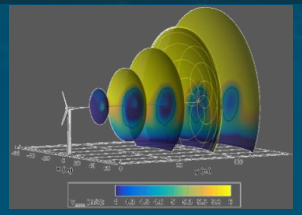
SAND2023-04974C

Sandia National Laboratories

Investigations of Farm-to-Farm Interactions and Blockage Effects from AWAKEN Using Large-Scale Numerical Simulations



PRESENTED BY

Lawrence Cheung

Wake Conference 2023, Visby, Sweden

June 21, 2023

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summit

U.S. DEPARTMENT OF ENERGY
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Motivation

Wakes and blockage are important phenomena at both the wind turbine and wind farm level

- Complex interactions between wakes, wind farms, and ABL
- Blockage effects from one farm can affect wind resource to other wind farms

Large-scale ABL and wind farm measurement campaigns planned or currently underway to capture interactions

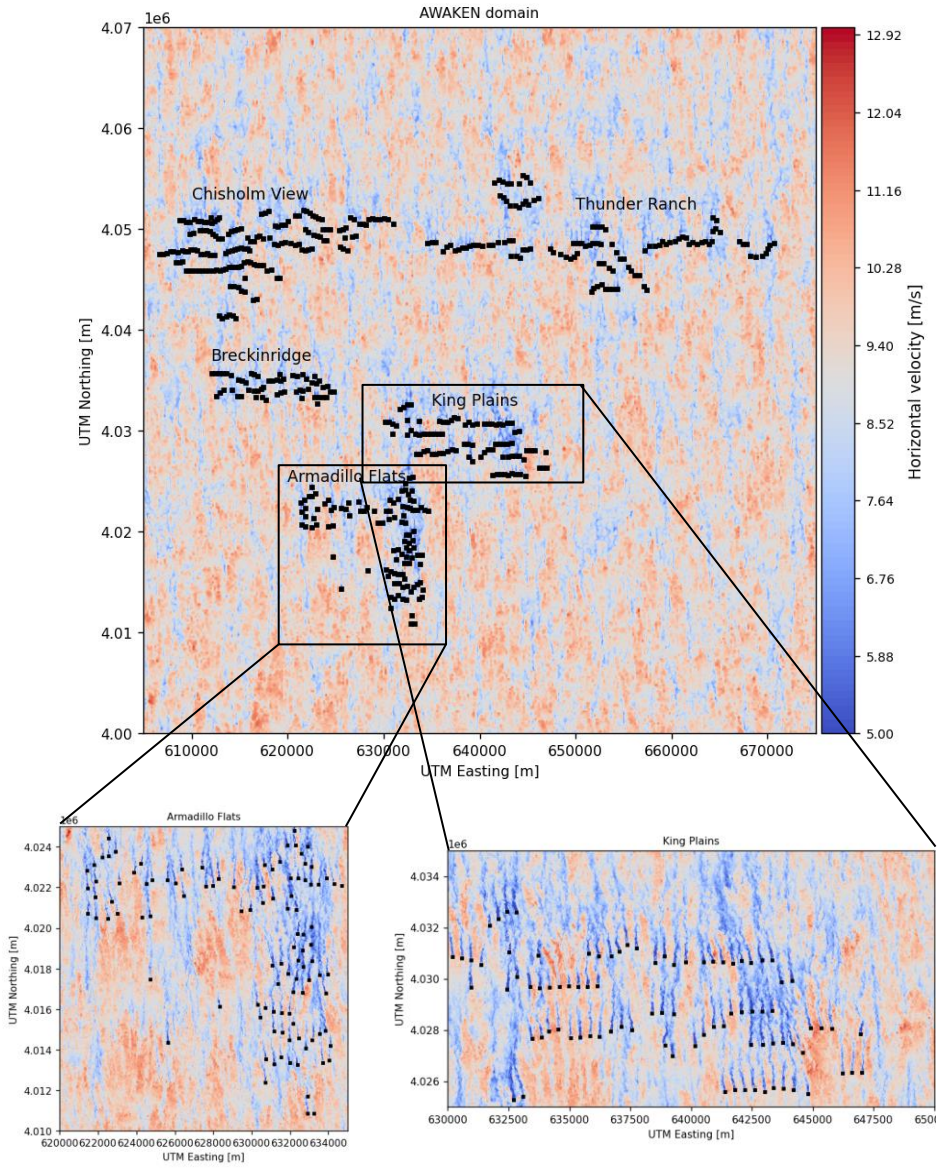
- Onshore: AWAKEN (5 wind farms in northern Oklahoma)
- Offshore: WFIP3 (Marine ABL in northeast Atlantic)

Large scale CFD studies of entire wind farm groups now also possible

- High performance LES solvers (ExaWind) and Exascale computing resources available

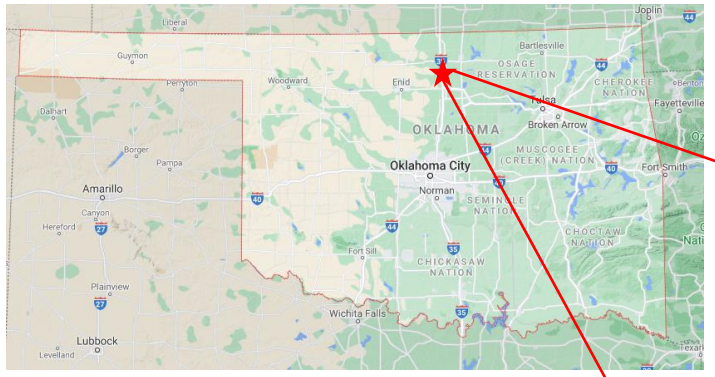
➢ Combined measurement and simulation studies can advance our understanding of complex wake and blockage phenomena

Simulation of multiple wind farms at AWAKEN site

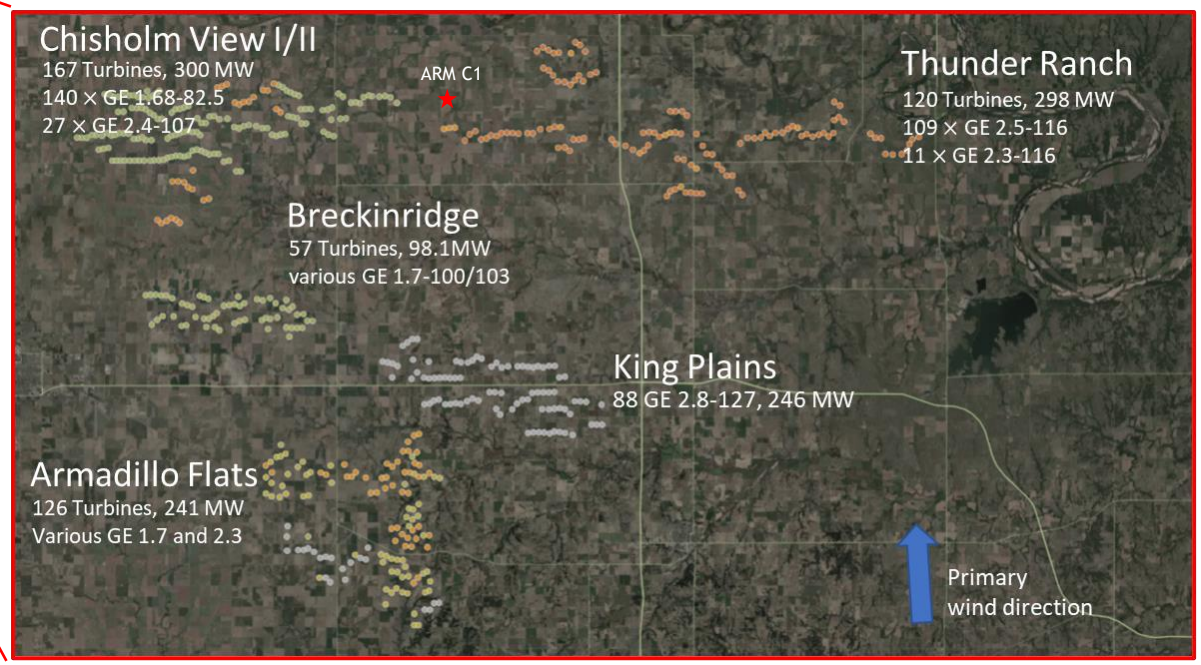


AWAKEN: American WAKE ExperimeNt Project

- Large-scale field campaign focused on detailed observations of wind farm-atmosphere interactions
- AWAKEN will instrument site to fundamental questions around wakes, blockage, farm control, turbulence/loading behaviors



