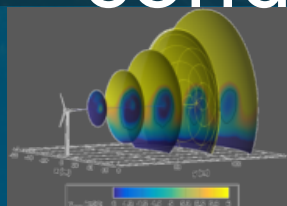




Comparison of simulated and measured wake behavior in stable and neutral atmospheric conditions



PRESENTED BY

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- Predicting wind turbine wake behavior is a complex endeavor
- Wake behavior depends on multiple factors, including:
 - Atmospheric inflow conditions and stratification
 - Characteristics of wake add-turbulence
 - Interactions between the ABL and turbine wake
- Previous work (Doubrawa et al, 2020; Hsieh et al, 2021) has shown that high fidelity CFD simulations can accurately capture turbine wake behavior

Questions to address

- How does wake-added turbulence differ from inflow ABL turbulence?
- Does atmospheric stability affect wake-added turbulence?



Motivation & objectives

Methodology

- SWiFT facility
- LES computations

Results

- Inflow profile and spectra comparisons
- Turbine performance comparisons
- Wake comparisons

Conclusions

Experimental measurements

Scaled Wind Farm Technology (SWiFT) Facility

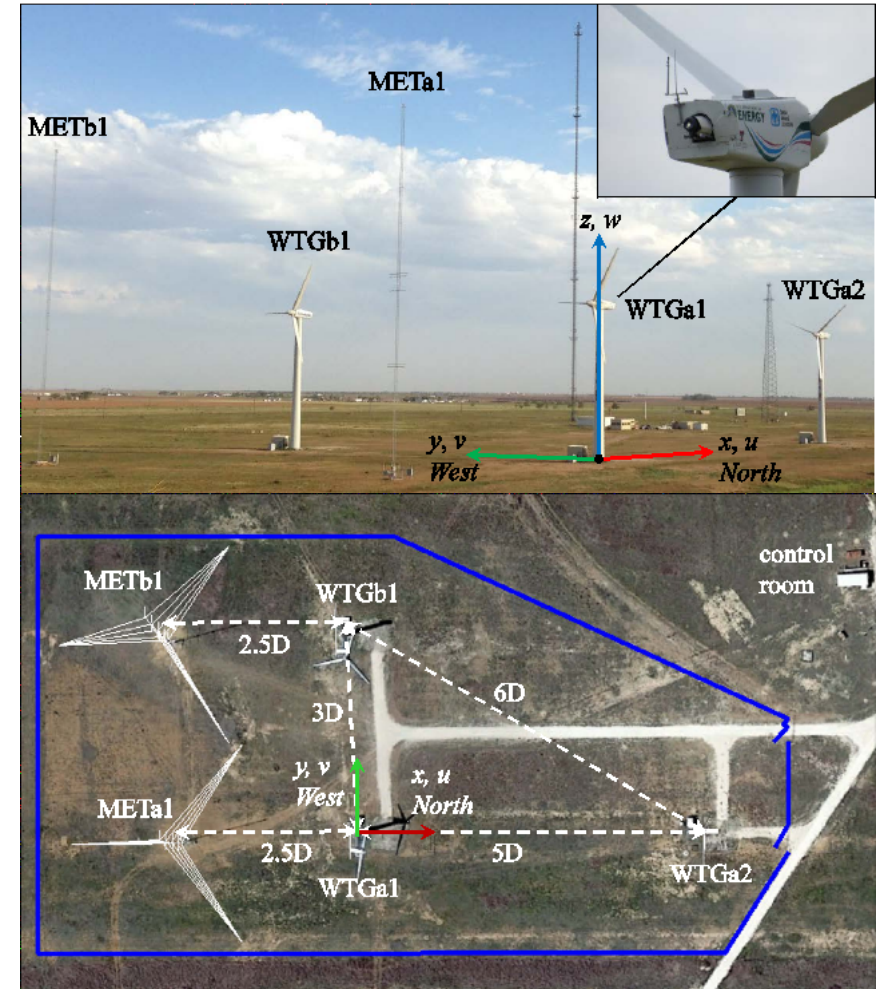
- Operated by Sandia National Laboratories in Lubbock, TX

Three research-scale wind turbines and two meteorological towers

- Vestas V27 wind turbine blades
- DTU SpinnerLidar to measure wake planes downstream of WTGa1 turbine
- **High-quality measurement data for uncertainty characterization of atmospheric inflow parameters, turbine parameters and wake characteristics**

Open-source information and data repository at the A2e Data Archive Portal (DAP):
<https://a2e.energy.gov/projects>

- Mesoscale-Microscale Coupling Experiment (MMC).
March 2015 – Sept. 2018



SWiFT site layout and coordinate system.
 $D = 27 \text{ m}$

Experimental measurements

Meteorological Evaluation Towers (MET)

- 2.5 D in front of 1st turbine
- 60 meter tall – 6 heights
- 3D sonic anemometers and thermometers

SpinnerLidar for Wake Measurements

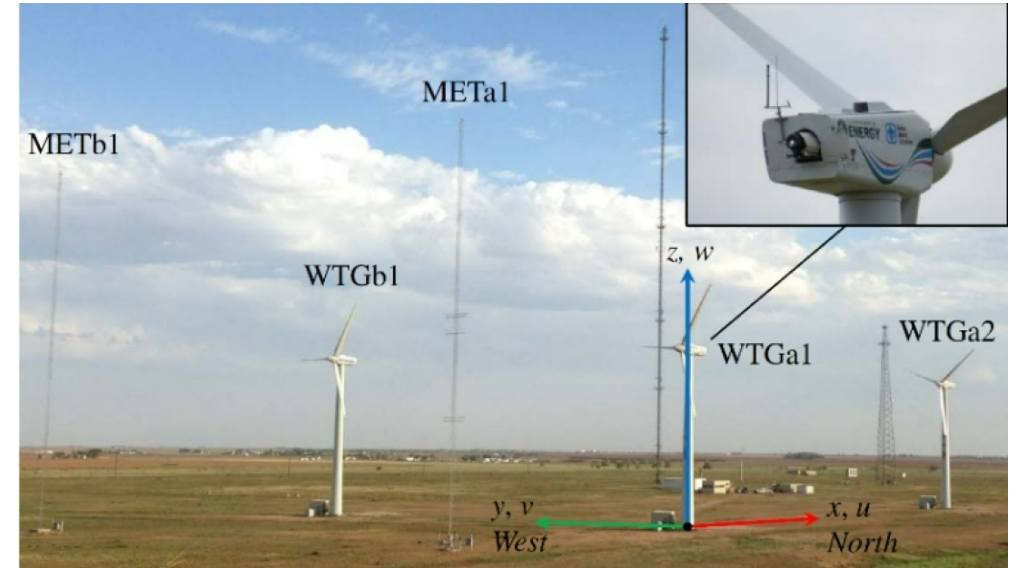
- Continuous wave DTU SpinnerLidar rear-mounted on WTGa1
- Rosette pattern scan completed in 2s and consists of 984 measurement locations between 0.5D – 5D downstream

Vestas V-27 Turbines

- Rotor diameter 27 m, Hub height 32.1 m
- Strain gages: root-bending & tower
- Rotor azimuth and yaw angle measurements

Two measured conditions of interest from SWiFT:

- Neutral ABL stratification
- Stable ABL stratification



Measured inflow conditions

ABL Stability	Hub height WS	Shear exponent α	TI
Neutral	8.69 m/s	0.14	0.108
Stable	4.75 m/s	0.50	0.034

Large Eddy Simulation Methodology



ExaWind/Nalu-Wind¹ Solver:

Numerics

- Unstructured, node-centered finite-volume solver
- Implicit BDF2 time-stepping algorithm
- Uses Sierra Toolkit libraries (STK) for unstructured mesh data structure

Flow solver

- Solves incompressible Navier-Stokes with buoyancy and Coriolis forcing terms
- LES with 1-equation k-SGS model
- Wall model BC based on Moeng (1984) and Monin-Obukhov similarity theory

Turbine model

- Nalu-Wind coupled to OpenFAST for aeroelastic
- Actuator line model (ALM) with Filtered lifting line correction (FLLC) to model blade forces

