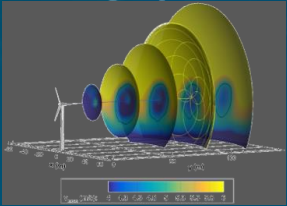


# Model Validation of the ABL, Turbine, and Wakes for AWAKEN Simulations under Neutral Stability Conditions



PRESENTED BY

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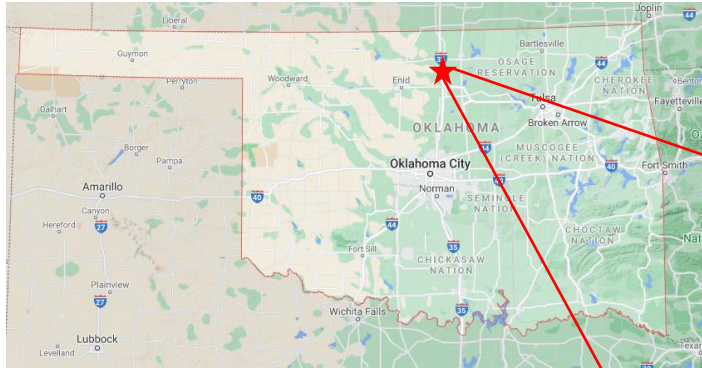


- AWAKEN and Research Background
- Experimental Data Overview
- Simulation Cases Overview
- Inflow Comparison
- Turbine/Wake Model Intercomparison
- Turbine/Wake Field Data
- Conclusions and Next Steps

### 3 AWAKEN Research Scope



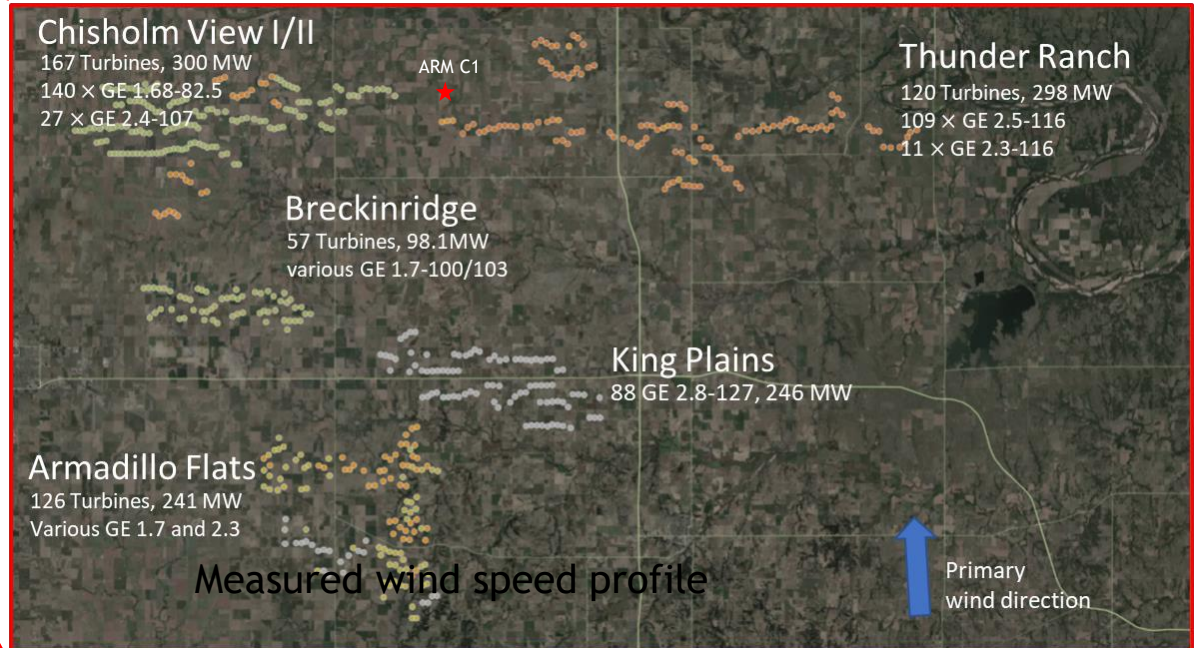
- Large-scale field campaign focused on detailed observations of wind farm-atmosphere interactions from several wind farms in northern Oklahoma
- AWAKEN will instrument site to fundamental questions around wakes, blockage, farm control, turbulence/loading behaviors



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

#### Instrumentation:

- Lidar
- X-band radar
- Balloon system
- MET stations
- Turbine (SCADA) instrumentation

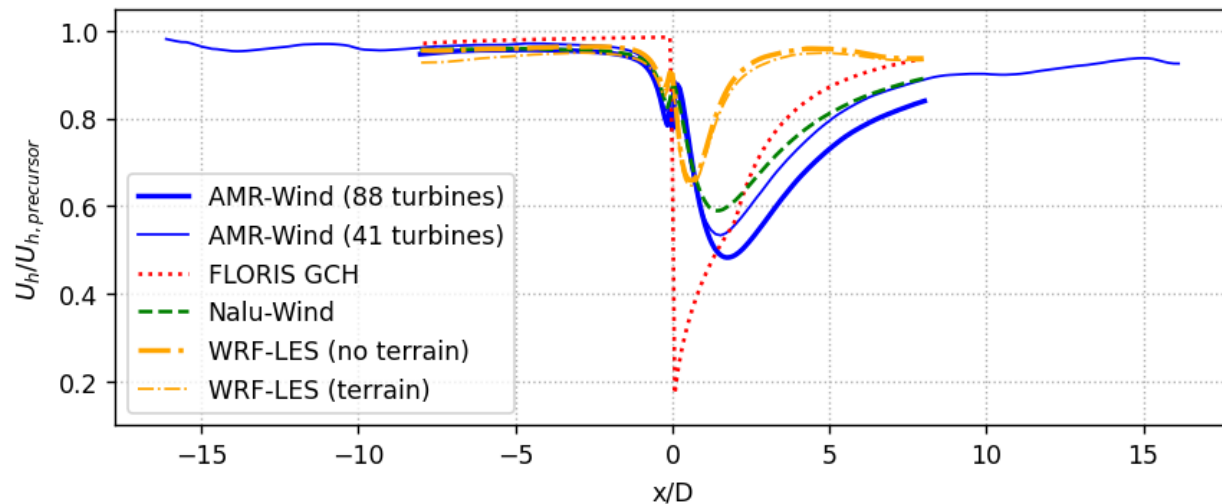


## 4 AWAKEN Research Scope

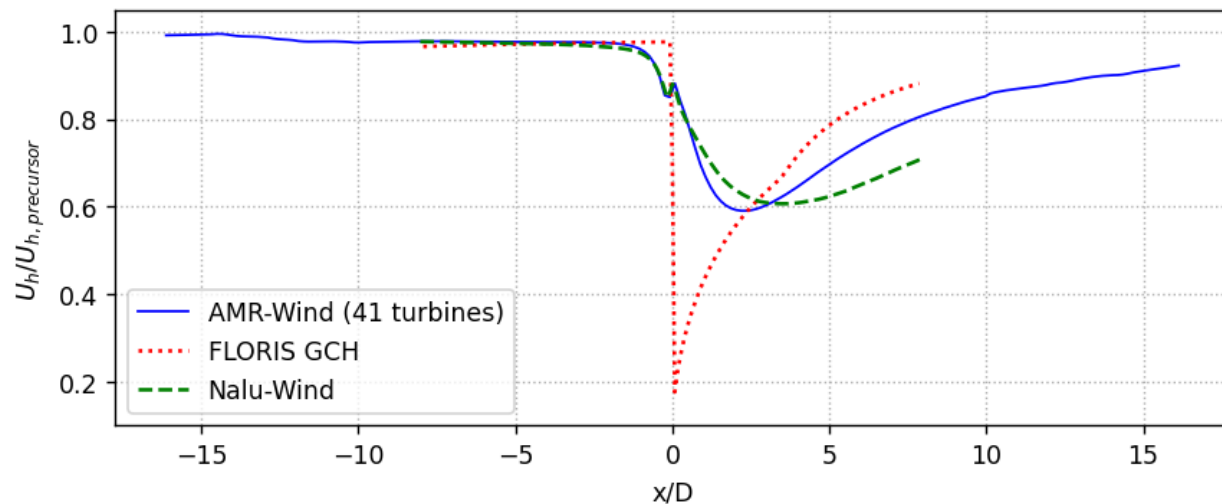
Previous AWAKEN simulation research in 2023 (Cheung et al., 2023) showed significant discrepancies for stable and unstable comparisons of modeled AWAKEN wind farms, especially in the wake

