Momentum flux variability observed around Oklahoma Wind Farms

August 8, 2023

ARM and PNNL

Objective

- How much do wind turbines surrounding SGP affect ARM lidar measurements?
- Develop methods to detect such conditions/cases from ARM lidar data
  - Challenge no inflow condition
- Develop scaling analysis to assess the growth of internal boundary layer

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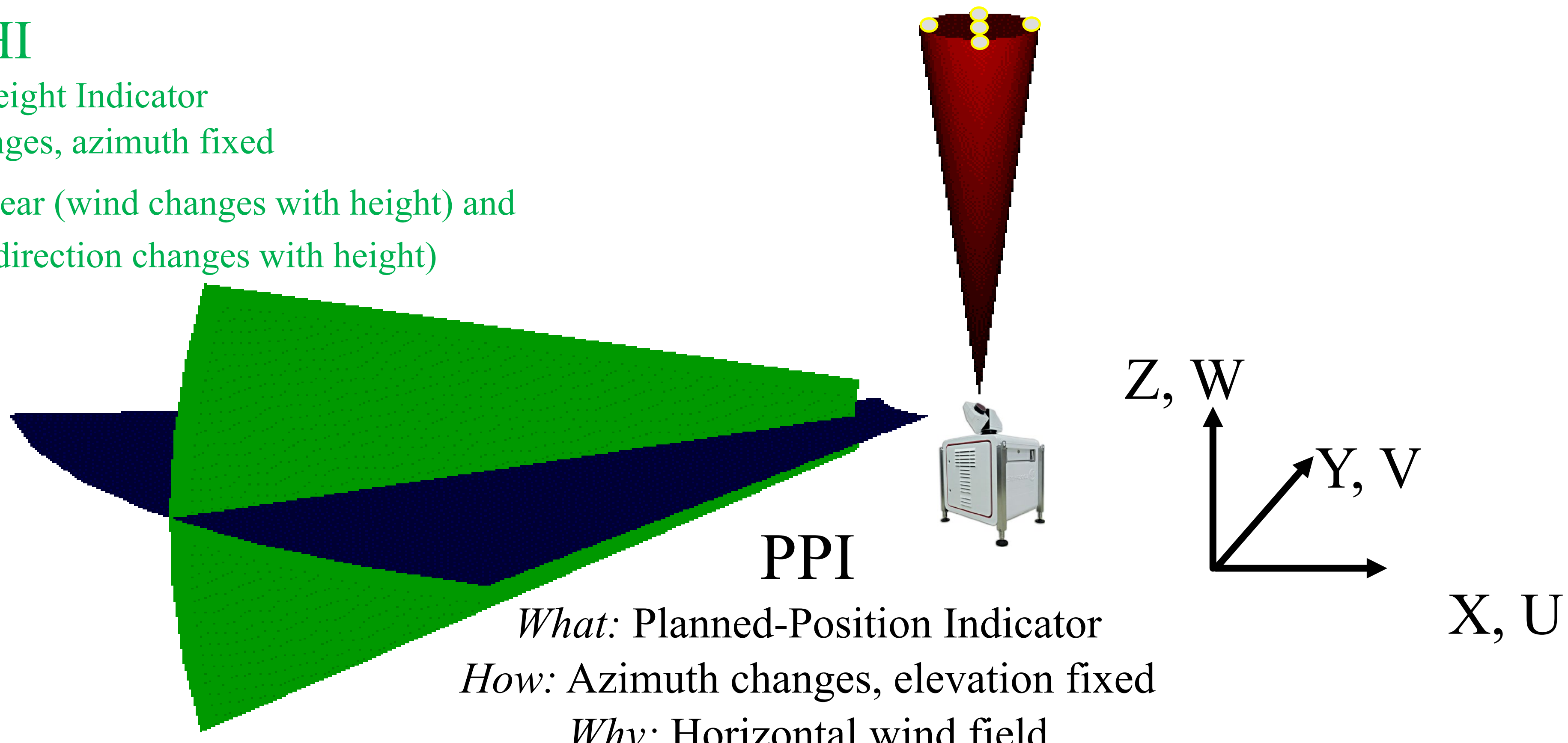
Doppler lidar scan patterns

DBS/VAD

What: Velocity Azimuth Displays
How: Conical scan or variation
Why: Vertical profile of the horizontal and vertical velocity

RHI

What: Range-Height Indicator
How: Elevation changes, azimuth fixed
Why: Vertical cross sections, wind shear (wind changes with height) and wind overturning events (wind direction changes with height)



PPI

What: Planned-Position Indicator
How: Azimuth changes, elevation fixed
Why: Horizontal wind field

What can different scan types provide?