5 wind farms at AWAKEN site
558 total wind turbines
1.19 GW total generating capacity



Instrumentation:

- Lidar
- X-band radar
- Balloon system
- Airborne measurements
- Turbine (SCADA) instrumentation

Measured wind conditions

- Atmospheric Radiation Measurement (ARM) Data processed by Mithu Debnath (NREL)
- Two different cases based on central location (ARM-C1)
  - Data used: 2015-01-01 to 2020-11-11
  - Primary wind direction: 175 ± 10 deg

Variables	Unstable (median data/similarity theory)	Stable (median data/similarity theory)
Wind speed (91 m height) (m/s)	9.0	10.05
Wind shear exponent (10 m -169 m)	0.0898	0.322
Inverse of Monin-Obukhov stability parameter	-0.0128/-0.0095	0.0122/0.0145
Potential temperature (3 m height) (K)	305.803	302.34
Friction velocity (m/s)	0.486/0.48	0.323/0.29
Kinematic heat flux (K. m/s)	0.11443/0.082	-0.0315/-0.027
Surface roughness height (m)	0.0172	0.04
Turbulence intensity (%) at 60m	18.04/17.15	9.56/9.17

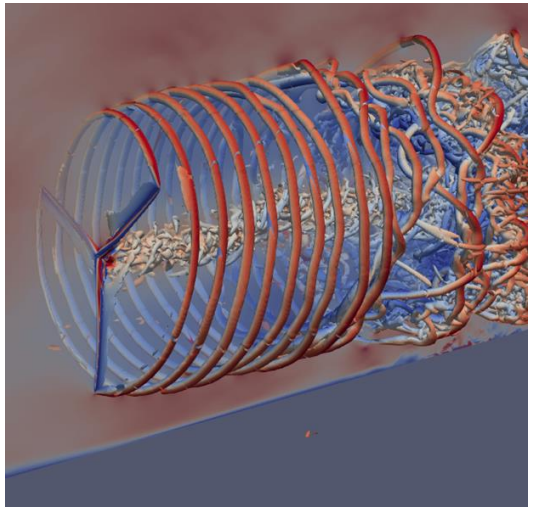
Large Eddy Simulation Methodology

AMR-Wind[1] Solver

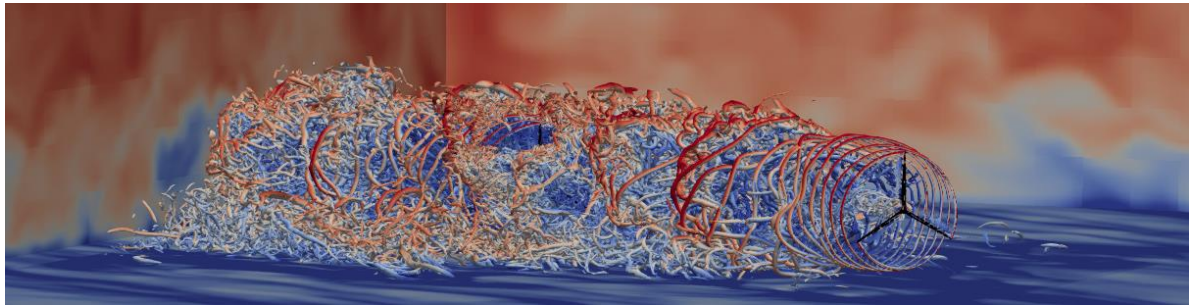
Focused on scalable on next-generation exascale supercomputers with GPU acceleration

- Structured grid finite-volume background solver with **adaptive mesh refinement (AMR)**
- Built on AMReX libraries
- Multi-level geometric multigrid linear-system solvers

- Capabilities:
  - Atmospheric boundary layers
  - Actuator line/disk turbine models
  - Multiphase flow



Blade resolved NREL 5MW wind turbine simulation



[1] http://github.com/Exawind/amr-wind

AWAKEN Simulations

Use high fidelity, large scale simulations to complement field measurements

- Optimize instrumentation placement
- Enhance understanding of physical phenomena and confirm observations

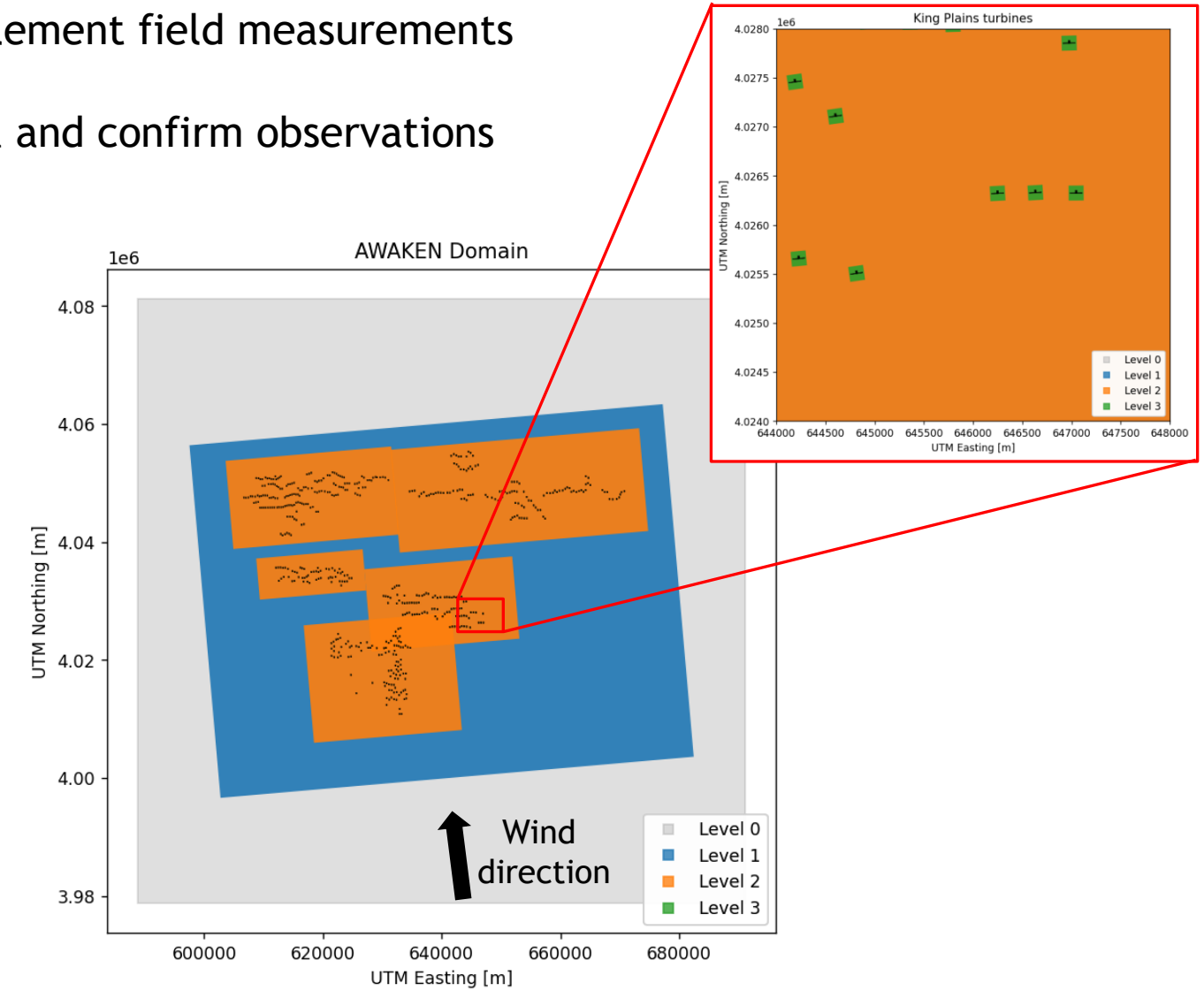
Multiple simulations being run under AWAKEN

