University of Colorado

Department of Atmospheric & Oceanic Sciences

Best practices for simulating wind farm wakes with the WRF Wind Farm Parameterization

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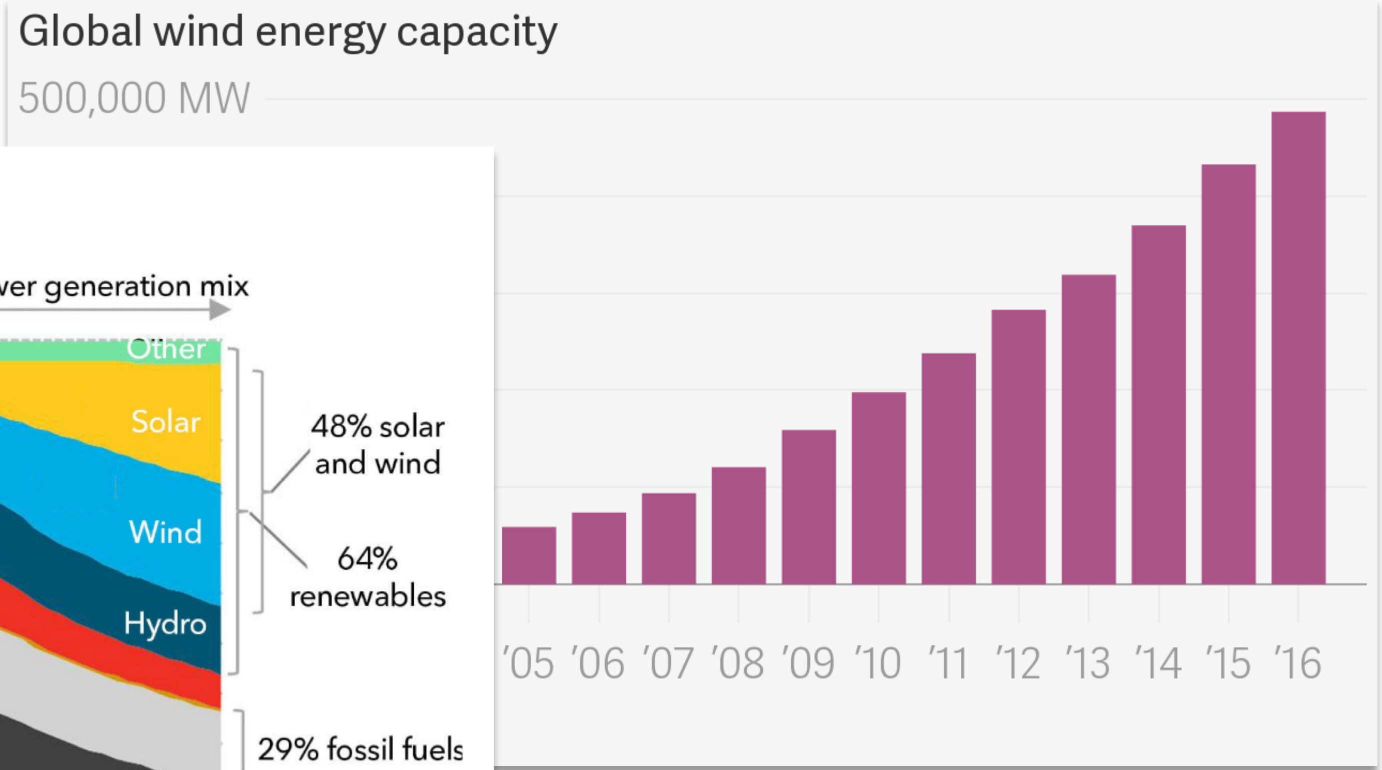
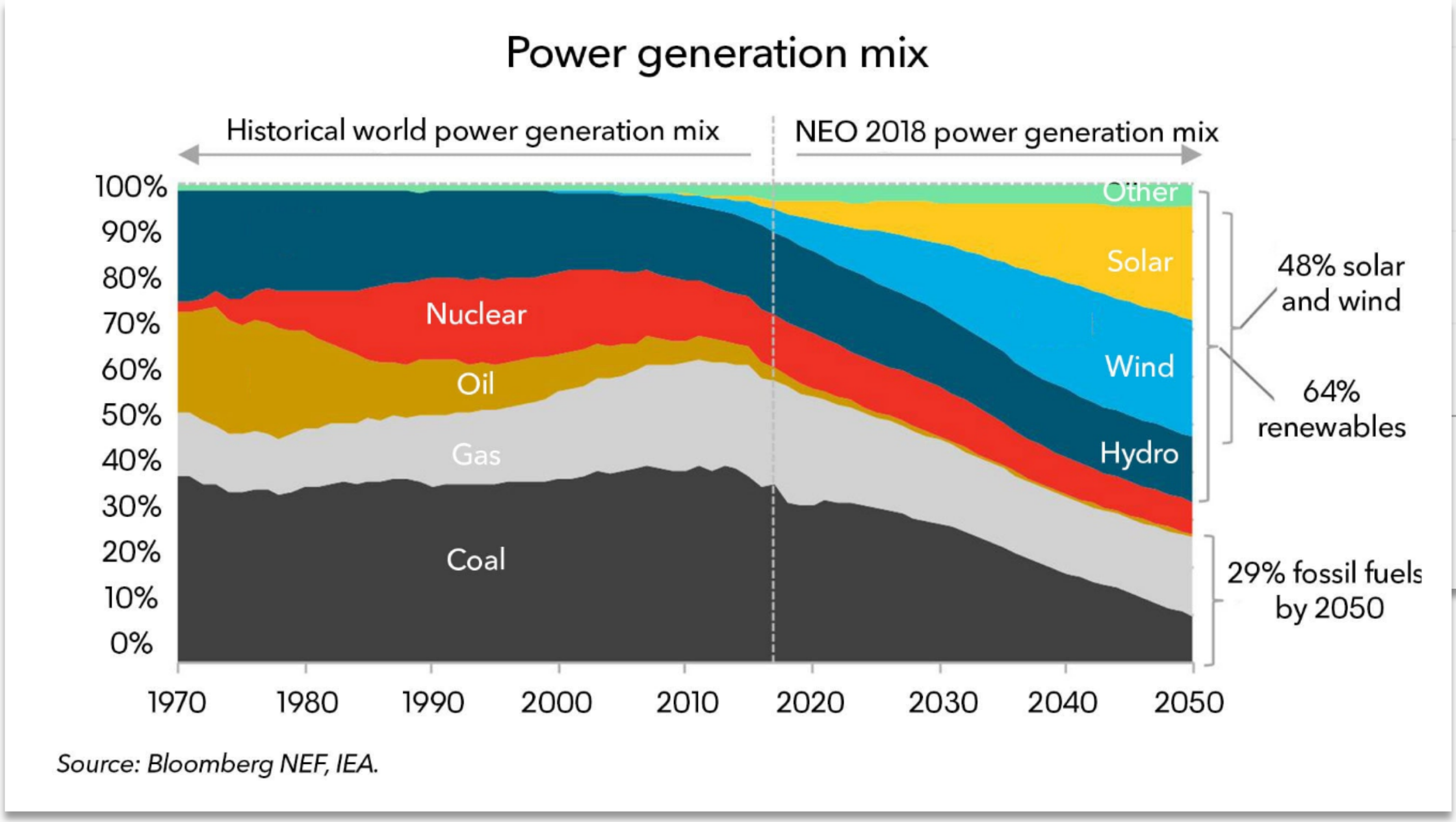
Renewable energy sources in demand globally



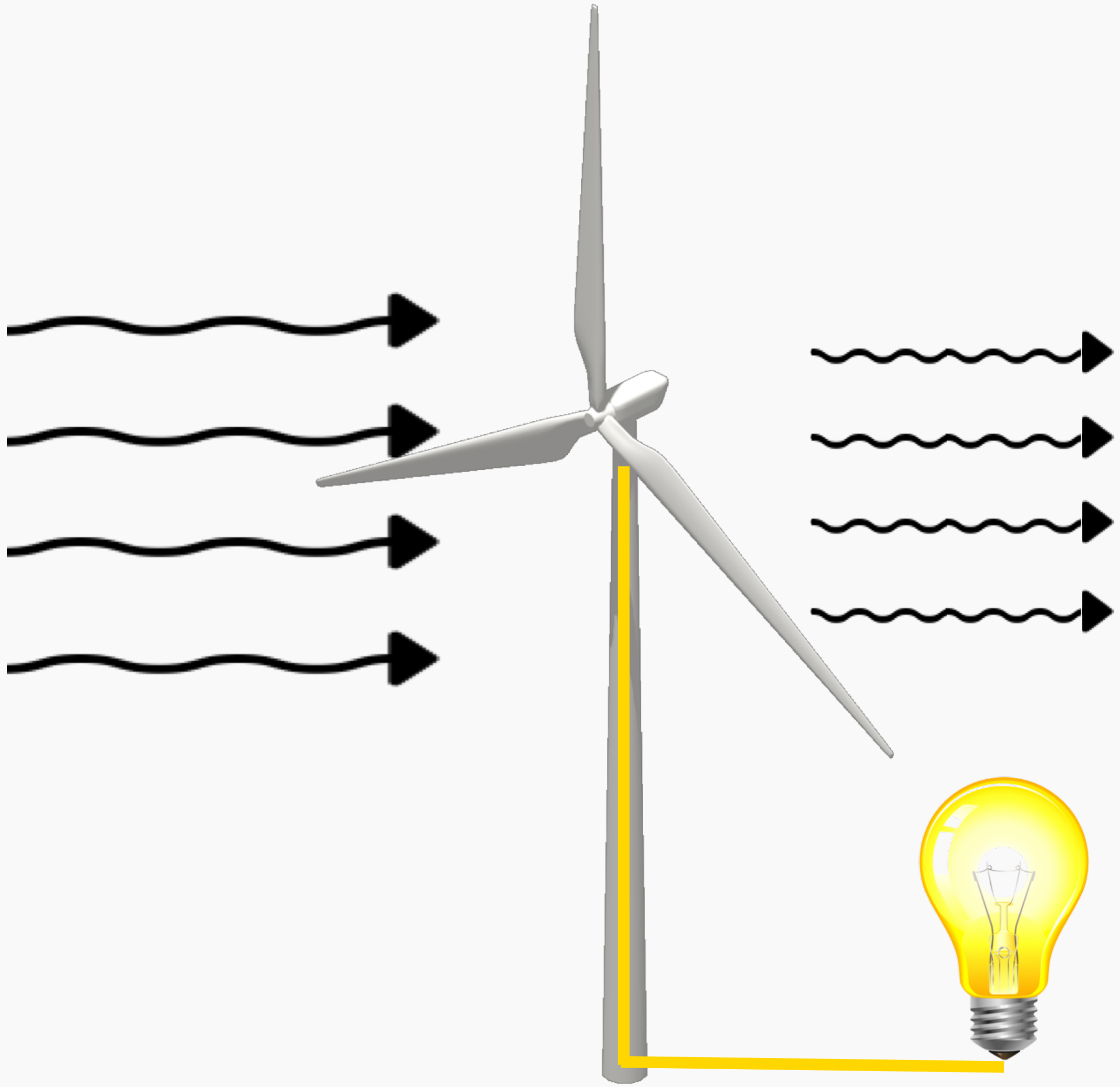


Wind turbines generate electricity - and wakes

Wind turbines generate electricity by using the momentum in the wind to turn their blades and spin a generator, leaving a “wake” behind them

Wakes are characterized by:

Wind speed deficit &
increased turbulence downwind



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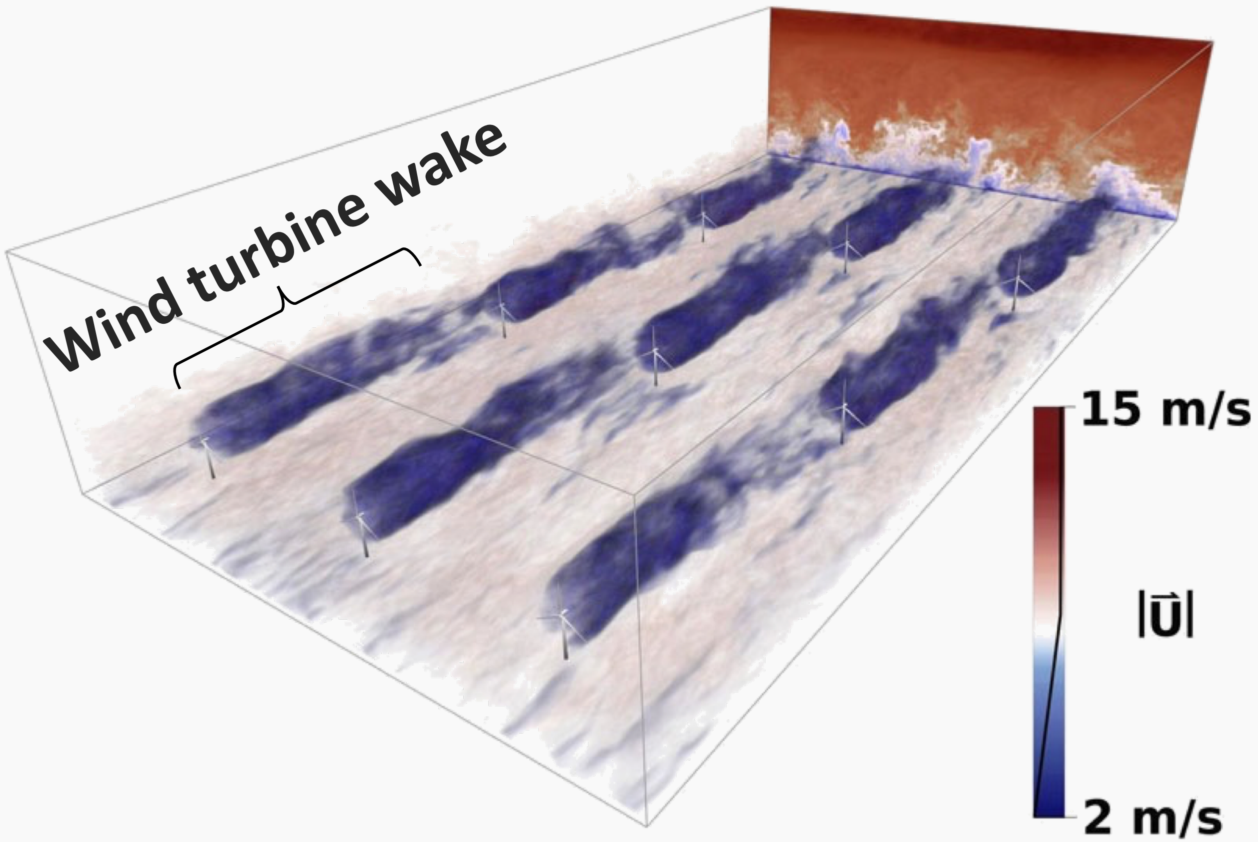