- Joint collaboration between SNL, PNNL, NREL, others

Motivation of present research is to reduce model variability for future benchmark simulations and begin preliminary model comparisons with experimental data



AWAKEN Model comparison for unstable ABL (Cheung et al., 2023)



AWAKEN Model comparison for stable ABL (Cheung et al., 2023)



- ABL/Turbine Inflow
  - Ground-based Profiling Windcube v2 Lidar (sa1.lidar.z02)
  - Ground-based Scanning Halo XR Lidar (sa1.lidar.z03)
  - Nacelle-mounted forward-facing Windcube Lidar (rt1.lidar.z01)
  - Surface meteorology station (sa1.sonic.z01)
- Turbine Data (H05)
  - 10-min averaged SCADA data from GE (kp.turbine.z01)
  - Standardized high-frequency (50 Hz) mechanical loads turbine data (kp.turbine.z03)
    - Not fully QA/QC'd, needs further calibration to account for instrument drift
- Turbine Wake
  - Rear-facing Halo XR+ lidar on Turbine H05 (rt1.lidar.z02)
  - Data post-processed using LiDARGO and LiSBOA suites from NREL
  - Presentation shows clustered wake lidar statistics
    - Toolkit from Stefano Letizia from NREL
    - Averaged 10-min bin instances over entire wake lidar data set using specified parameter ranges
      - Wind Speed: 5 – 8 m/s, Wind Direction: 135 – 225 deg, TI: 5 – 10%

() refers to instrumentation code on the A2e Wind Data Hub (<https://a2e.energy.gov/data>)

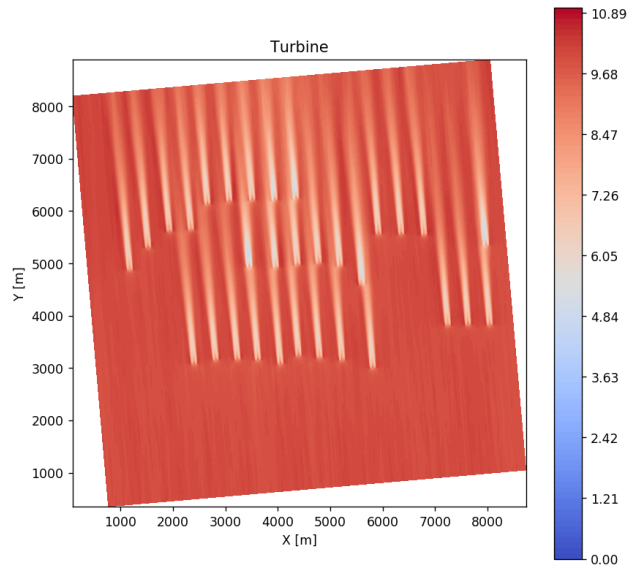
# 6 Simulation Model Overview



## ExaWind/Nalu-Wind<sup>1</sup> Solver:

LES flow solver

- Unstructured, node-centered finite-volume solver
- Implicit BDF2 time-stepping algorithm
- Uses Sierra Toolkit libraries (STK) for unstructured mesh data structure
- Wall model BC based on Moeng (1984) and Monin-Obukhov similarity theory



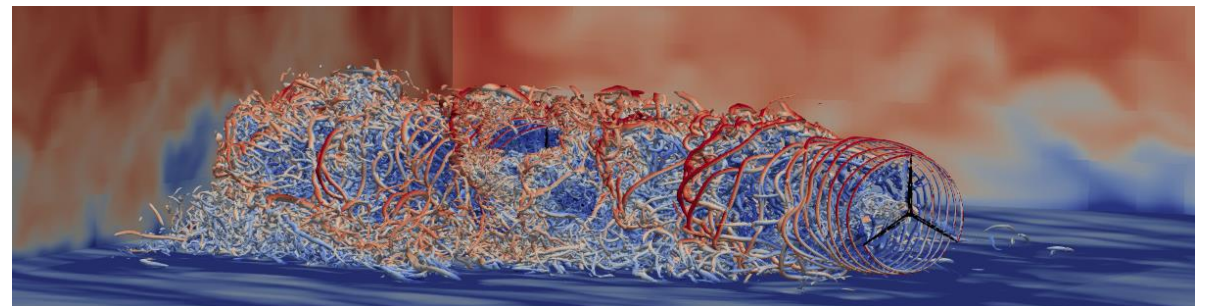
Sandia Wind farm simulation (Nalu-Wind)

## AMR-Wind<sup>2</sup> Solver

LES code 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

Blade resolved NREL 5MW wind turbine simulation (AMR-Wind)



<sup>1</sup><http://github.com/Exawind/nalu-wind>

<sup>2</sup><http://github.com/Exawind/amr-wind>

# 7 Simulation Model Overview



## Advanced-Research WRF model<sup>3</sup>:

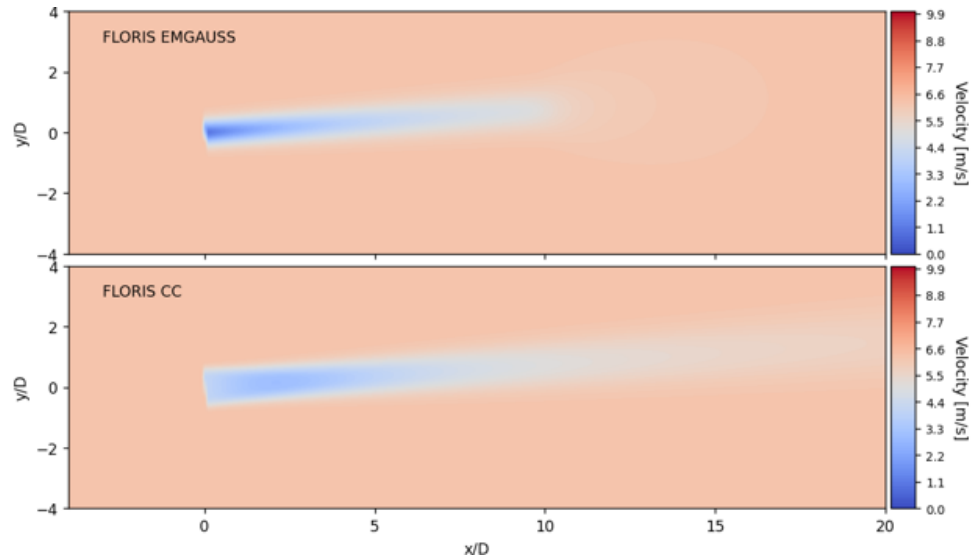
LES flow solver

- Solves compressible Euler equations
- Third-order Runge-Kutta scheme
- Multiscale framework which models turbulence differently between mesoscale and microscale ranges