Parameters of Interest	Scan Pattern Options	Preferred Scan Patterns	Advantages	Dis-advantages
10-min averaged winds and direction through boundary layer	Multi-PPI, DBS, Single elevation angle VAD	**DBS or Single elevation angle VAD**	High repetition rate and lower uncertainty in wind estimates	Spatial variability is not captured as well as a Multi-PPI scan. Very low elevations (< 40 m will not be captured by any lidar, as profiling lidars are typically above 40 m, except CW lidars).
30-min TKE, Dissipation rate, and momentum flux profiles (u'w' and v'w')	6-pt DBS at 1 elevation, Single elevation angle VAD, stares along mean wind direction	**6-pt DBS at 1 elevation angle (say 60 deg or 72 deg)**	Can estimate Reynolds stresses, high repetition rate and lower uncertainty in wind	Uncertainty can vary a little as a function of wind direction, hence having more beams could increase accuracy. Winds below 75 m cannot be estimated.
PBL height and vertical velocity variance	Vertical stares	**Vertical stares**	Can estimate velocity variance, kurtosis etc., directly.	Might not reach the top of the boundary layer depending on the lidar signal strength and does not provide night-time PBL (ASSIST/Ceilometer).
Spatial variability of winds	RHI scans at fixed azimuth angle, RHI scans along mean wind direction, multiple sector PPI scans, stares along the mean wind direction	**180^{o} RHI scans at a fixed angle? (offshore and onshore)**	High-resolution vertical structure of winds	Range of the lidars is typically 3-5 km offshore, less information when winds are perpendicular to the beam angle.

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Momentum Flux from Lidars

- Estimate streamwise momentum flux ($\overline{u'w'}$) and average wind speed ($\bar{u}$) using DBS scans from a Doppler lidar

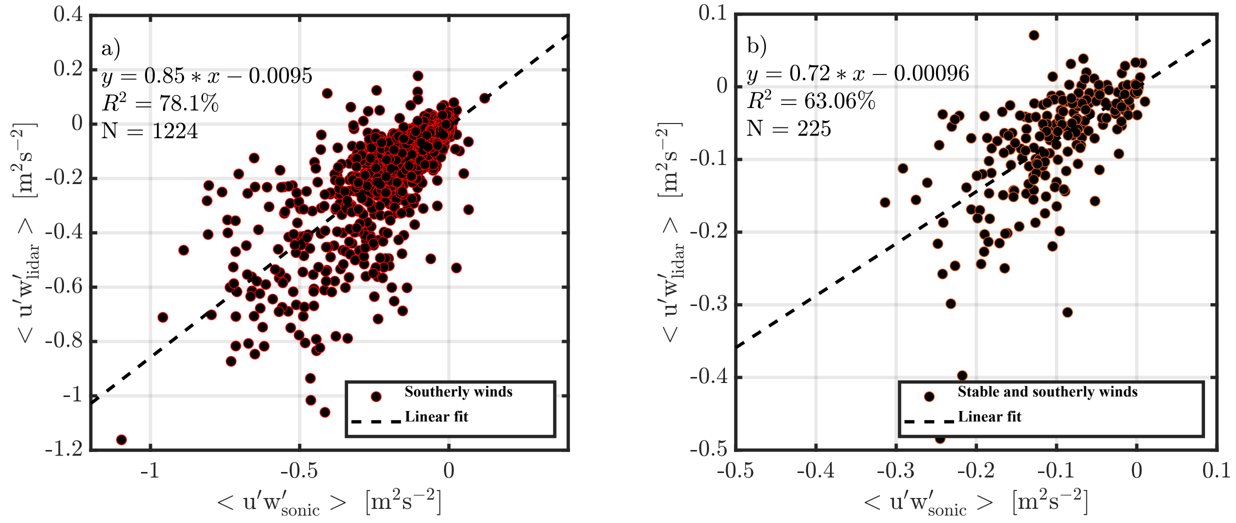
- The variance of the radial velocity (v_r) equation of a Doppler lidar is given by

$$\sigma^2[v_r(R,\theta)] = \sigma_u^2 \sin^2\varphi \cos^2\theta + \sigma_v^2 \sin^2\varphi \sin^2\theta + \sigma_w^2 \cos^2\varphi + 2\langle u'v'\rangle \sin^2\varphi \cos\theta \sin\theta + 2\langle u'w'\rangle \cos\varphi \sin\varphi \cos\theta + + 2\langle v'w'\rangle \cos\varphi \sin\varphi \sin\theta.$$

- The streamwise momentum flux is then given by

$$\langle u'w'\rangle = \frac{\sigma^2[v_{r\,down}] - \sigma^2[v_{r\,up}]}{2\sin 2\varphi}$$

where, R is the range, φ is the half-opening angle of the conical scan (30º), θ is the azimuthal direction of the lidar beam, [u, v, w] are the wind components at each range-gate center, $\langle\cdot\rangle$ represents ensemble averaging, [u', v', w'] are the velocity fluctuations, and $\sigma^2[v_{r\,down}]$ and $\sigma^2[v_{r\,up}]$ are the radial velocity variances from the nearest downwind and upwind azimuth angles relative to the mean wind direction, respectively



30-minute averaged along-wind momentum flux ($\langle u'w'\rangle$) measurements from lidar at 75 m and sonic at 60 m AGL from October 8, 2020, to January 14, 2021, for a) southerly (150 – 200 deg) wind directions under all atmospheric conditions and b) for southerly wind directions under very stable atmospheric conditions.