Credit: Kenny Gruchala, NREL

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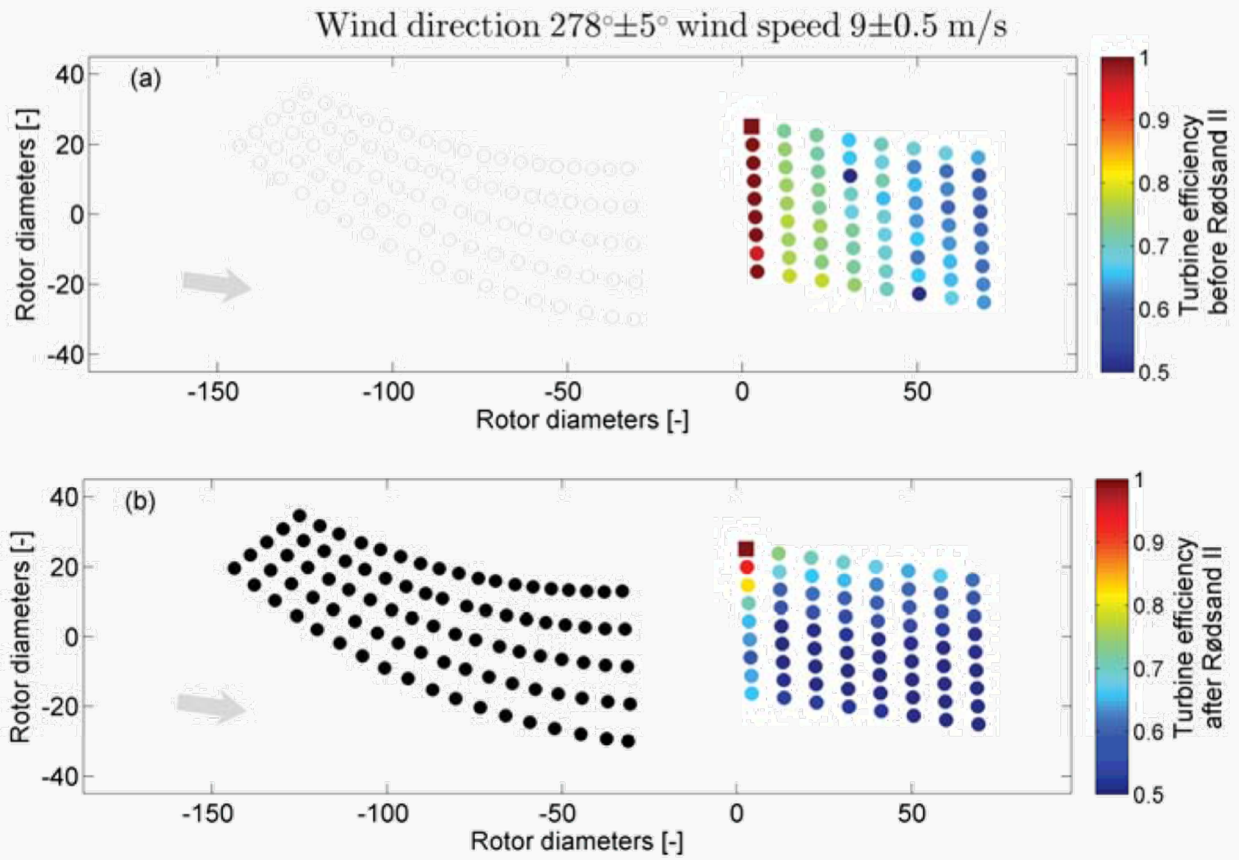
Credit: Christian Steiness

Wakes impact their ambient environment

Hub-height wind speed deficits cause loss in power and revenue for downwind wind farms[1,2]



Nygaard 2014

[1]Nygaard, N. G. Wakes in very large wind farms and the effect of neighbouring wind farms. *J. Phys. Conf. Ser.* (2014).
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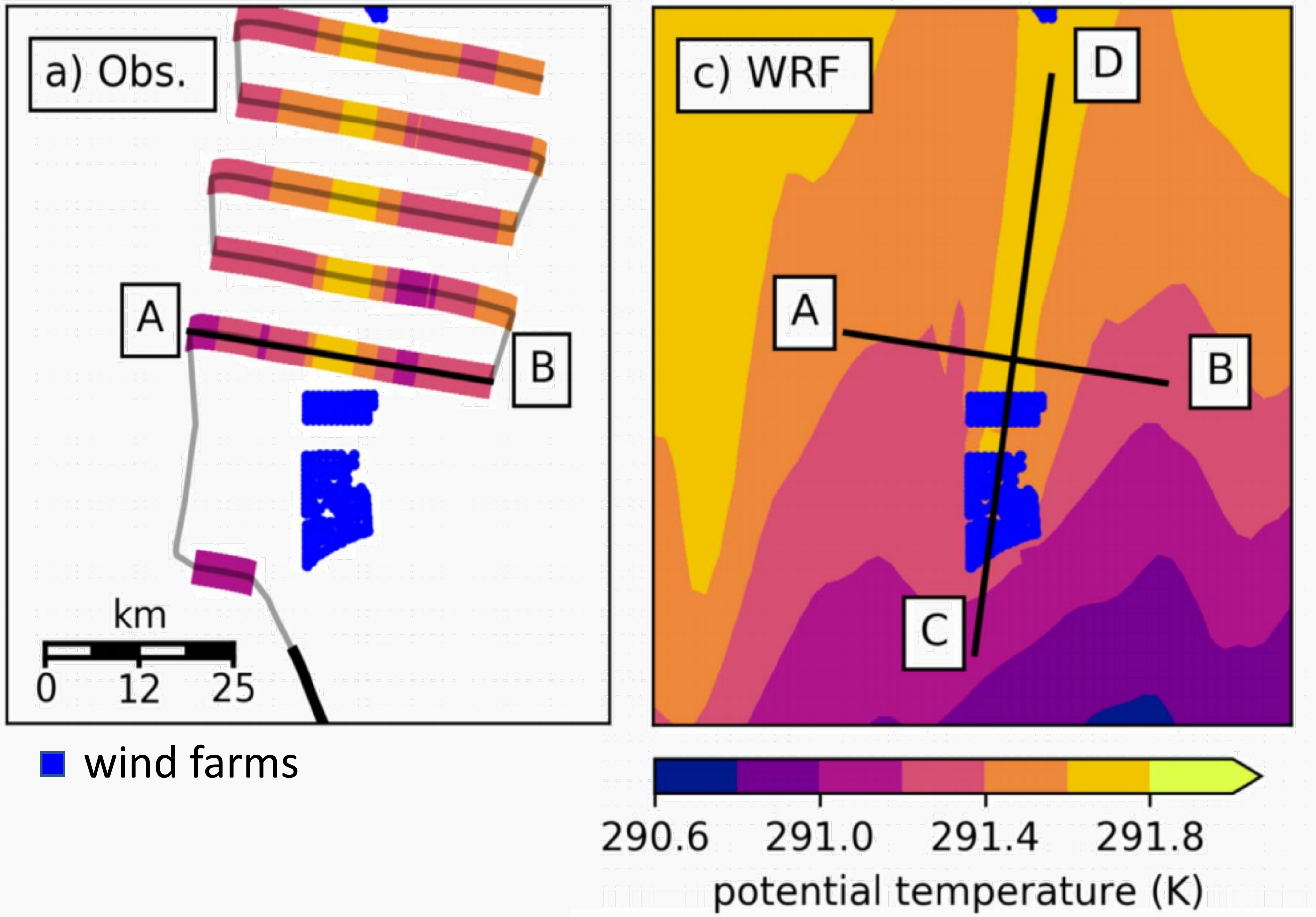
Siedersleben et al. 2018

Hub-height wind speed deficits cause loss in power and revenue for downwind wind farms[1,2]

Increased turbulence mixes warmer air from nighttime inversions to surface[3]