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

Instantaneous Wake Deficit

Instantaneous contours of horizontal velocity ratio

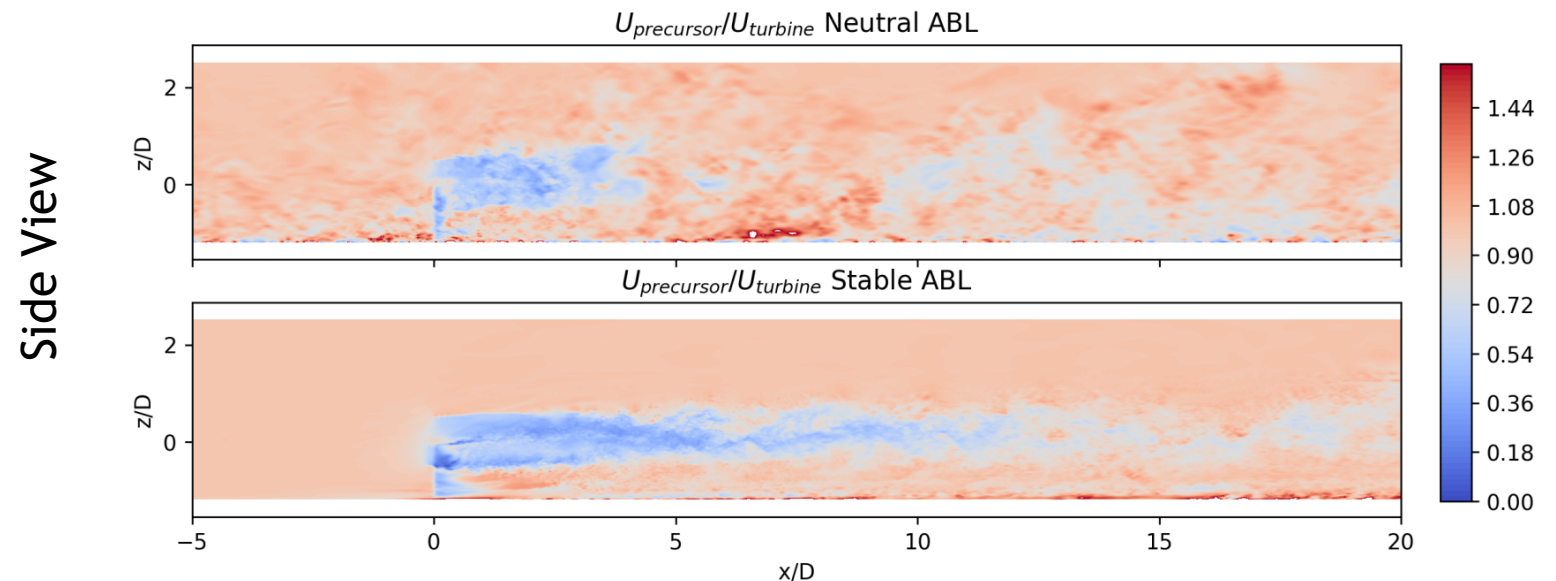
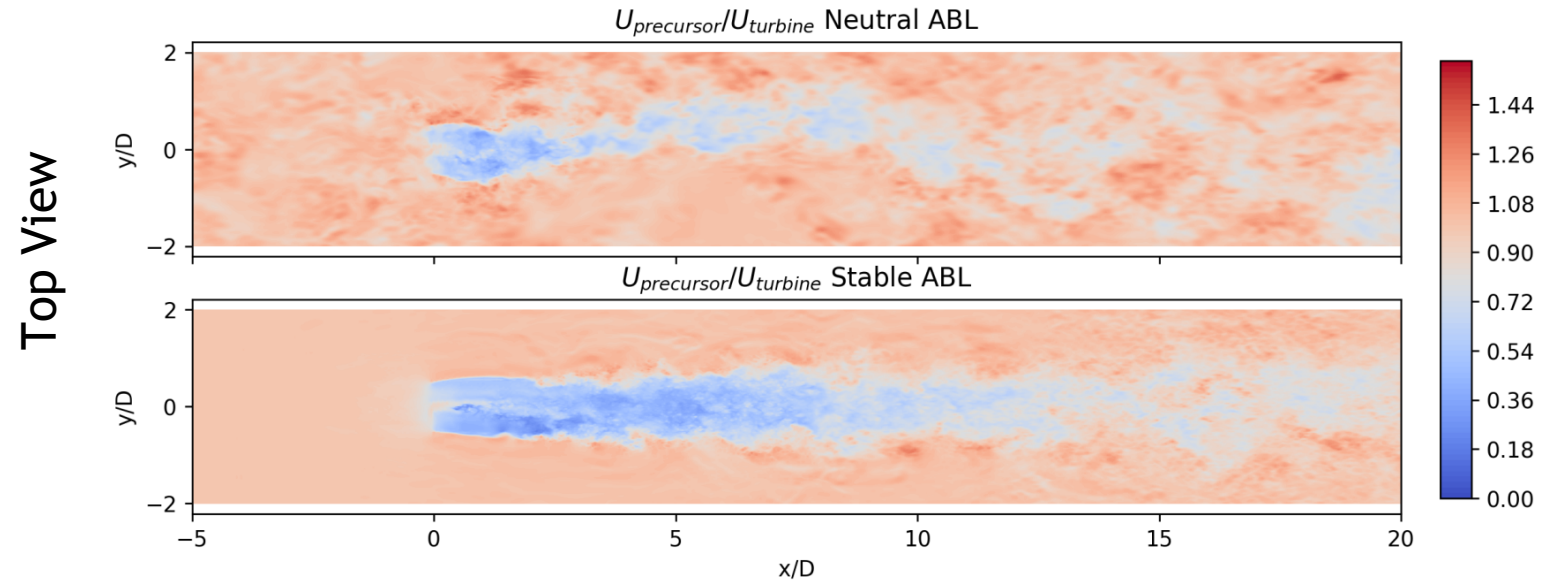
$$\frac{U_{precursor}}{U_{turbine}}$$

Neutral ABL case

- Higher inflow TI: more interactions between inflow turbulence and wake
- More wake meandering

Stable ABL case

- Fewer interactions between inflow turbulence and wake
- More persistent wake downstream

