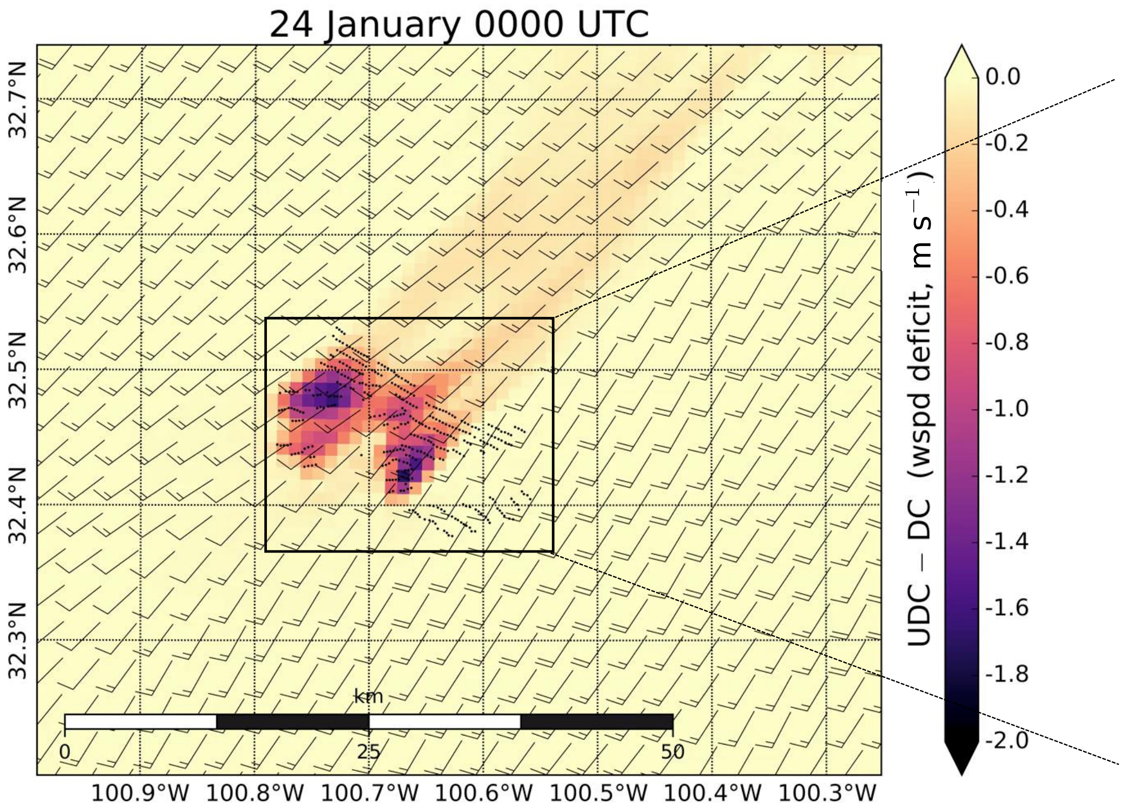
Subtract model solutions to isolate wake effects