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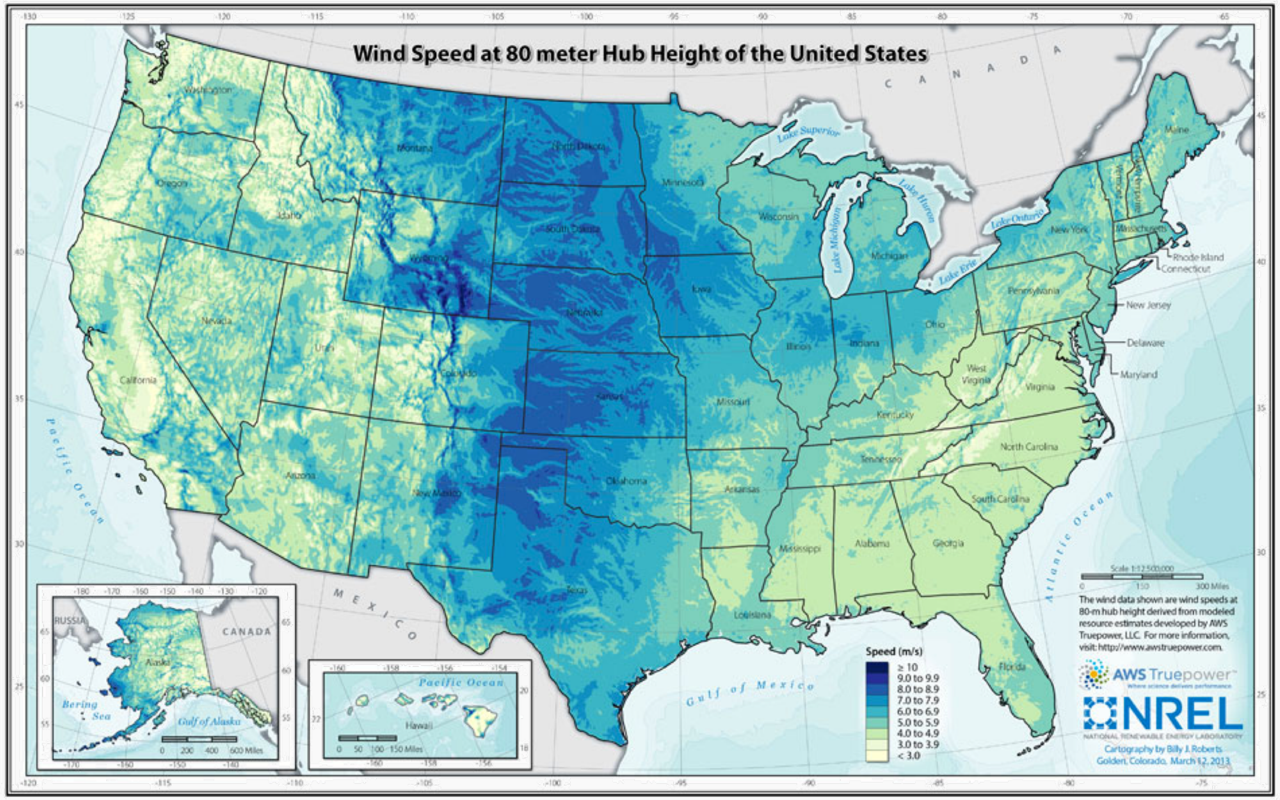
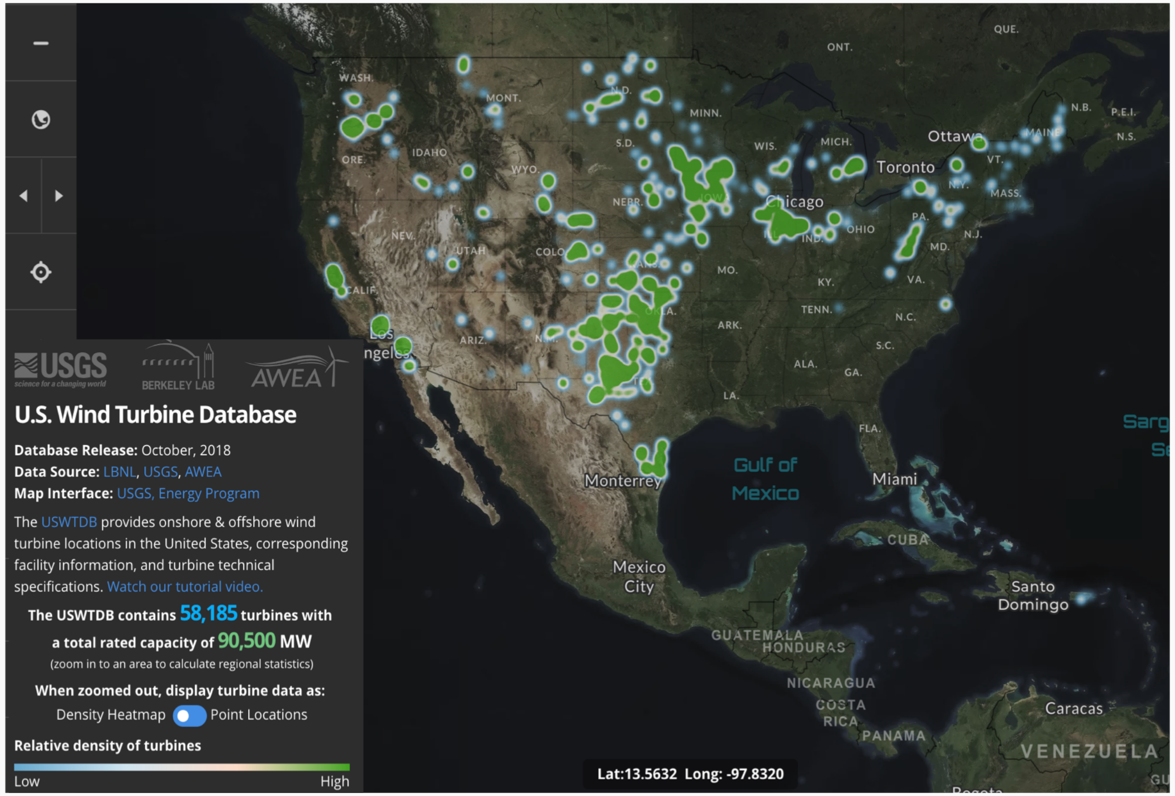
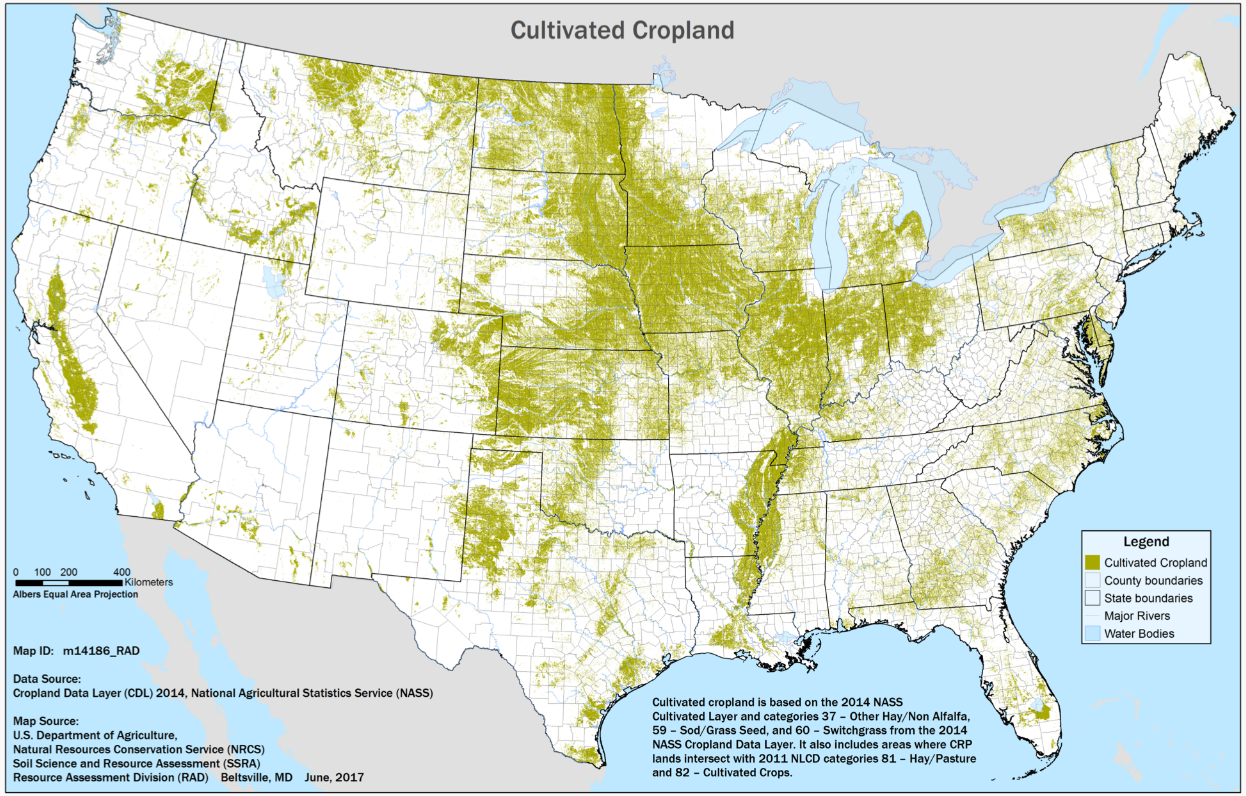
Wind farms built near each other, over cropland



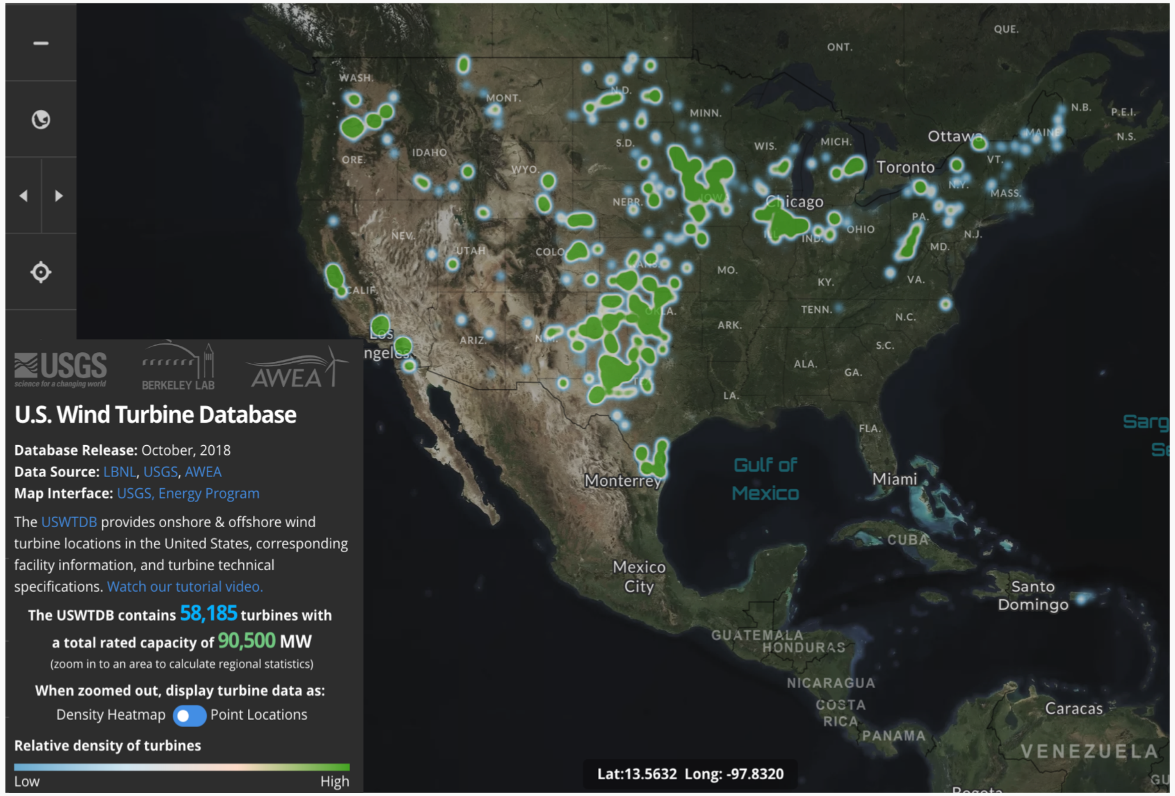


https://eerscmap.usgs.gov/uswtdb/viewer/

Wind farms built near each other, over cropland



Chances for wind farm wakes to impact cropland



And other wind farms

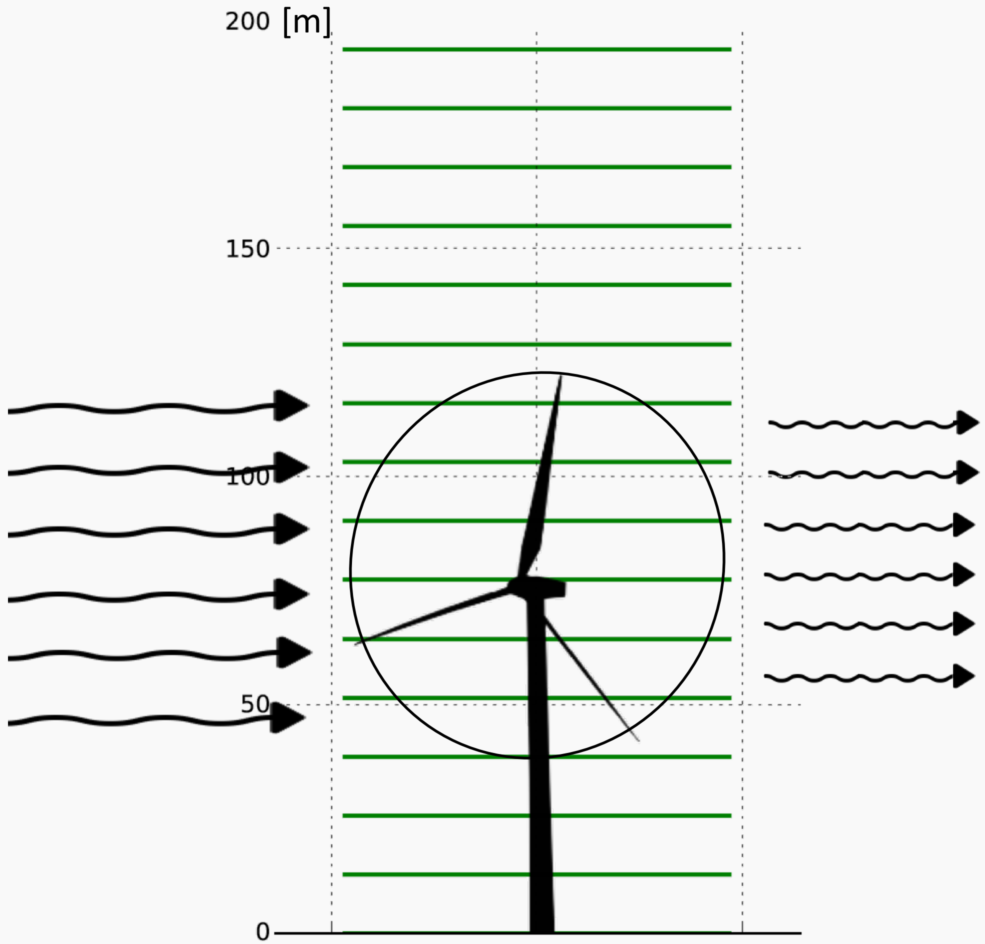
Objectives

Encourage deployment of sustainable energy sources and integration into society

Simulate the impacts of wind farm wakes as accurately as possible

Hypothesis: choices in WRF WFP settings impact the surface temperature and wind speed deficits of wind farm wakes

Wake effects can be simulated with WRF WFP



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

WFP 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

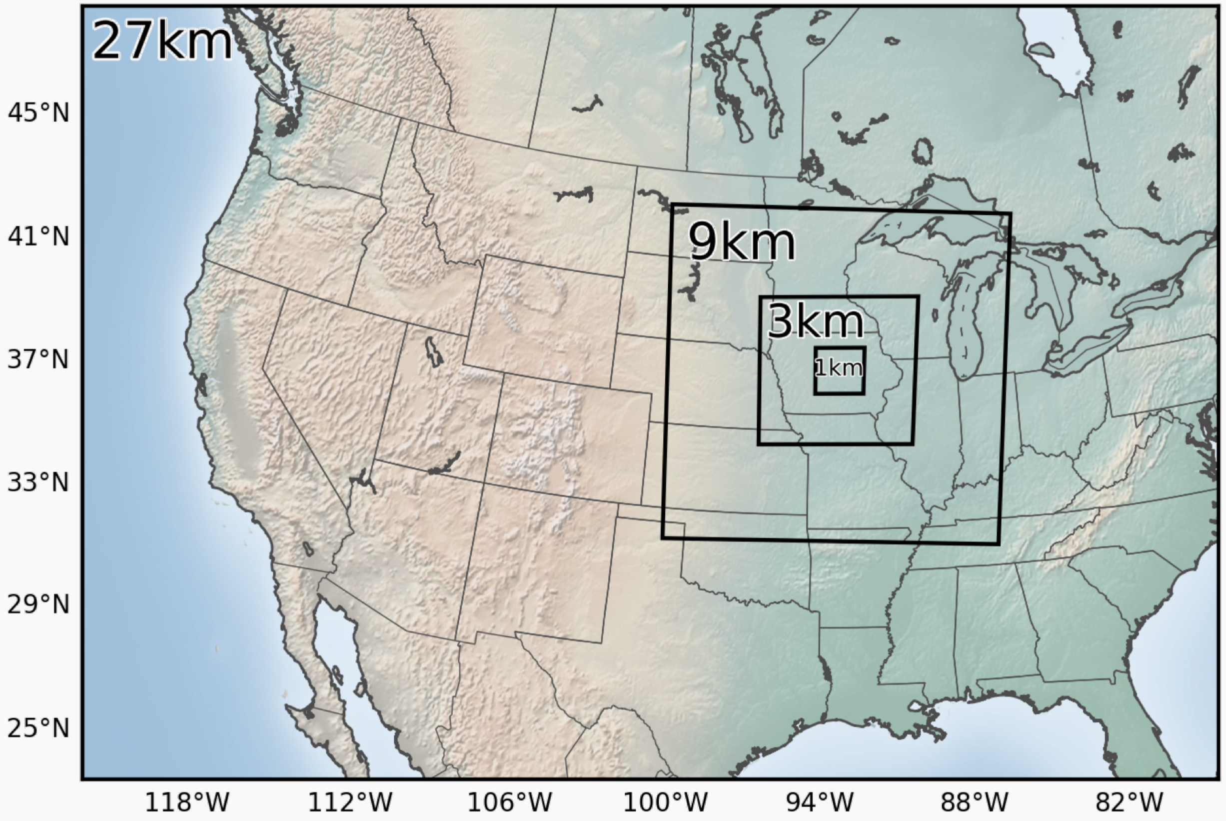
[1]Fitch et al. Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model. *Mon. Wea. Rev*. (2012)