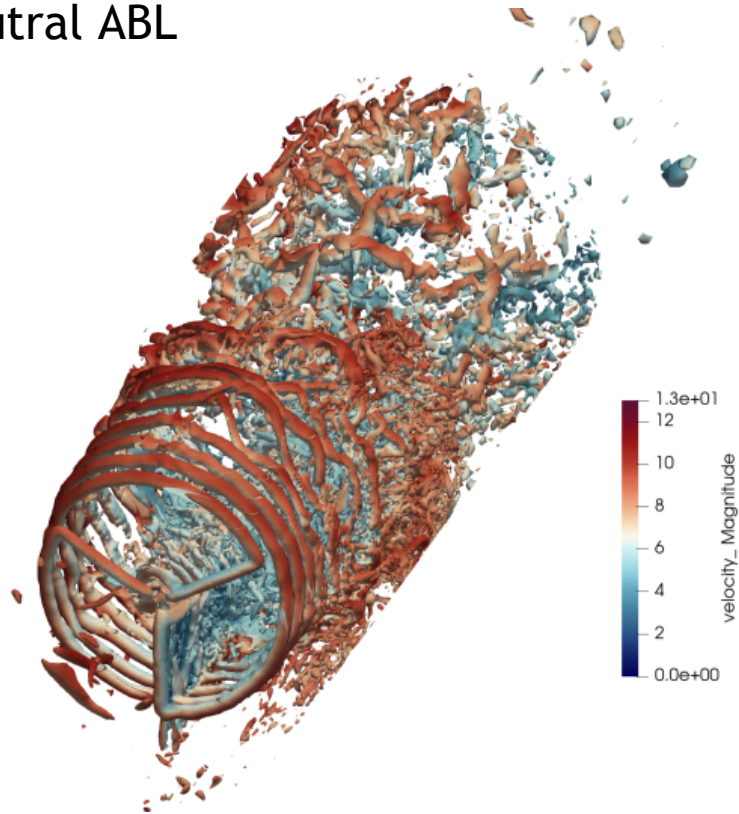


8 Tip vortex visualization

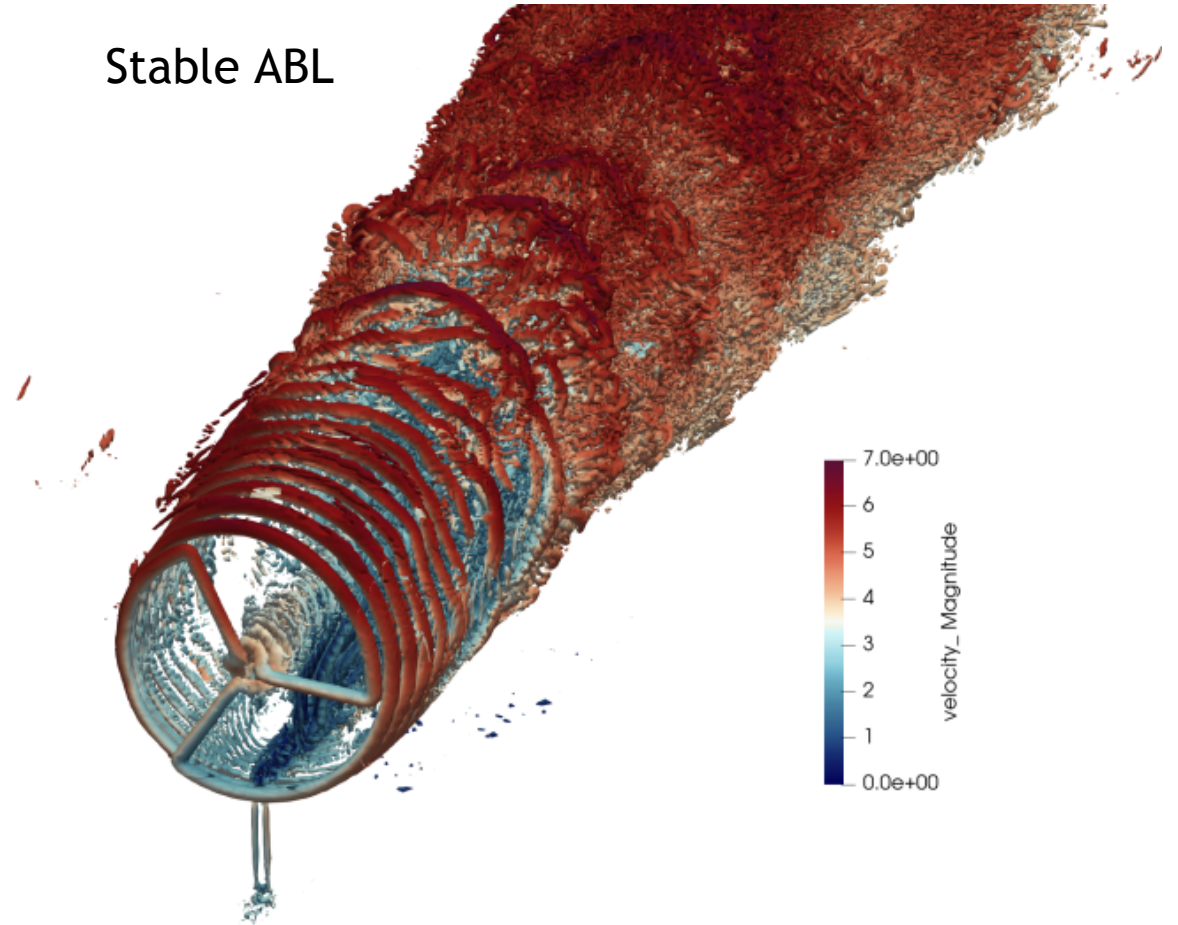


Instantaneous Q-criteria iso-contours highlighted by velocity magnitude

Neutral ABL

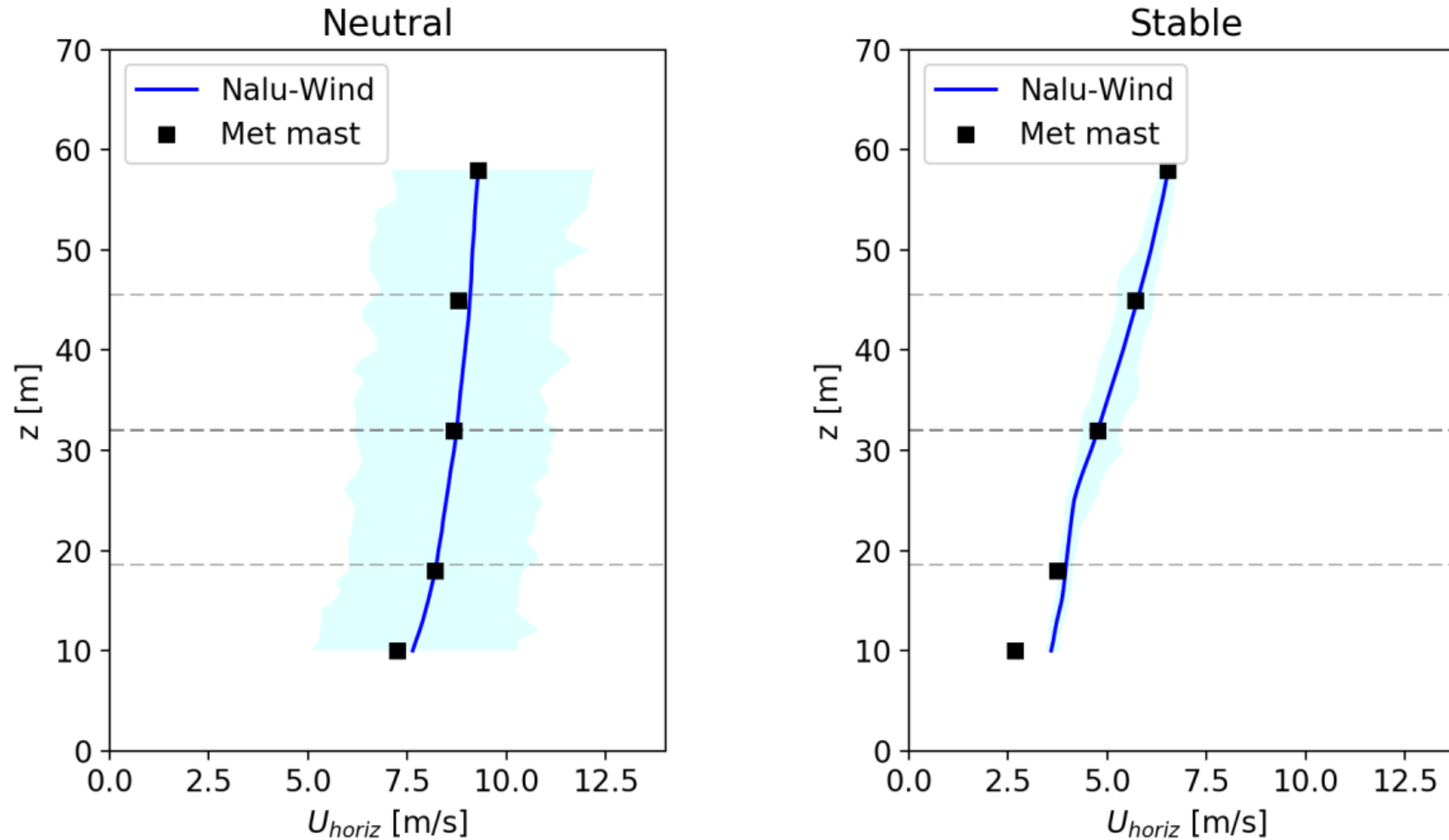


Stable ABL



- Faster tip vortex decay in neutral ABL case
- Downstream emergence of large scale structure in stable ABL case

Comparison of Inflow Profile



- Good agreement between simulated and SWiFT measured velocity profile

Inflow wind spectra

Compare precursor inflow spectra with measured SWiFT met mast data

Wind spectra $S_i(f)$:

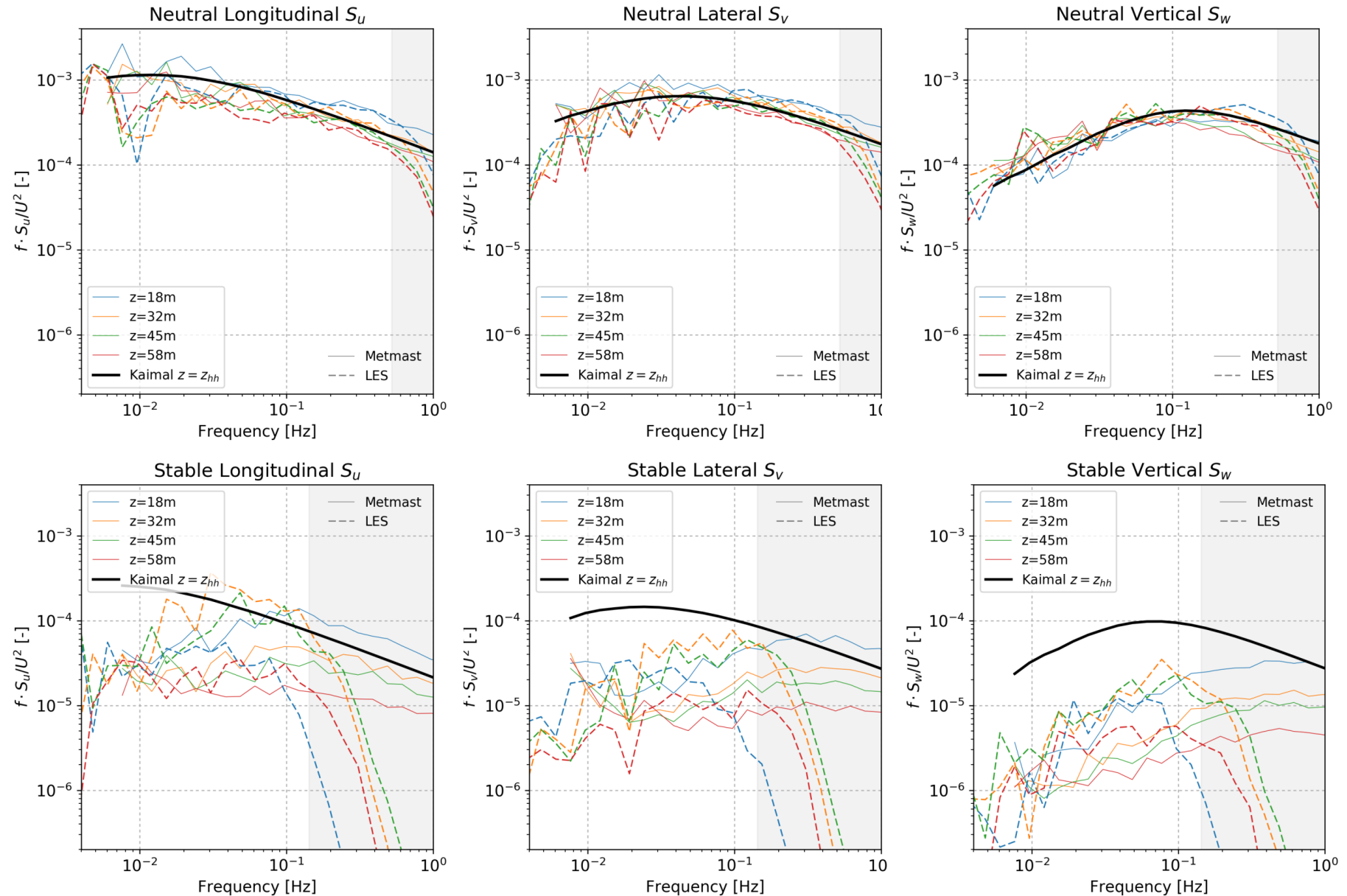
$$\int_0^{\infty} S_i(f) df = \sigma_i^2$$

Neutral ABL case

- LES spectra generally follows SWiFT measurements
- Good agreement with Kaimal spectrum

Stable ABL case

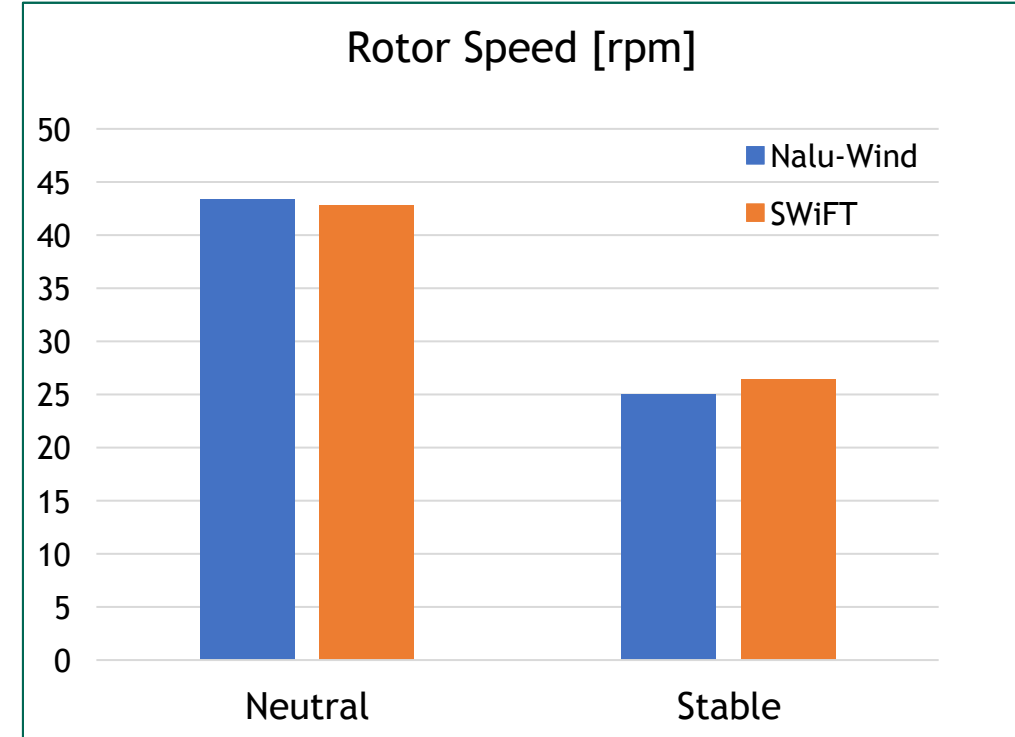
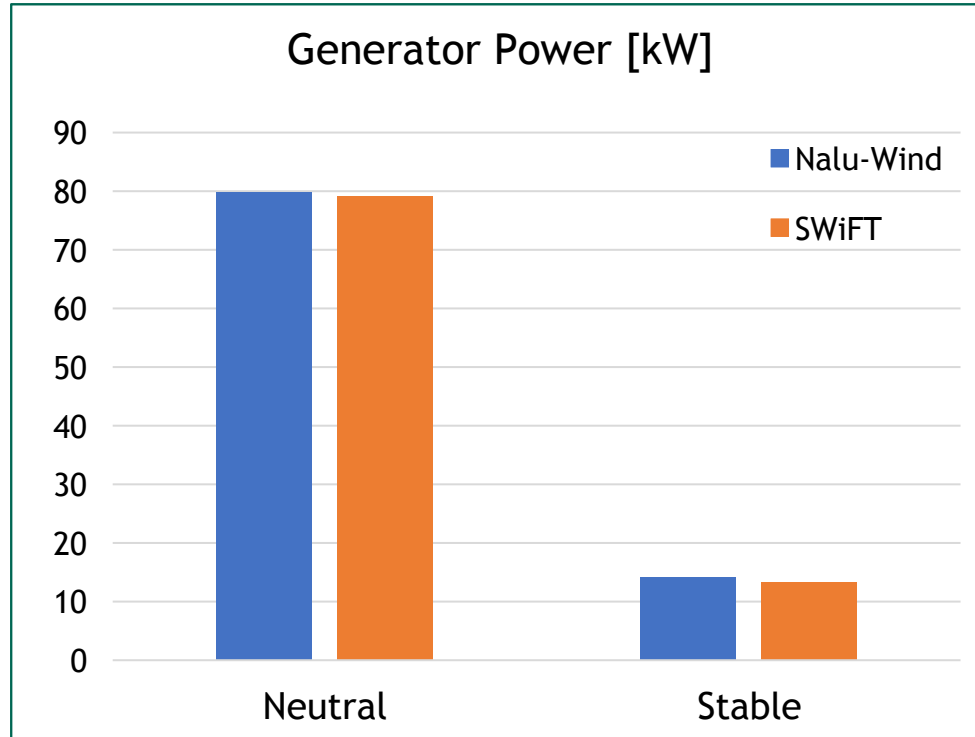
- LES and SWiFT spectra contain less energy at lower frequencies



Turbine performance comparison



Good agreement between simulated and measured turbine power and rotor speed



- Computed aerodynamic rotor thrust coefficient available from LES, but not SWiFT:
 - Neutral $C_t=0.73$, Stable $C_t=0.81$
- Simulated turbine yaw set to 0.0 degrees yaw
- Measured SWiFT turbine yaw:
 - Neutral turbine yaw=1.0 degrees, Stable turbine yaw=8.2 degrees