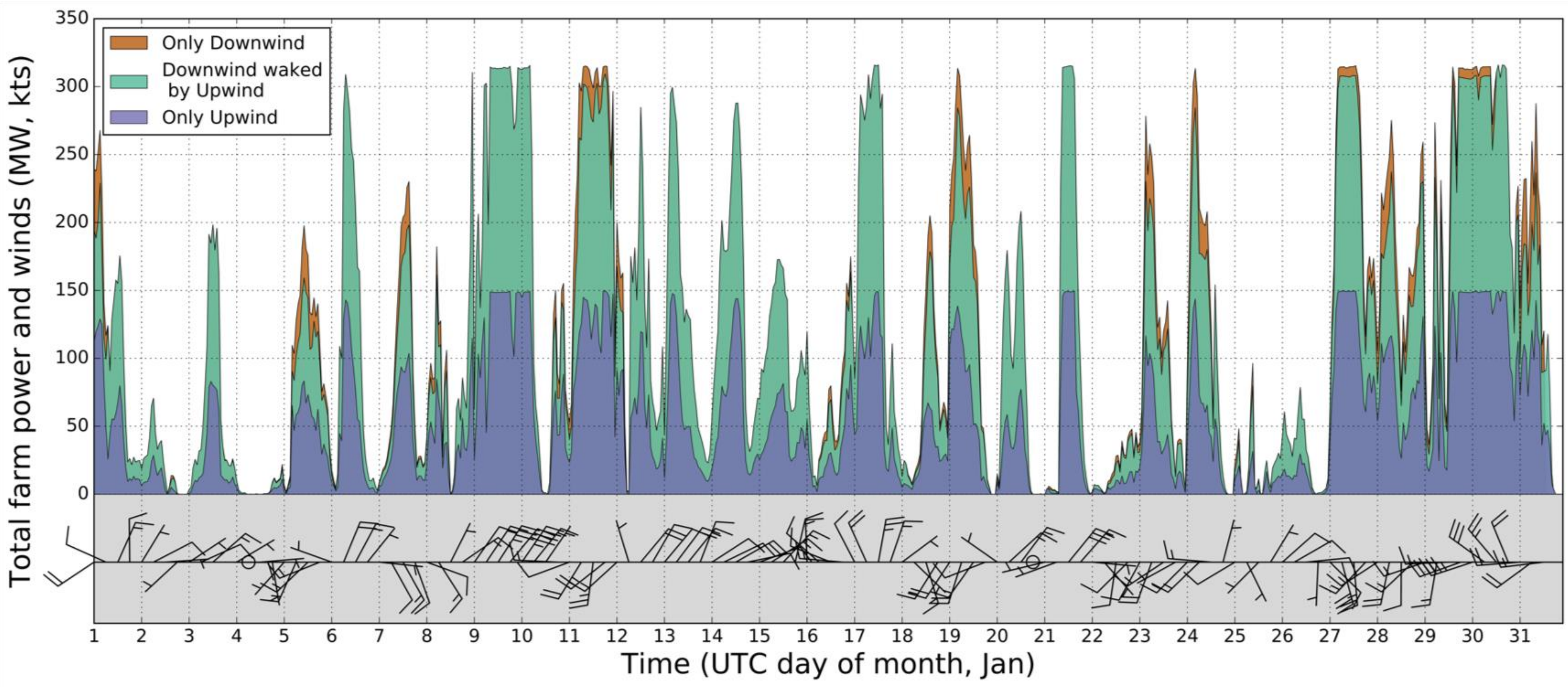
UDC – DC ⟹

Wakes vary throughout day, strongest at night



UDC – DC = U wake effect on D

Waking causes ~7% drop in capacity factor in Jan

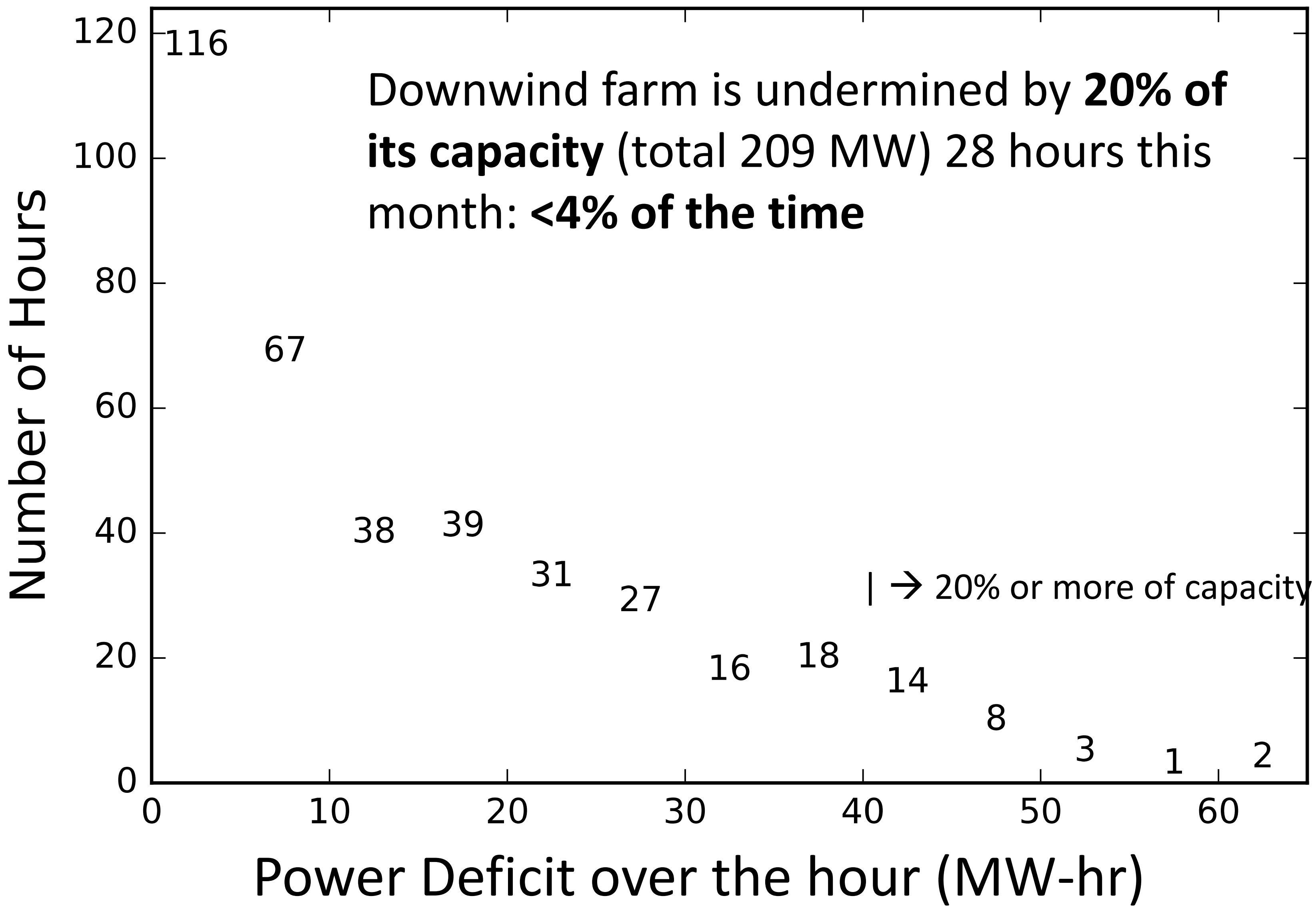


Only Downwind (unwaked) = 0.393 CF

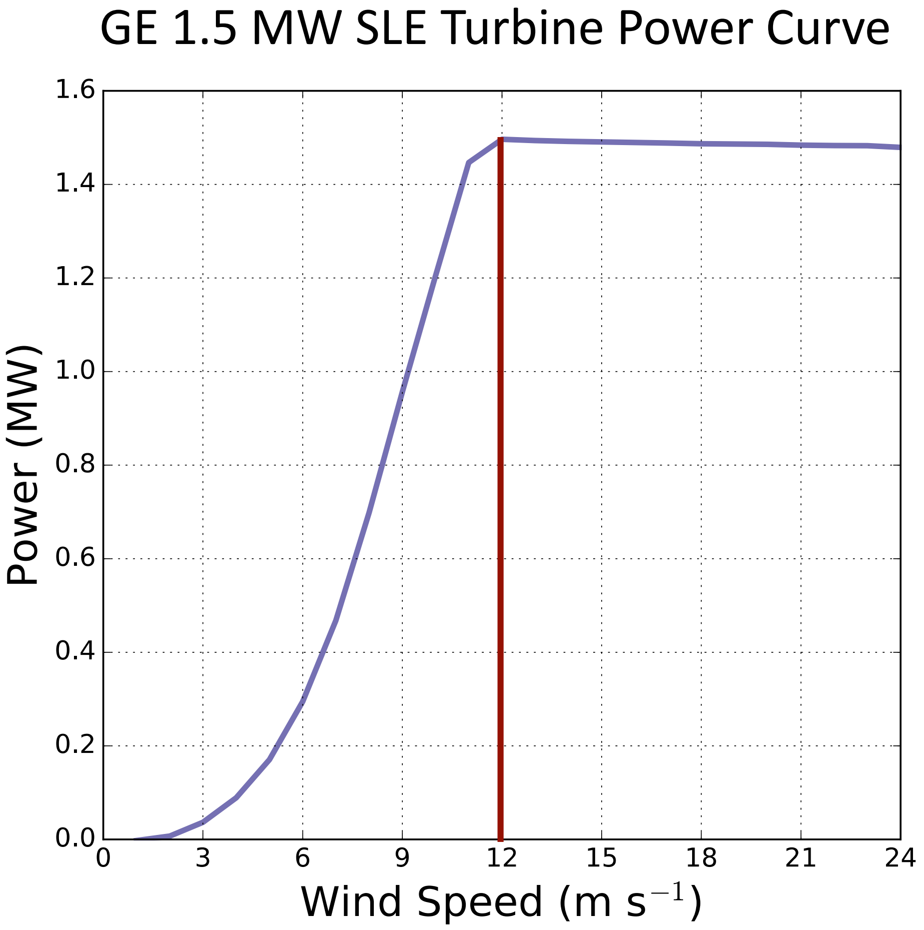
Downwind waked by Upwind = 0.366 CF

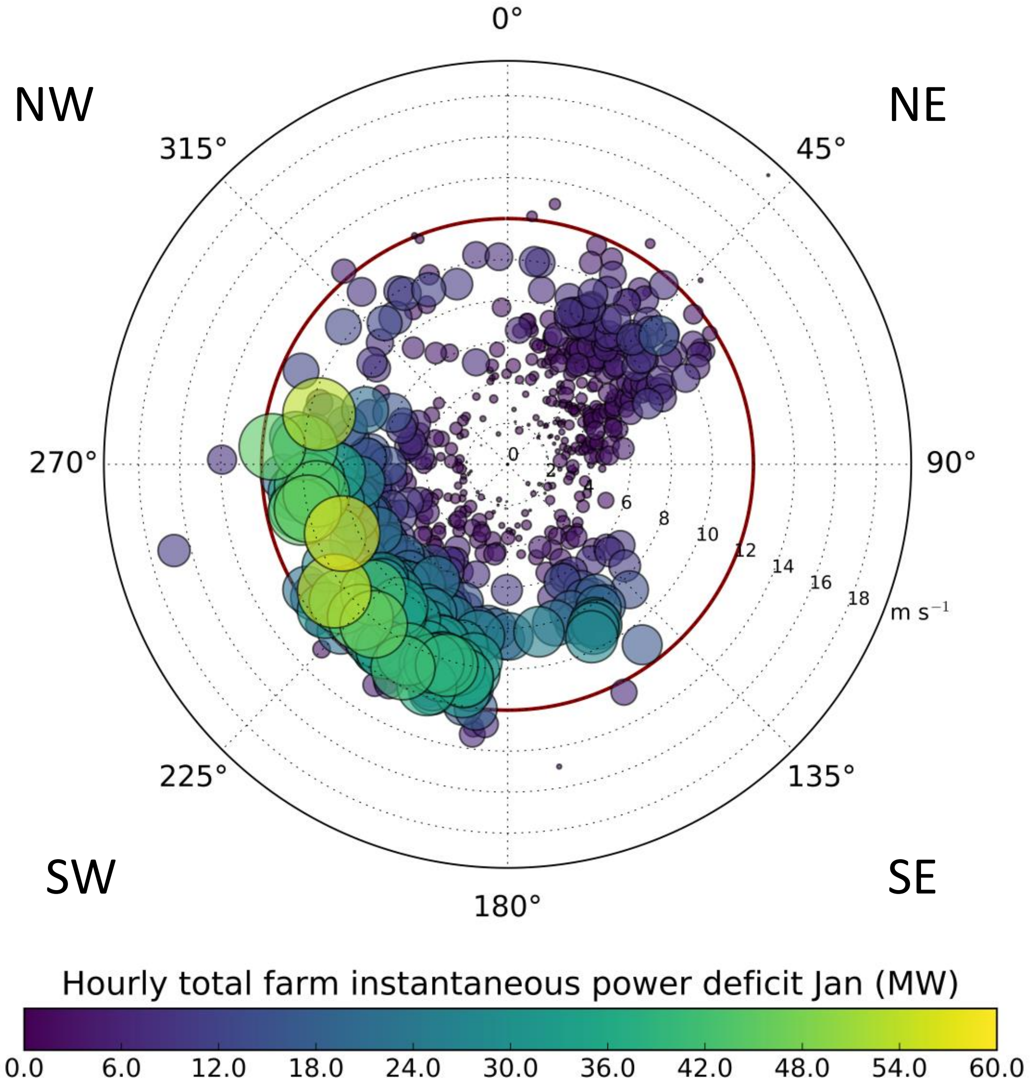
↓ 6.8% drop

Strong wakes are not frequent

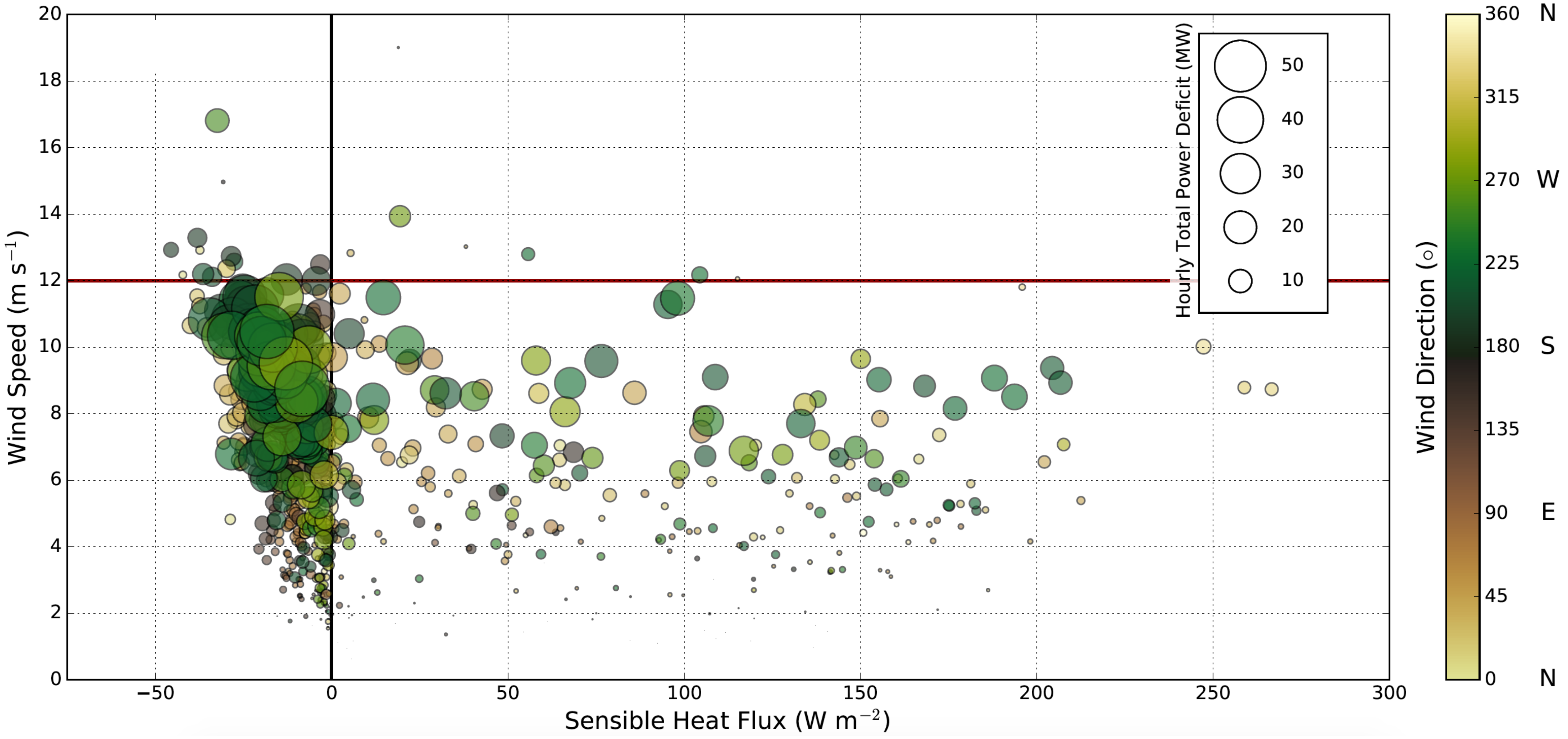


More power lost during aligned (SW) winds, 8 – 12 m s^{-1}