We test several WRF WFP configurations

Constant settings

Initial & boundary conditions	ERA-Interim
PBL	MYNN
Period simulated	24-28 Aug 2013, in 24-hr analysis periods
Spin-up time	12 hr
Wind farm	200 GE 1.5 MW SLE (80 m hub height & rotor diameter) turbines from Story County wind farm*

*Site of the Crop Wind Energy Experiment (CWEX)[1,2]

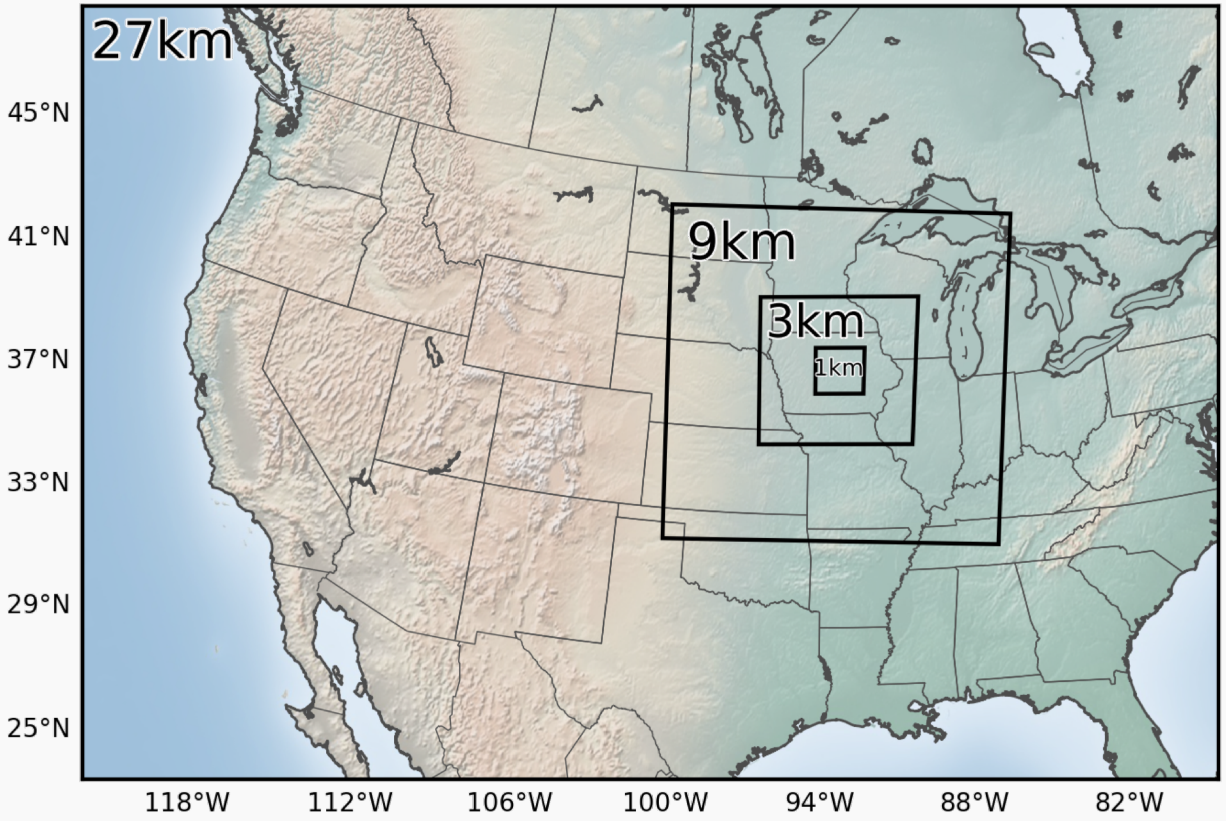


[1]Rajewski, D., et al. Crop Wind Energy Experiment (CWEX): Observations of Surface-Layer, Boundary Layer, and Mesoscale Interactions with a Wind Farm. *Bull. Amer. Meteor. Soc.* (2013).
[2]Lee, J. C. Y. and Lundquist, J. K. Evaluation of the wind farm parameterization in the WRF model with meteorological and turbine power data. *Geosci Model Dev.* (2017).

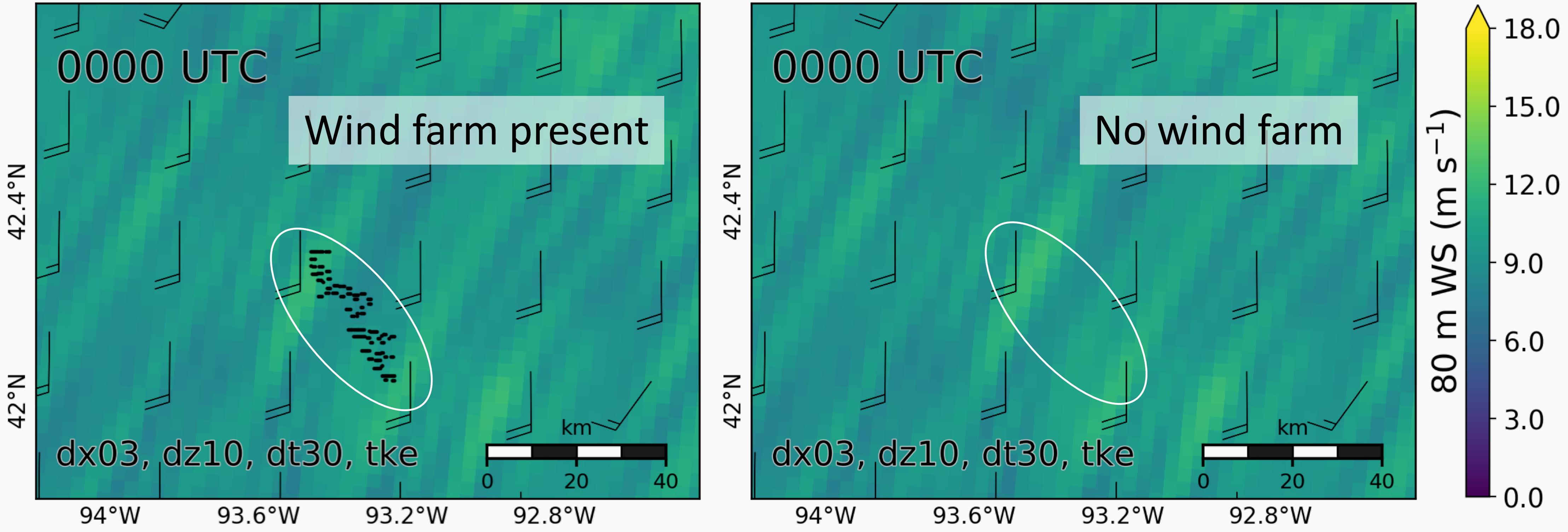
We test several WRF WFP configurations

Varied settings

Horizontal resolution (dx)	27, 9, 3, 1 km
Vertical resolution 0-200 m (dz)	30, 10 m
Time step (dt)	30, 10 sec
Turbine-generated TKE option (tke/ntke)	On, off