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SGP C1 analysis

- Wind farm simulations using FAST Farm (Jonkman et al., 2018) show wind turbine wakes reach SGP C1 during stable conditions
- Momentum flux divergence observed above the rotor layer during very stable atmospheric conditions at SGP (wake recovery)

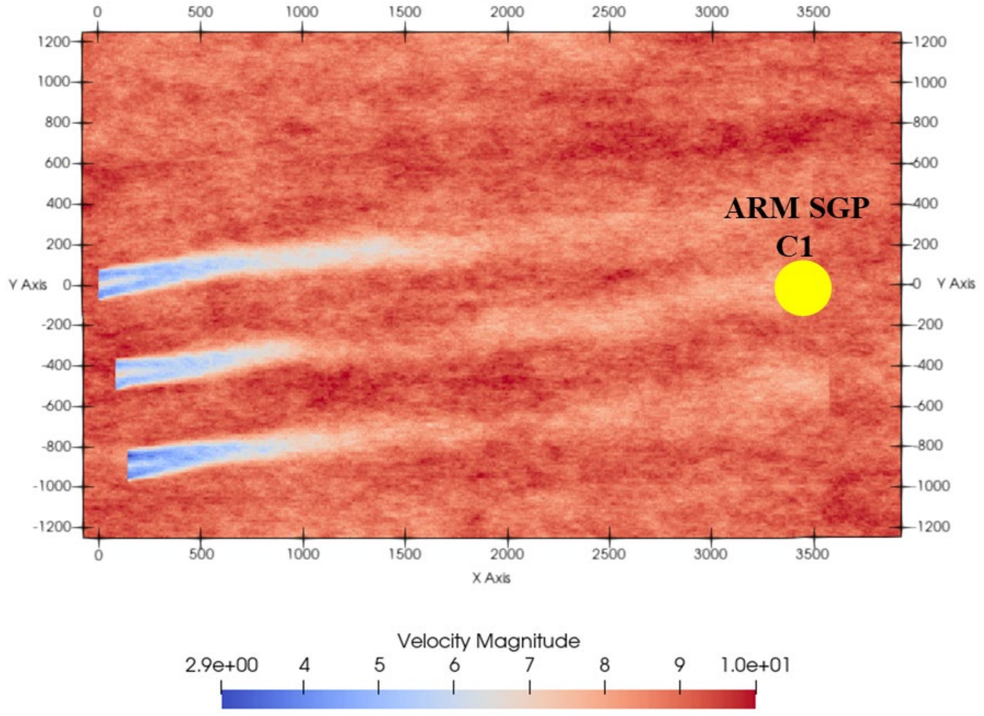


Figure: FAST Farm simulation of three wind turbines south of the SGP C1 under stable ($Ri_g = 0.2$) atmospheric boundary layer conditions. The color bar represents the horizontal wind speed in m s^{-1}. The location of the ARM Doppler lidar at the SGP C1 is at ~ 3500 m from the turbines.