Comparison of simulated and lidar measured wake deficit

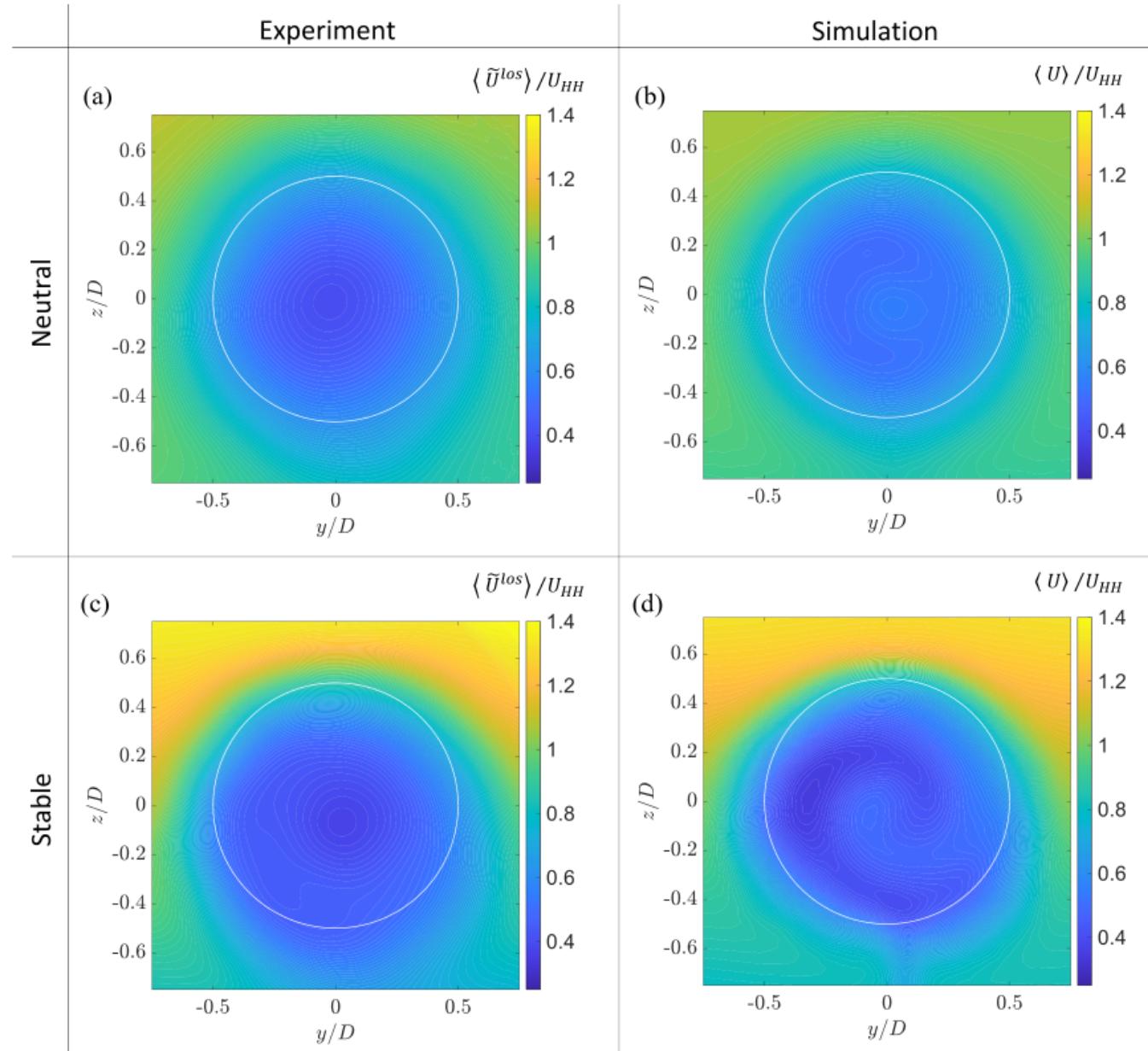


Compare wake deficit at $x=2.5D$ plane

$$\text{lidar : } \frac{\langle U^{los} \rangle}{U_{HH}}$$

$$\text{LES: } \frac{\langle U \rangle}{U_{HH}}$$

- General qualitative agreement between lidar and LES for both neutral and stable ABL cases
- Stable ABL wake contours shows stronger swirl and more defined tower shadow



Wake profile comparison: LES and Lidar



Compare hub-height wake deficit profiles

$$\text{lidar : } \frac{\langle U^{los} \rangle}{U_{HH}}$$

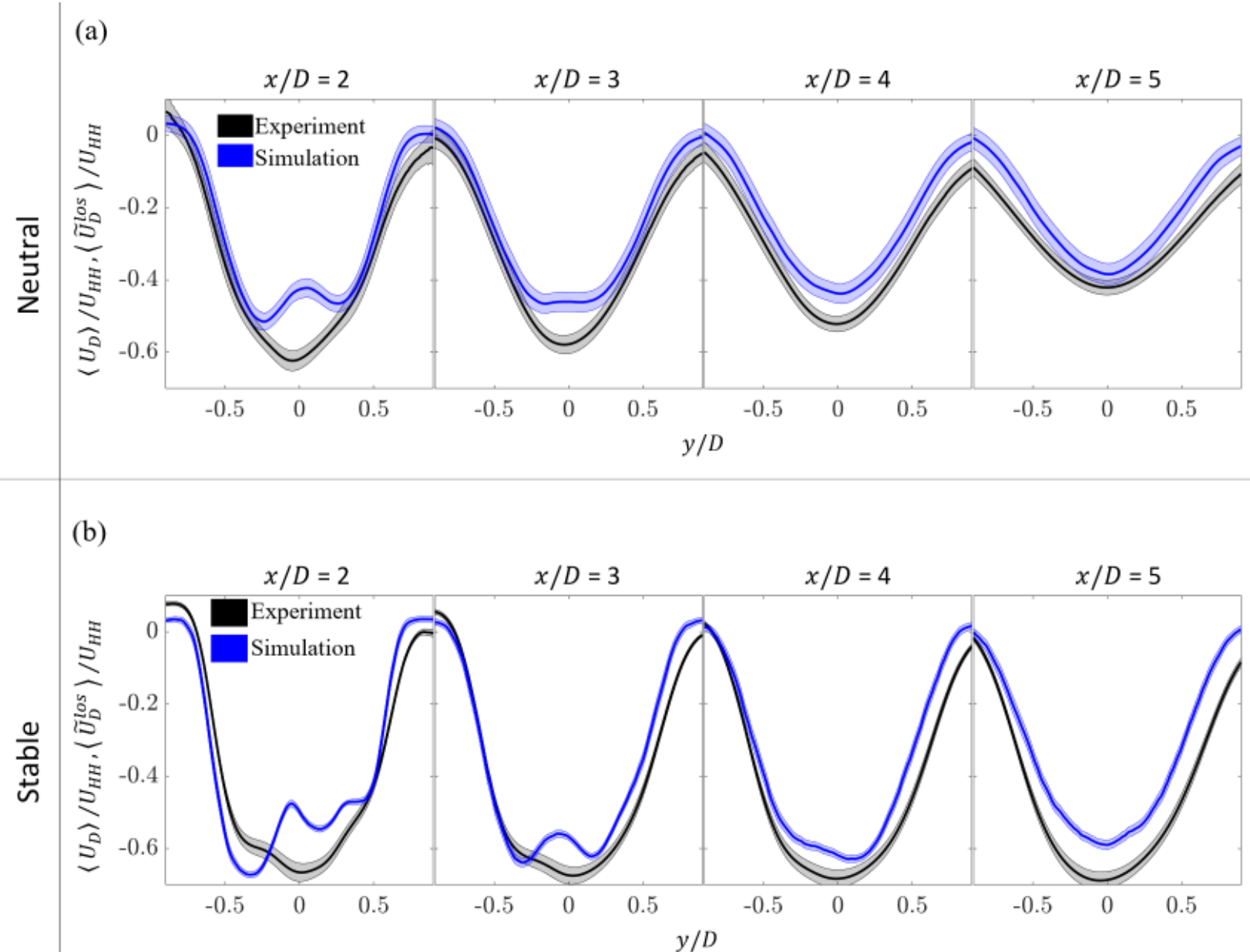
$$\text{LES: } \frac{\langle U \rangle}{U_{HH}}$$

Neutral ABL

- LES shows larger centerline wake deficit compared to lidar

Stable ABL

- Similar centerline wake deficit in near wake region
- Lidar wake profile asymmetric in far wake region