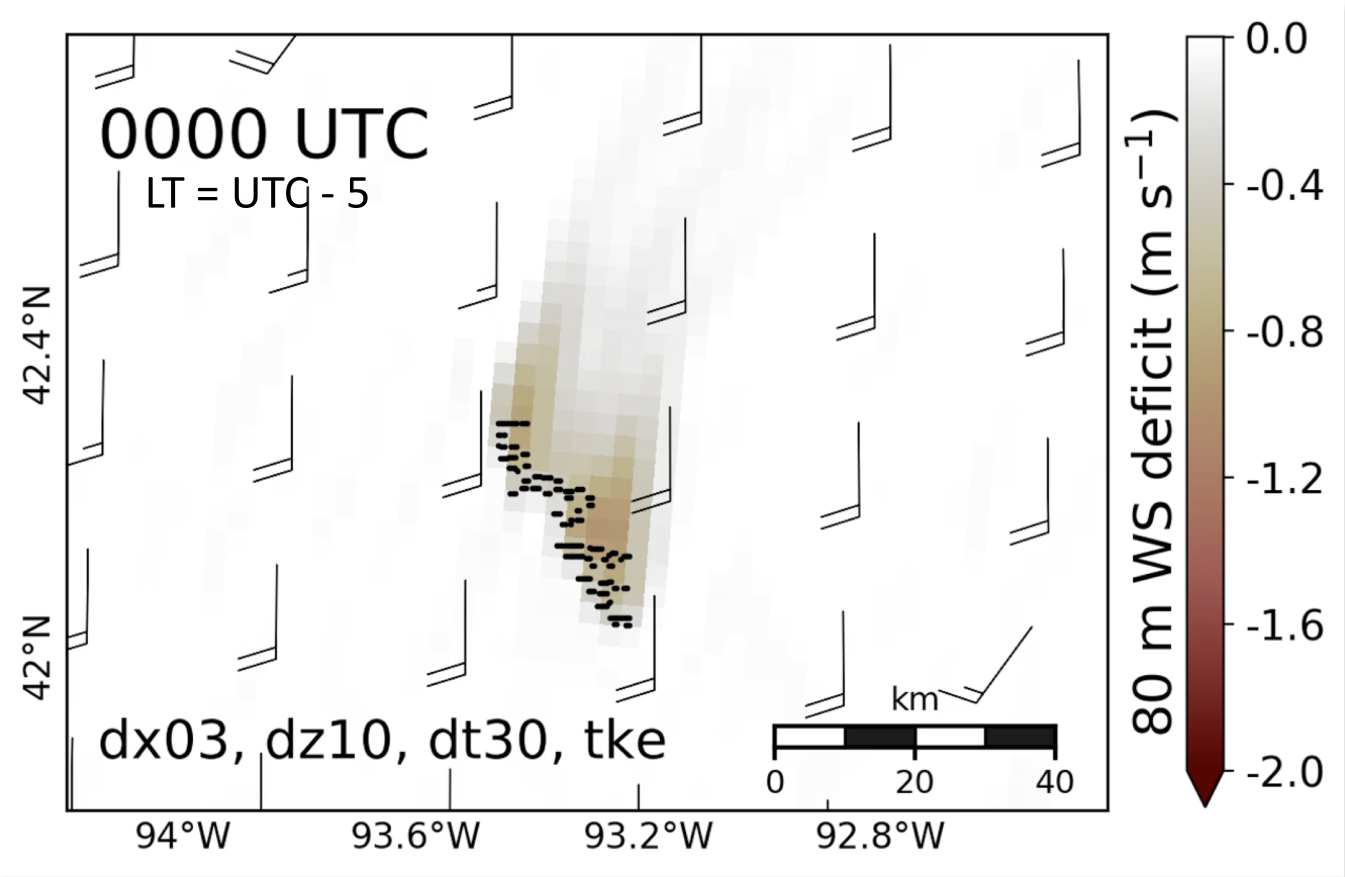


Subtract model solutions to isolate wake effects



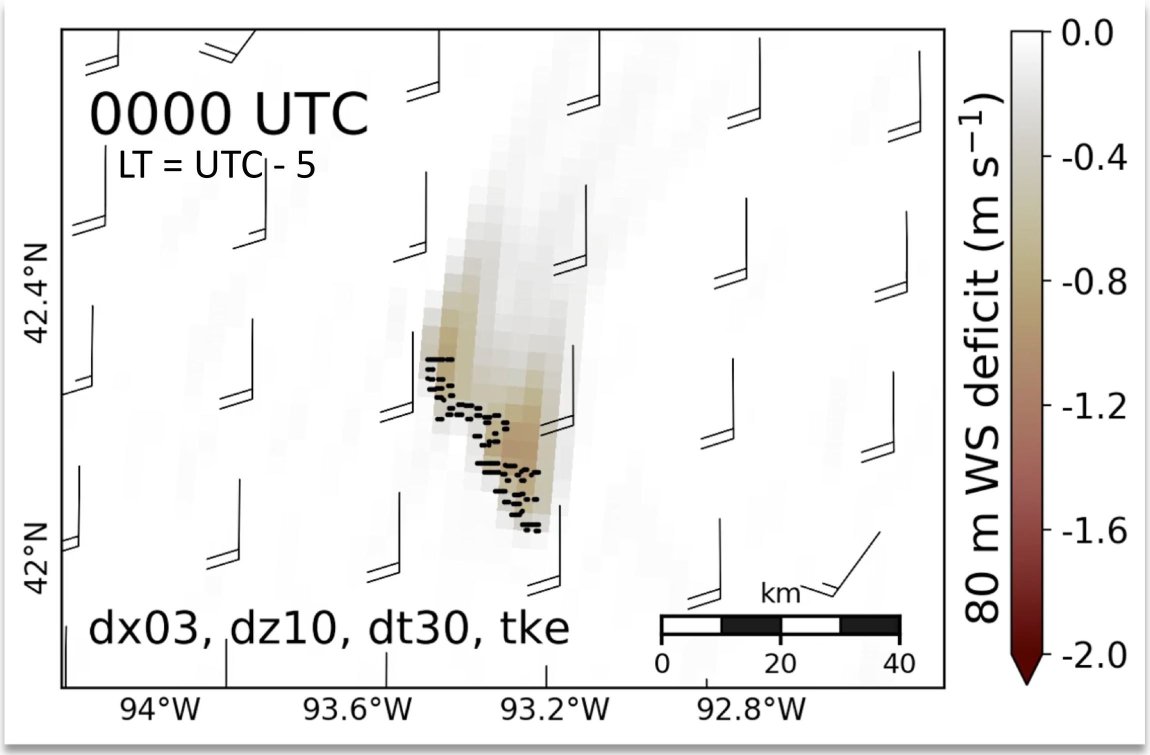
WFP $-$ NWF $\Longrightarrow$

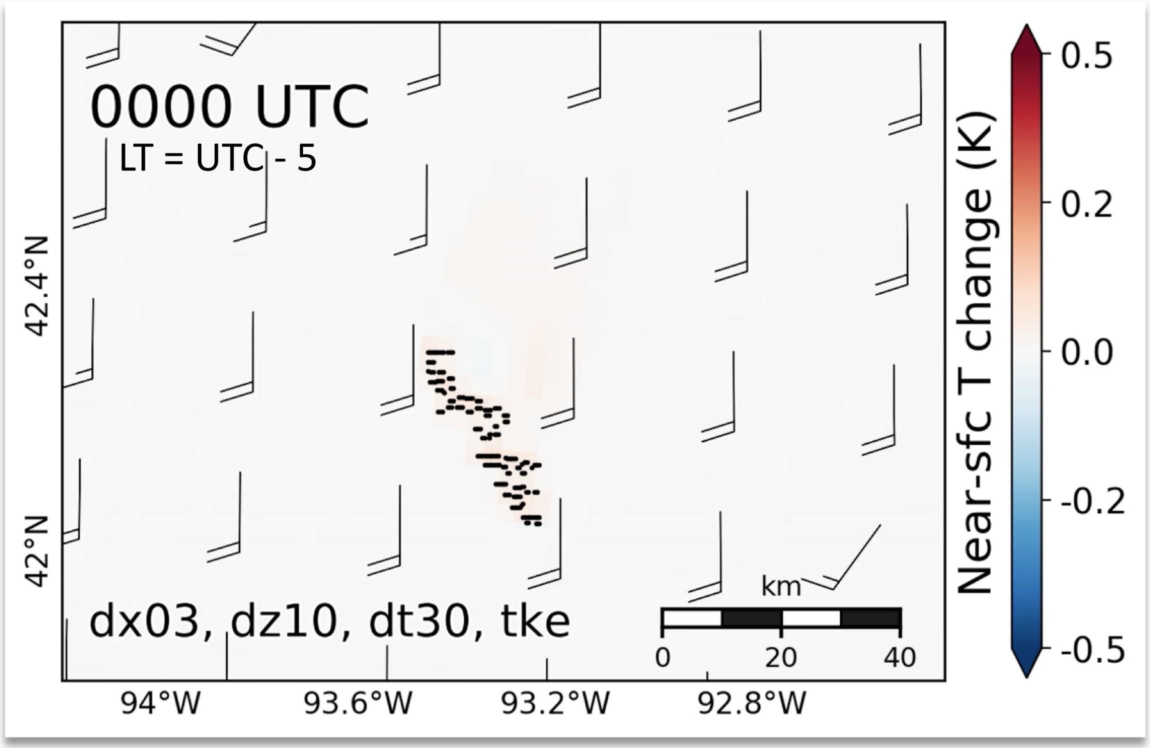
Subtract model solutions to isolate wake effects



WFP – NWF = wake effect

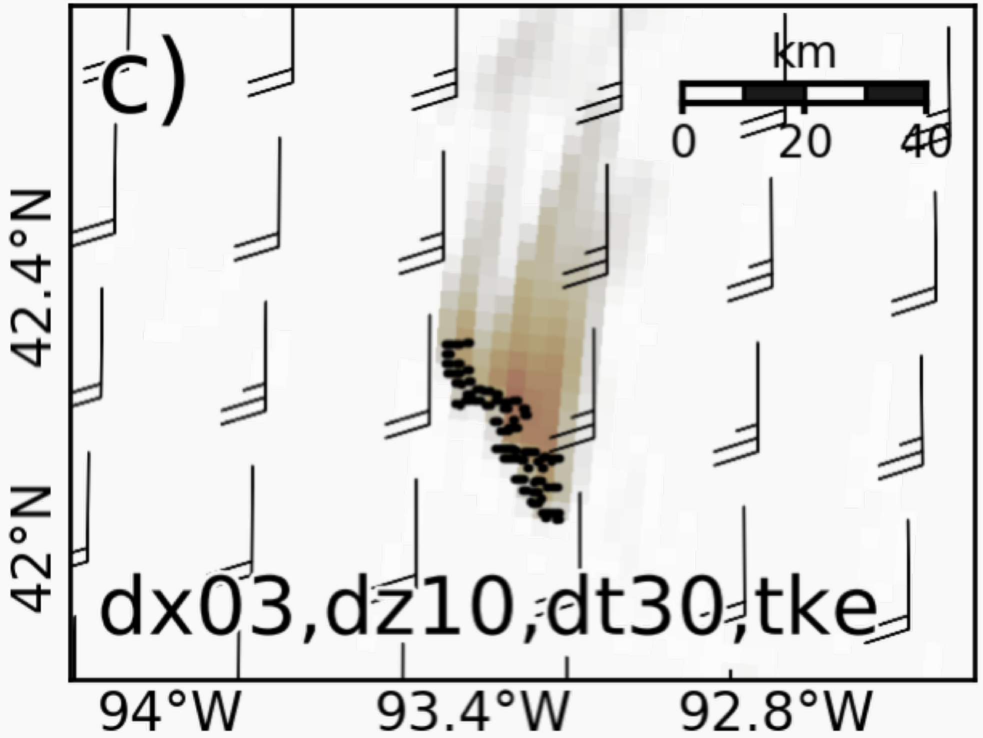
Subtract model solutions to isolate wake effects





WFP – NWF = wake effect

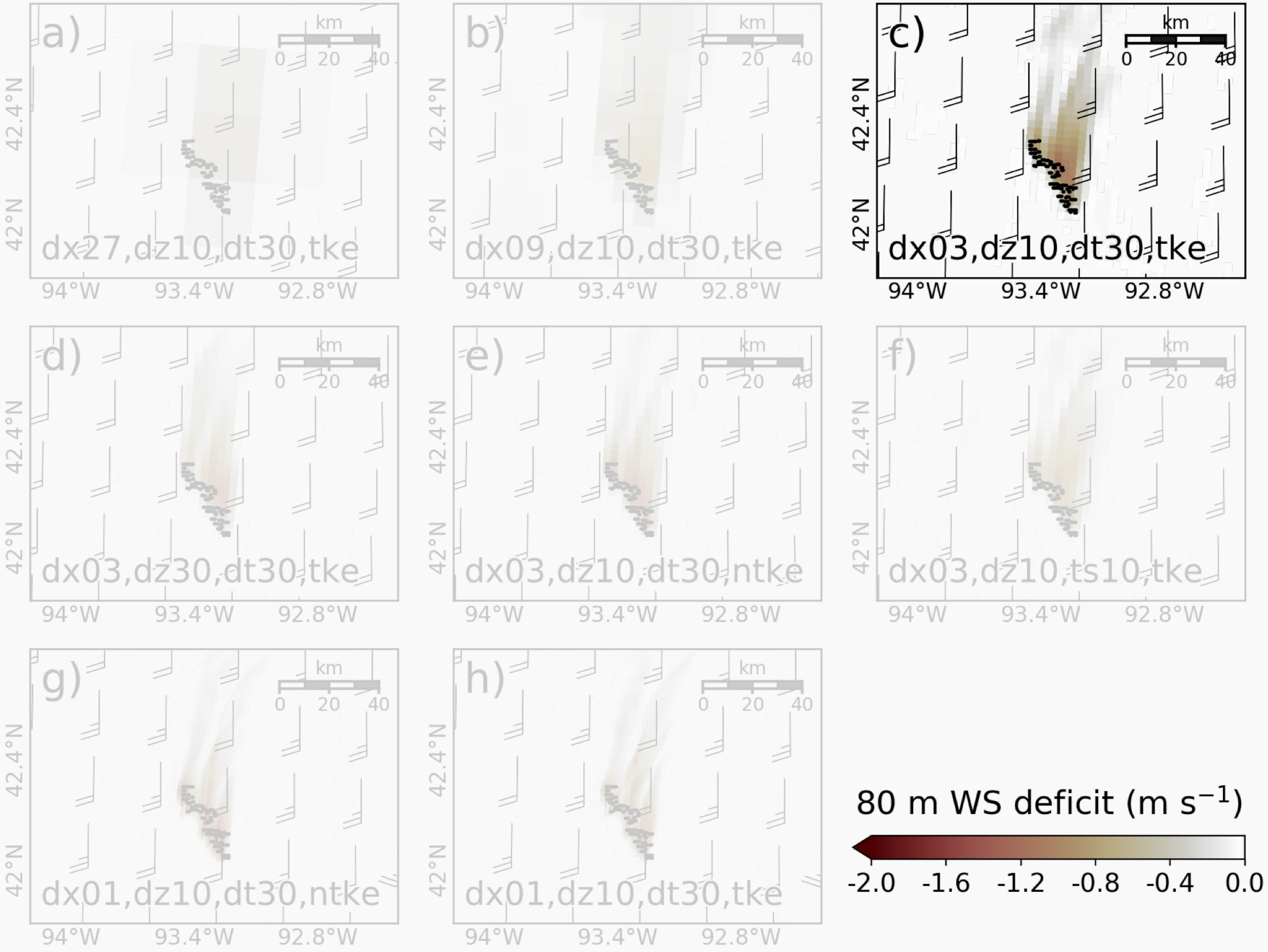
80 m WS deficit is sensitive to WRF WFP config



80 m WS deficit is sensitive to WRF WFP config

Coarse dx (a,b) reduces WS deficit but spans larger area

Coarse dz (d) or TKE opt. off (e) modifies far-wake shape



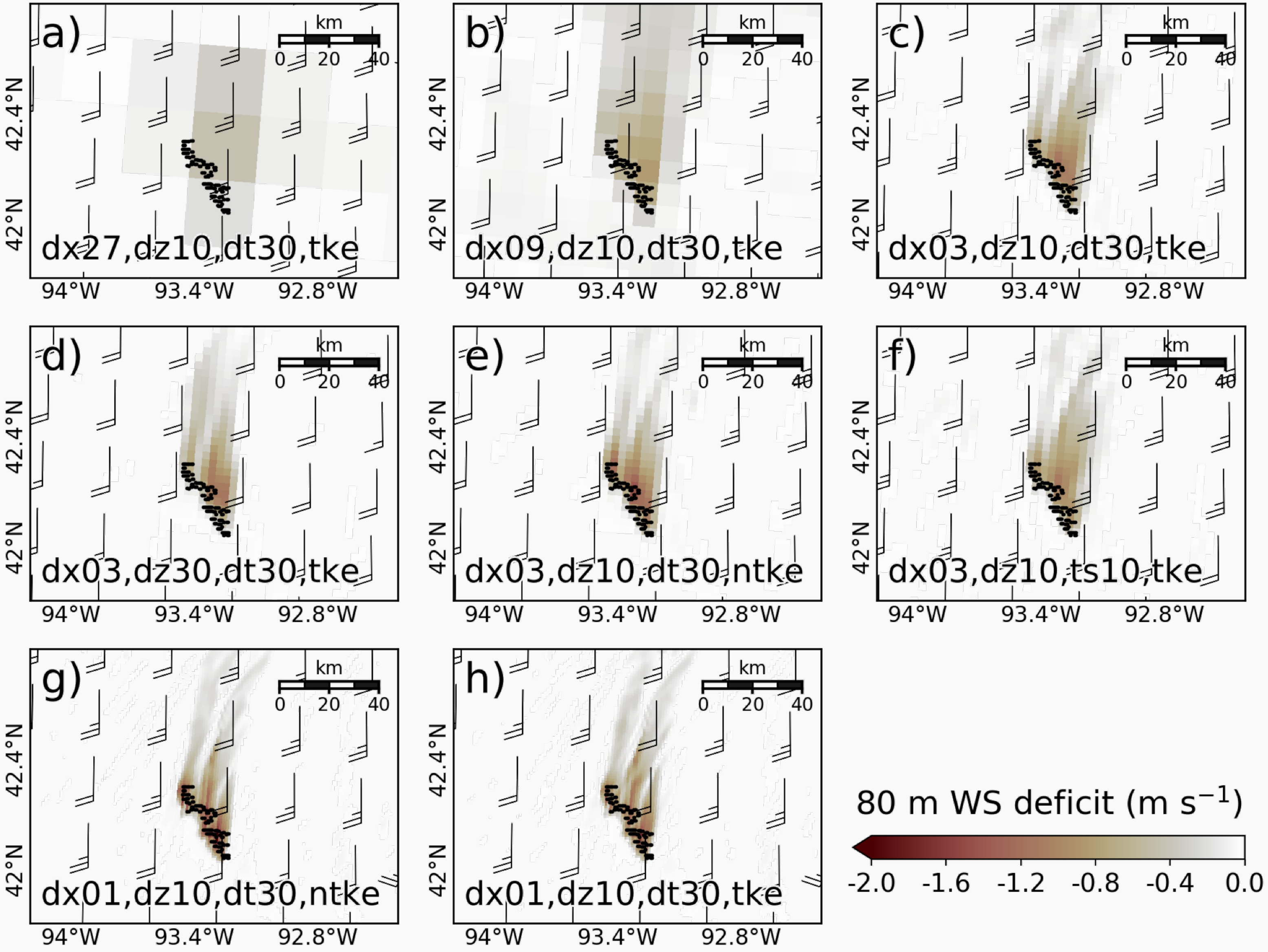
Changing dt (f) has minimal impact

80 m WS deficit is sensitive to WRF WFP config

Coarse dx (a,b) reduces WS deficit but spans larger area

Coarse dz (d) or TKE opt. off (e) modifies far-wake shape

Fine dx (g,h) dominates effect of changing TKE opt. (g)