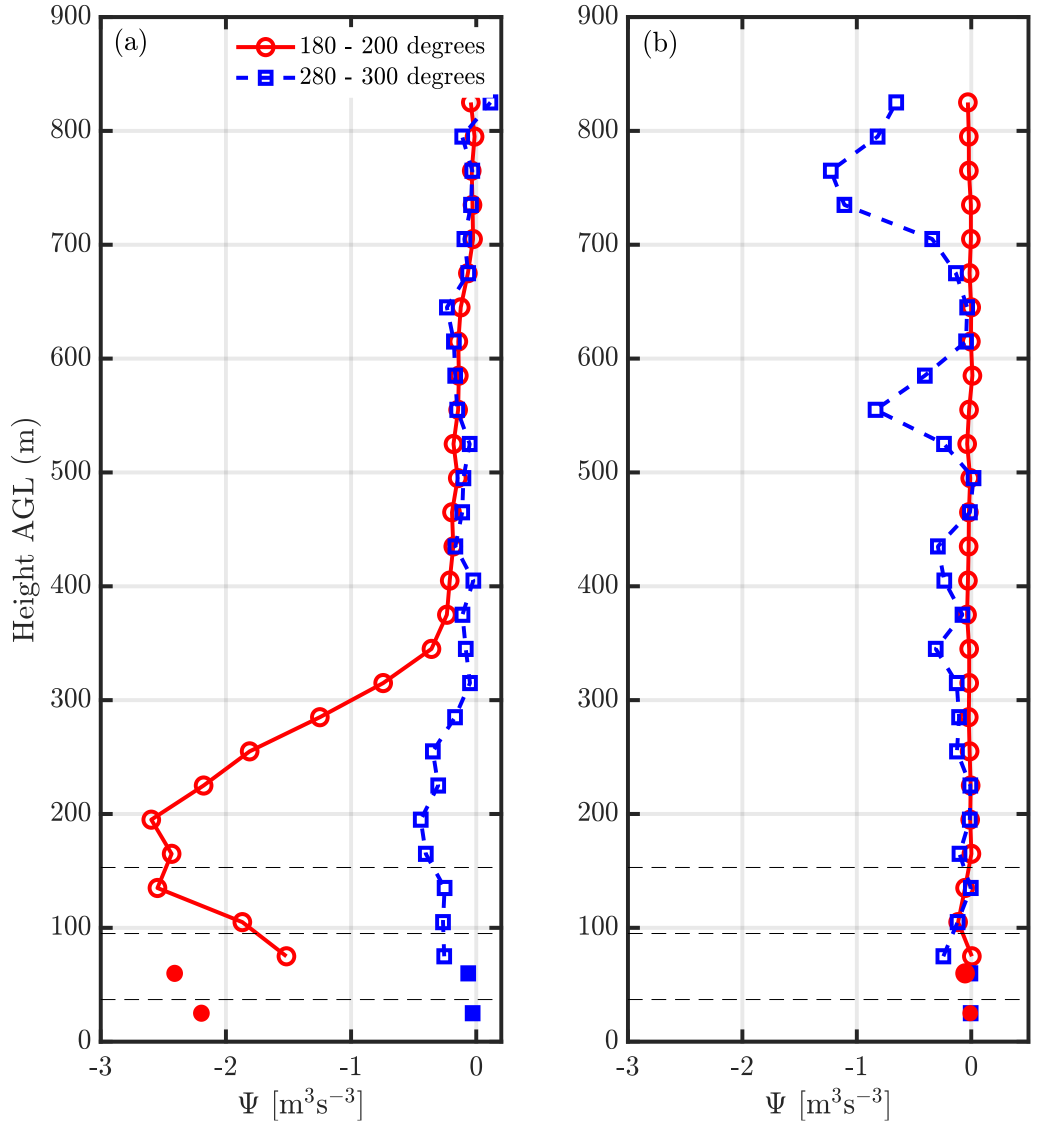