Strongest wakes occur in stable conditions



Nighttime Stable ← | → **Daytime Convective**

Econometrics find significant wake effects

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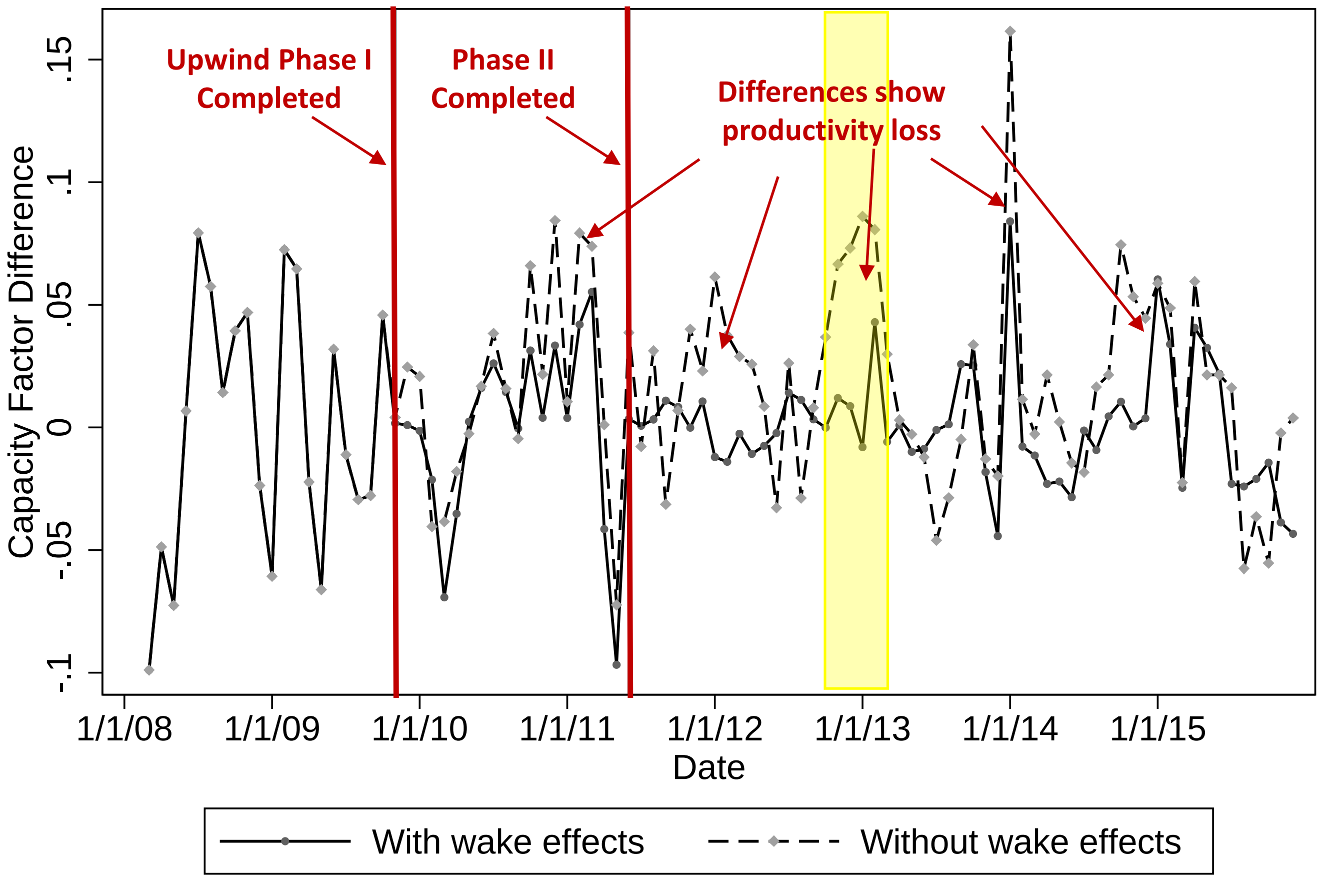
Predicted capacity factor minus Actual at Downwind site



Uses publicly-available EIA power data, NOAA surface wind data to compare electricity generation at Downwind site before and after Upwind site was built

Predicts a total generation loss of **405,443 MWh ($5M)** due to wakes Nov 2009 – Dec 2015

