

Influence of simple terrain on the spatial variability of a low-level jet and wind farm performance in the AWAKEN field campaign

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Abstract. In wind energy research, scientific challenges are often associated with *complex terrain* sites, where orography, vegetation, and buildings disrupt flow uniformity. However, even sites characterized as *simple terrain* can exhibit significant spatial variability in wind speed, particularly during stable boundary layers (SBLs) and low-level jets (LLJs). This study investigates these terrain interactions using both simulations and observations from the American WAKE Experiment (AWAKEN). We employ a multiscale Weather Research and Forecasting (WRF) model simulation, integrating mesoscale forcing in the coarse domains and representing three rows of turbines from the King Plains wind farm as generalized actuator disks (GAD) in the large-eddy simulation (LES) domains. During a nocturnal LLJ event on 3 April 2023, the downstream, wake-affected turbine rows outperformed the upstream, unwaked row by 25–51 %. This counterintuitive result arises from terrain-induced streamwise variations in hub-height wind speed of approximately 4 m s^{-1} over 5 km—equivalent to $\sim 50 \%$ of the upstream reference speed. This enhancement outweighs the wake-induced reduction in mean wind speed ($\sim 12 \%$) and global blockage effects reported in the literature ($\sim 1\text{--}3.4 \%$). The multiscale simulations capture the intra-farm spatial variability in power performance observed in SCADA data. Terrain-induced vertical displacement of the LLJ, coupled with large wind shear below the jet maximum, drives the substantial streamwise acceleration within the wind farm. These findings underscore the importance of accounting for spatial variability related to terrain, even in simple landscapes, particularly during LLJ conditions. Incorporating such effects into reduced-order modeling frameworks for wind farm design and control could significantly enhance their effectiveness.

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1 Introduction

One of the grand challenges in modern wind energy science is to measure, model and understand physical processes in atmosphere–wind farm interactions that span a wide range of spatio-temporal scales (Veers et al., 2019, 2022). The societal motivation is to reduce the cost of energy, which can be achieved by at least two means. First, during the wind farm design stage, an accurate understanding of the processes that modulate wind farm performance, backed up by observations and models, can help reduce uncertainty in the estimation of the annual energy production and design a wind farm that maximizes the energy conversion. Second, for existing wind farms, appropriate observations and models that represent the relevant physical processes are necessary for wind farm control. The existence of processes that create spatial gradients within the wind farm area enhance the complexities associated with the design and optimization stages.

Spatial gradients in wind speed have paramount importance for the atmospheric sciences and wind energy. The vertical gradient in wind speed is the wind shear and affects turbine performance (Sanchez Gomez and Lundquist, 2020; Murphy et al., 2020) and loads (Sathe et al., 2013b; Robertson et al., 2019; Lundquist, 2021). The wind results from interactions between pressure gradient forces, Coriolis forces, and turbulent stresses. Horizontal gradients appear whenever a local imbalance in the forces that drive the wind occurs, such as in the transition from surfaces of different roughness or heat flux (Stull, 1988), or for flows over terrain with variable height (Baines, 1995). Horizontal gradients of velocity can be negligible compared to vertical gradients over isothermal flat terrain with uniform roughness and thermal properties in the microscale range. Indeed, landmark field campaigns were held in sites with flat and homogeneously covered terrain (Kaimal and Wyngaard, 1990; Holtslag et al., 2012) to minimize such spatial variability.

During the nighttime over land, surface cooling produces thermal stratification that inhibits turbulent motions in the planetary boundary layer, resulting in a stable boundary layer (SBL). A myriad of processes can occur in SBLs, such as atmospheric gravity waves, topographic acceleration or blocking of winds, turbulence intermittency, and low-level jets (LLJs) (Poulos et al., 2002; Fernando et al., 2019). A LLJ is a stream of fast-moving air with a maximum in wind speed relatively close to the ground, which is enabled by the suppression of frictional forces in the upper portion of the SBL. The physical mechanisms that form LLJs generally involve nocturnal frictional decoupling, sloping terrain, and synoptic pressure gradient forces (Blackadar, 1957; Holton, 1967; Stensrud, 1996; Banta et al., 2002; Banta, 2008; Klein et al., 2015; Smith et al., 2019), and once formed, LLJs can manifest at least three turbulence regimes (Banta, 2008): a weakly-stable regime with continuous turbulence, a very-stable regime with almost no turbulence, and a transitional or intermittent regime with occasional bursts of turbulence. In the Southern Great Plains (SGP) of the United States, LLJs display these different turbulence regimes (Klein et al., 2015) and accompanying large spatio-temporal variability in their evolution (Banta et al., 2002; Smith et al., 2019).

There is an important link between terrain complexity, SBLs and LLJs in the modulation of the spatial variability of the wind. The existence of horizontal variability introduces an additional complexity, because one can no longer assume a single

wind profile is representative of the entire site. In stable conditions, the low-level wind decelerates upstream of obstacles more than it would in neutral conditions because of the downward buoyancy (Mahrt and Larsen, 1990; Baines, 1995; Hunt et al., 1988) forcing the flow to stay at the same altitude rather than rising over the obstacles. Likewise, the flow accelerates more in the lee, and this combination enhances the spatial variability in wind speed. This behavior happens, to a lesser or higher degree, to any SBL, from which the LLJs are a particular case. This variability is one of the main scientific challenges associated with complex terrain, and motivated for example a large-scale field campaign and model development effort in the New European Wind Atlas (NEWA) project (Mann et al., 2017). The Perdigão (Fernando et al., 2019) and the Alaiz (Santos et al., 2020) experiments from the NEWA revealed with unprecedented detail the variability in flow patterns that occurred when stable boundary layers (SBLs) and nocturnal low-level jets (LLJs) interacted with complex terrains (Peña and Santos, 2021; Wagner et al., 2019; Wise et al., 2022). In Banta et al. (2002), sometimes the LLJ observations suggested the flow followed the terrain, whereas sometimes it remained at a constant height above mean sea level (AMSL). Other investigations also pointed out to the terrain-induced variability in wind speed in stable conditions (Mahrt et al., 2021; Radünz et al., 2020).