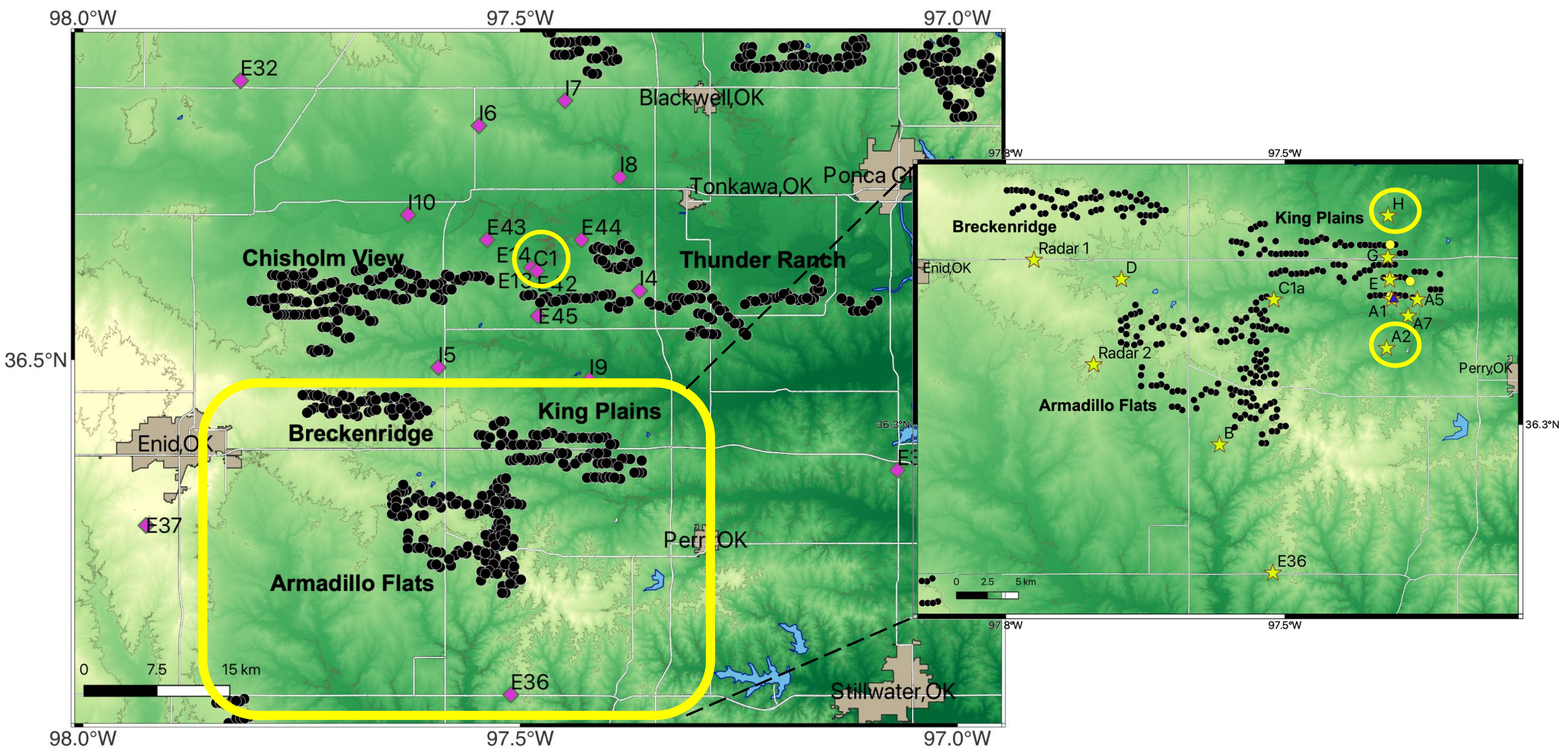