## FLORIS model<sup>4</sup>

Low-cost python-based engineering tool used to simulate steady-state turbine and wake behavior

- Wake represented by four separate models for wake deficit, deflection, turbulence, and combination
- No temperature and complex phenomena (geostrophic, Coriolis forcing) modeled
- Turbine represented by actuator disk



**Comparison of wind turbine wakes between two FLORIS wake models**

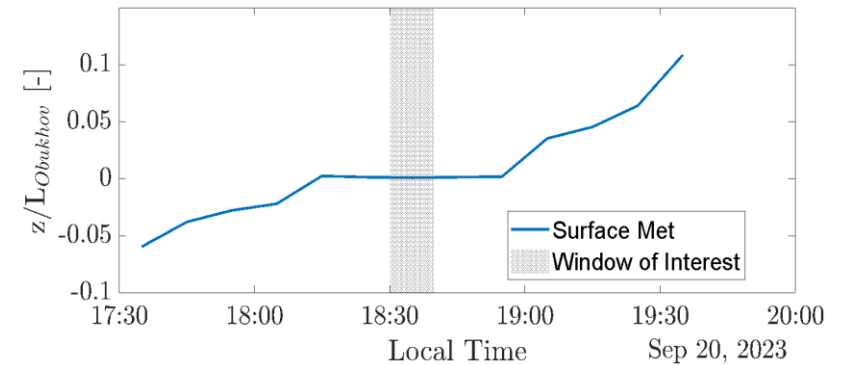
<sup>3</sup><https://github.com/wrf-model/WRF>

<sup>4</sup><https://github.com/NREL/floris>



# Measured wind conditions

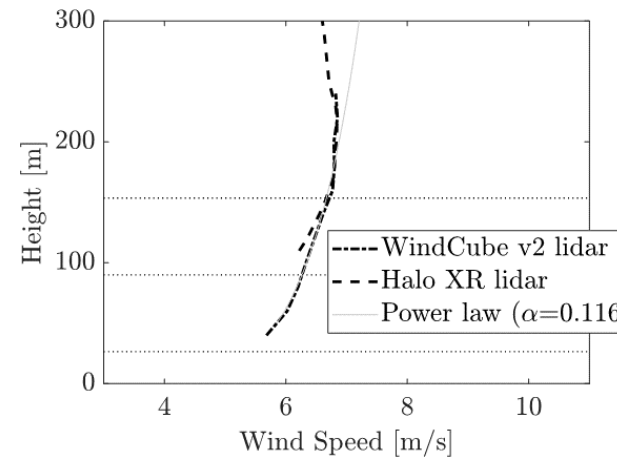
- Neutral ABL conditions were defined from AWAKEN data from the A2e Wind Data Hub (WDH)
- Primary instruments used for characterization
  - Windcube v2 profiling lidar
  - Halo XR scanning lidar
- Selected time period
  - 20-Sep-2023, 23:30:00 to 23:40:00 UTC



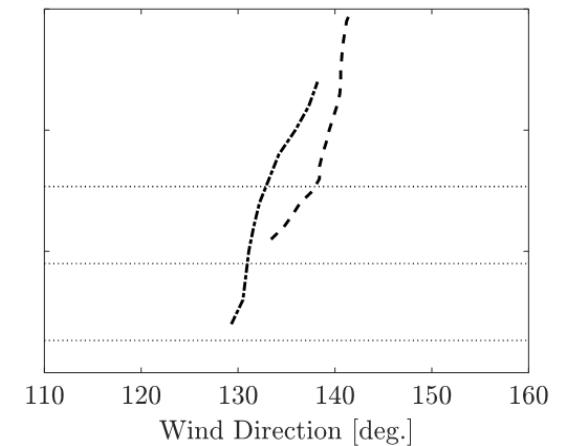
Measured Inverse Monin-Obukhov length

## Targeted 10-min neutral ABL conditions

Quantity	Value	Units
Hub-height wind speed	6.27	m/s
Turbulence intensity over rotor	0.097	-
Shear exponent over rotor	0.116	-
Veer over rotor	3.28	°
Near-ground temperature of air	305	K
Density of air	1.09	kg/m <sup>3</sup>



Measured 10-min averaged wind speed profile



Measured 10-min averaged wind dir. profile

# Computational Setup

One turbine cases were simulated for the four models under the aforementioned neutral ABL conditions

## Models:

### AMR-Wind

- Mesh size: 83 million cells
- Refinement regions around turbine

### Nalu-Wind

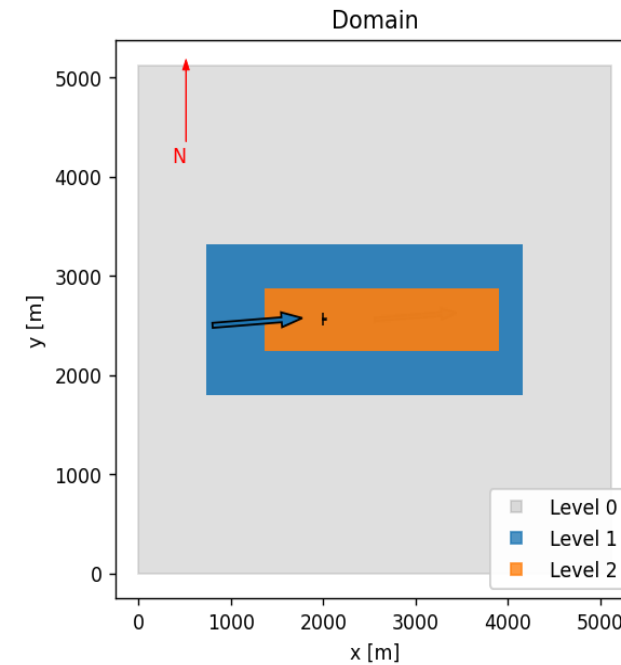
- Mesh size: 29 million cells
- Refinement regions around turbine

### WRF-LES

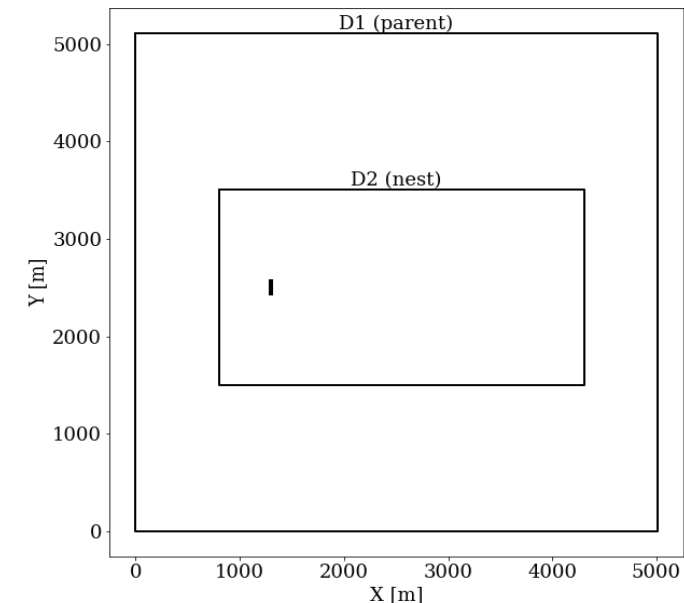
- Mesh size: 32 million cells
- Two coupled computational setups with parent and nested domains

### FLORIS

- Single simulation needed (no precursor)
- Actuator disk used to represent wind turbine