- Two atmospheric conditions:
  - Unstable ABL (9 m/s)
  - Stable ABL (10 m/s)

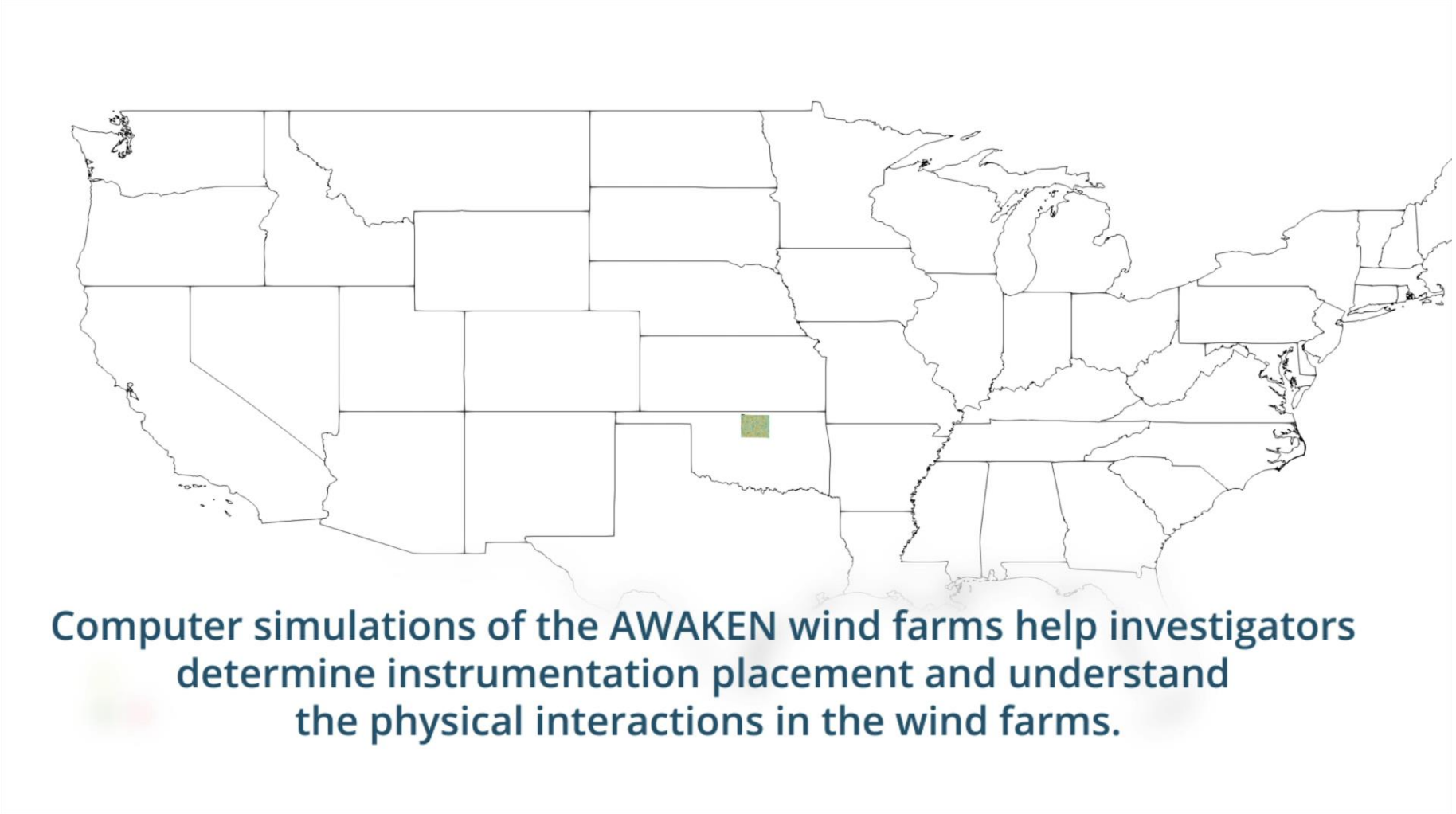
Details of larger simulation

- Run on Summit using AMR-Wind with 6000 GPUs
- 100km×100km×2.5km domain, 500+ turbines
- 21 Billion mesh elements
- Mesh resolution varies from 2.5m to 20m
- Use actuator disk models to capture turbine behavior