The terrain-induced variability in wind speed during SBLs and LLJs causes important spatial differences in the performance of wind turbines operating in complex terrain (Radünz et al., 2021, 2022). Other physical processes that modulate wind turbine and farm performance in SBLs include wind farm wakes (Doosttalab et al., 2020; Gadde and Stevens, 2021) and blockage (Wu and Porté-Agel, 2017; Bleeg et al., 2018; Sebastiani et al., 2021; Schneemann et al., 2021; Sanchez Gomez et al., 2022). In Radünz et al. (2021), wind farms located in complex terrain exhibited surprising performance patterns: turbines in the back rows sometimes produced twice as much power as those in the front rows, despite being affected by wake effects. This performance pattern was associated with a strong downstream flow acceleration in stable conditions. The back rows were closer to the lee of the plateau, and thus had stronger winds available in comparison with the front rows. Later on, the occurrence of nocturnal jets and the depth of the stable layer were shown to amplify the horizontal variability in the winds and turbine performance (Radünz et al., 2022).

Specific attributes of the LLJ may make it particularly susceptible to terrain-induced accelerations, even in the presence of simple topographic features, potentially causing substantial changes in wind speed and wind farm performance. However, most existing research on LLJ interactions with wind farms has relied on idealized numerical simulations, leaving a critical gap in the understanding of real-world interactions involving LLJs, terrain, and operational wind farms. This gap underscores the need for field measurements and operational data to validate and improve models. The American WAKE Experiment (AWAKEN), an international wind energy science project funded by the United States Department of Energy (DOE) and led by the National Renewable Energy Laboratory (NREL), aims to address this gap by advancing the physical understanding and modeling of atmosphere–wind farm interactions (Debnath et al., 2022; Moriarty et al., 2024). The study site, located in the U.S. Southern Great Plains (SGP) of northern Oklahoma, was chosen due to its dense concentration of wind farms, the availability of high-quality historical observations from the Atmospheric Radiation Measurement (ARM) Program’s SGP facility (?), and the frequent occurrence of meteorological phenomena of interest for wind energy, such as southerly LLJs (Banta et al., 2002; Banta, 2008; Klein et al., 2015; Smith et al., 2019; Krishnamurthy et al., 2021). This field campaign provides an excellent setting for evaluating the two key goals of our investigation: (1) assessing whether simple terrain can induce significant spatial variability

in wind speed, thereby influencing turbine wakes and performance, and (2) determining whether specific LLJ characteristics amplify terrain-induced spatial wind variability.

This paper investigates the interaction between a southerly nocturnal LLJ on 3 April 2023 and a seventeen-turbine subset of the King Plains wind farm, the most heavily instrumented site in the AWAKEN project. The terrain at the site is neither traditionally complex (e.g., mountainous or hilly) nor entirely flat, consisting of shallow river valleys with elevation changes of less than 50 m—referred to here as simple terrain. The remainder of the paper is organized as follows. Section 2 describes the orography and land use characteristics of the AWAKEN site, the observational dataset, criteria for case selection, and the simulation setup. The simulations use a multiscale WRF-LES-GAD (generalized actuator disk) approach, realistically driven by High-Resolution Rapid Refresh (HRRR) v4 analysis data. Section 3 integrates observations from ground-based scanning and profiling lidars, an atmospheric emitted radiance interferometer, and a sonic anemometer to validate the simulations and analyze the planetary boundary layer (PBL) winds, stability, and turbulence across the wind farm. Turbine performance is assessed using supervisory control and data acquisition (SCADA) system data. Section 4 provides a conceptual description of terrain-induced wind variability and compares its significance with wake and blockage effects. It also discusses the implications of terrain effects for multiscale modeling and wind farm control, as well as the potential long-term manifestation of terrain-induced variability associated with LLJs. Finally, Section 5 presents the main conclusions and outlines directions for future research.

2 Methods

2.1 The AWAKEN field campaign observations and case study selection

Five wind farms were selected for the AWAKEN field campaign, which are King Plains, Armadillo Flats, Breckenridge, Chisholm View, and Thunder Ranch (Fig. 1). This investigation focuses on the eastern portion of the King Plains wind farm because it is the most well instrumented location in AWAKEN. Furthermore, in the prevailing southerly winds (Debnath et al., 2022; Moriarty et al., 2024), it is not directly downstream of other wind farms. Therefore, the power performance patterns in eastern King Plains are solely caused by the terrain effects and turbine interactions that belong to that wind farm. We focus on a subset of 17 turbines organized into three rows.

The observations from the field campaign enable testing several scientific hypotheses, four of which are related to our work: the (i) wind farm wakes propagation (Bodini et al., 2024; Cheung et al., 2023; Krishnamurthy et al., 2025), (ii) blockage (Cheung et al., 2023; Sanchez Gomez et al., 2022), (iii) wake steering and (iv) individual turbine wake morphology. The AWAKEN site has relatively simple terrain, such that even the names of the wind farms bring this feature: *King Plains*, *Armadillo Flats*. Thus, understanding the terrain-induced spatial variability and influence of LLJs is relevant to the aforementioned scopes.