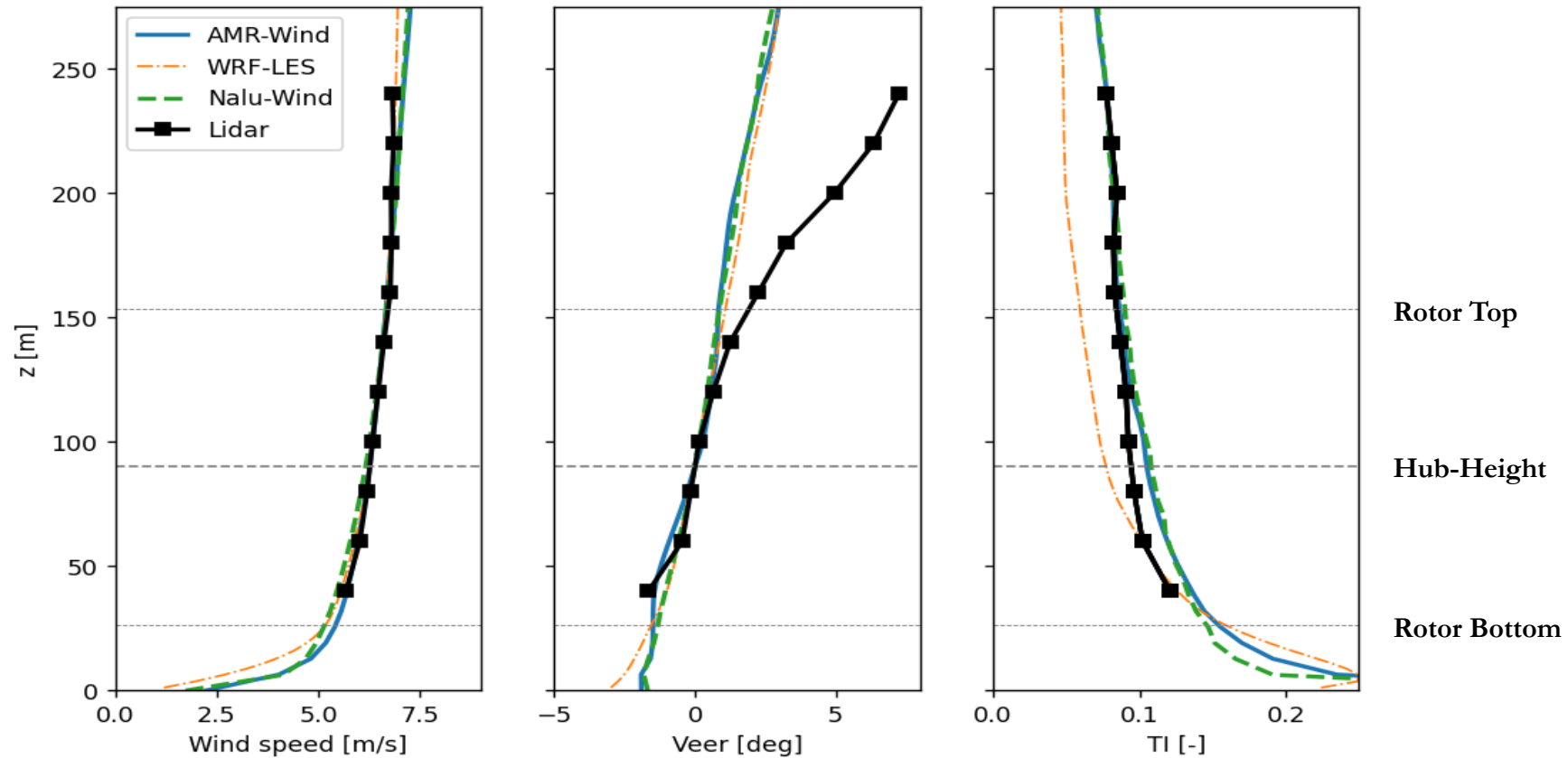
**Simulated domain for AMR-Wind/Nalu-Wind cases**



**Simulated domain for WRF case**

Comparison of simulated precursor flows from LES codes to profiling Windcube lidar

- Good agreement for wind speed profiles in turbine region
- Veer has reasonable agreement in turbine region but LES results significantly deviate above the turbine
- AMR-Wind and Nalu-Wind over-predicts TI compared to field data, WRF-LES significantly under-predicts TI

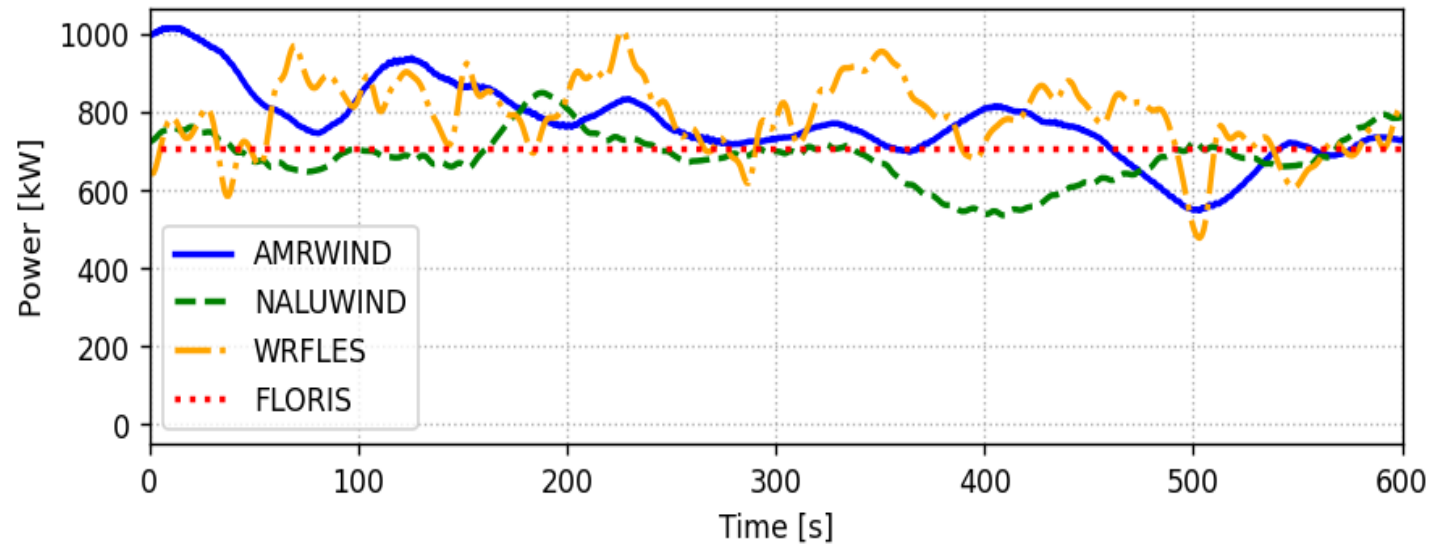




### Comparison of hub-height/rotor parameters from field data to simulation results

Quantity	Field Data	AMR-Wind	Nalu-Wind	WRF	FLORIS
Hub-height wind speed [m/s]	6.27	6.26	6.16	6.27	6.27
Hub-height wind direction [deg]	265.67	265.73	265.84	265.55	265.67
Turbulence intensity over rotor [-]	0.097	0.109	0.110	0.087	0.097
Shear exponent over rotor [-]	0.116	0.117	0.147	0.137	0.116
Veer over rotor [deg]	3.28	2.33	2.18	2.62	N/A