Compare streamwise wake deficit profiles

$$\text{lidar : } \frac{\langle U^{los} \rangle}{U_{HH}}$$

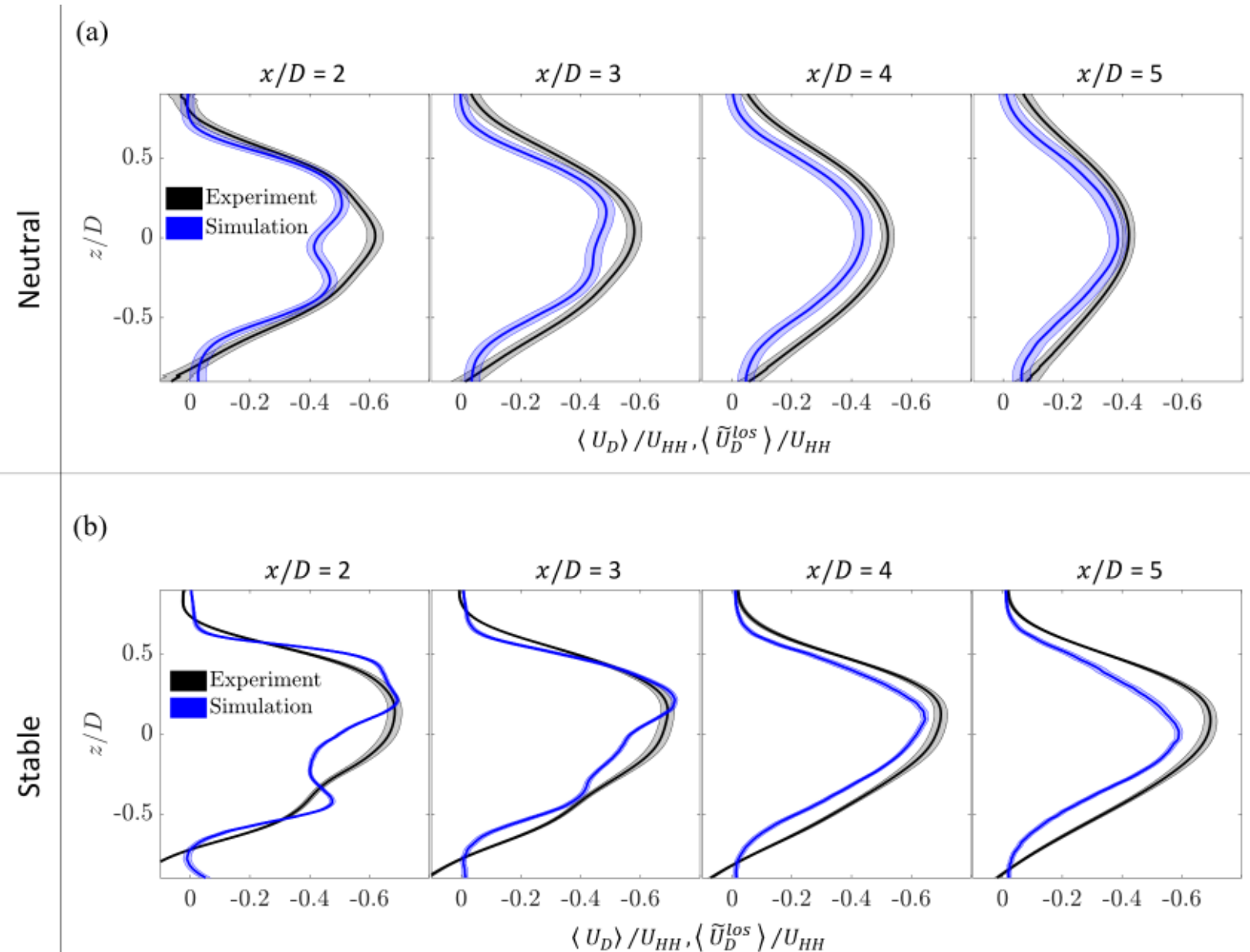
$$\text{LES : } \frac{\langle U \rangle}{U_{HH}}$$

Neutral ABL

- LES shows larger centerline wake deficit compared to lidar

Stable ABL

- Better agreement in near wake region ($x < 4D$)
- Larger wake deficit for lidar profiles at $x = 4D, 5D$
- Discrepancies possibly due to yaw mismatch



Comparison of simulated and lidar wake velocity fluctuations

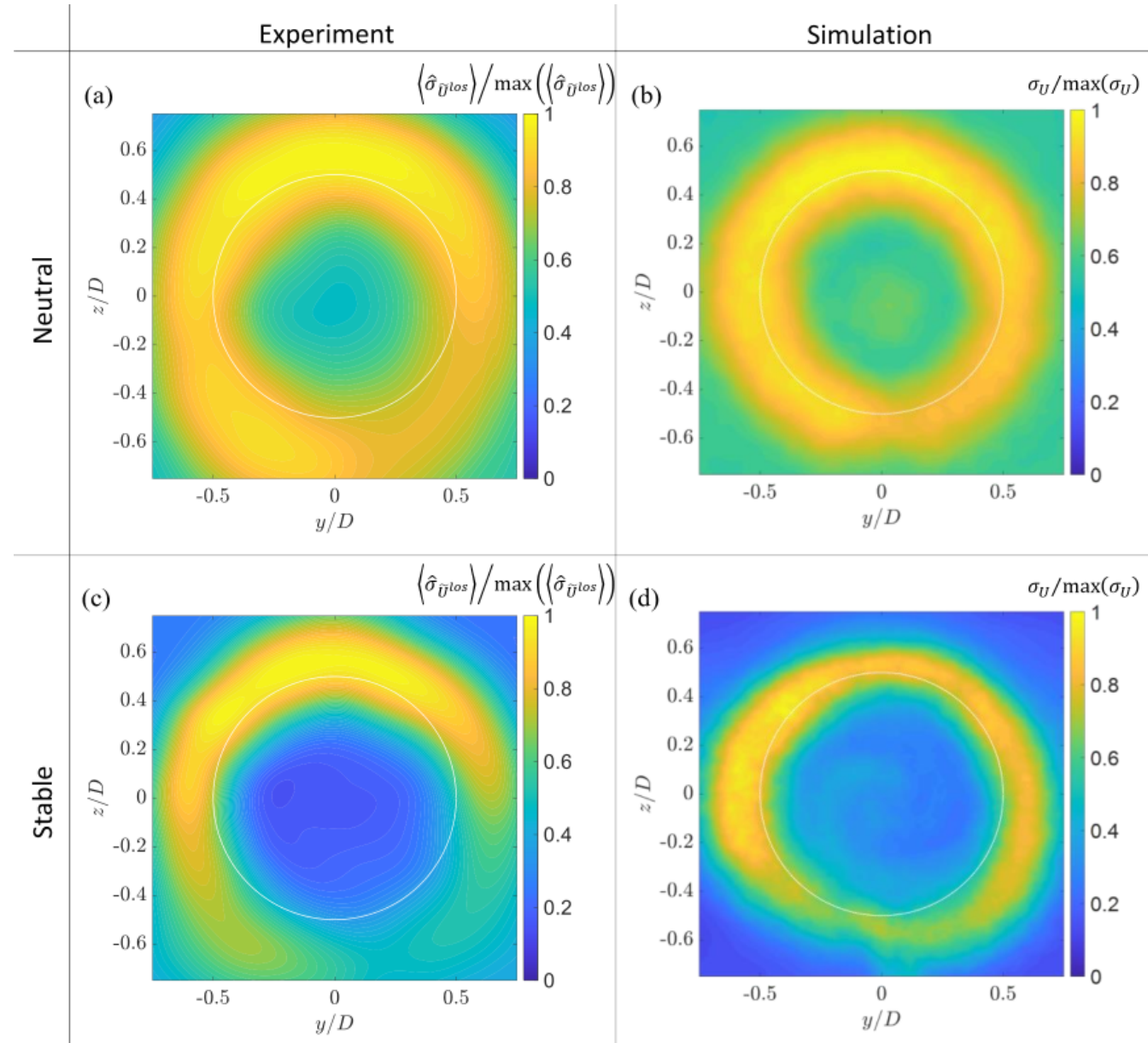
Compare fluctuations at $x=2.5D$ plane through a normalized quantity

$$\text{lidar}^*: \frac{\langle \sigma_U \rangle}{\max(\langle \sigma_U \rangle)}$$

$$\text{LES}: \frac{\sigma_U}{\max(\sigma_u)}$$

*Lidar quantity approximate due to probe averaging

- Fluctuation distribution corresponds to regions of shear in the wake
- Fully annular distribution for neutral ABL case; partially annular distribution for stable ABL case
- Slightly broader distribution in lidar measurements compared to LES