Smaller simulations run on subset of King Plains domain with 30-50 turbines

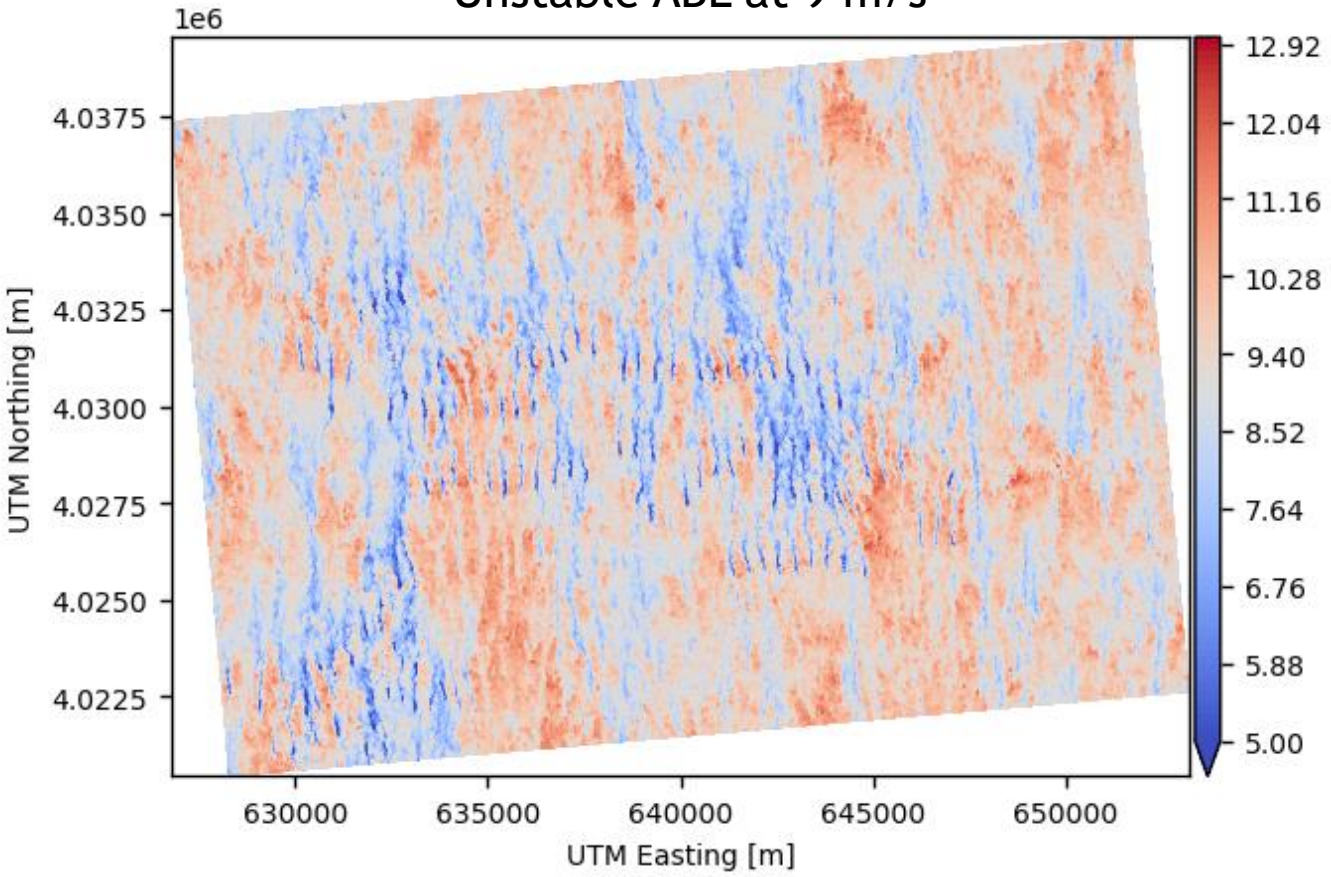


Simulation visualization: large AMR-Wind run

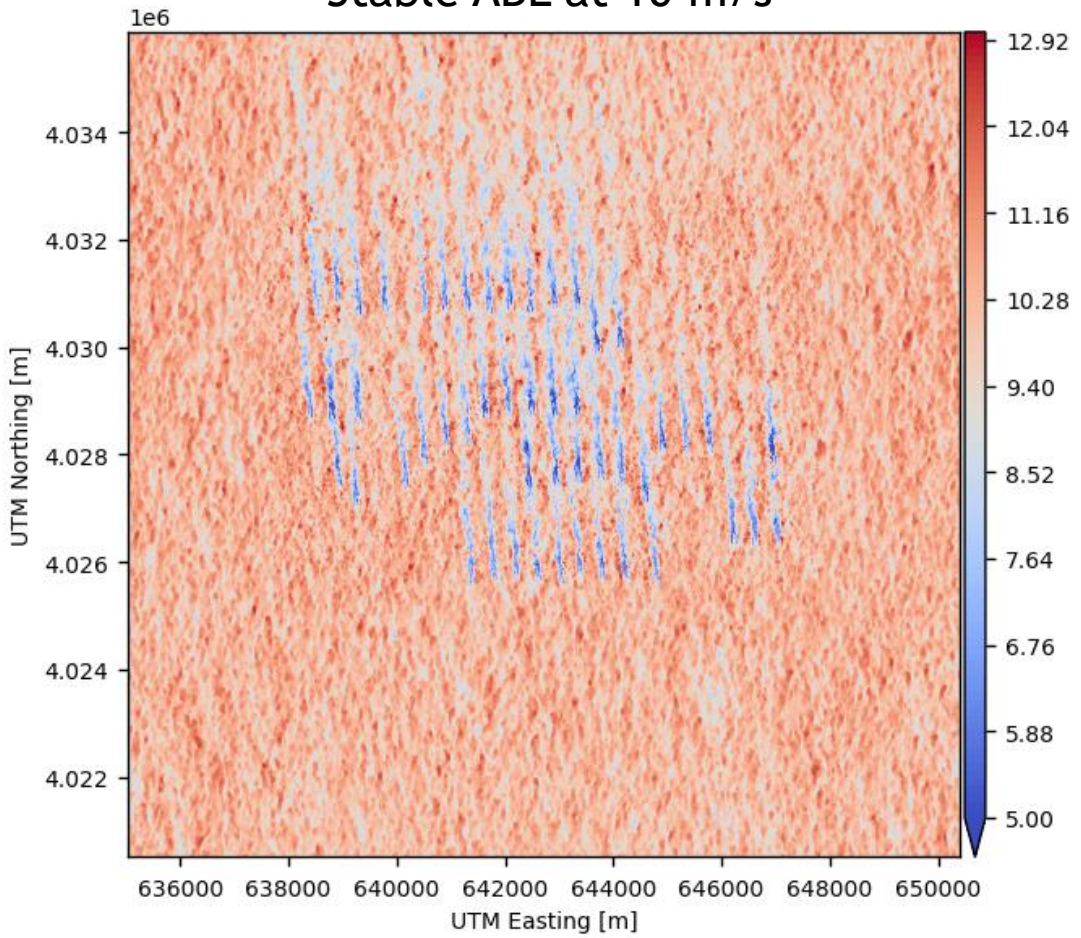


King Plains: Instantaneous hub-height velocity contour

Unstable ABL at 9 m/s



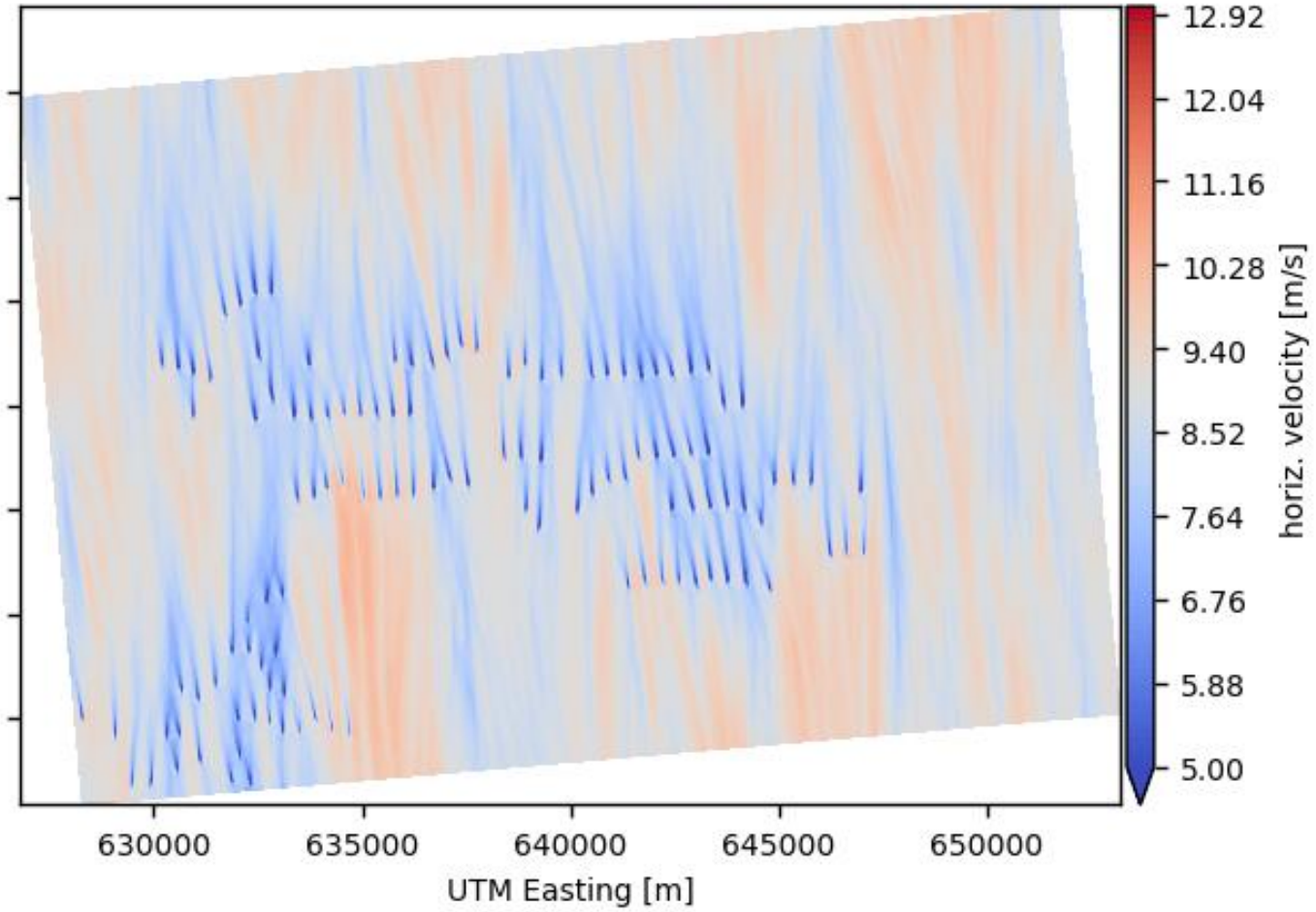
Stable ABL at 10 m/s



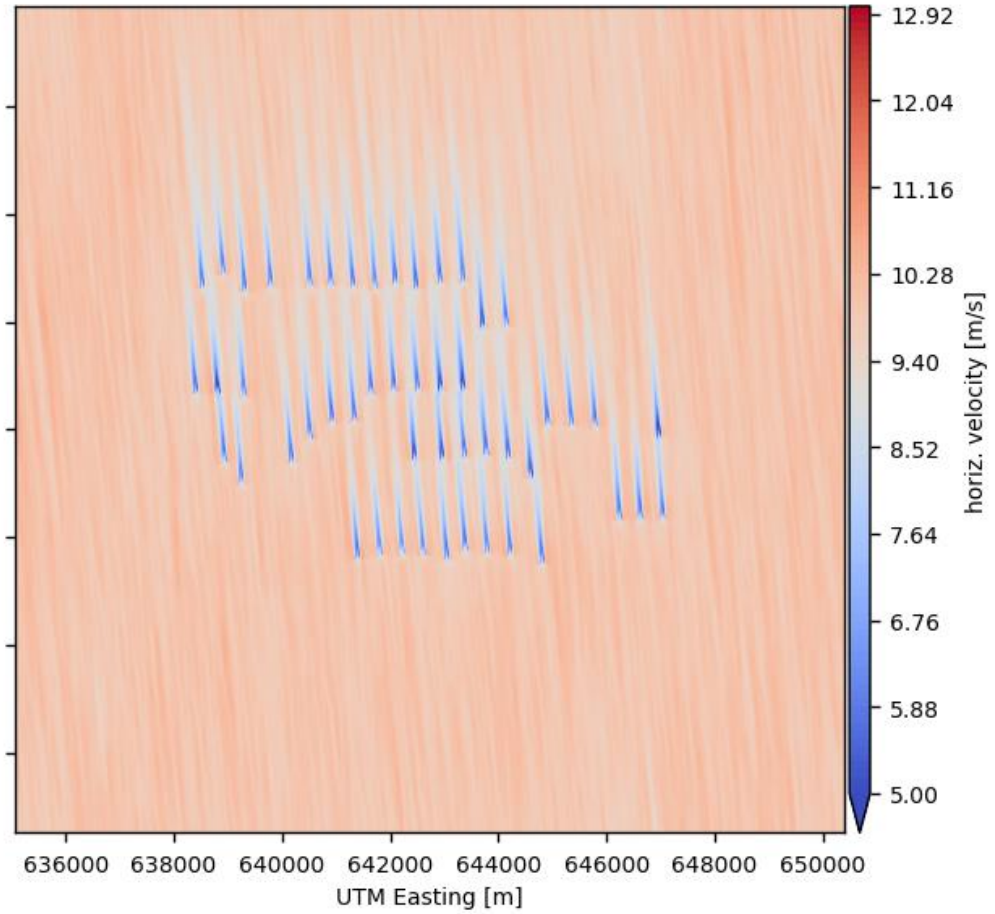