### Comparison of 10-minute generator power distributions between the four models



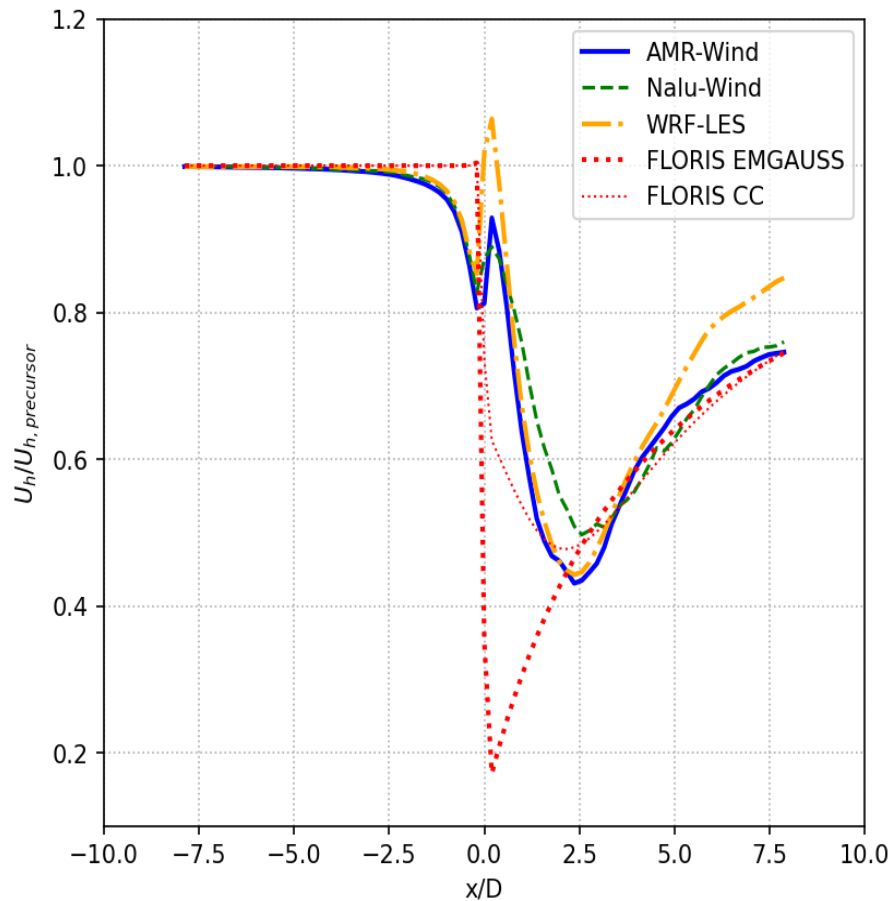
### Turbine coefficient comparison between design curves and model results

Turbine quantity	Design	AMR-Wind	Nalu-Wind	WRF-LES	FLORIS
$C_p$	0.459	0.455	0.424	0.462	0.416
$C_T$	0.887	0.944	0.906	-	-
TSR	8.00	7.76	7.59	-	-
$C_Q$	0.0320	0.0324	0.0311	-	-

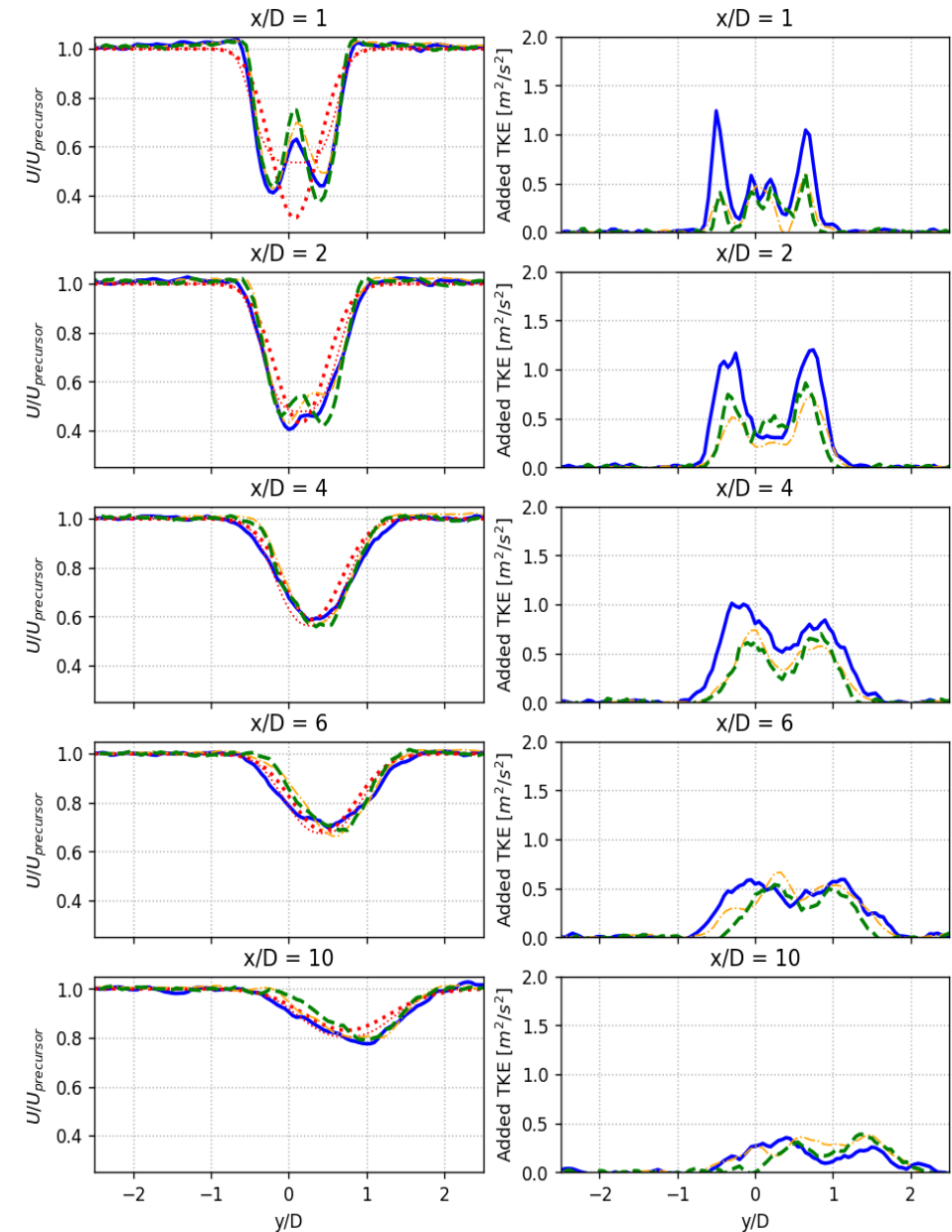
# Wake Model Intercomparison

Comparison of wake QoIs between the four models

- Significantly better agreement between modeled wake deficit and TI profiles, especially beyond near-wake ( $>3D$ )