Observations from the A1 and A2 sites characterize the inflow because they contain no interference from nearby wind farms (Fig. 2) and are used for the case selection and model validation. At site A1, immediately upstream of the King Plains wind farm in the southerly wind direction, wind speed components were measured with a Halo scanning lidar (Letizia and Bodini, 2023). Reynolds stresses from this lidar were estimated based on the six-beam method of Sathe et al. (2015). Also at site A1,

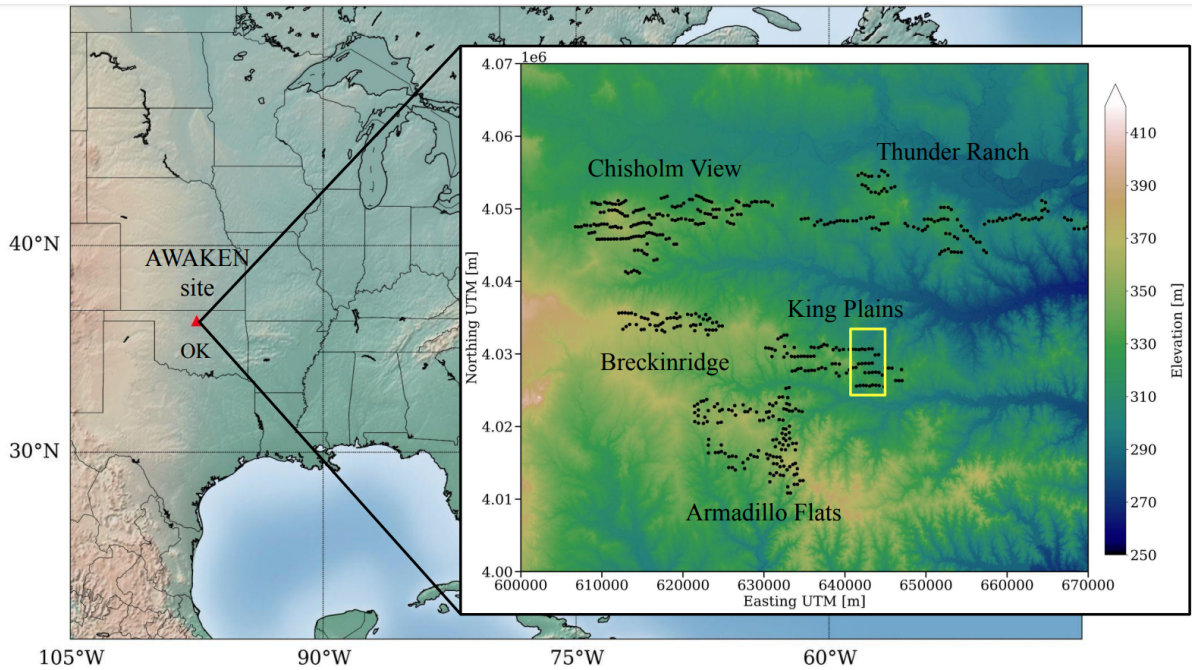


Figure 1. The background map of the United States of America (USA) shows the location of the AWAKEN site in Oklahoma (OK) near [36.5 °N, -97.5 °W]. In the foreground, the five wind farms that integrate the AWAKEN field campaign are shown overlaid on the terrain elevation map: King Plains, Armadillo Flats, Breckenridge, Chisholm View, and Thunder Ranch. The eastern portion of the King Plains wind farm is the focus of our investigation (yellow rectangle).

122 a Windcube v. 2 profiling lidar measured the wind speed components with a sampling rate between 0.5 to 1 s between 40 and
240 m above ground level (AGL) with a vertical resolution of 20 m (Wharton, 2023). A sonic anemometer at an upstream site
124 A2 measured wind speed components at a sampling rate of 20 Hz at 4 m AGL (Pekour, 2023). Although a profiling lidar was
also located at A2, its poor data quality from 04:00 to 06:00 UTC during this case study was insufficient for analysis. Potential
126 temperature profiles at site C1 (Atmospheric Radiation Measurement Southern Great Plains Central Facility) were derived
from ground-based atmospheric emitted radiance interferometer (AERI) observations (Shippert and Zhang, 2016) using the
128 TROPoe retrieval algorithm (Turner and Löhnert, 2014; Turner and Blumberg, 2019).

The case study consists of a southerly LLJ during a somewhat stationary window to mitigate the influence of larger-scale
130 dynamic events in the analysis. The stationary window excludes larger-scale processes like cold fronts and cyclones, as well
as mesoscale drainage flows over hundreds of kilometers, which cause significant wind and stratification changes. However,
132 submeso motions, including drainage flows from smaller topographic features, are inherent to stable boundary layer dynamics
(Mahrt, 2009) and are included in the analysis. Also, we selected nights with sufficiently strong winds to create turbulent
134 motions resolvable with a $\Delta x = 5$ m grid (Skamarock, 2004), but not as strong as to cause turbines to operate near rated
capacity, and thus impair our capacity to assess spatial variability in performance. Nights with weak winds create relatively