- Very large-scale convective structures visible in unstable ABL
- Lower turbulence levels in stable ABL case; flow is more homogeneous

King Plains: Time averaged hub-height velocity contour

Unstable ABL at 9 m/s

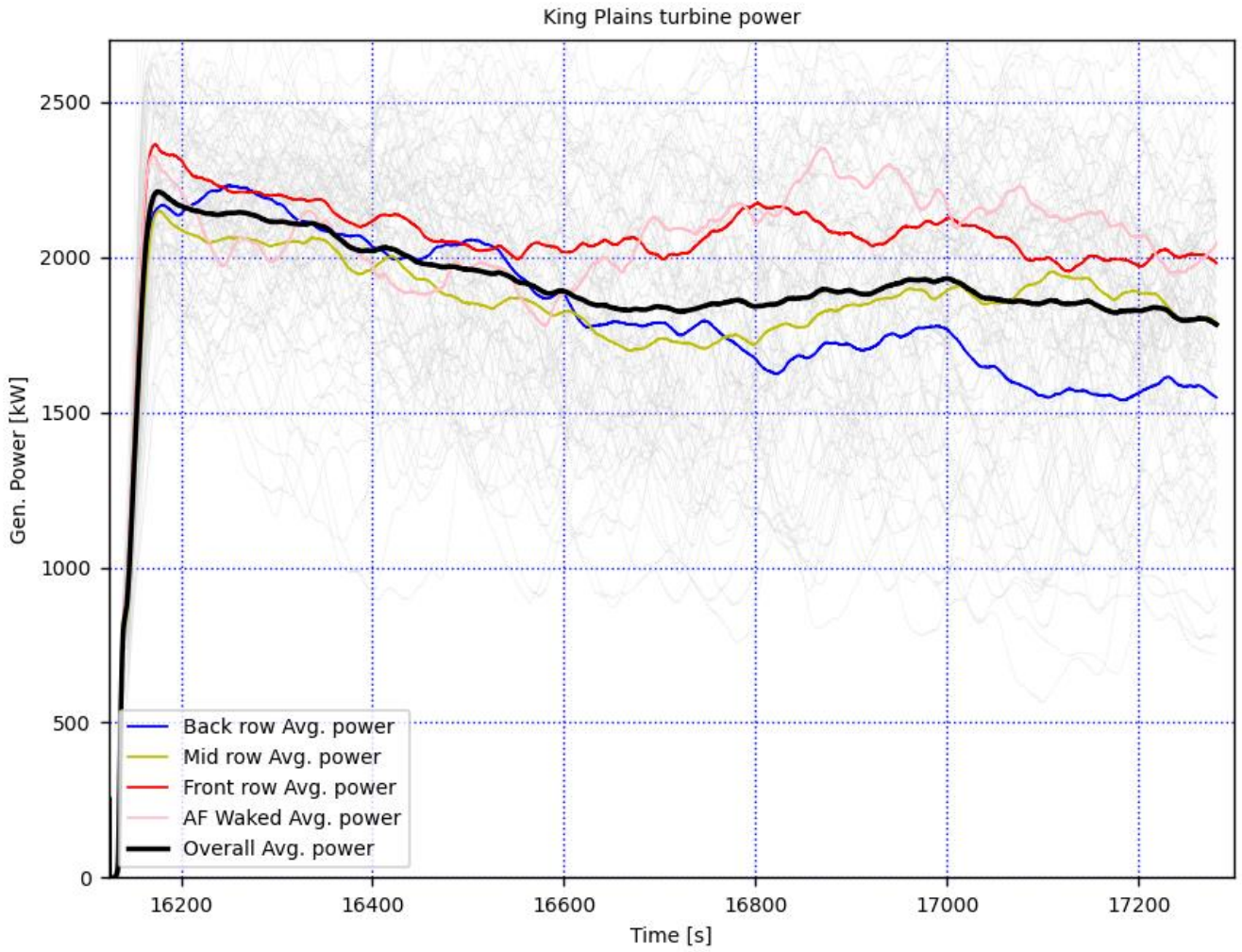


Stable ABL at 10 m/s

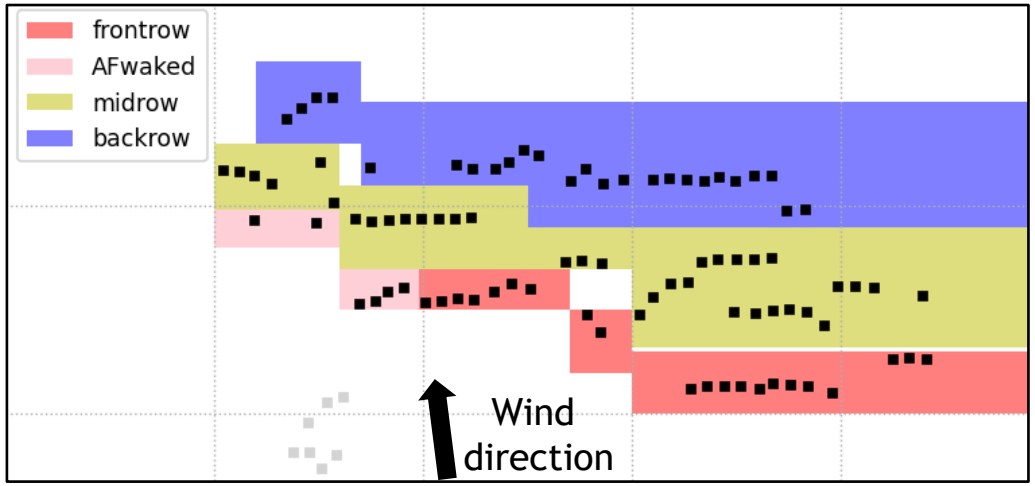


- Local wind directions vary in unstable ABL case → changes in throughout wake direction farm