Wake spectra (longitudinal)

Examine turbulent spectra in the wake region at $x=3D$, $5D$, $7D$

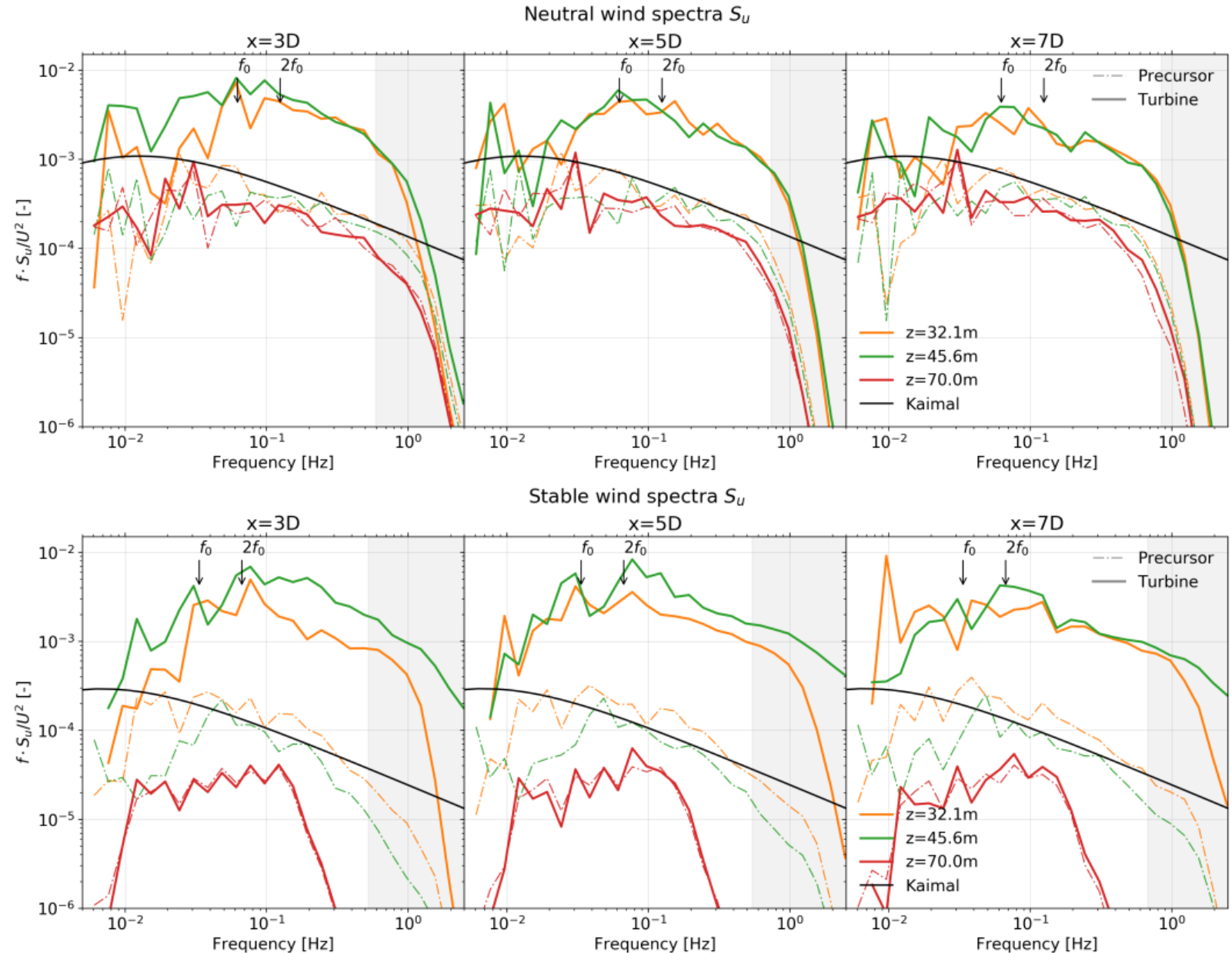
Wind spectra $S_i(f)$ definition:

$$\int_0^{\infty} S_i(f) df = \sigma_i^2$$

Observations

- Most wake-added spectra occurs in the inertial range
- Stable ABL wake-added turbulence is more height-dependent
- Peak of wake-added spectra occurs near characteristic shedding frequency f_0 or first harmonic $2f_0$ at

$$St_0 = \frac{f_0 U}{D} \approx 0.19$$





Examine turbulent spectra in the wake region at $x=3D, 5D, 7D$

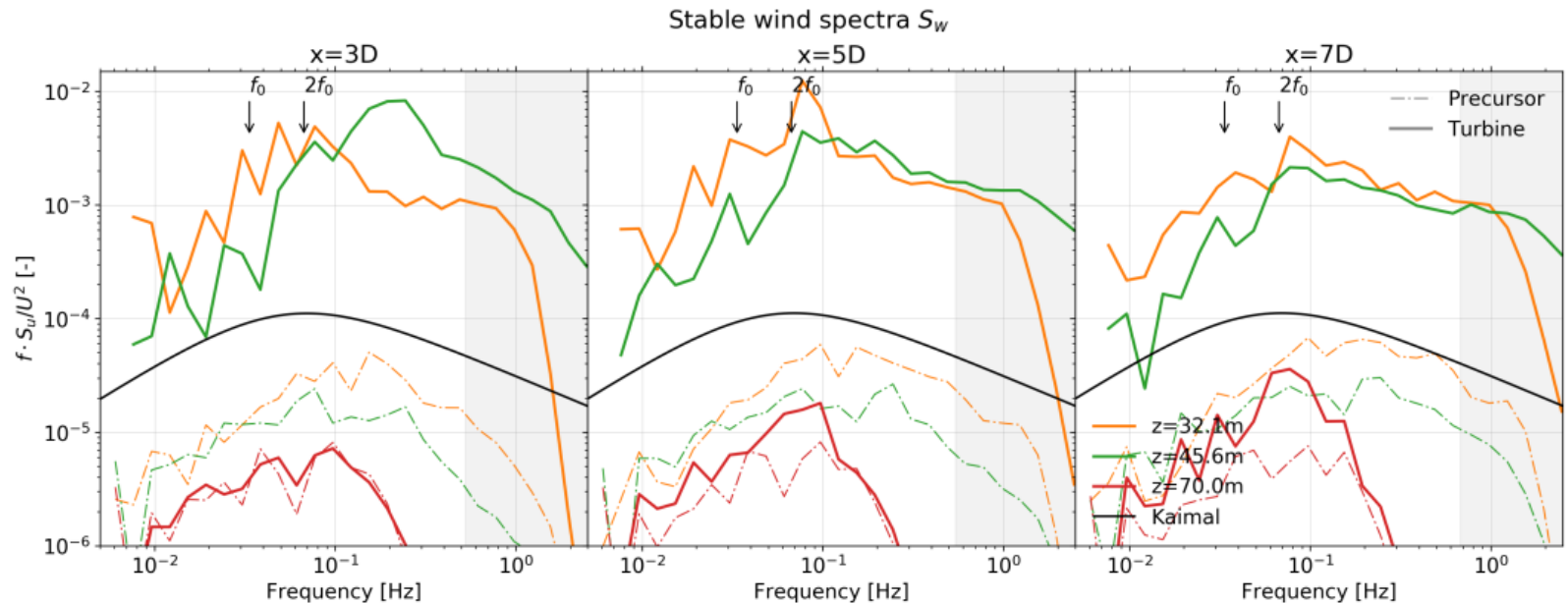
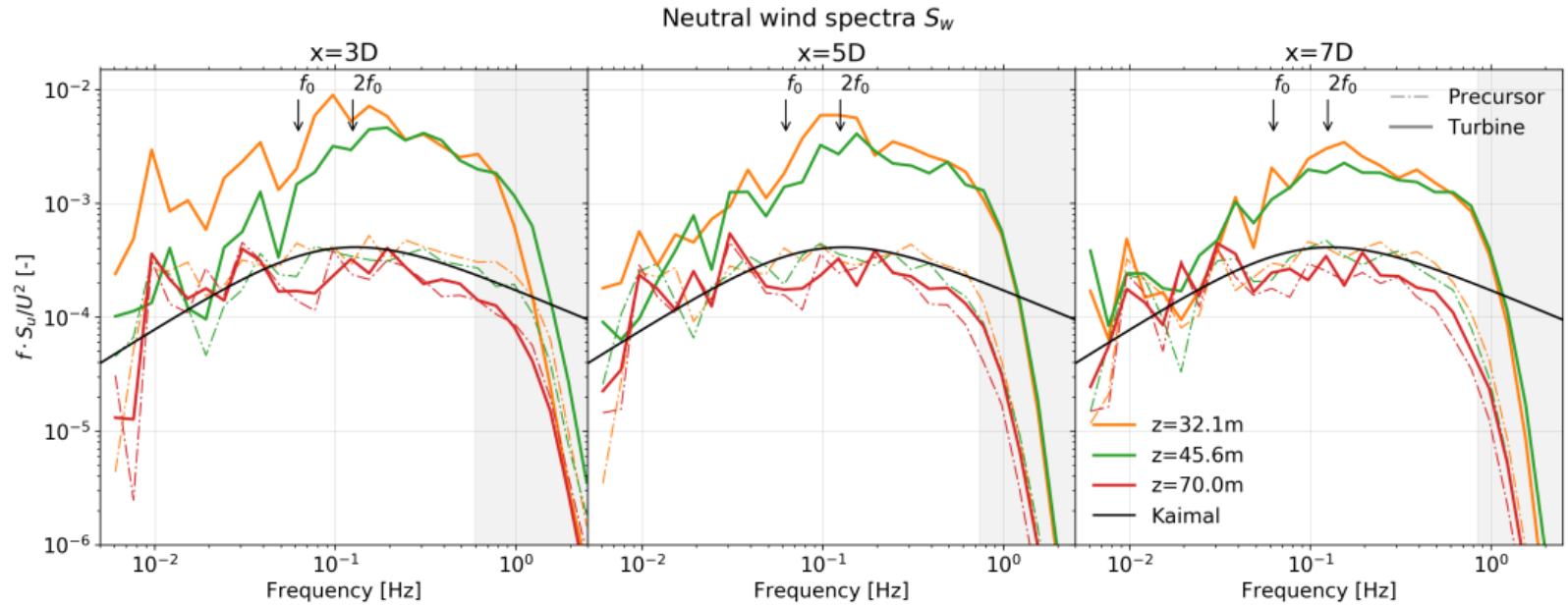
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Turbulent lengthscale