Legal constructs rarely consider wind farm wakes

KK DuVivier
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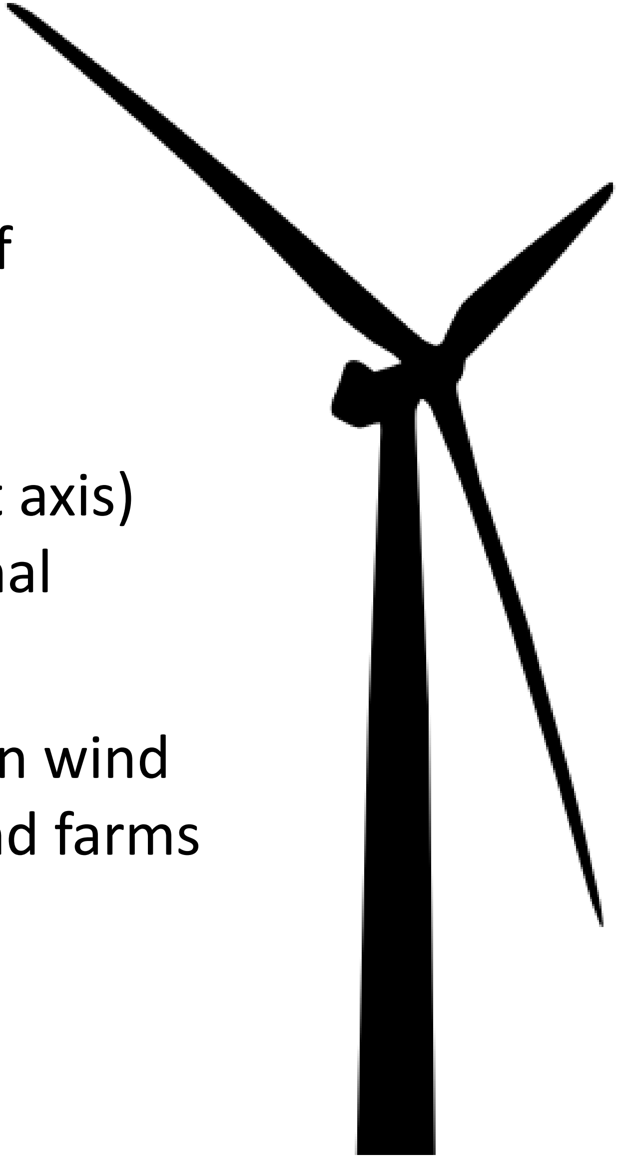
- Siting laws are not based on empirical study of physical or economic effects of wakes

Exception: Minnesota, US

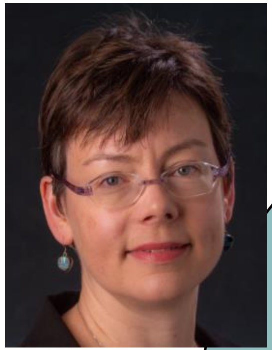
3 RD (on secondary) & 5 RD (on predominant axis) as the standard buffer for internal and external spacing

- This decentralized wind development results in wind developers ignoring wake effects on other wind farms

Will become more consequential as onshore/offshore sectors grow



Next Steps: Wakes Offshore

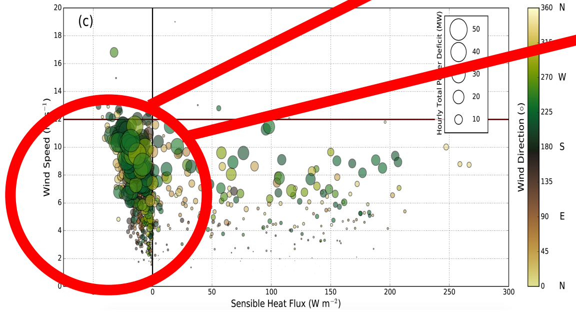


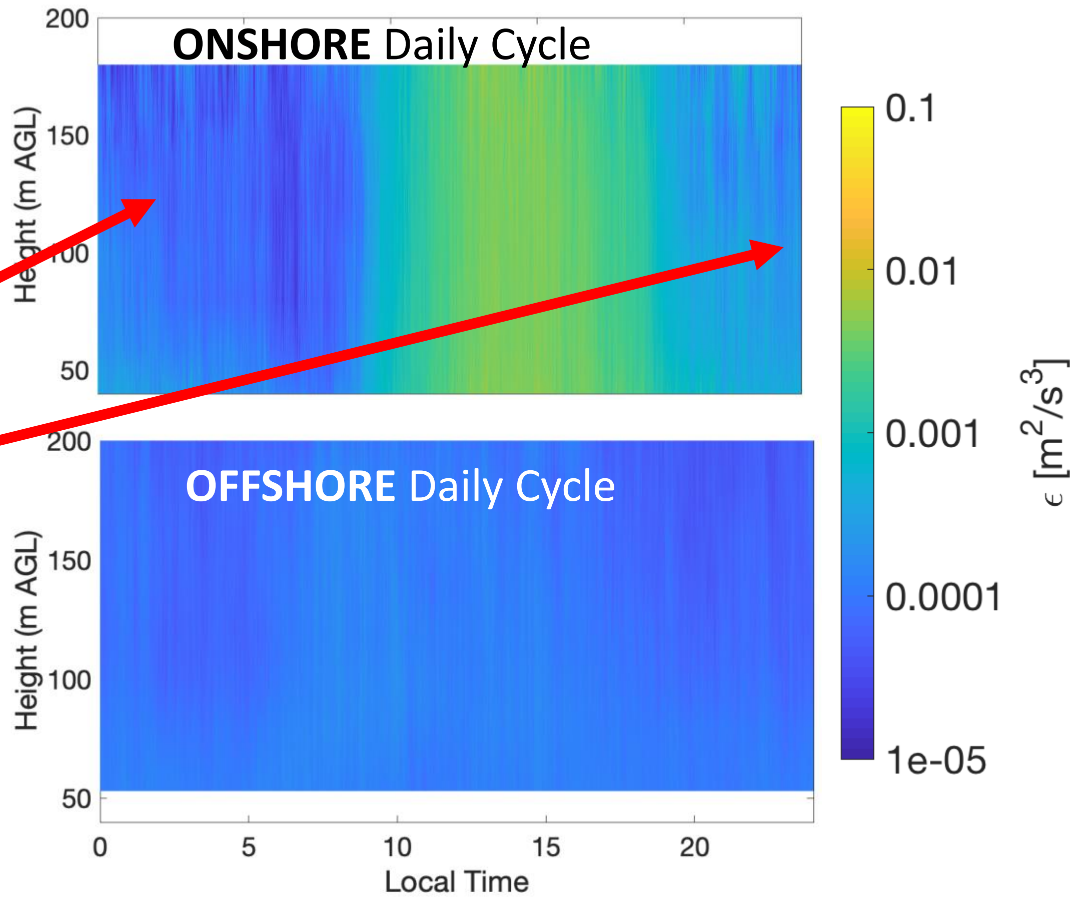
J. Tomaszewski

Atmospheric Science:

How might wakes from **offshore** wind farms affect grid integration?

One-year of lidar observations from offshore lidar[1] show far less turbulence offshore, suggesting that wakes will be significant and persistent





[1] Bodini, N., J. K. Lundquist, A. Kirincich, 2019: Offshore wind turbines will encounter very low atmospheric turbulence. *Geophysical Research Letters*. https://doi.org/10.1029/2019GL082636

Next Steps

D. Kaffine

Economic:

Crops seem to benefit from co-location with wind farms:

Corn ↑ (100 MW → 1% yield increase)

Soy, Hay ↑

Wheat ←→

Paper forthcoming in *Journal of Environmental Economics and Management*, “Microclimate effects of wind farms on local crop yields”