Streamwise hub-height wake profile comparison between models



Modeled hub-height wake deficits

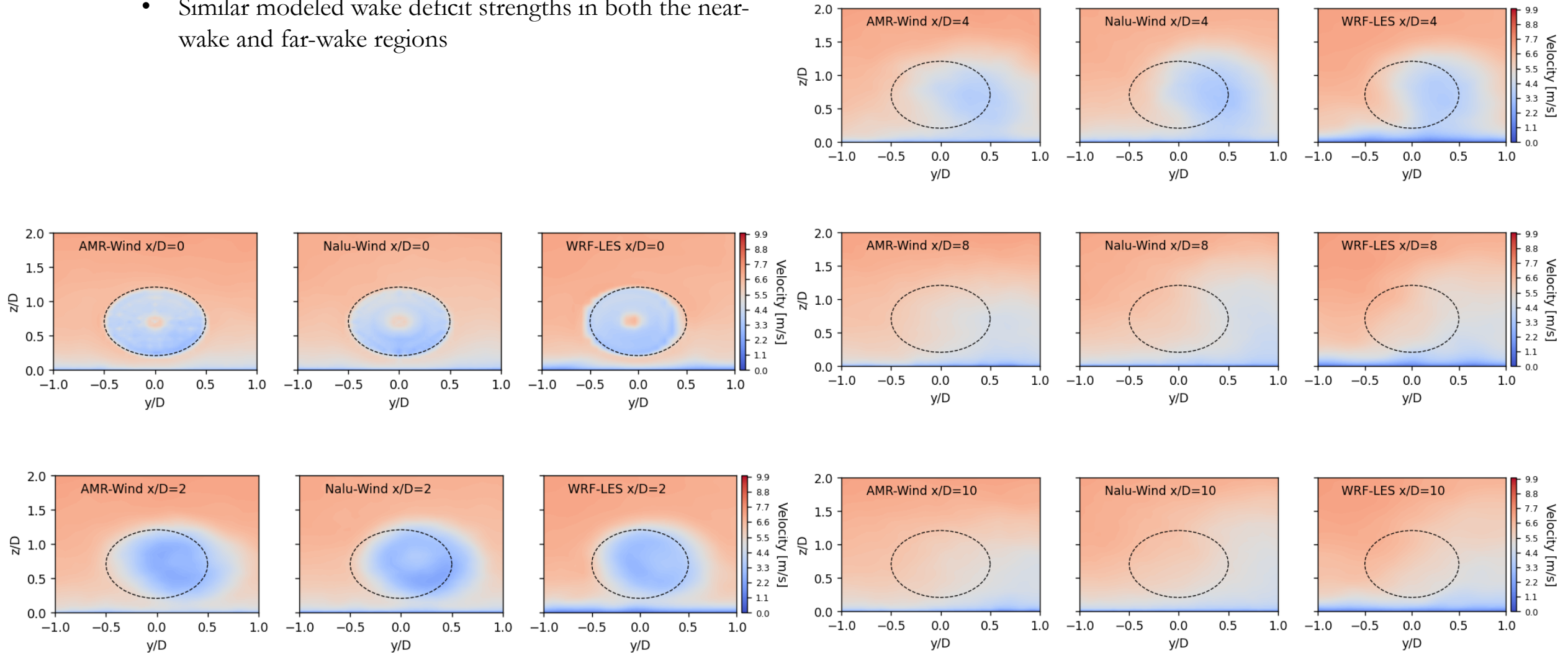
Modeled hub-height TI

# Wake Model Intercomparison



Comparison of wake deficits at different downstream distances between the three LES models

- Similar modeled wake deficit strengths in both the near-wake and far-wake regions



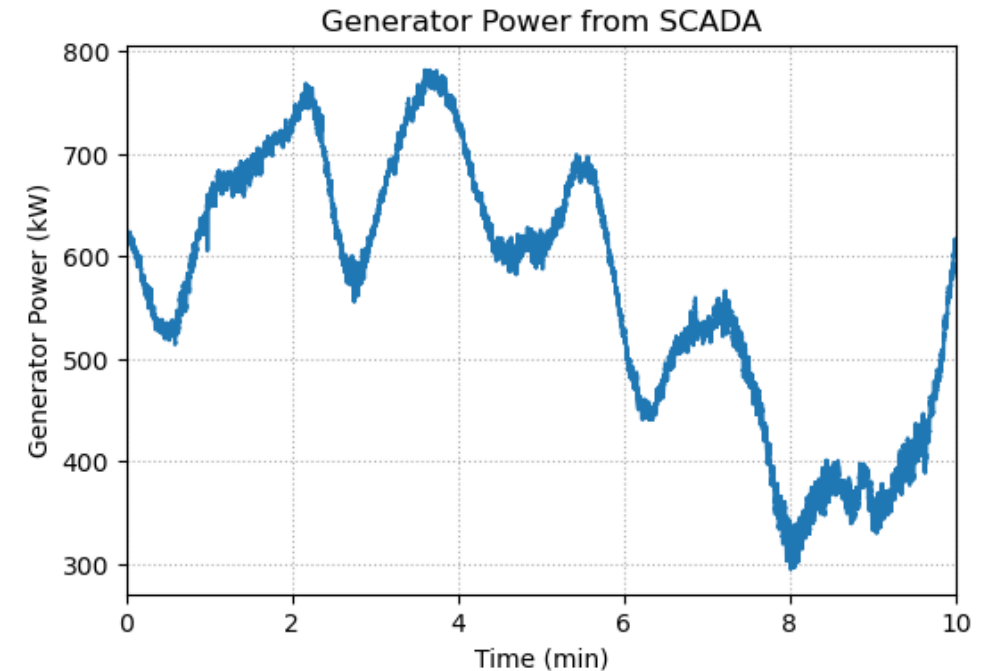


Preliminary comparison of turbine QoIs between the field data and LES models

- Modeled generator power for both AMR-Wind and Nalu-Wind is significantly different from field data
- Modeled blade-root flapwise moment for both AMR-Wind and Nalu-Wind correspond well with field data results
- Note: Post-processed field turbine data has not been QC'ed for instrument drift

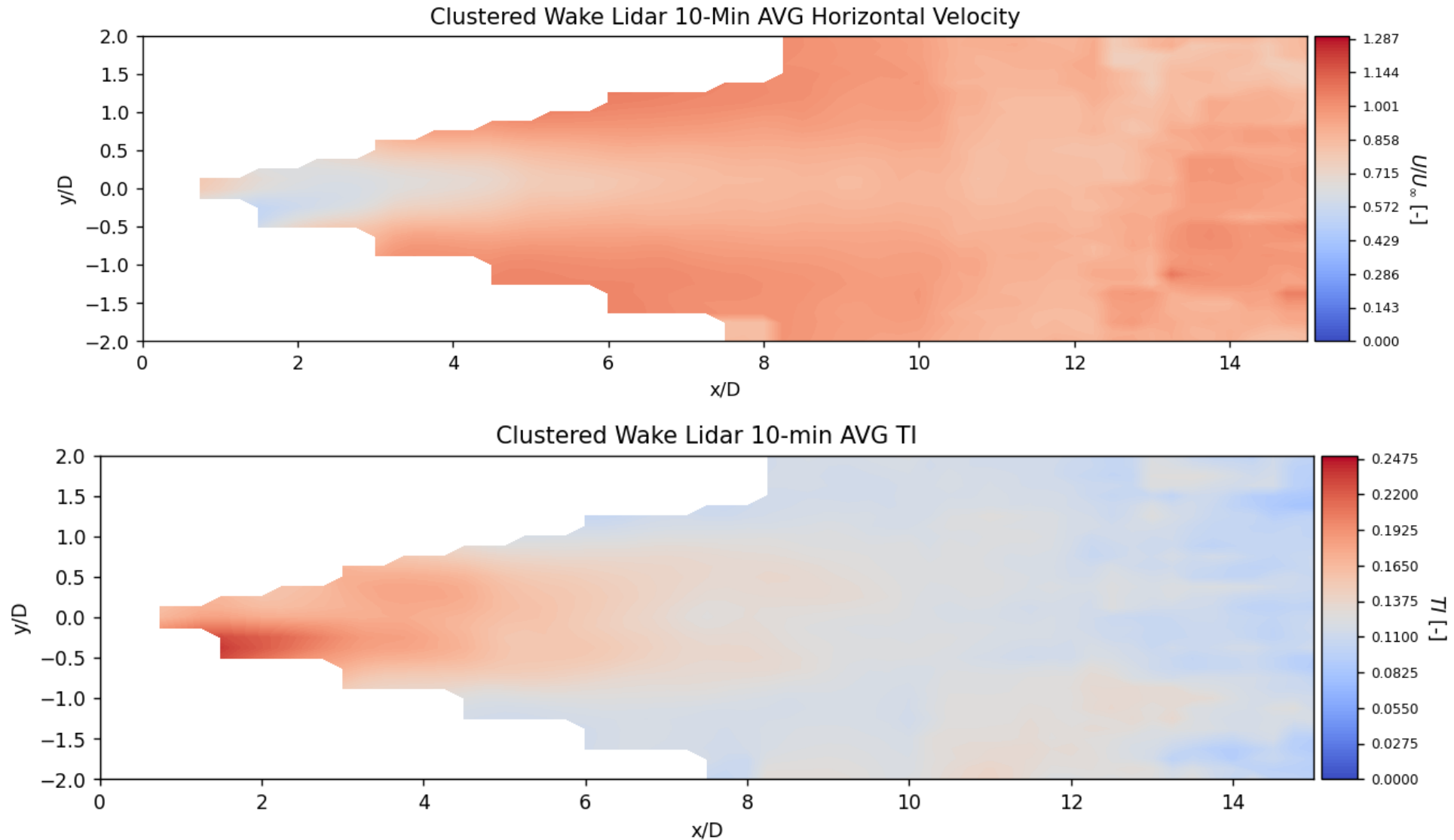
**Relative difference of field data values to AMR/Nalu-Wind Results**