King Plains turbine power (Unstable ABL)



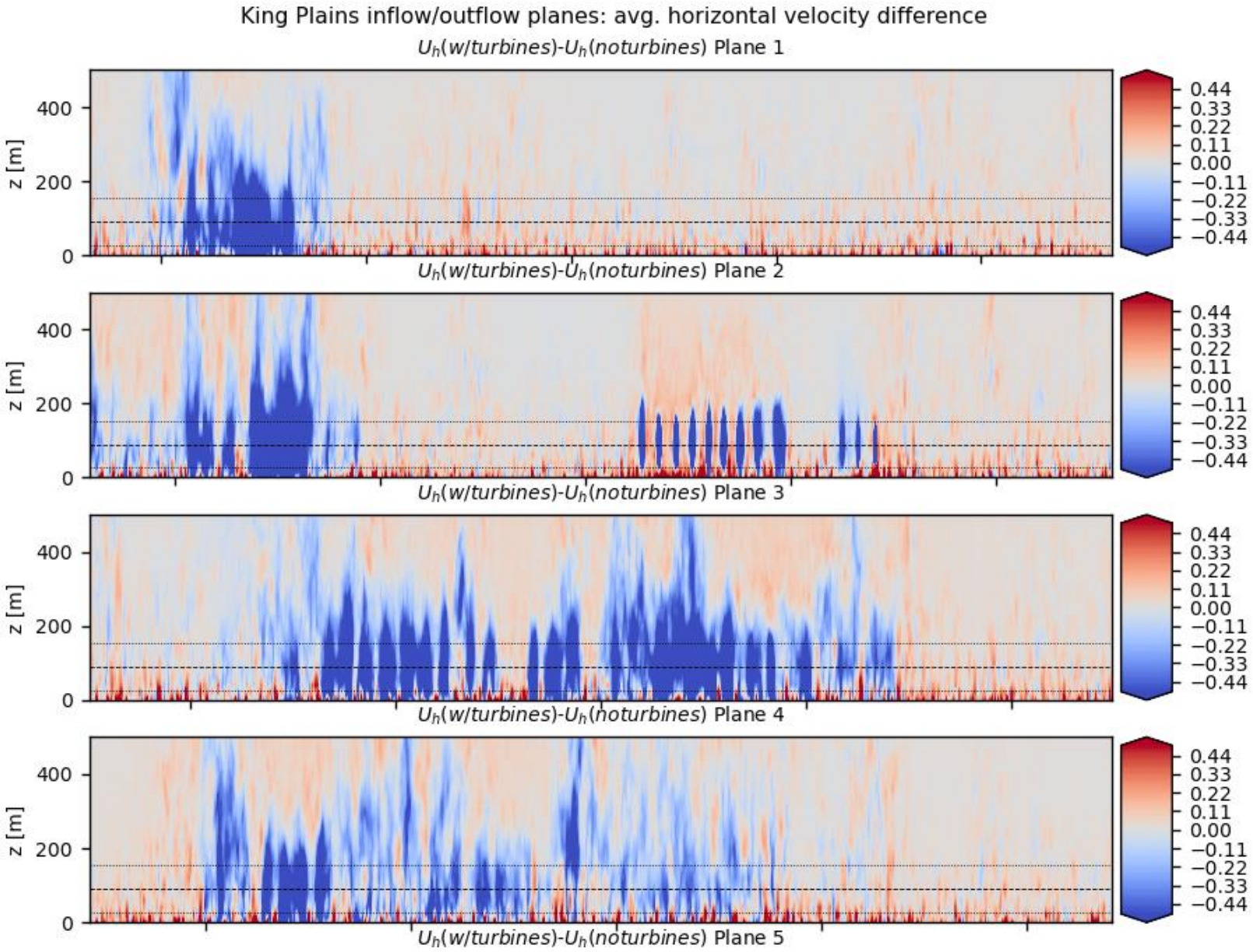
King Plains turbine layout

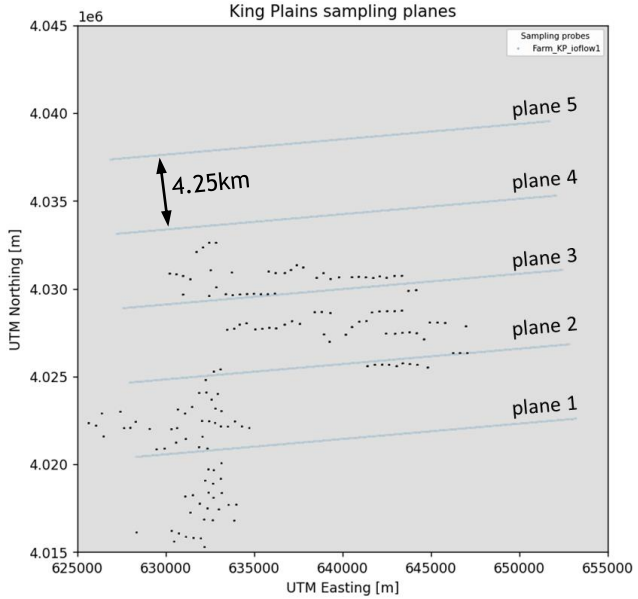


Turbine power generation depends on location within wind farm

- Upstream turbine rows produce more power than downstream turbine rows

Inflow and outflow planes

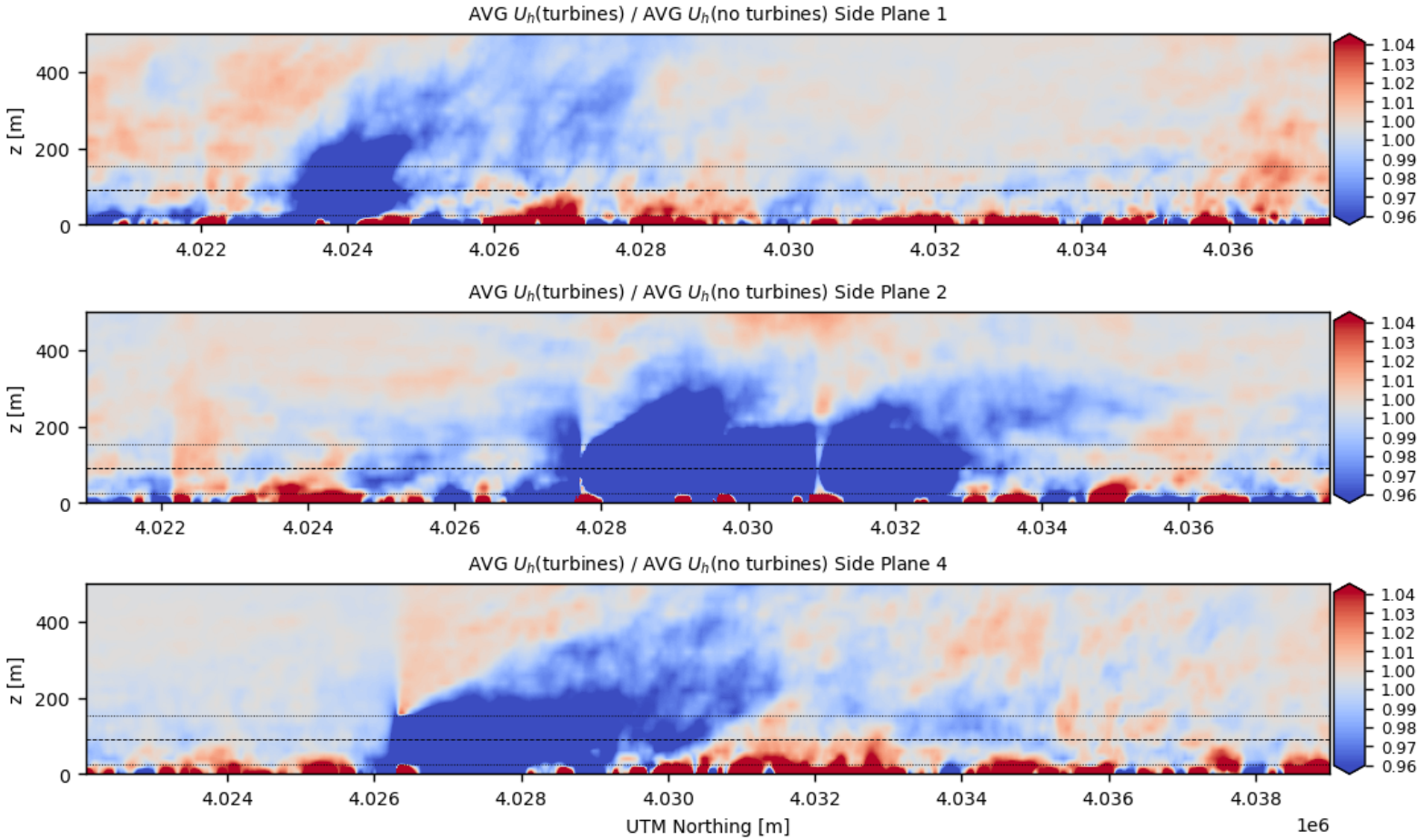


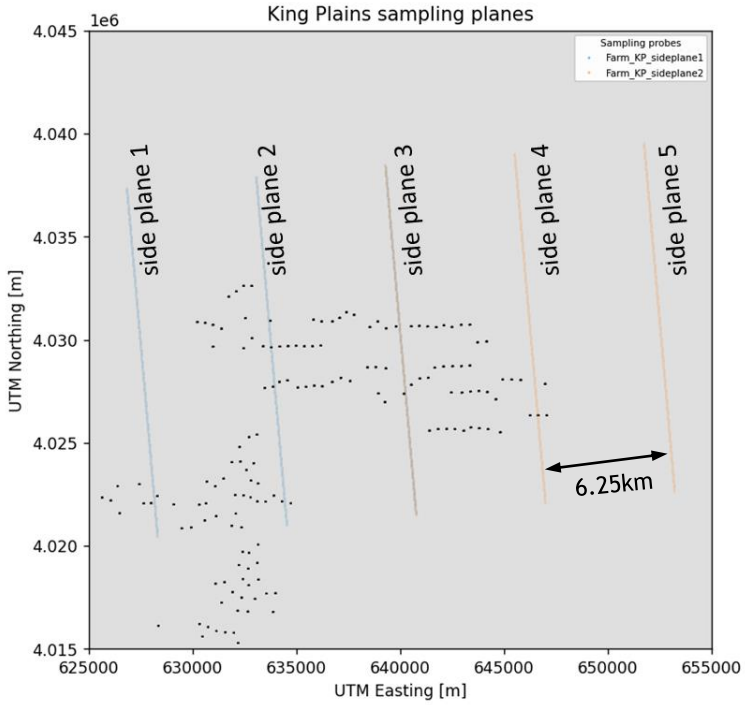


- Wake deficits extend vertically into the unstable ABL
- Impact of turbines felt far above rotor tips

Wake behavior near King Plains wind farm (Unstable ABL)

Contours of nondimensionalized horizontal velocity