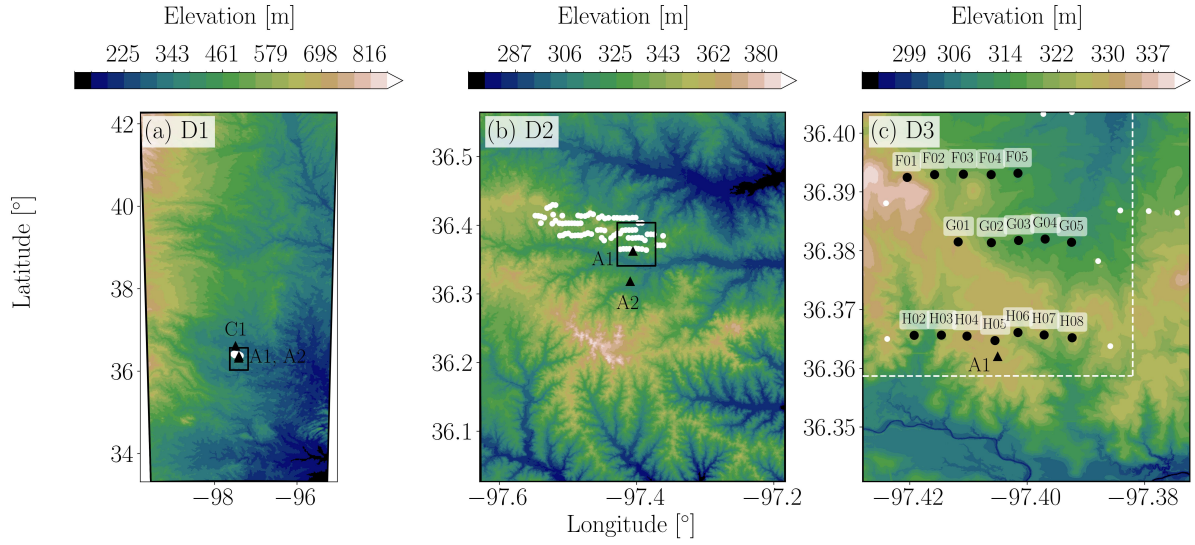


Figure 2. Horizontal extent and terrain elevation maps associated with the WRF model simulations mesoscale domain D1 (a) and LES domains D2 (b) and D3 (c). The King Plains wind farm consists of 88 turbines (white dots), from which a subset of 17 wind turbines was represented in the simulation (black dots). Within domain D3, some turbines near boundaries were removed (white dots). Inflow fetches of 2 and 1 km in the southerly and easterly boundaries, respectively, were removed from the analyses (white dashed lines). The observation sites A1, A2 and C1 (black triangles) are also shown.

136 small-scale turbulent motions that require a fine computational grid to be resolved. We also wanted stationary and moderate
 138 values for the sensible heat flux to avoid changes in the surface forcing. There were no requirements for the spatial variability
 in winds and performance. The case selection considered the following requirements. During the nighttime between 04:00
 and 12:00 UTC, the time-averaged (i) wind speed at 100 m AGL should be between 5 and 14 m s⁻¹, (ii) wind direction at
 100 m AGL between 160° and 200°, (iii) the standard deviation in wind direction at 100 m AGL below 50°, (iv) the sensible
 heat flux lower than -20 W m⁻² and the (v) friction velocity lower than 0.5 m s⁻¹.

142 The dates from the year of 2023 that meet these criteria are 3 April, 18 April and 15 May 2023. Ultimately, 3 April 2023
 was selected because of the predominant southerly wind direction (180°) and the moderate winds with large sensible heat flux,
 144 suggesting vigorous nighttime turbulence. The selected analysis window was from 04:50 to 05:25 UTC because of curtailment
 events at other times and the occurrence of clouds in the simulations later on at 08:00 UTC.

146 2.2 Simulation setup

The multi-scale simulations were performed with the Advanced-Research Weather Research and Forecasting (WRF) model
 148 version 4.1.5 (Skamarock et al., 2019), which solves the compressible Euler equations for the three spatial dimensions and
 time. Three computational domains with a progressive increase in spatial resolutions and smaller areas were used to represent
 150 and bridge the large-scale, mesoscale, and microscale atmospheric processes (Fig. 2). The grid details specific to each domain

Table 1. Computational grid and temporal information by domain.

Parameter	D1	D2	D3
$\Delta x, \Delta y$ [m]	2000	100	5
Δz_{sfc} [m]	30	20	4
n_x	201	401	1001
n_y	501	601	1401
n_z	101	121	168
Start time	2 April 2023 12:00 UTC	3 April 2023 03:00 UTC	3 April 2023 04:30 UTC
End time	3 April 2023 05:25 UTC	3 April 2023 05:25 UTC	3 April 2023 05:25 UTC
Time step [s]	12	0.6	0.025

are described in Table 1. Each domain used a different vertical grid (vertical nesting (Daniels et al., 2016)), and the innermost domains were finer, such as done in other multiscale simulations (Wise et al., 2022; Sanchez Gomez et al., 2022; Wagner et al., 2019). For instance, the outermost domain (D1) had 201, 501 and 101 cells in the x (west to east), y (south to north) and z (vertical) directions with a fixed horizontal resolution of $\Delta x = \Delta y = 2000$ m. In the vertical direction, the grid consisted of a finer and near-constant layer of $\Delta z_{sfc} = 30$ m in the first 1 km AGL, which was stretched out to a maximum of $\Delta z = 300$ m at the domain top. The large jump in spatial resolution between domains D1 ($\Delta x = 2000$ m) and D2 ($\Delta x = 100$ m) was intended to skip over the *terra incognita* (Wyngaard, 2004), where turbulence length scales are of the same order as the horizontal grid spacing ($100 < \Delta x < 1000$ m) (Muñoz-Esparza et al., 2017; Rai et al., 2019), as in the multiscale simulations of Muñoz-Esparza et al. (2017). The innermost nest domain (D3) has a fixed horizontal resolution of $\Delta x = 5$ m, determined based on a grid sensitivity study conducted at the same site using WRF-LES-GAD for a weaker LLJ case (see the Appendix of Sanchez Gomez et al. (2022)). Their study shows that most turbulence above 30 m AGL is adequately resolved with a 3.94 m grid. In our LLJ case, turbulence is stronger, with a vertical velocity variance of approximately $0.21 \text{ m}^2 \text{ s}^{-2}$ at 90 m AGL, compared to $0.15 \text{ m}^2 \text{ s}^{-2}$ in their study. To ensure turbulence is adequately resolved, we use a 5 m grid in the innermost domain.