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Next Steps

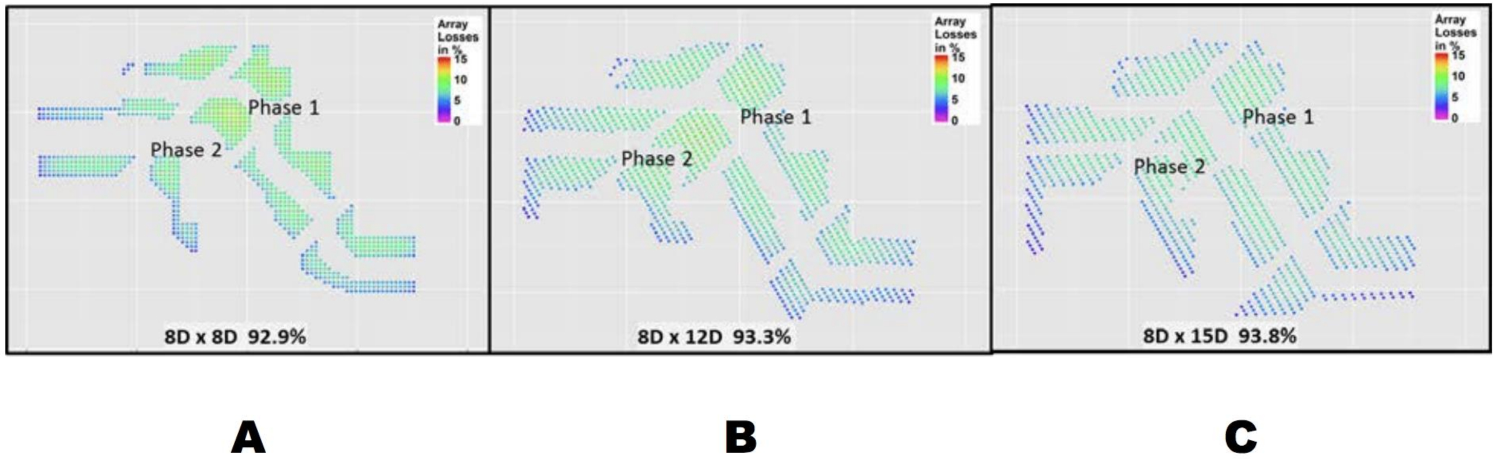


Figure 25. MA WEA for Alternative 3 leasing area delineation showing the effect of turbine spacing and buffers on array efficiencies with two 500-MW projects in each leasing area: (A) 8 D x 8 D spacing; (B) 8 D x 12 D spacing; (C) 8 D x 15 D spacing
(Source: NREL)

KK DuVivier

Legal:

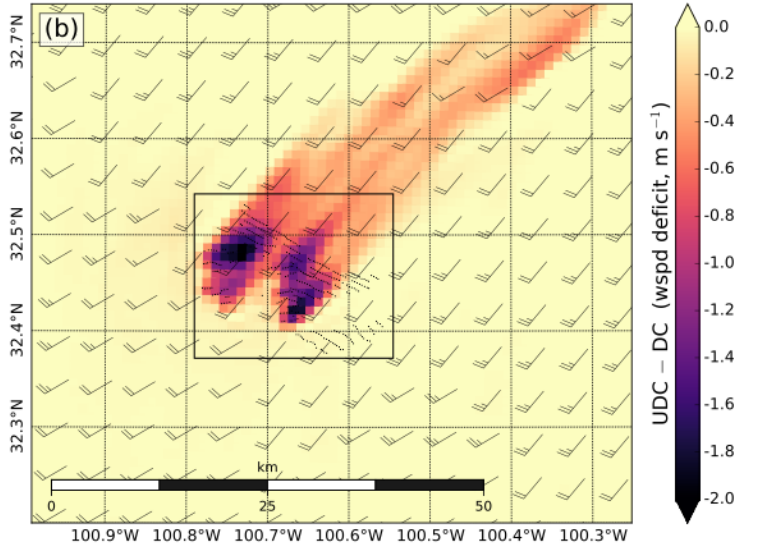
Can buffer zones between farms be managed to increase public advantage of the resource?

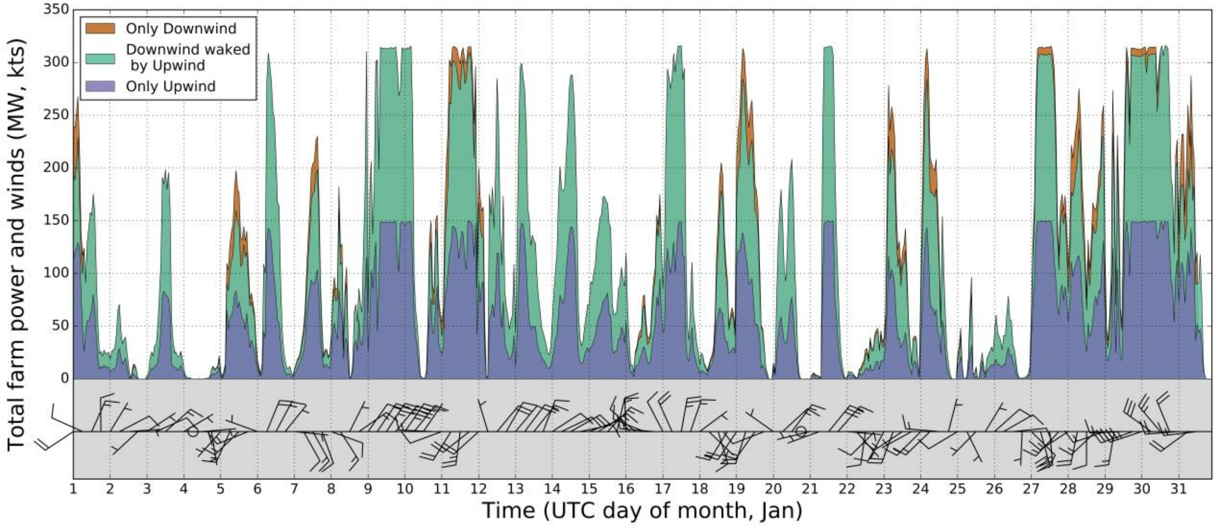
kkduvivier@law.du.edu

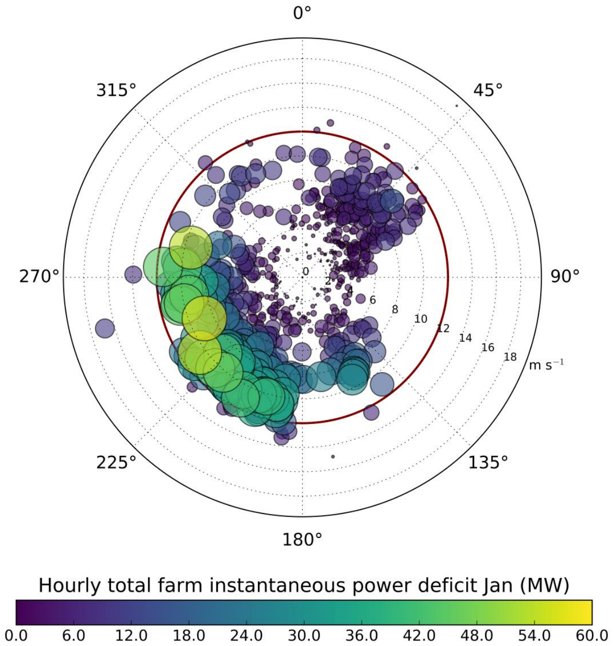
Musial et al. 2013: Assessment of Offshore Wind Energy Leasing Areas for the BOEM Massachusetts Wind Energy Area, NREL/TP-5000-60942, https://www.nrel.gov/docs/fy14osti/60942.pdf

Wind farm wake variability will impact grid integration

1. Wake impacts seen in econometric analysis can be captured by WRF WFP
2. Wake effects depend on wind speed, wind direction, and stability (through mediation by ambient turbulence)







Lundquist et al. 2019, *Nature Energy,*
https://doi.org/10.1038/s41560-018-0281-2

Thank you!

Any questions?

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National Science Foundation grant BCS-1413980 (Coupled Human Natural Systems)
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National Science Foundation grant ACI-1053575 (NSF GRFP)

Photo by: Jessica Tomaszewski

WFP simulations could aid in “voluntary bargaining”

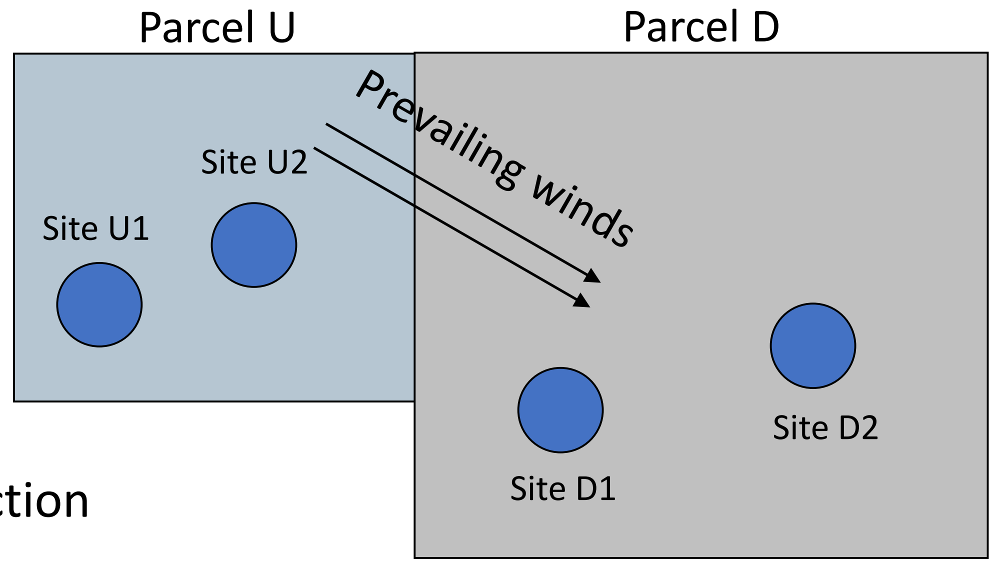
Suppose[1]:

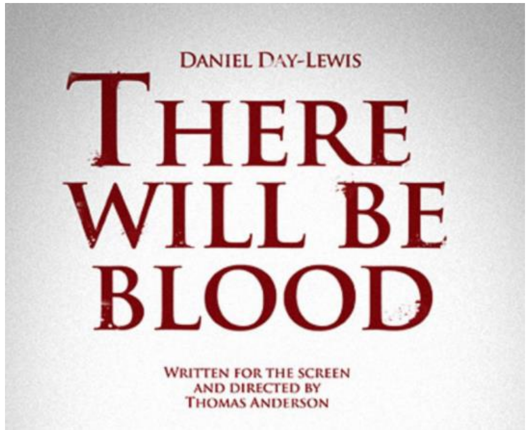
Parcel U profits best from current proposed layout

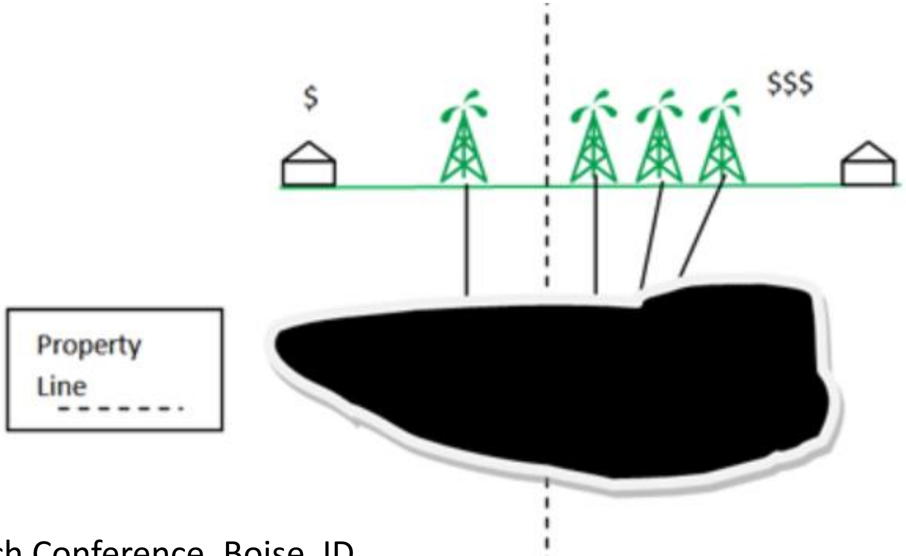
However, wake studies show conflicts with Parcel D degrade overall productivity of the region

Bargain: D pays U to relocate to Site U_2

Avoid: “Rule of Capture” laws that plagued oil extraction in 19th century US



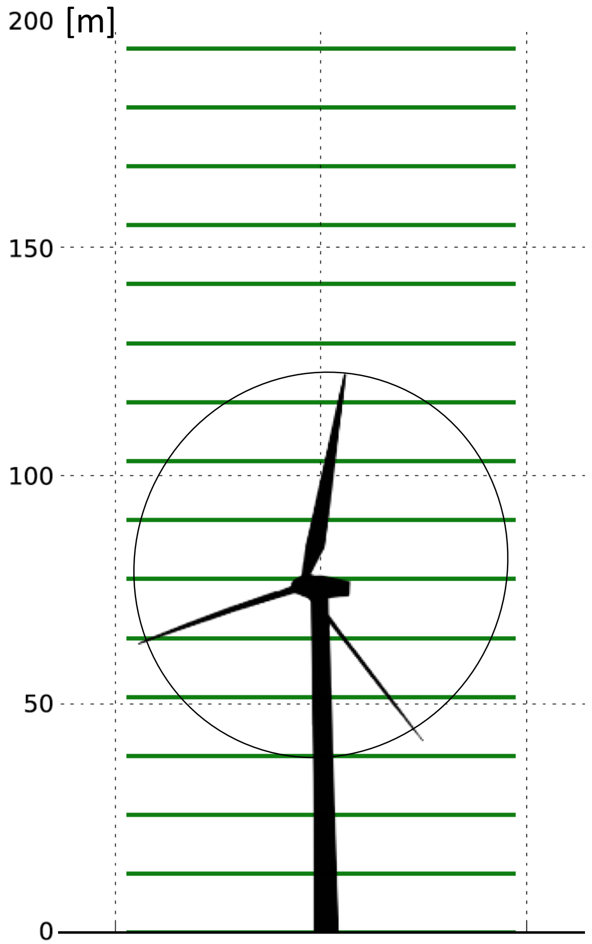




Paramount Vantage and Miramax Films, 2007

[1]Troy Rule, 2018: The economics of wind turbine wakes. Energy Policy Research Conference, Boise, ID.

Wake effects can be simulated with WRF WFP



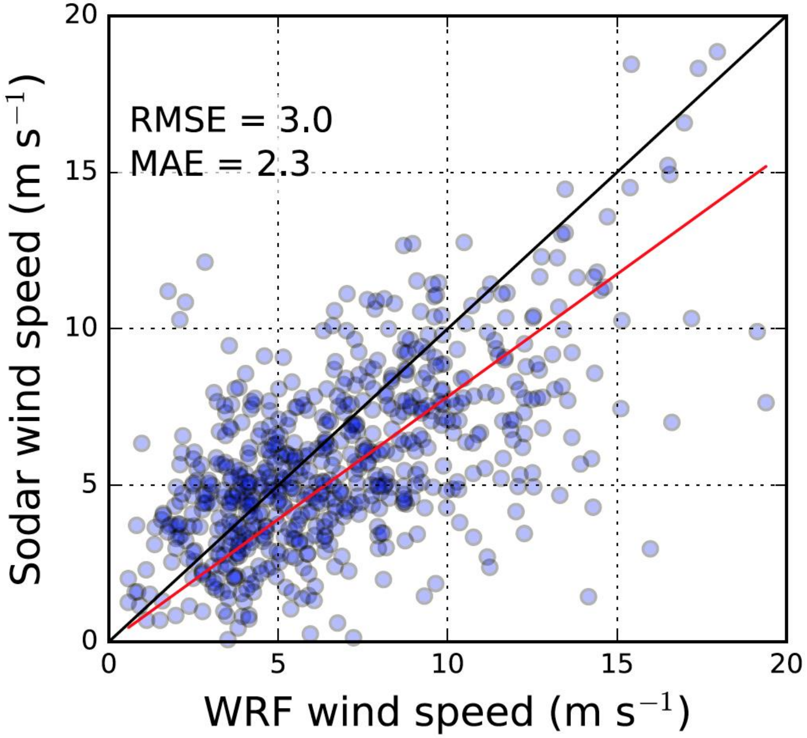
WFP[1] imposes a momentum sink on the mean flow at realistic heights within rotor-swept area