	% Difference AMR-Wind	% Difference Nalu-Wind
Gen. Power	35.8%	12.7%
Blade-Root Flapwise Moment	1.3%	3.8%
Blade-Root Edgewise Moment	17.4%	6.5%

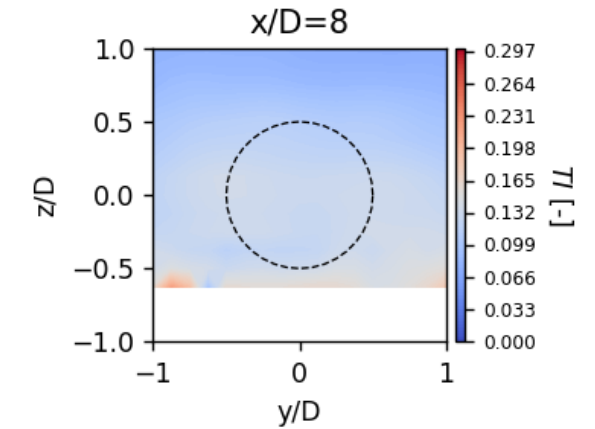
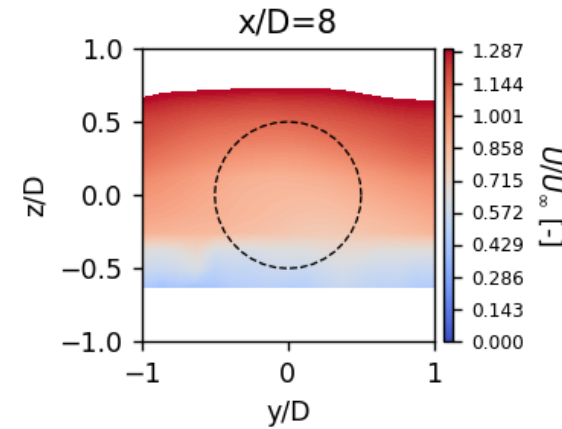
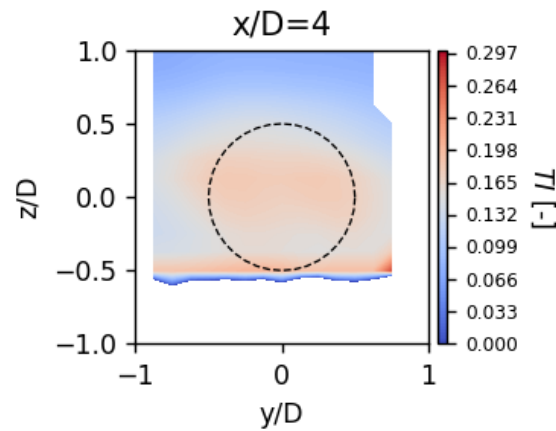
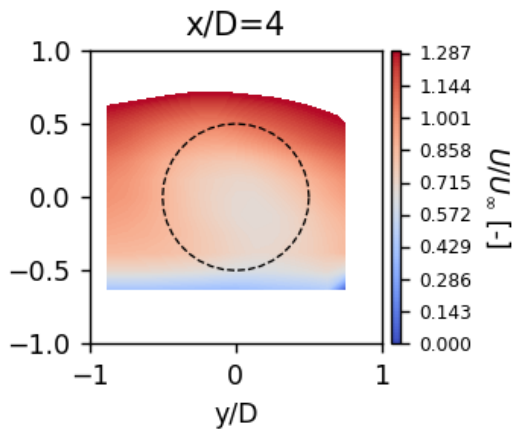
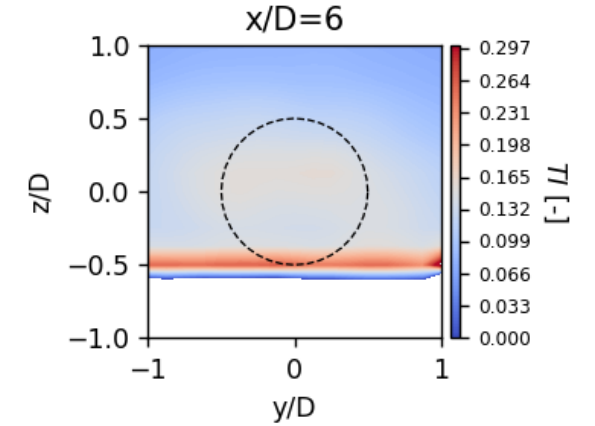
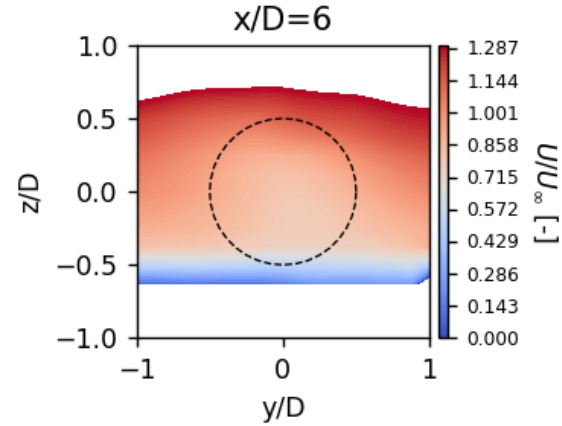
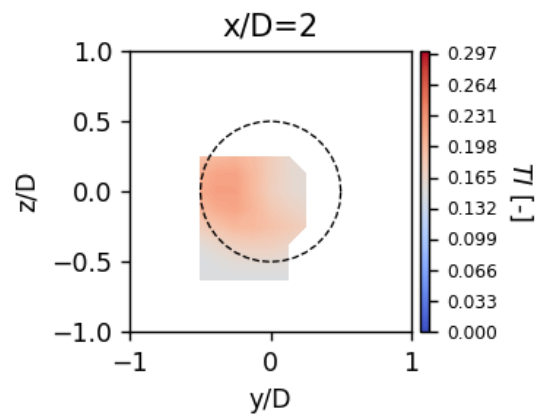
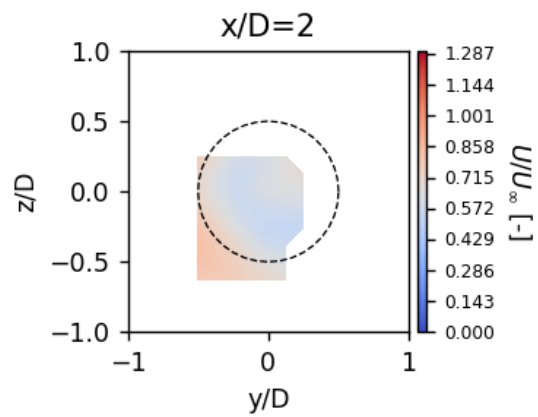