The static datasets employed for the terrain elevation and land use categories were the United States Geological Survey (USGS) 1/3 arc-second ($\Delta x \approx 10$ m) dataset (U.S. Geological Survey., 2020) and the National Land Cover Dataset 2019 1 arc-second ($\Delta x \approx 30$ m) dataset (U.S. Geological Survey., 2019), respectively. The coarser Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch, 2011) with a resolution of 30 arc-second ($\Delta x \approx 1000$ m) was used for domain D1.

The terrain features can be described in terms of various scales. The domain D1 covers the foothills east of the Rocky Mountains to the west and the sloping terrain that includes the SGP in the center and eastern regions (Fig. 2a). The domain D2 demonstrates that the terrain near the AWAKEN site is characterized by small river valleys and ridge lines with a domain-wise maximum variation in elevation (amplitude) of 118 m (Fig. 2b). The innermost domain D3 displays the microscale terrain features in the King Plains wind farm area, with a domain-wise elevation amplitude of 49 m (Fig. 2c). The succession of the small river valley depression near the southern boundary, the smooth ridge line and the beginning of the down-slope area that leads to the larger river valley further north appear at higher resolution. A subset of 17 turbines is represented in the finest domain of the simulations. The turbines in the first row (H02–H08) are sited over slightly higher ground ($z \sim 330$ m AMSL),

176 and those in the second (G01–G05) and third (F01–F05) rows are sited in the small down-slope area ($z \sim 320$ m AMSL),
 178 which is shown in detail in the Appendix (Fig.A1c). Because of microscale terrain features, turbines H02, H03 and H06–H08
 are located at local lower ground, and turbine F01 is at higher ground.

The initial and boundary conditions were provided by the High-Resolution Rapid Refresh (HRRR) model v4 (Dowell et al.,
 180 2022), with horizontal spatial and temporal resolutions of 3 km and 1 h, respectively. In this case study, simulations driven
 by initial and boundary conditions from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5)
 182 (Hersbach et al., 2020) and the North American Mesoscale Forecast System (NAM) (Rogers et al., 2009) models data sets
 produced an exaggerated stratification and a weaker LLJ (not shown), although other studies of LLJ in this region (Smith
 184 et al., 2019) have found success with NAM. The WRF model simulation was from 2 April 2023 12:00 UTC to 3 April 2023
 05:25 UTC, allowing 12 hours of spin-up time before the evening transition period at 00:00 UTC (Table 1). The domains
 186 were activated sequentially during the spin-up time. Considering an estimated 20-minute spin-up time for the D3 domain, the
 analysis period was between 3 April 2023 04:50 and 05:25 UTC (35 min). In the Appendix D, Fig. D1 presents a flowchart of
 188 the simulation framework.

Several processes were included via parameterization schemes, such as for cloud microphysics, radiation, and the exchange
 190 of momentum, heat, and moisture with the land surface. The main physics options adopted for each domain are summarized
 in Table 2. All domains used the WRF model Single-Moment 3-class simple ice scheme (Hong et al., 2004) for cloud mi-
 192 crophysics, the RRTM (Mlawer et al., 1997) scheme for short- and longwave radiation processes, and the Noah land surface
 model (Chen and Dudhia, 2001). No cumulus parameterization option was included in any domain due to the fine resolution.

Table 2. Physics parameterization by domain. The model references are found in the text.

Physics	D1	D2	D3
Cumulus	–	–	–
Microphysics	WSM3	WSM3	WSM3
Longwave radiation	RRTM	RRTM	RRTM
Shortwave radiation	RRTM	RRTM	RRTM
Land surface	Noah	Noah	Noah
Surface layer	MYJ	MYJ	MYJ
Planetary boundary layer	MYJ	–	–
LES SGS	–	1.5TKE	NBA2
CPM	–	–	on
GAD	–	–	on

194 Turbulent processes in the planetary boundary layer (PBL) were accounted for differently in mesoscale and microscale
 domains. In the outermost domain D1, turbulence was modeled using the Mellor–Yamada–Janjic (MYJ) PBL parameterization
 196 scheme (Janjić, 1990; Janić, 2001), such as in other LLJ studies in the SGP (Storm et al., 2009; Storm and Basu, 2010;
 Vanderwende et al., 2015). The Mellor–Yamada–Janjic (MYJ) surface-layer (SL) scheme was employed for all domains. In
 198 the nested domains (D2 and D3), LES resolves turbulent motions larger than the grid size, and the influence of the interaction

between subgrid and resolved-grid motions on the resolved-grid flow field were modeled via subgrid-scale (SGS) models. As in Zhou and Chow (2014) and Wise et al. (2025), different SGS models were used for the coarse and the fine LES domains. The Deardorff 1.5 TKE SGS model (Deardorff, 1980) was used for domain D2. The nonlinear backscatter and anisotropy (NBA) SGS model (Kosović, 1997), which accounts for backscatter and can improve turbulence dynamics, was used for the innermost domain D3. SGS models that include backscatter are useful in multiscale simulations of stratified flows (Zhou and Chow, 2014; Sanchez Gomez et al., 2022; Wise et al., 2025).