Probe changes to the turbulent structure through the integral lengthscale

Two point spatial correlation tensor

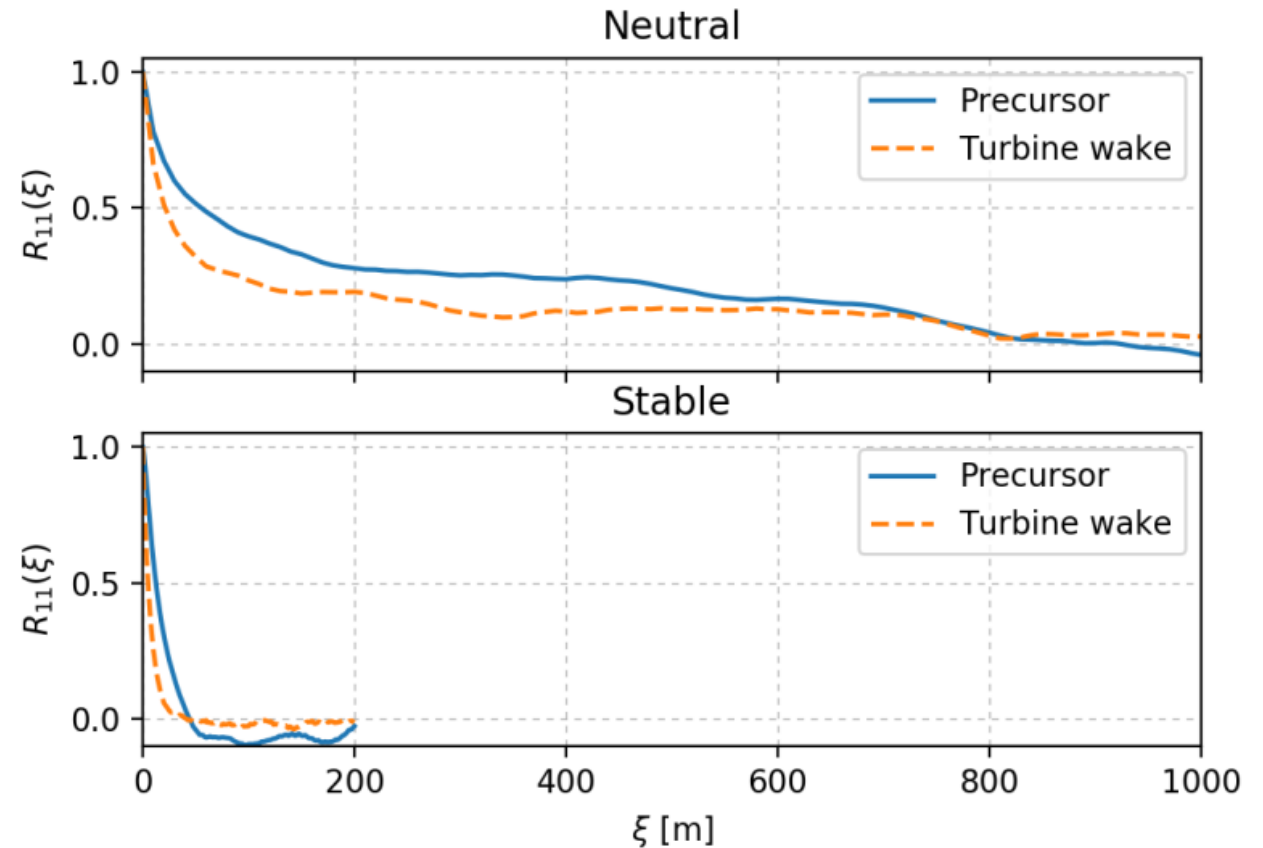
$$R_{ij}(x, \xi) = \frac{\langle u'_i u'_j \rangle}{\sqrt{\langle u_i'^2 \rangle \langle u_j'^2 \rangle}}$$

Turbulent integral lengthscale

$$L = \int_0^{\infty} R_{11}(\xi) d\xi$$

Integral Lengthscale L (longitudinal)

ABL Stability	Precursor Run	Turbine run
Neutral	206.3 m	137.6 m
Stable	15.5 m	7.3 m



- Wake turbulence dramatically decreases the integral lengthscale in both stable and neutral conditions

Conclusions



- Compared simulated and measured wake behavior under neutral and stable ABL conditions
- LES inflow profiles and spectra match SWiFT measurements
- Simulated turbine performance quantities match V27 data
 - Possible discrepancies in turbine yaw and turbine thrust
- Qualitative agreement between lidar and LES wake velocity and fluctuation contours
- Examined wake added turbulent spectra
 - Peak frequency related to characteristic wake shedding frequency at $St=0.19$
- Shorter integral lengthscale for wake turbulence compared to precursor turbulence



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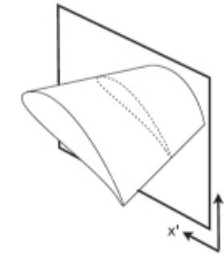
Filtered Lifting Line Correction (FLLC)

- Corrects for non-optimal epsilon
- Adds the induced velocity that can't be resolved from the mesh
- Higher accuracy with larger mesh size
- This is first time with turbulent flow

$$\hat{\mathbf{u}}(\mathbf{x}_i) = \tilde{\mathbf{u}}(\mathbf{x}_i) + \Delta u_y^n(z_i) \mathbf{j}.$$

Apply correction to the velocity, compute forces with corrected velocity

Compute forces from velocity using aerodynamic model



Extract lift distribution along the blade from the forces

Apply original ALM steps, up to velocity interpolation from fluid domain

From lift distribution, compute an induced velocity twice, with and ϵ^{opt} - get correction

$$\Delta u_y = u_y(z_i; \epsilon^{opt}) - u_y(z_i; \epsilon^{LES})$$

Filtered lifting line theory and application to the actuator line model, 2019

Luis A. Martínez-Tossas and Charles Meneveau