**Field data 10-minute power distribution**

Hub-height contours of normalized horizontal velocity and turbulence intensity from wake lidar



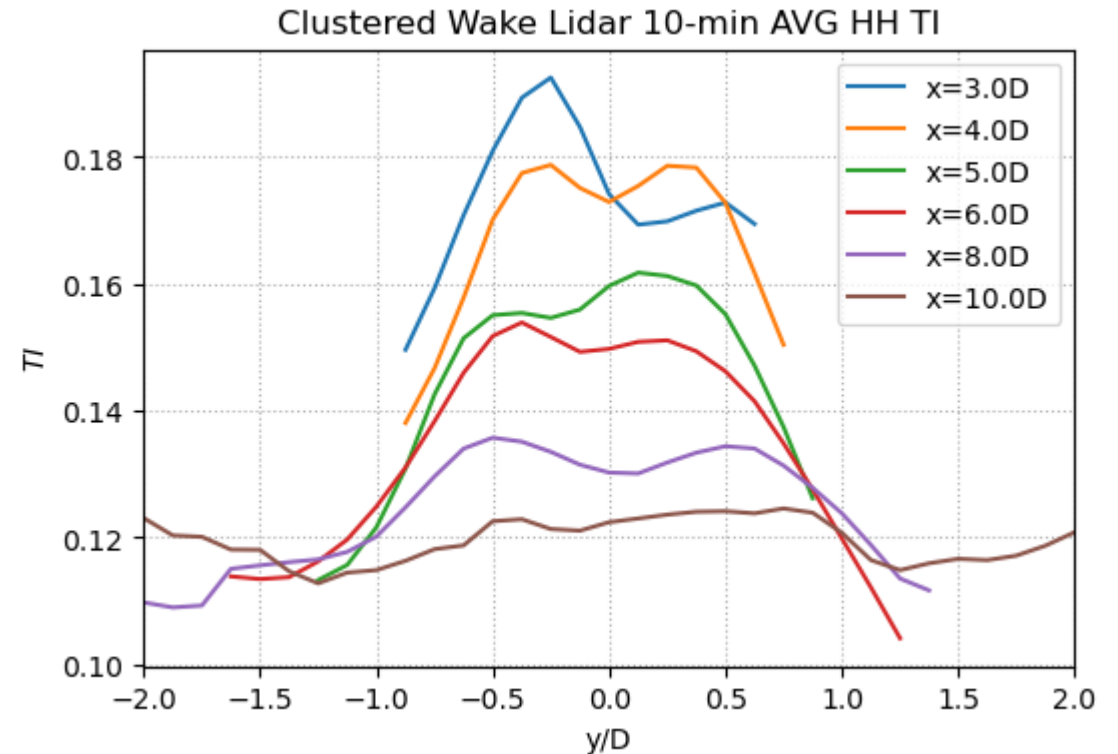
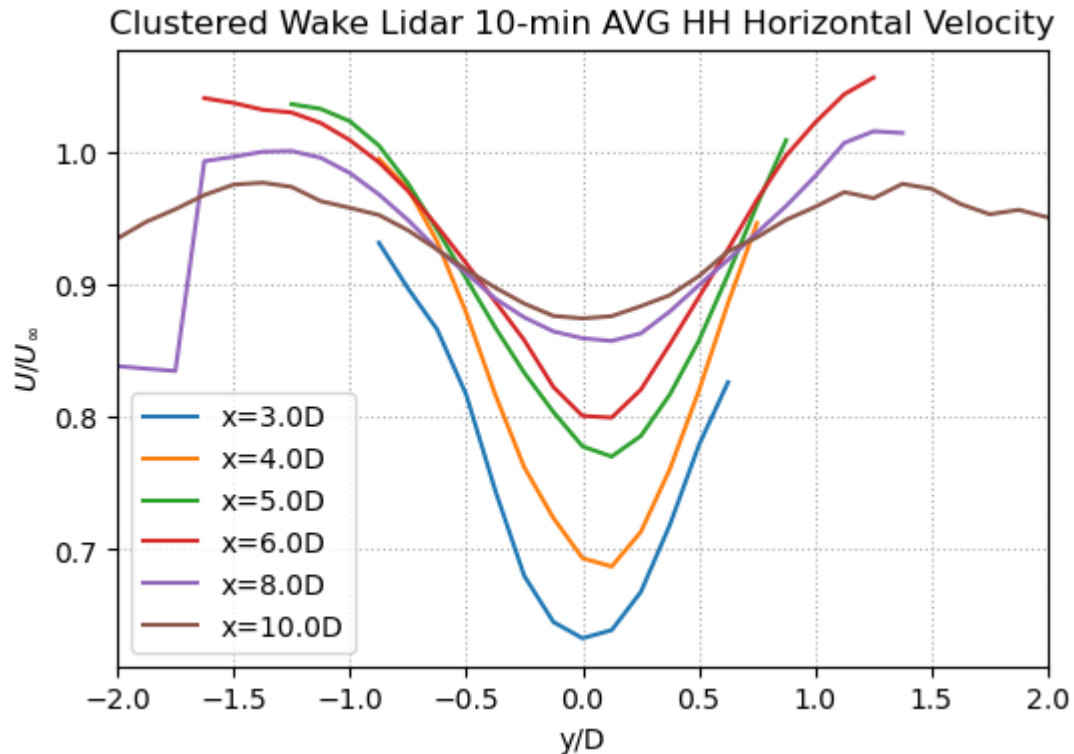
YZ contours of normalized horizontal velocity and turbulence intensity from wake lidar





Hub-height profiles for normalized horizontal velocity and turbulence intensity from wake lidar at different downstream distances

- Field data wake deficits have significantly more noise, less strength than corresponding models
- Field data TI doesn't have the significance near-wake peak prominence in modeled TI profiles
- Use of clustered wake lidar statistics is less valuable for comparing exact values with modeled results



## Summary



- Four models of varying fidelity simulated an *AWAKEN* turbine in neutral ABL conditions
- Improvements to simulation methodologies from previous studies resulted in better matching inflows to the prescribed ABL conditions along with more similar turbine QoIs and wake profiles between the codes
- A preliminary comparison with *AWAKEN* field data from various sources (wake lidar, MET) were made with the simulation results from the four models
- Various issues with available post-processed wake and turbine data prevented a complete validation study and analysis
- Next steps:
- Perform full model validation study and remove obvious sources of variability/error
  - Complete QA/QC of turbine loading data
  - Perform full post-processing of primary 10-min bin of wake lidar data
  - Compare turbine DELs between experiment and simulation

THANK YOU FOR LISTENING