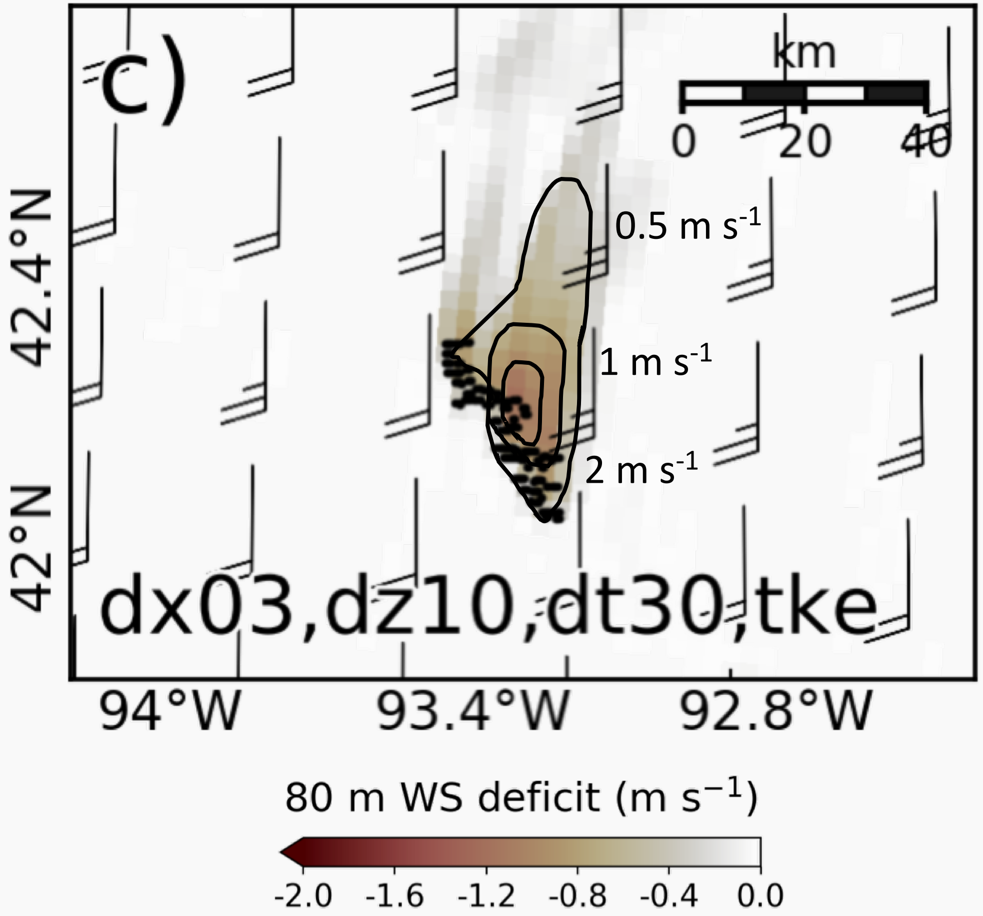


Changing dt (f) has minimal impact

How much space does the config predict is impacted by large WS deficits of 2 m s^{-1}?

Or of 1 m s^{-1}?

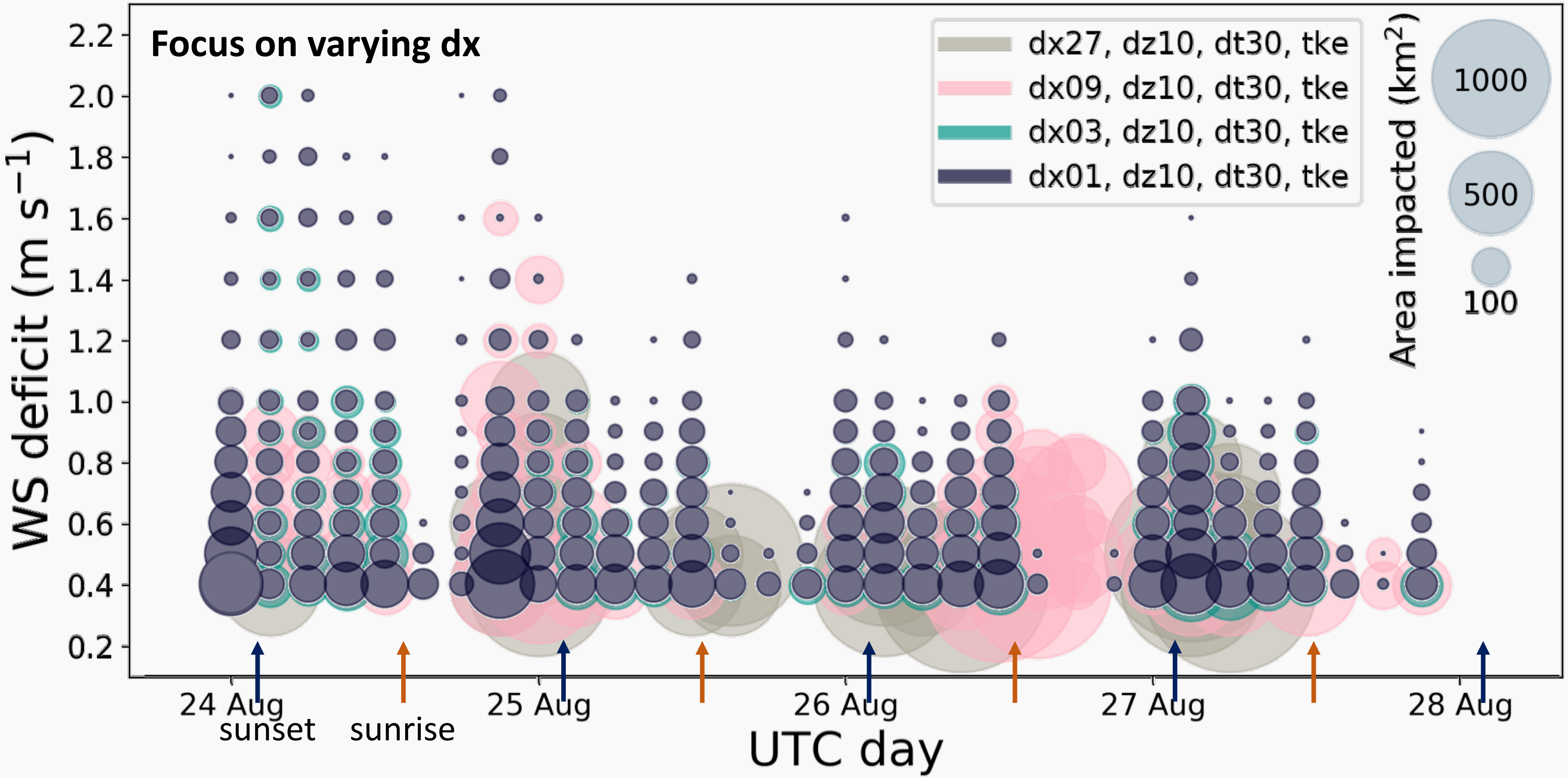
Of 0.5 m s^{-1}?



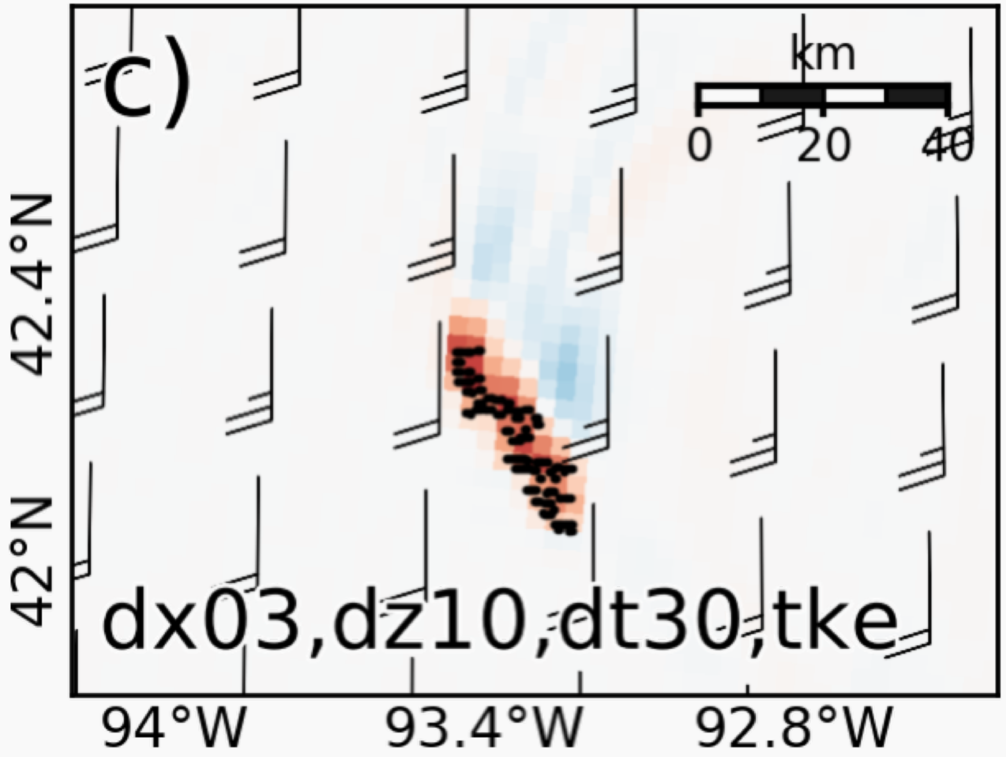
And how often?

During which times of day?

Smaller dx needed to capture higher WS deficits



Near-sfc T is also sensitive to WRF WFP set up



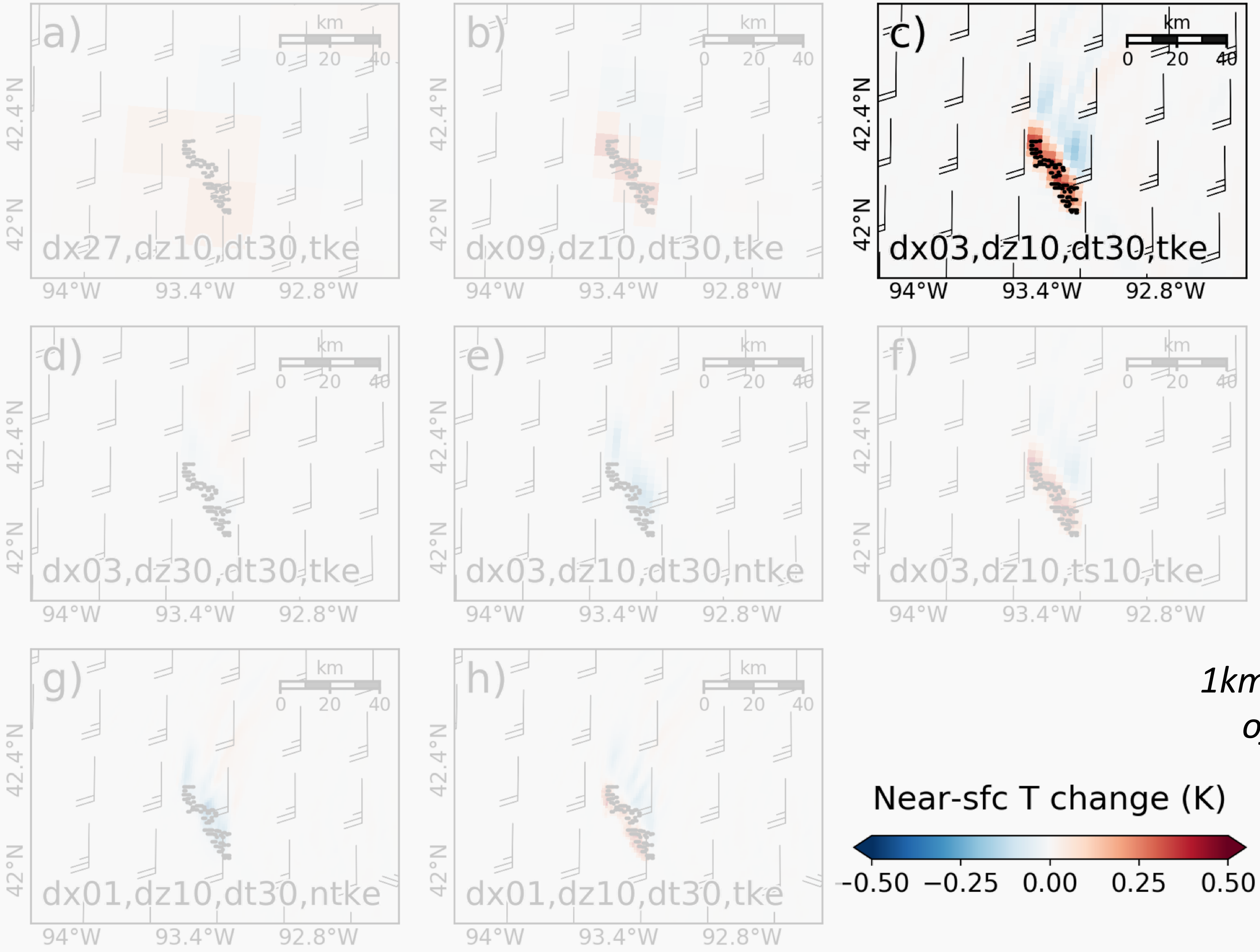
Even the sign of sfc T change depends on config