To accelerate the spin-up of turbulence within the innermost domain, we applied the cell perturbation method (CPM) (Muñoz-Esparza et al., 2014, 2015; Muñoz-Esparza and Kosovic, 2018) in the southern and eastern boundaries. The CPM applies random perturbations to the potential temperature field to trigger buoyancy fluctuations and shorten the fetch required for turbulence spin-up. The current implementation in the WRF model dynamically uses information from the diagnosed PBL height (~ 500 m AGL) from the mesoscale domain to confine perturbations vertically. The potential temperature perturbation amplitude was calculated based on Muñoz-Esparza and Kosovic (2018) for a turbulent Eckert number (E_c) of 0.2, which was effective in several applications in simple (Muñoz-Esparza et al., 2017; Sanchez Gomez et al., 2022) and complex terrain (Connolly et al., 2020). The CPM was deactivated for domain D2 because it was too coarse to resolve turbulence in stable conditions, the same rationale used in (Wagner et al., 2019). The turbulence was sufficiently spun-up between 1.5 and 2 km from the southerly boundary of domain D3 (Fig. B1 in the Appendix). Thus, the analysis considers as a fully spun-up region a domain subset of 4 by 5 km, where 2 km and 1 km are removed from the southerly and easterly boundaries of domain D3, respectively (Fig. 2c). Without the CPM, upstream fetches 4–5 times longer would be needed (Muñoz-Esparza and Kosovic, 2018), doubling domain size and computational cost.

Wind turbines were represented in the simulations as generalized actuator disks (GAD) (Mirocha et al., 2014; Aitken et al., 2014; Arthur et al., 2020). The GAD computes the axial and tangential forces imparted by the turbine to the flow based on the aerodynamic properties of the blade and turbine control strategy. To circumvent the need for proprietary data, the GE 2.8-127 turbine model installed in King Plains was emulated using an OpenFAST model. Publicly available turbines were used as a template, and characteristics were tuned to match the GE 2.8-127 power and thrust curves (Quon, 2022). In addition to the simulation with the wind turbines, a second simulation with the same configuration but without the wind turbines was performed. This procedure enabled isolating the turbine wake effects.

3 Results

3.1 Wind, stability and turbulence in the planetary boundary layer

To assess the simulation skill in representing relevant rotor layer and surface quantities, a time series of selected variables is compared against observations from a profiling lidar at site A1 and a nearby sonic anemometer at site A2 at 4 m AGL (Fig. 3). A 10 minute rolling window is used to compute the instantaneous turbulence-related variables sensible heat flux (H_s) and vertical velocity variance ($\overline{w'w'}$). The gray shaded area in Fig. 3 marks the 20 minute spin-up time, and the analysis is conducted during the period between 04:50 and 05:25 UTC. The time averaged summary of the inflow conditions are shown in

232 Table 3. The subscripts in the variables denote the height AGL. The variables are the wind speed (WS_{90} and direction (WD_{90}
at 90 m AGL, wind shear exponent between 40 and 160 m AGL (α_{40-160}), wind veer between 40 and 160 m AGL expressed in
234 degree every 100 m (β_{40-160}), sensible heat flux at the surface (H_s) and vertical wind velocity variance at 90 m AGL ($\overline{w'w'}_{90}$).

Table 3. Time averaged values associated with the wind inflow of the 3 April 2023 case study between 04:50 and 05:25 UTC.

Source	WS_{90} [m s^{-1}]	WD_{90} [$^{\circ}$]	α_{40-160} [-]	β_{40-160} [$^{\circ}$ 100 m^{-1}]	H_s [W m^{-2}]	$\overline{w'w'}_{90}$ [$\text{m}^2 \text{s}^{-2}$]
WRF-A1 (D3)	8.22	167	0.094	4.4	-43	0.23
OBS-PL-A1	8.09	167	0.170	7.5	-	0.21
OBS-SNC-A2	-	-	-	-	-57	-

The wind speed ($\approx 8.22 \text{ m s}^{-1}$) and direction ($\approx 167^{\circ}$) remain in the range between $5\text{--}10 \text{ m s}^{-1}$ and $160\text{--}175^{\circ}$ (southerly
236 winds), respectively, matching well the observations (Fig. 3a and b). Again, the reader may refer to Table 3 to verify the
average values. The wind shear exponent (Fig. 3c, calculated between 40 m and 160 m) is underestimated in the simulations
238 (~ 0.094) relative to the observations (~ 0.170). Observed wind speed (shear) decreases (increases) between 05:00 and 05:20
UTC, which does not occur in the simulations. Noticeably, the temporal fluctuations in the wind speed and direction signals
240 are similar in amplitude and frequency to the observed ones. As in Muñoz-Esparza et al. (2017), this behavior indicates that
the turbulent motions were consistently resolved in the simulations.

242 Simulated turbulence metrics are within the range of values observed. The turbulence-related metrics, sensible heat flux at
the surface (Fig. 3d) and vertical velocity variance at 90 m AGL (Fig. 3e), approach the observed values. The simulated heat
244 flux time series is, on average, (-43 W m^{-2}), weaker than observed values (-57 W m^{-2}). The simulated vertical velocity
variance ($0.23 \text{ m}^2 \text{s}^{-2}$) is, on average, close to the observed values ($0.21 \text{ m}^2 \text{s}^{-2}$).

246 The vertical structure of the boundary layer associated with the LLJ computed in the simulations matches well the observed
time-averaged wind speed, direction and potential temperature profiles, with a few differences (Fig. 4a–c). The observed LLJ
248 speed profile has a maximum of about 24 m s^{-1} at roughly 500 m AGL with an almost linear increase with height from the
surface to the nose (Fig. 4a), such as described in Banta (2008). The simulation results displays a somewhat flatter nose, below
250 which the wind shear is stronger than in the observations ($300 < z < 400 \text{ m AGL}$). Between 26.5 and 300 m AGL, the wind
shear is slightly weaker than in the observations. The potential temperature profile is stably stratified as in the observations,
252 but the stratification is weaker between 26.5 and 300 m AGL in the simulations (Fig. 4c). Conversely, the stratification in
the simulation is higher than in the observations between 300 and 400 m AGL. However, the interpretation of the observed
254 potential temperature profile should be used with caution: AERI retrievals are affected by poorer vertical resolution away from
the ground compared to the LES (Turner and Löhner, 2014), which could explain some differences with the simulations.
256 Also, the potential temperature profile at the C1 site is merely a proxy for the stratification at the A1 site, since there are
no measurements of this type there. The magnitude and vertical variation with height of the wind direction (veer) is well
258 represented. The wind direction veers considerably with height, by about 4.4° every 100 m near the rotor (40 to 160 m AGL).
Scanning and profiling lidar observations are consistent, although the profiling lidar displays more variability, likely due to the
260 smaller measurement volume and shorter temporal averaging period (Robey and Lundquist, 2022).