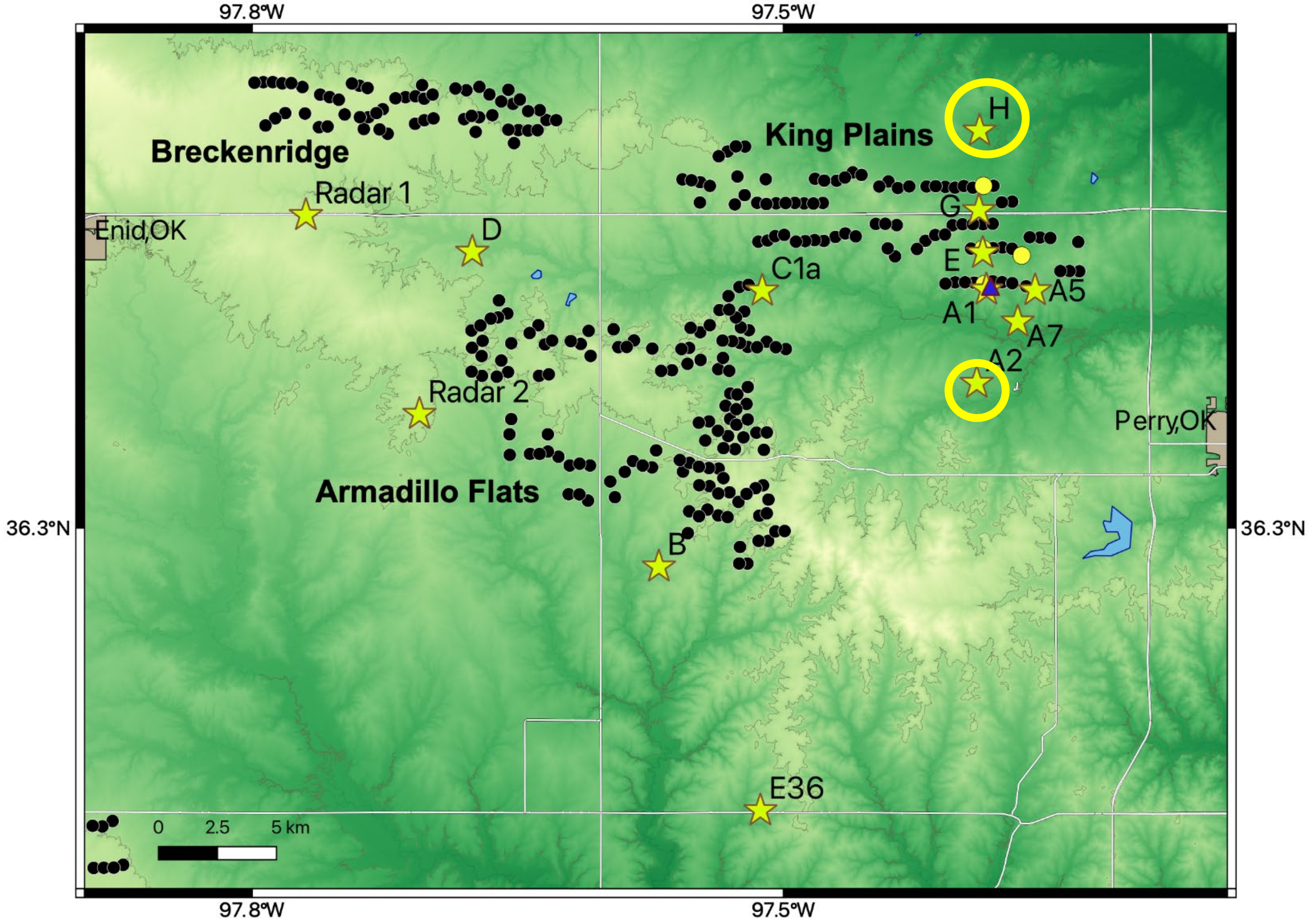
Figure: Median vertical kinetic energy flux (ψ) profiles from Doppler lidar (open symbols) and sonic anemometer (filled symbols) during nocturnal (from 00 to 12 hours UTC) a) **stable** (50 < L < 500) and b) **unstable** (-10 < L < -500) atmospheric conditions from October 8, 2020 to January 14, 2021. Measurements from two wind direction sectors 180-200 degrees which align with the nearest wind turbines south of the SGP and 280-300 degrees is free-stream wind direction with wind turbines up to at least 50 km from the lidar location. At least 10 samples are used to calculate the median for each profile. The rotor swept area accounting for the terrain difference between the southern wind turbines and the SGP C1 (Δ ~15 m) is shown as black dashed lines.