Coarse dx (a,b) has larger areas of subtle warming

Coarse dz (d) or TKE opt. off (e) changes sign of T change

Reducing dt (f) has minimal impact

1km dx (h) warms sfc only of cells with turbines

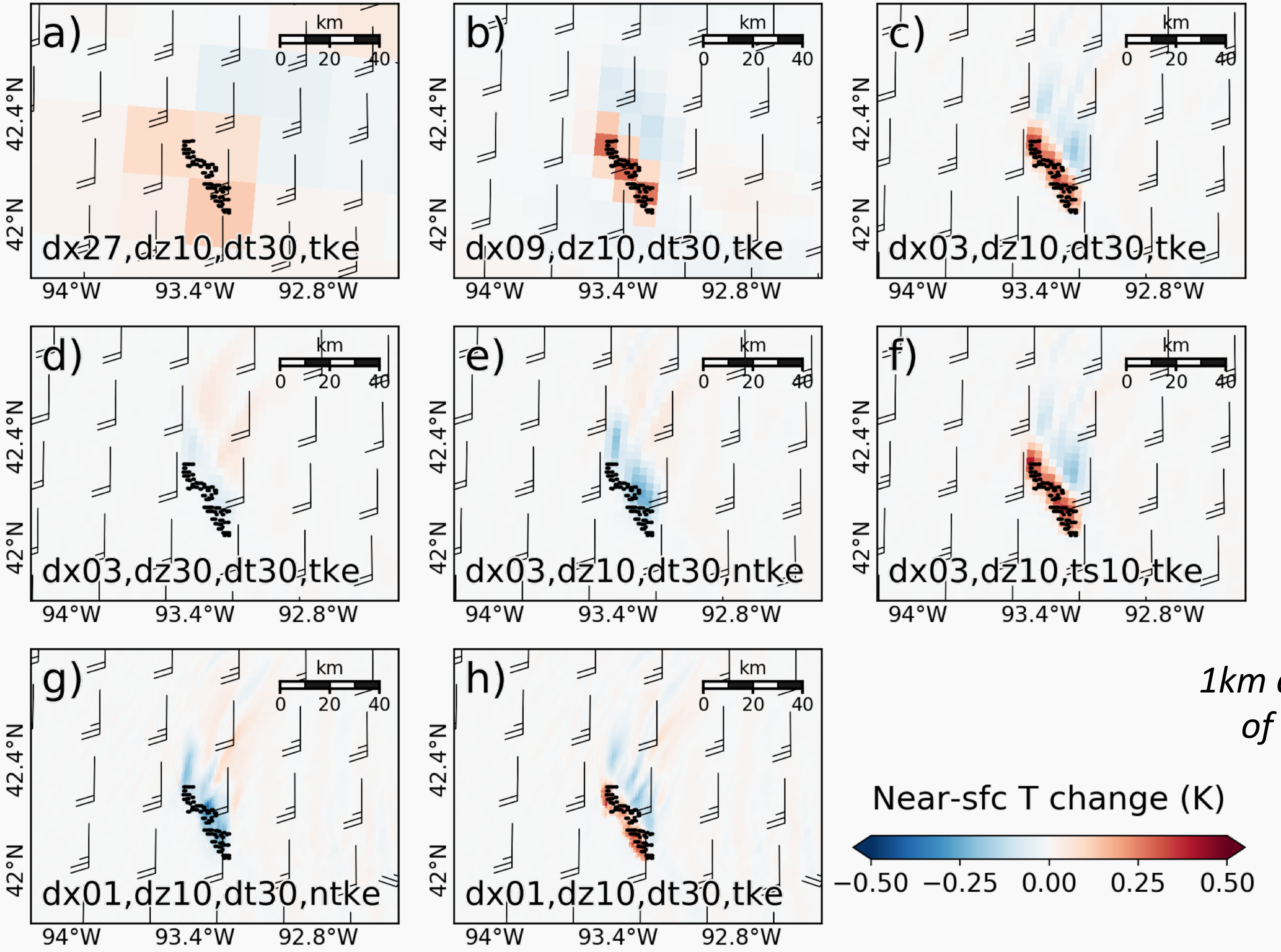


Even the sign of sfc T change depends on config

Coarse dx (a,b) has larger areas of subtle warming

Coarse dz (d) or TKE opt. off (e) changes sign of T change

TKE opt. off (g) cools surface even at finer dx



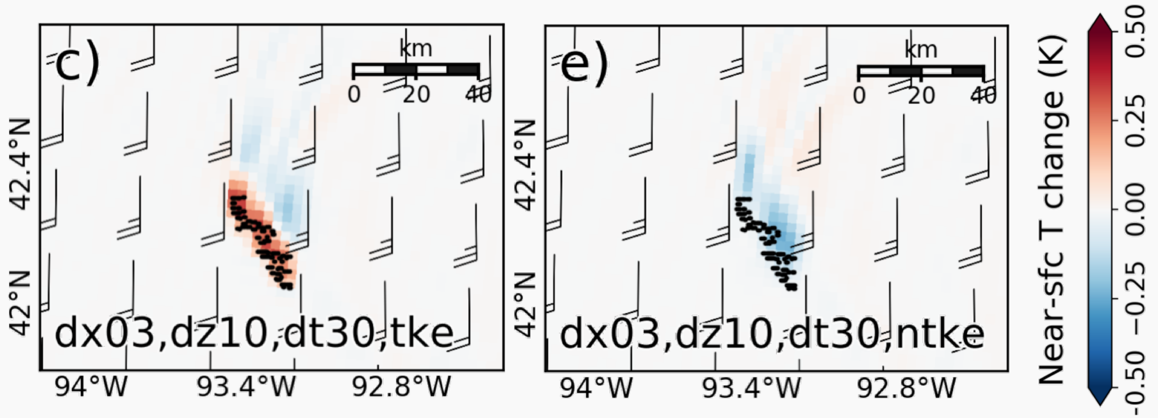
Reducing dt (f) has minimal impact

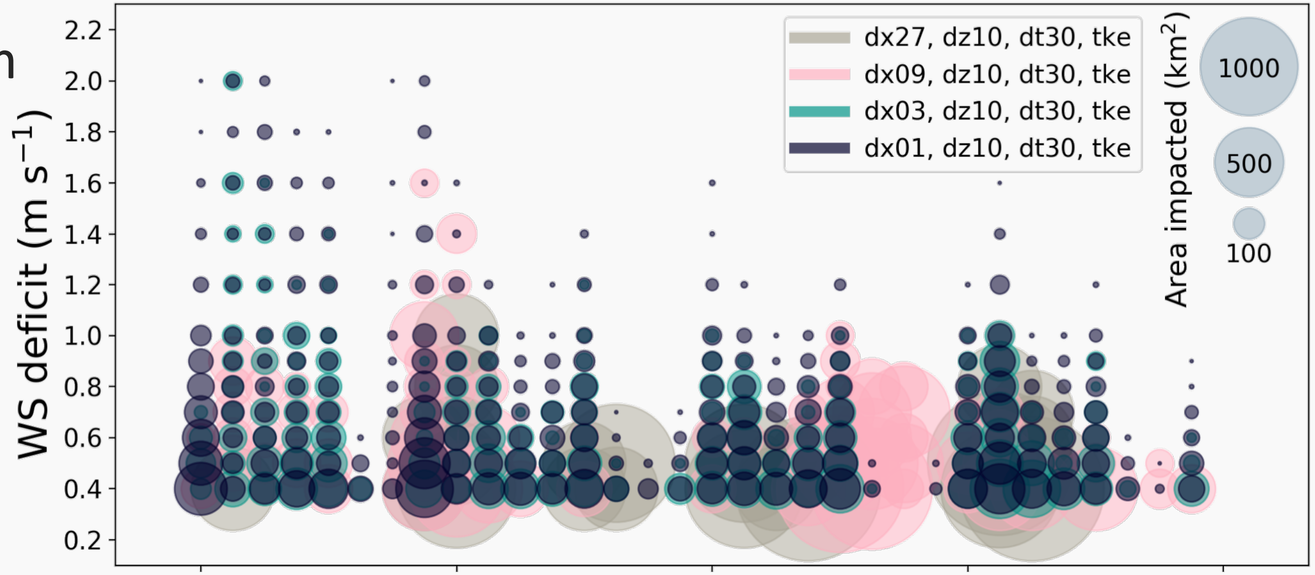
1km dx (h) warms sfc only of cells with turbines

Wake effects are sensitive to WRF WFP settings

WRF WFP Recommendations:

1. Horizontal resolution (dx): no coarser than 3 km
2. Vertical resolution (dz): 10 m preferable to 30 m
3. Time step (dt): 30 sec at 27 km dx (3.33 at 3 km dx) is sufficient
4. TKE option must be turned on to match observed sfc T change





Thank you!

Any questions?

Acknowledgments
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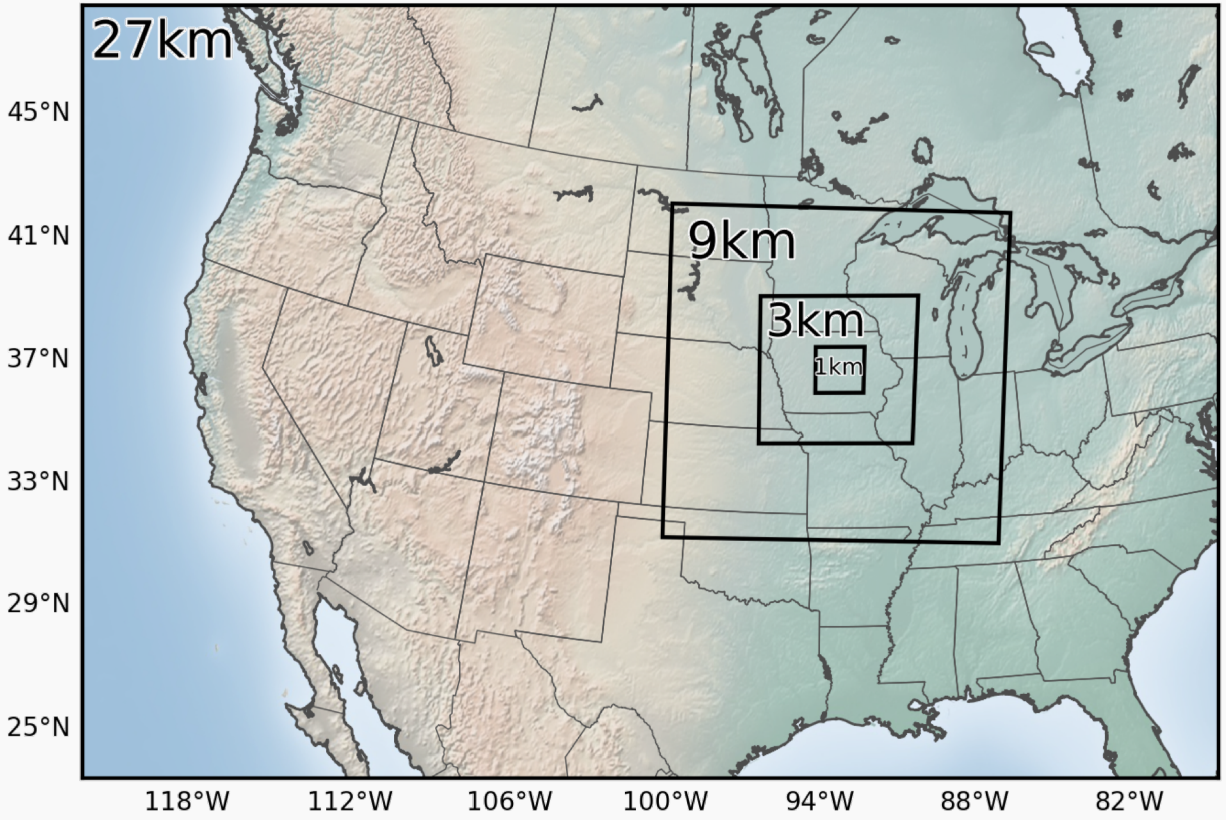
Computing resources provided by the Extreme Science and Engineering Discovery Environment (XSEDE)
National Science Foundation grant ACI-1053575 (NSF GRFP)