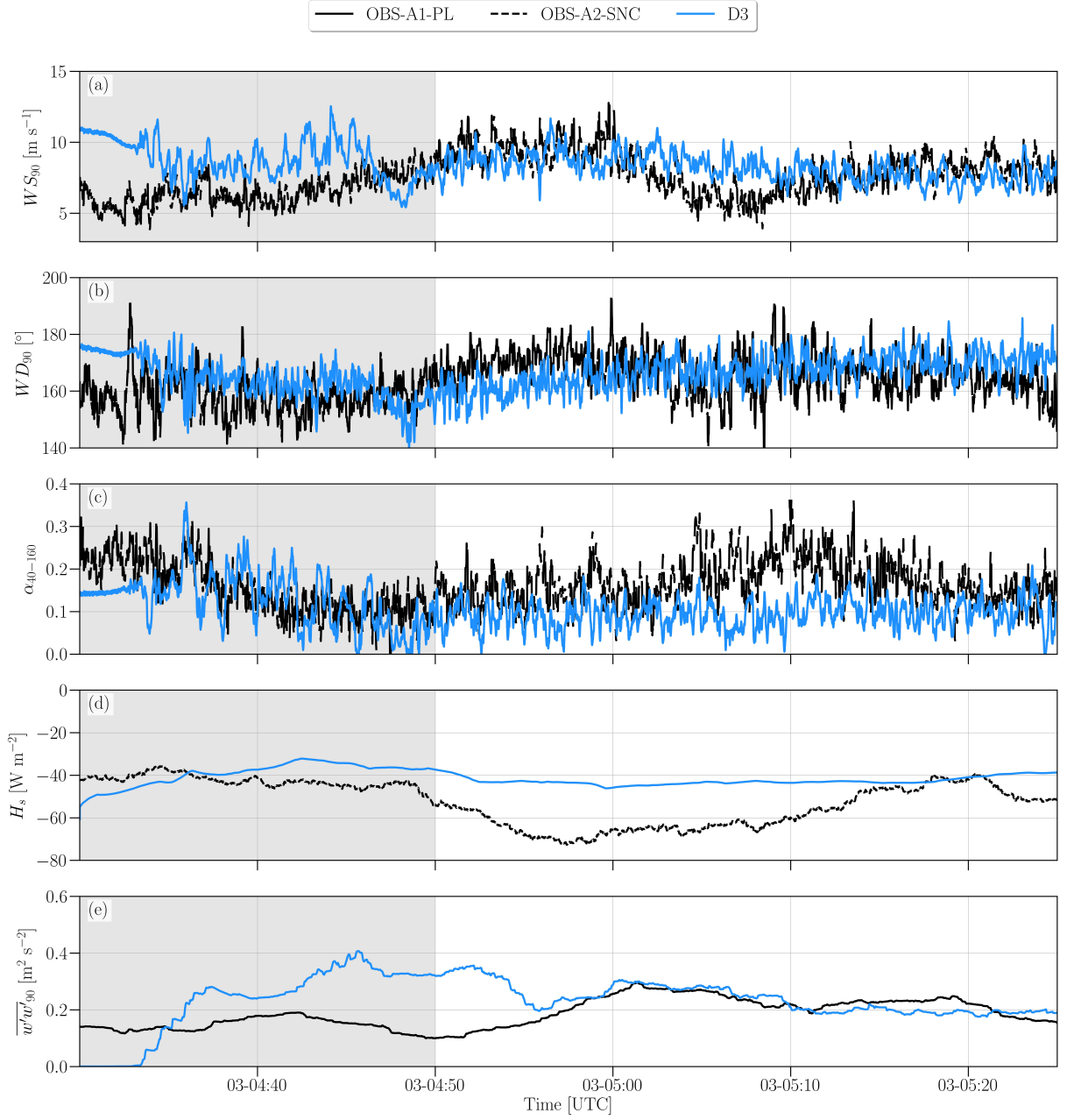


Figure 3. Time series of wind speed (WS_{90} , a) and direction (WD_{90} , b) at 90 m AGL, wind shear exponent between 40 and 160 m AGL (α_{40-160} , c), sensible heat flux at the surface (H_s , d) and vertical wind velocity variance at 90 m AGL ($\overline{w'w'}_{90}$, e). The subscripts in the variables denote the height AGL. A 10-minute rolling window is used to compute H_s and $\overline{w'w'}$. Observations from the profiling lidar at site A1 (OBS-A1-PL) and the sonic anemometer at site A2 (OBS-A2-SNC) are represented as continuous and dashed black lines, respectively. Simulation results for domain D3 are represented as continuous blue lines. The gray shaded area marks the 20 minute spin-up time.