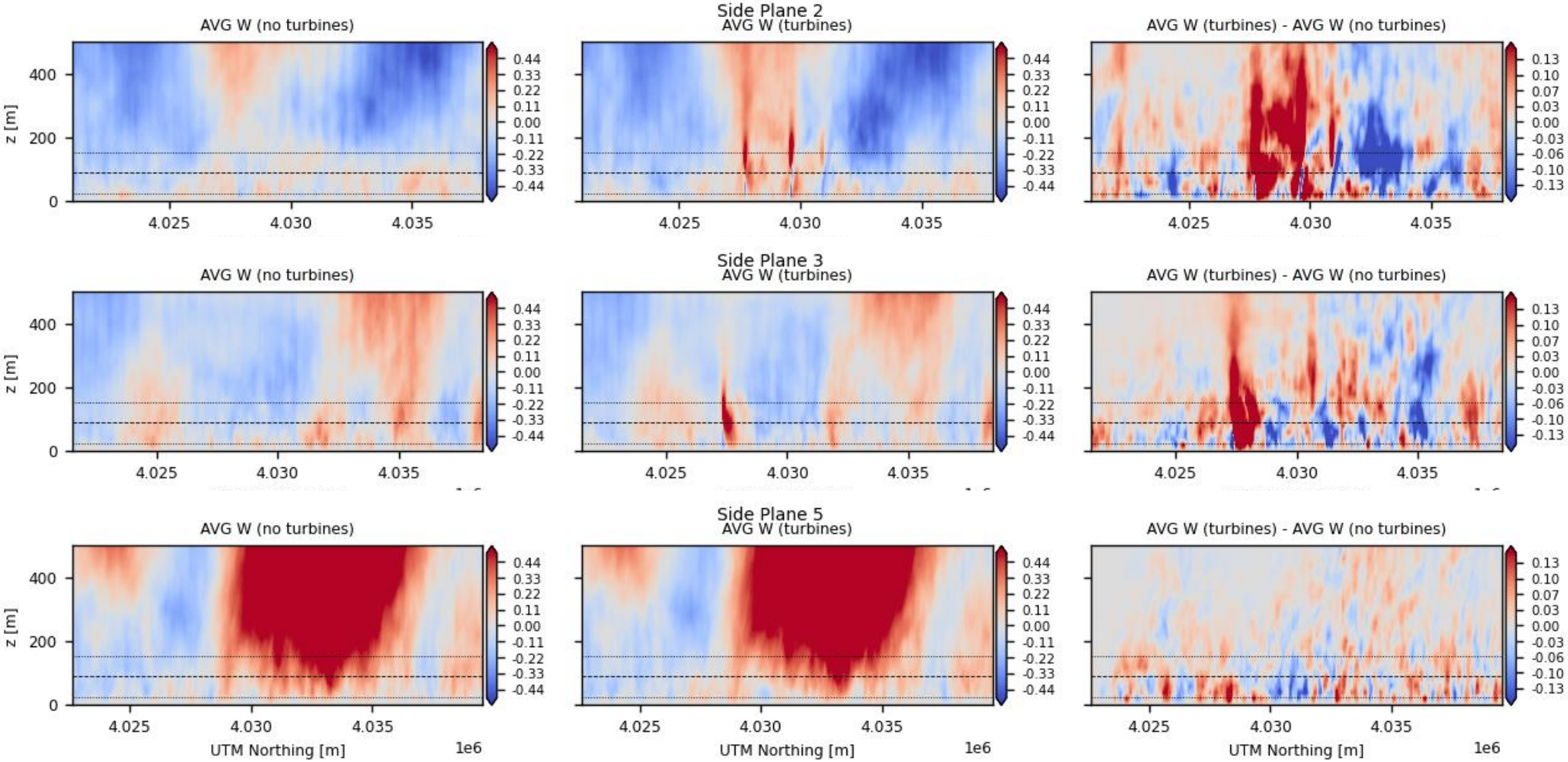


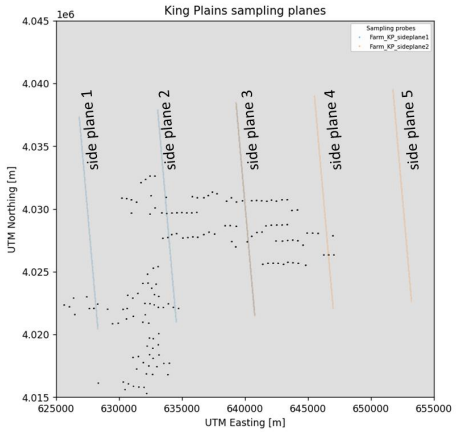


- Large scale convective structures transport wake deficit upwards into the ABL
- Affects the incoming blockage pattern, upstream slowdown persists to very high elevation

Wake behavior near King Plains wind farm (Unstable ABL)

Contours of averaged vertical velocity





- Momentum is transported both upward and downwards near the turbine wakes

Modeling wind farm blockage

AWAKEN simulations can inform lower fidelity modeling efforts

Currently developing model for wind farm blockage that takes into account multiple effects:

- Ground effects
- Wind shear
- Stratification
- Updrafts/downdrafts

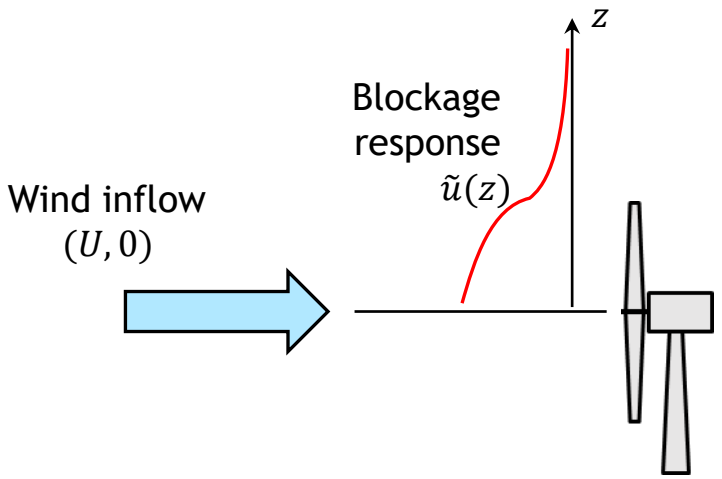
Use Green's function approach to determine blockage response to turbine forces

Prelimary findings consistent with AWAKEN results:

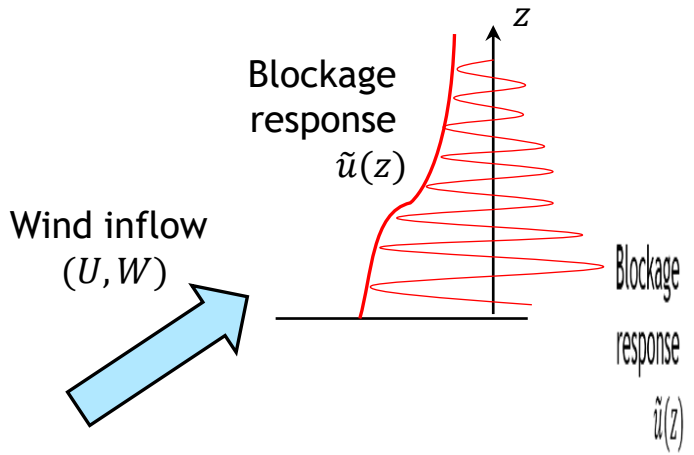
- ***Without*** vertical velocity (U component only), blockage response in z decays exponentially fast away from turbine

- ***With*** vertical velocity and thermal stratification, blockage response in z is oscillatory and persists much higher with altitude

Without vertical velocity



With vertical velocity



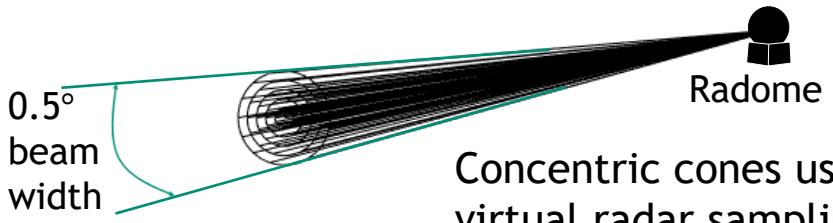
Measuring wind farm blockage?

AWAKEN simulations can inform measurement efforts

Virtual radar and lidar capabilities are being developed in Nalu-Wind and AMR-Wind to quantify sampling effects from the radar instruments deployed at the site

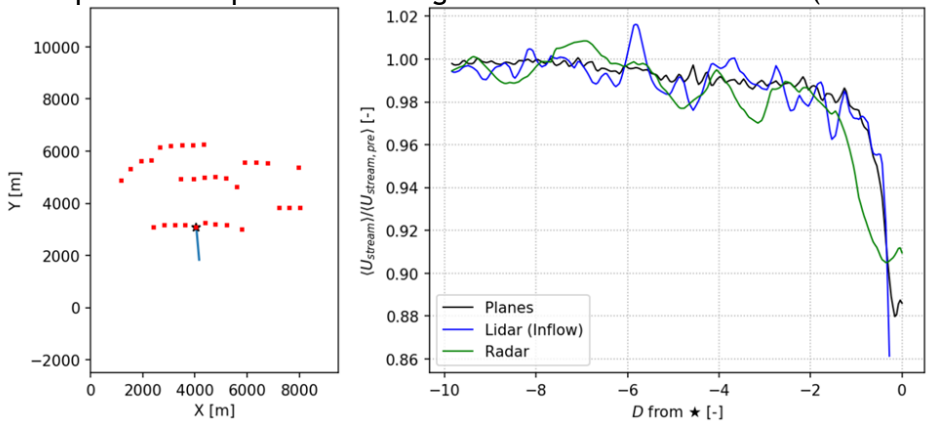
Modeled sampling effects include:

- Finite azimuthal and elevational resolution
- Line-of-sight averaging over range gates
- Transverse weighting function over the radar beam width
- Cosine correction of the lidar data



Concentric cones used for virtual radar sampling

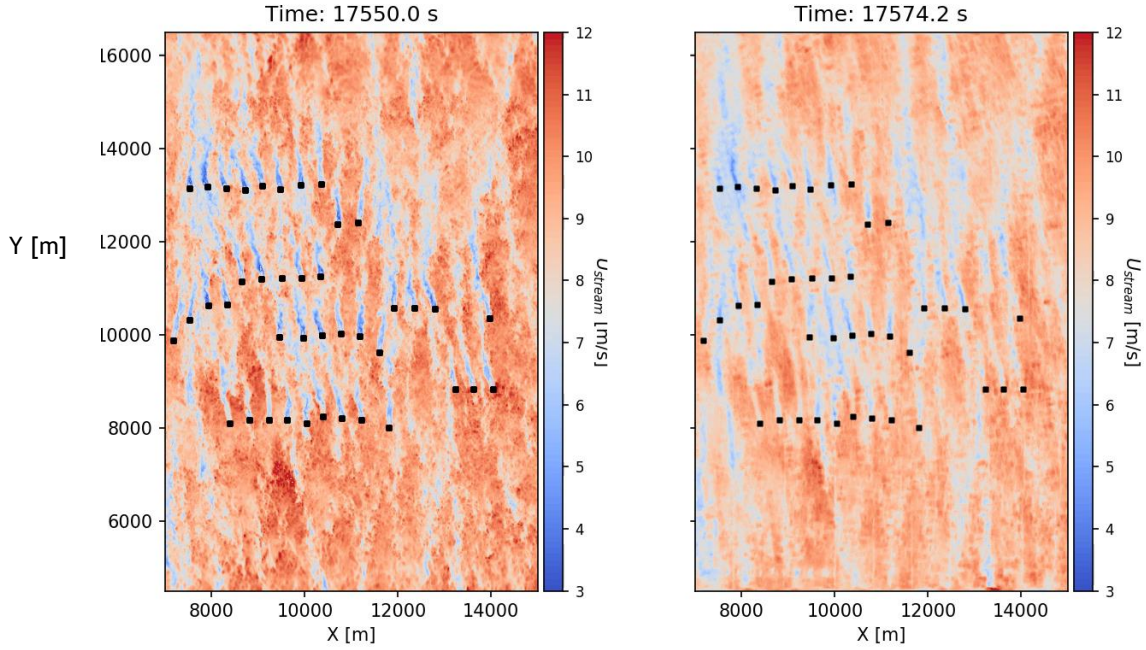
Comparison of upstream blockage with virtual lidar & radar (stable ABL)



Comparison of CFD output with virtual radar (unstable ABL)

Full planar output ($\Delta t = 4$ s)

Virtual radar ($\Delta t = 13.3$ s)



Videos played at 10x speedup

Summary

- Large Eddy Simulations can be used to model entire wind farm clusters from the AWAKEN measurement campaign
- Unstable and stable ABL conditions simulated
  - Largest case simulated 100km × 100km with >500 wind turbines
- Wind farms in unstable ABL case show complex behaviors
  - Turbine wakes modified by updraft/downdrafts in the convective structures
  - Blockage effects persist at high elevations
- New blockage models being developed to incorporate additional physics
- Simulation results can help inform lidar/radar measurement efforts

Acknowledgements

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