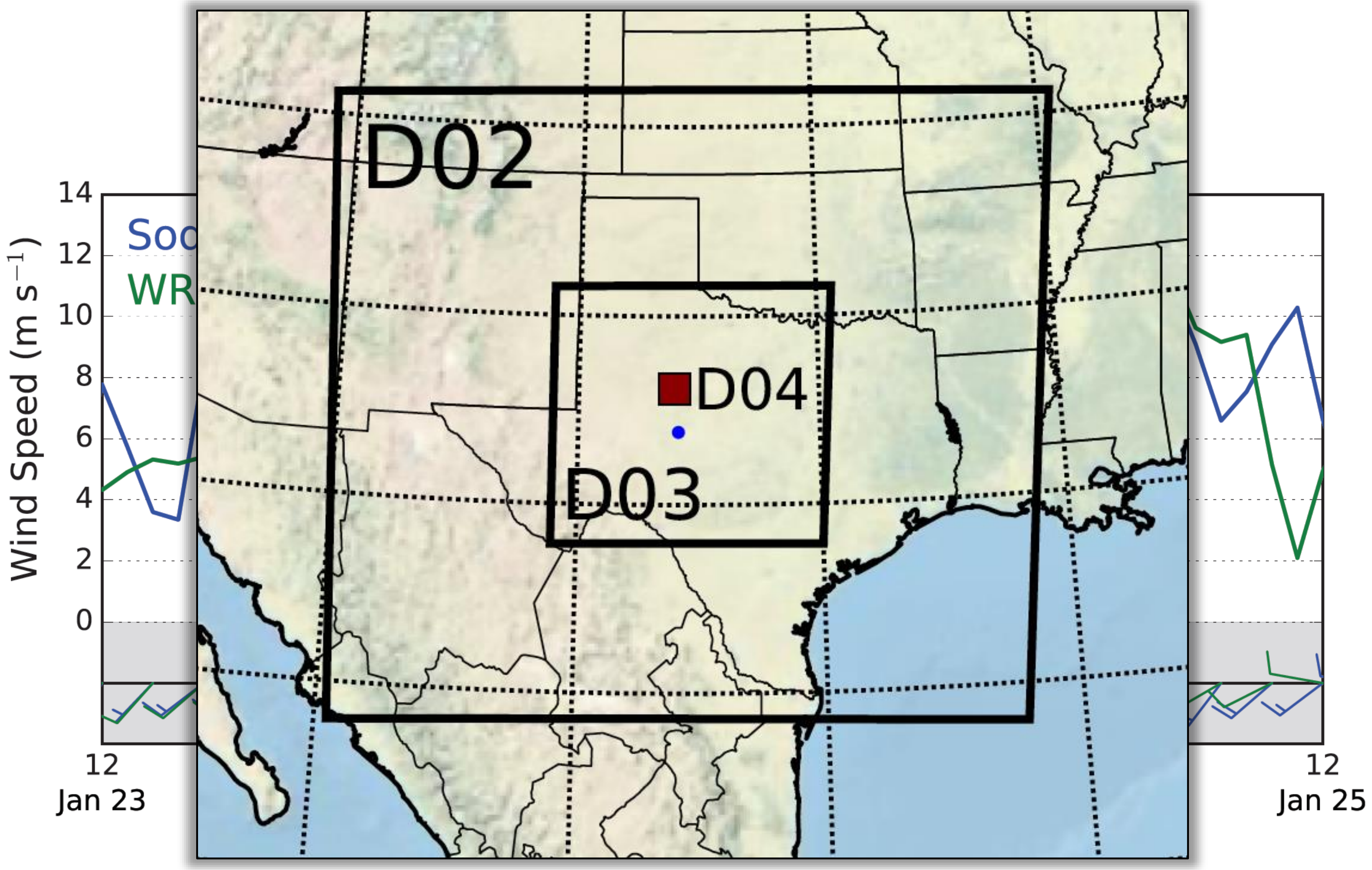
Kinetic energy in wind becomes electricity & TKE

User can input thrust coefficient, power curve of desired turbine, define locations of turbines

[1]Fitch et al., 2012: Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model. Mon. Wea. Rev., **141**, 1395–1395, doi: 10.1175/MWR-D-12-00341.1

Adequate agreement exists between WRF and sodar obs





[1]Sodar data provided by West Texas Mesonet[2] for Jan 2013 at San Angelo station

[2]Schroeder, J. L. et al., 2005: The West Texas Mesonet: A Technical Overview. *J. Atmospheric Ocean. Technol.* **22**, 211–222

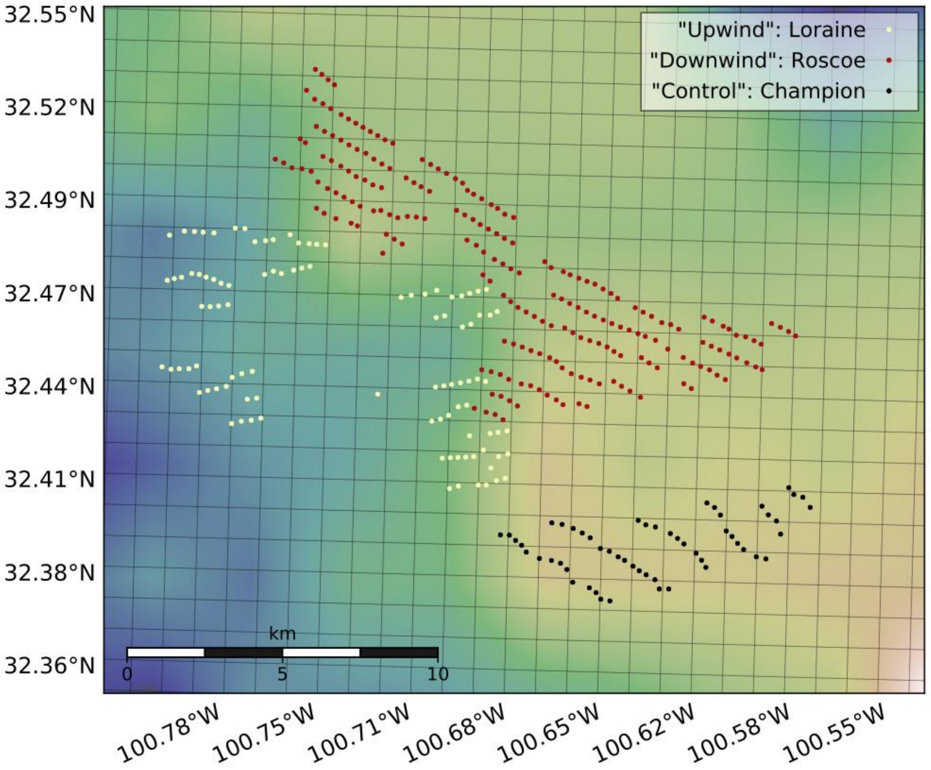
Methodology:

1. **Select a wind farm that operated *before* and *after* a neighboring project was built upwind**
   - Was already operating when the Upwind wind farm was constructed
2. **Identify a nearby "control" wind farm**
   - Needed to account for wind speed/direction variations in the area during the study period
3. **Use public data to compare electricity generation at Roscoe *before* and *after* Upwind was built** *(accounting for variations in wind speed and direction)*
   - Quantified using an econometric model
4. **Compute the *dollar value* of the resulting electricity generation losses at Downwind**
   - Multiply quantities of lost electricity generation by local wholesale electricity prices