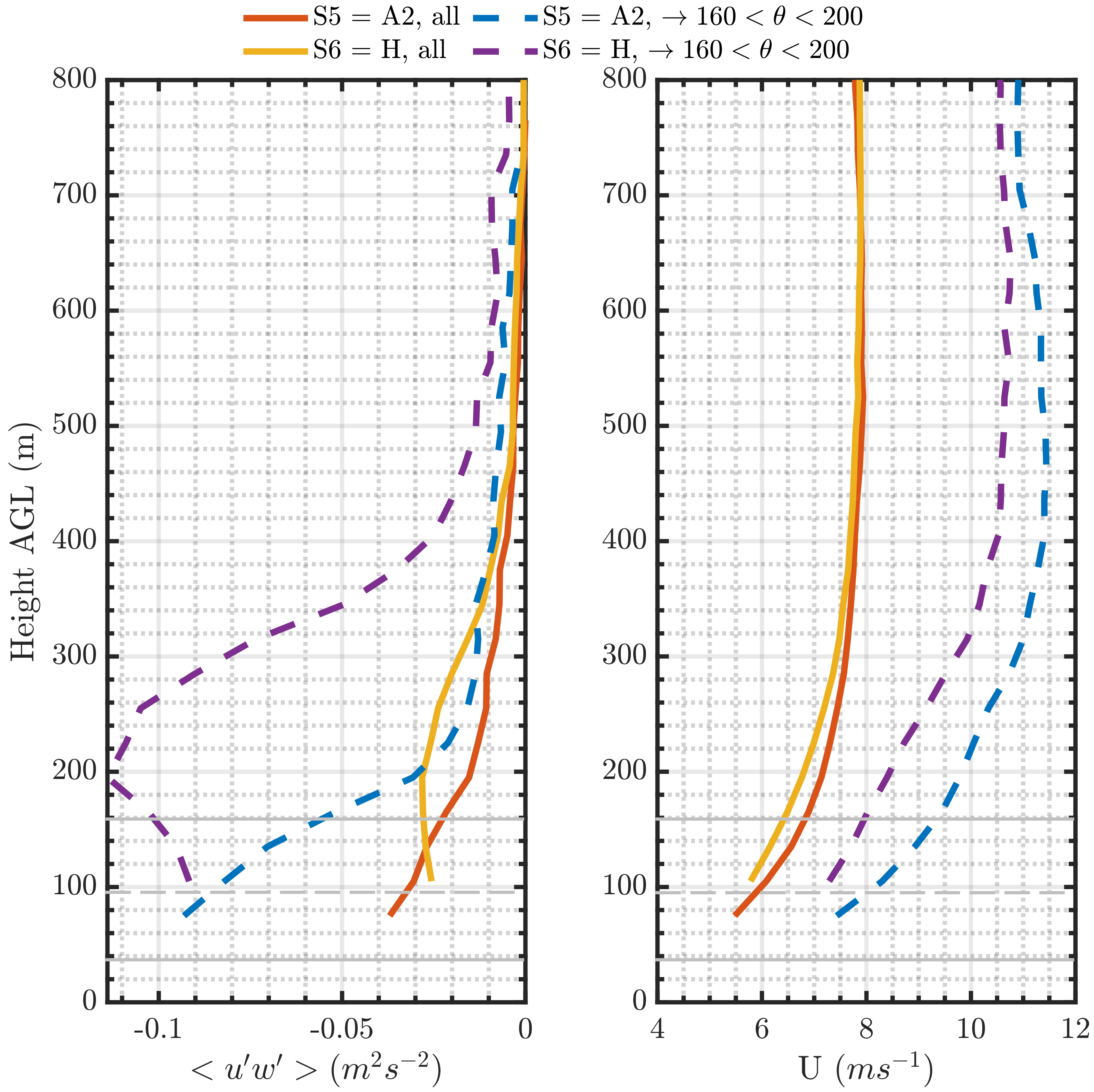
Analysis site – AWAKEN



Southerly wind directions

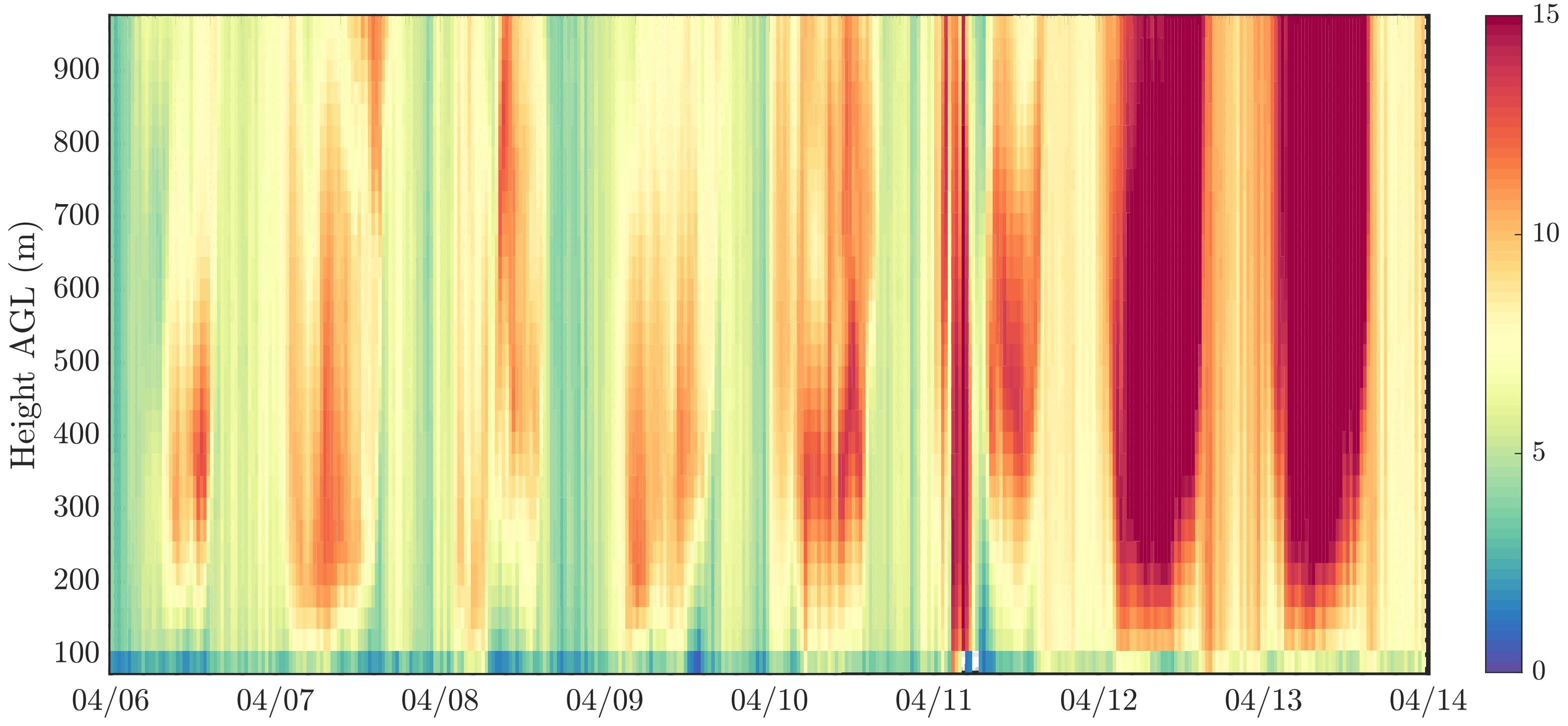
- Time period of analysis 17th Mar 2023 to 20-July 2023