Photo by: Jessica Tomaszewski

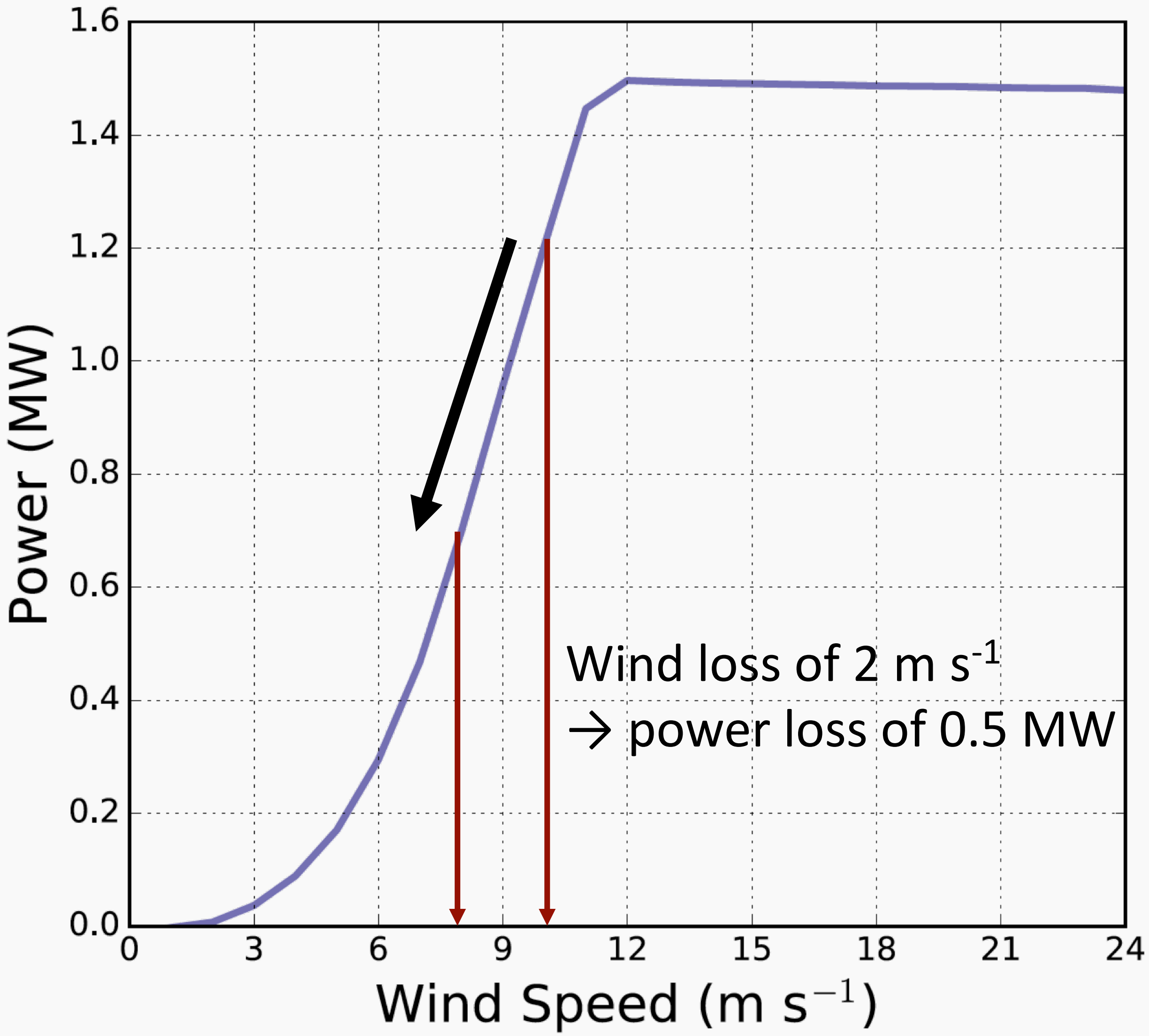
Computation expense per simulated day

config	core-hrs
dx27, dz10, dt30, tke	12
dx09, dz10, dt30, tke	48
dx03, dz10, dt30, tke	200
dx01, dz10, dt30, tke	630
dx03, **dz30**, dt30, tke	156
dx03, dz10, **dt10**, tke	650
dx03, dz10, dt30, **ntke**	200
dx01, dz10, dt30, **ntke**	630

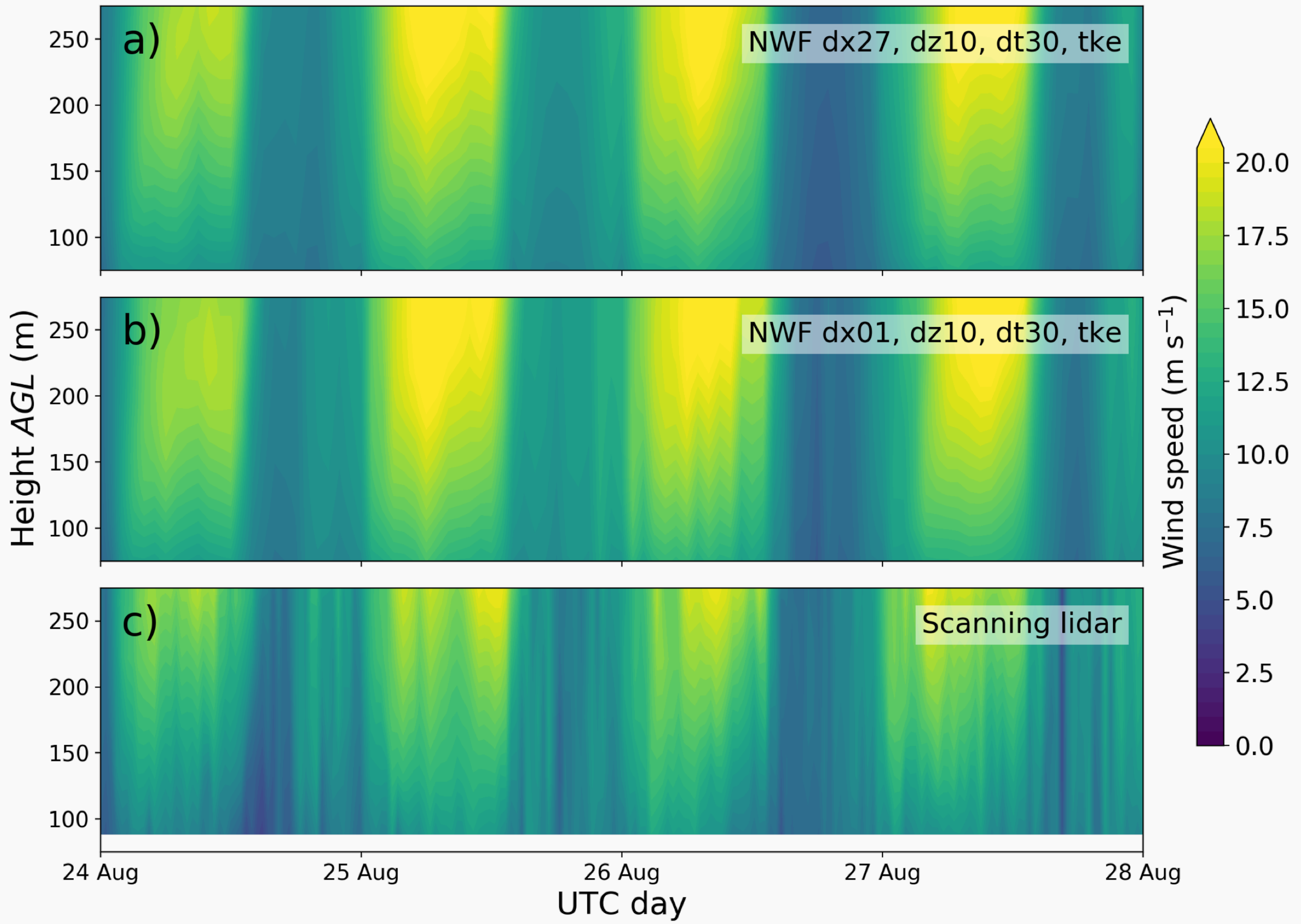


(each run 12 hrs spin-up + 24 hrs analysis)

Power curve

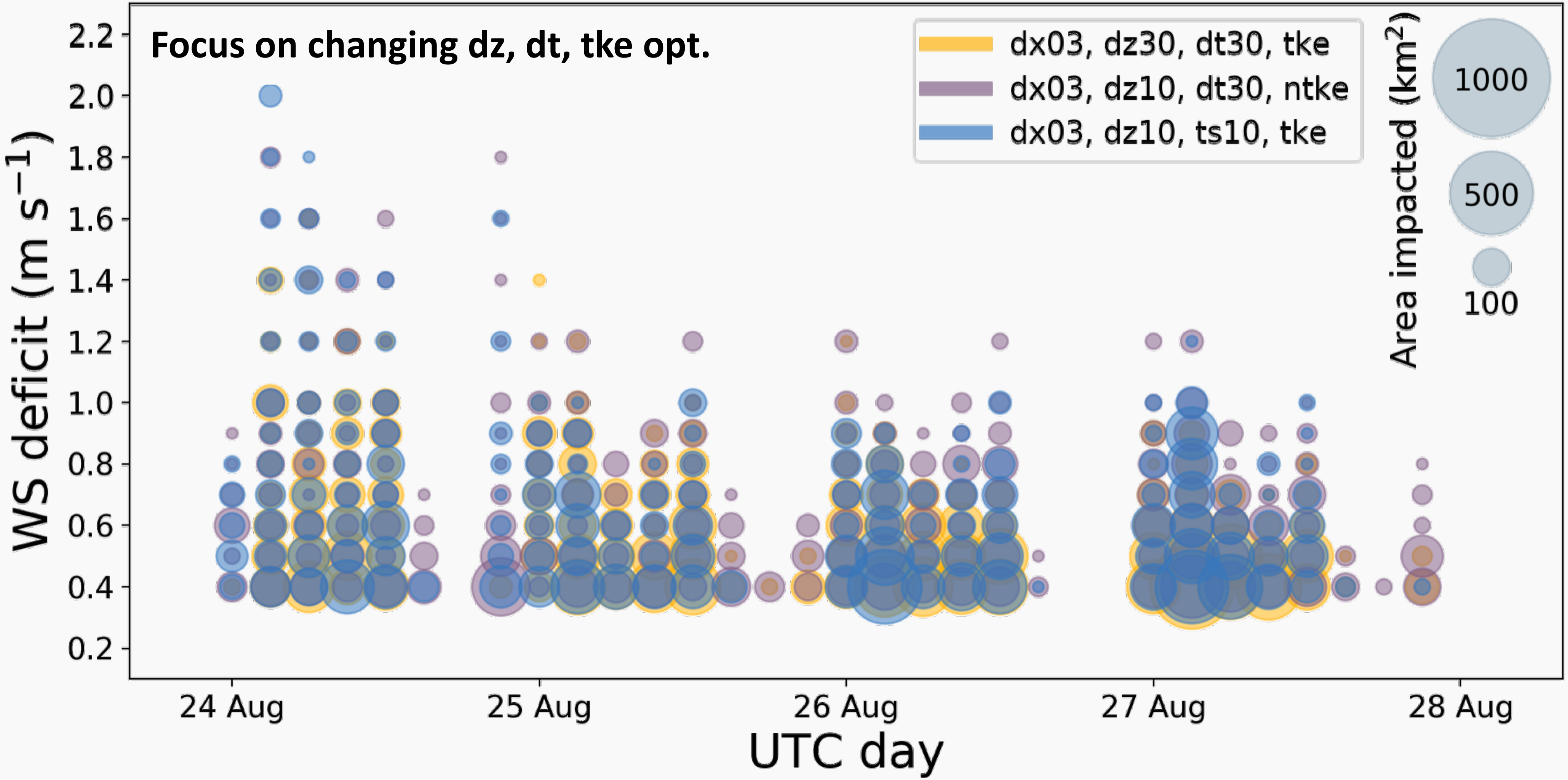

Power (MW)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
3
6
9
12
15
18
21
24
Wind Speed (m s^{-1})
Wind loss of 2 m s^{-1}
→ power loss of 0.5 MW

All WRF configs see high WS bias



dx01 resolves pulsing intensity of LLJ vs dx27

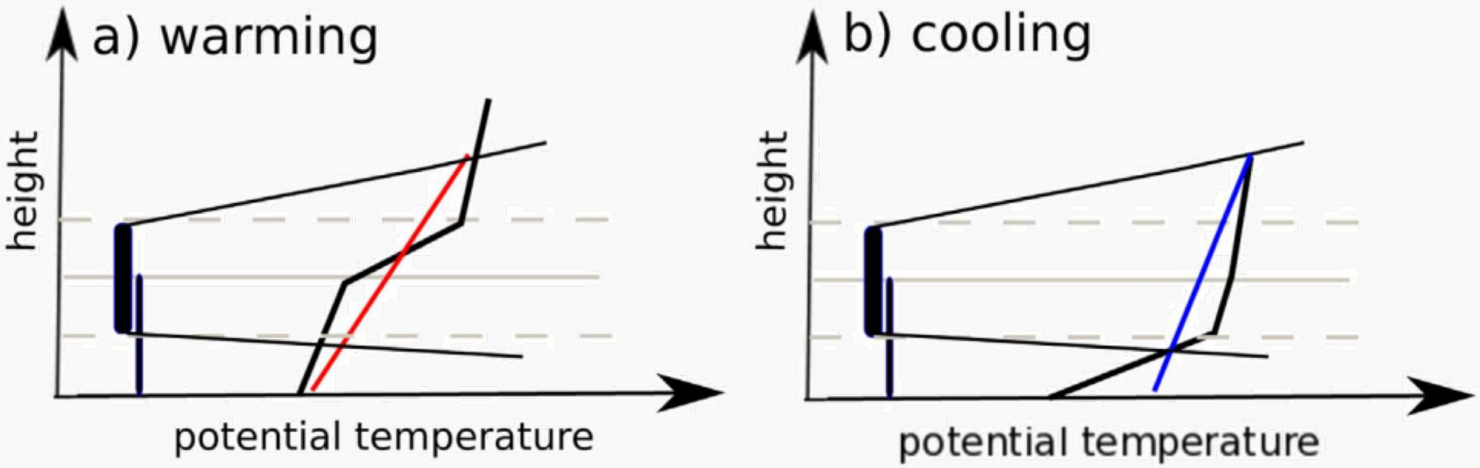
Larger dz predicts larger areas of low deficits



Wakes impact their ambient environment

Hub-height wind speed deficits cause loss in power and revenue for downwind wind farms[1,2]

Increased turbulence mixes warmer air from nighttime inversions to surface[3]



Siedersleben et al. 2018

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We test several WRF WFP configurations

8 configurations

dx	dz	dt	tke opt.
dx27, dz10, dt30, tke	dx03, **dz30**, dt30, tke	dx03, dz10, **dt10**, tke	dx03, dz10, dt30, **ntke**
dx09, dz10, dt30, tke			dx01, dz10, dt30, **ntke**
dx03, dz10, dt30, tke			
dx01, dz10, dt30, tke