Horizonal resolution affects power loss estimate

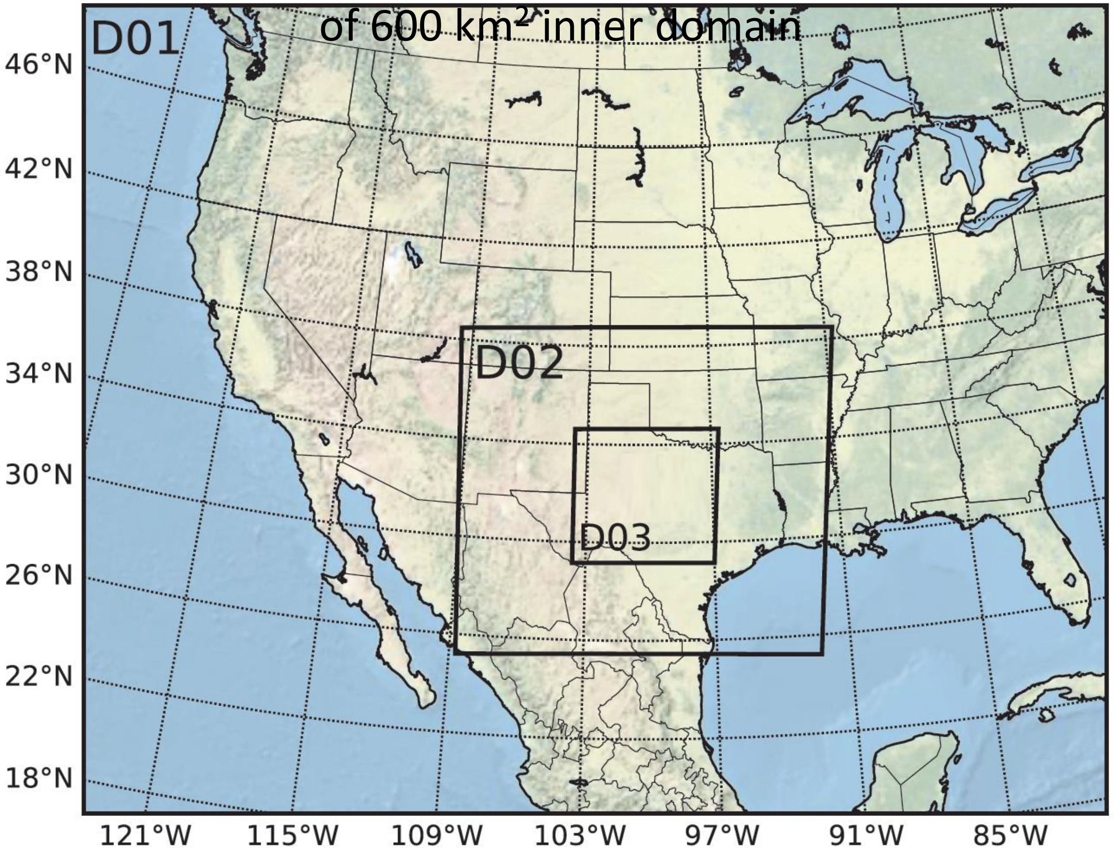
1-km horiz. resolution

400 core-hours for 36-hr simulation of 75 km^2 inner domain



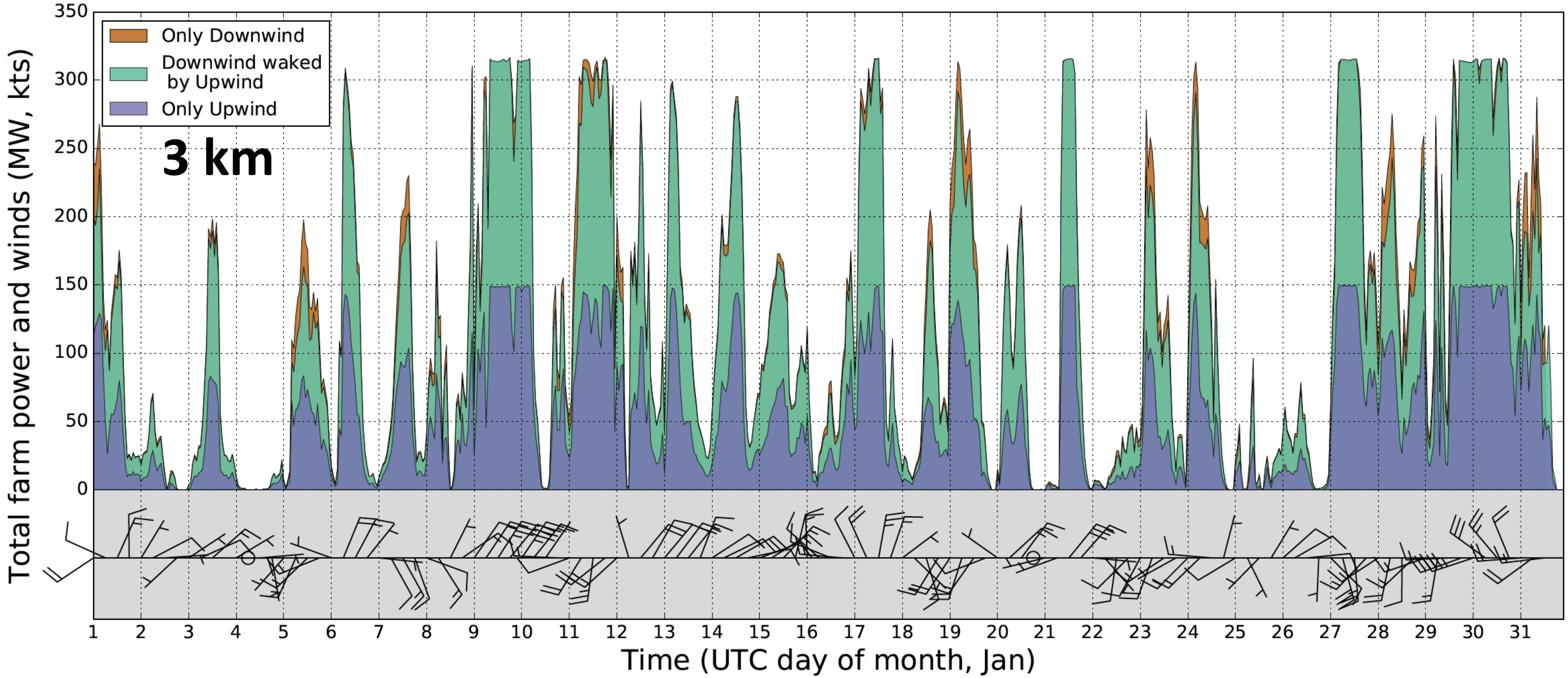
3-km horiz. resolution

250 core-hours for 36-hr simulation of 600 km^2 inner domain



WRF WFP treats each turbine in a cell as an un-waked turbine, all receiving the same inflow wind
➞ reduces wake impact that can be computed from the simulation at 3-km resolution

3 km: Waking causes ~5% drop in capacity factor in Jan



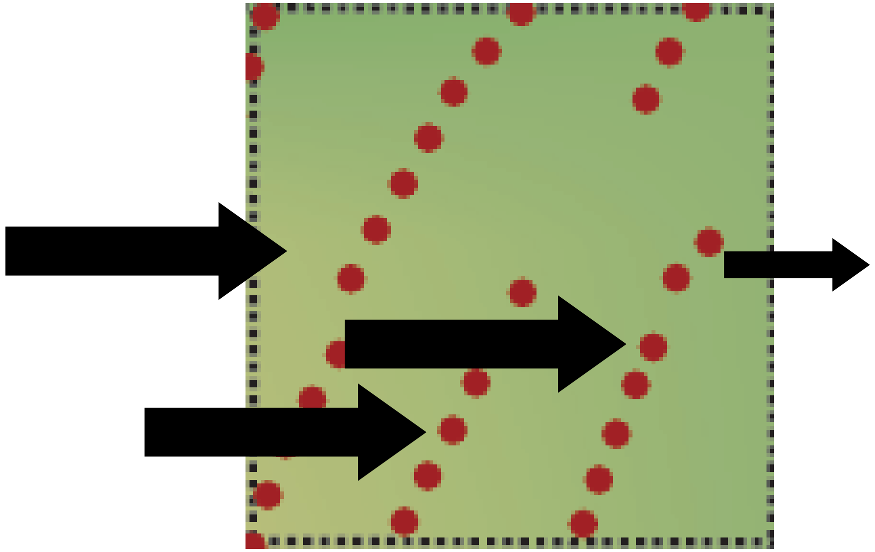
Only Downwind (unwaked) = 0.39 CF

Downwind waked by Upwind = 0.37 CF

↓ 5.1 % drop (vs. 6.8 in 1 km)

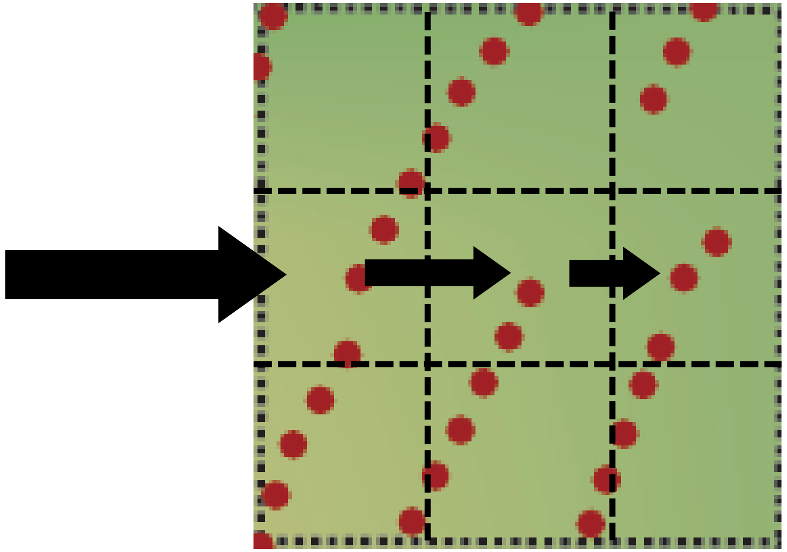
3-km resolution may be too coarse to capture all waking

3 km



All turbines in cell receive same inflow wind speed, disregarding waking within cell

1 km



Increasing resolution allows more turbines to feel waking, creating larger wake impacts