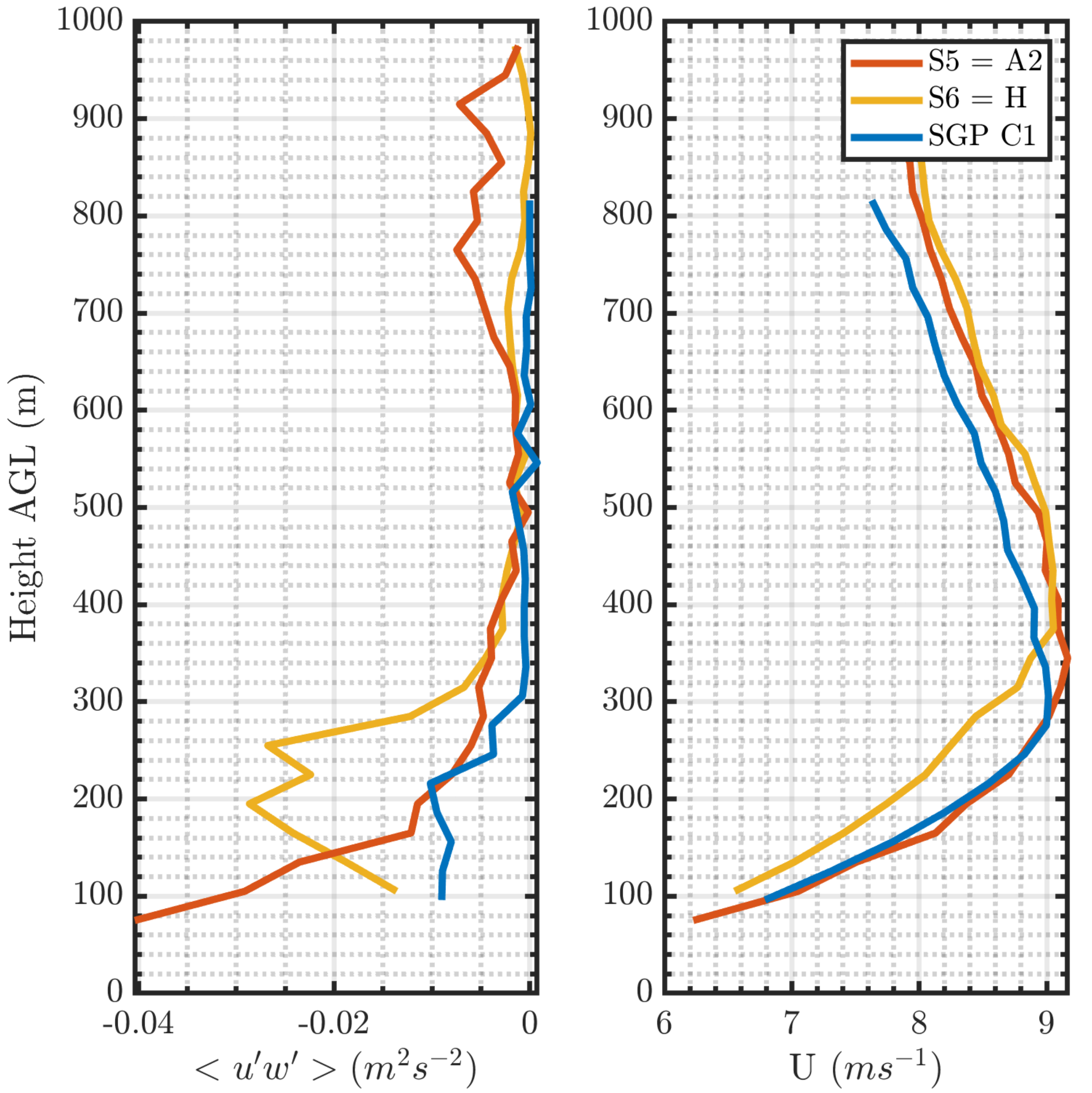




Case study – LLJ period

- Preliminary assessment of LLJ period indicates the entrainment of winds into the wake is higher compared to non-LLJ periods and thereby smaller momentum flux deficits





Next Steps

- Evaluate the impact of wake momentum recovery – for different atmospheric conditions (stability, LLJs, fronts etc.)

- Assess the internal boundary layer height (h) developed by the wind farms and study the turbulence generated downwind due to the roughness change and thereby impact of thermodynamic, boundary layer height, and aerosol/cloud properties at SGP
  - Scaling analysis – assess wind turbines as a surface roughness with enhanced TKE or momentum sink (drag)

$$h \approx f\left\{ {\langle u'w' \rangle}/{{\sigma_u}^2}, {z_i}/{z_{farm}}, {L_{farm}}/{W_{farm}} \right\}$$

Thank you