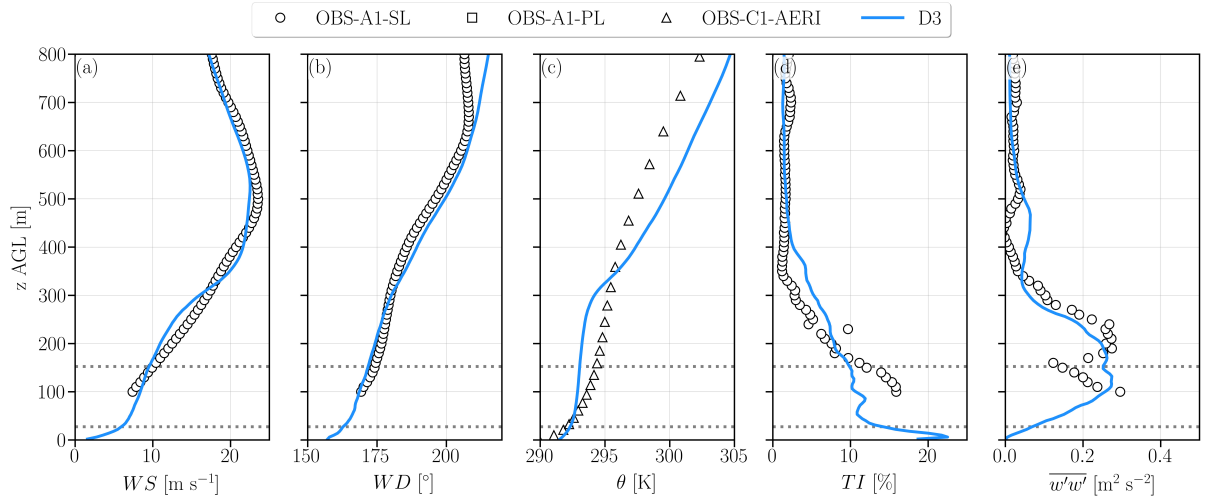


Figure 4. Vertical profiles of wind speed (a), direction (b), potential temperature (c), TI (d) and $\overline{w'w'}$ (e) for a 30 minute window between 04:55 and 05:25 UTC. Observations from the scanning lidar at site A1 (OBS-A1-SL), the profiling lidar at site A1 (OBS-A1-PL), and the AERI at site C1 (OBS-C1-AERI) are represented as markers. Results from domain D3 are represented as blue continuous lines. The dotted horizontal lines represent the rotor top and bottom tips of the turbines.

The turbulence-related variables calculated are consistent with observations (Fig. 4d,e) and the expected behavior for strong LLJs (Banta, 2008; Klein et al., 2015) as the strong wind shear results in mechanically-generated turbulence. The turbulence intensity (TI) was computed as the ratio between the standard deviation and the mean of the 10-minute wind speed. The $\overline{w'w'}$ profile displays strong turbulence above rotor bottom tip ($z < 26.5$ m AGL) and below 300 m AGL, with a maximum near the rotor top tip ($z < 153.5$ m AGL). This enhanced mixing weakens the stratification in the aforementioned layer. Below $z = 26.5$ m, the simulated $\overline{w'w'}$ is small and reaches zero at the surface. The associated peak in TI near the surface was caused by the very small wind speed. Thus, near the surface, the stratification increased. These features are consistent with a strong LLJ, whereby turbulence is continuously produced below the jet nose owing to mechanical shear (Banta, 2008; Klein et al., 2015). Because shear is small near the jet nose, so is turbulence, as mean shear is the main driver of mechanical production of turbulent kinetic energy.

Both the mean flow and the turbulence-related variables reasonably approximate the observations in the rotor layer and above. Therefore, the simulated flow field elsewhere is likely to approximate the behavior of the real flow field. Hence, we now examine the wind farm performance patterns and their relation to the flow field.

3.2 Wind farm performance

This section evaluates the power performance variability within the wind farm. The turbine power acquired with the supervisory control and data acquisition (SCADA) system is normalized as requested by the wind farm owner in the Non-Disclosure Agreement (NDA). The normalized mean power is computed as the ratio between the mean power of each row and the turbine

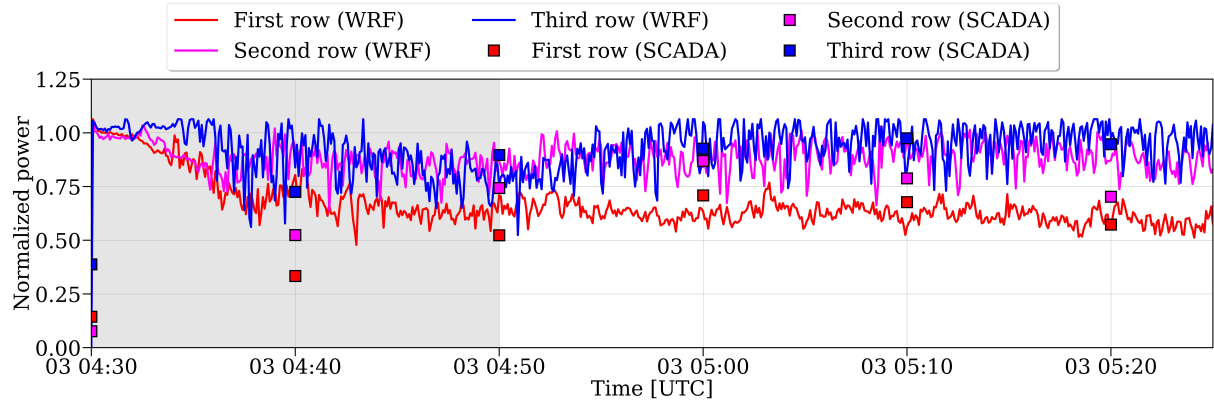


Figure 5. Time series of normalized mean power based on simulations (continuous lines) and SCADA data (markers). The gray shaded area marks the 20 minute spin-up time.

278 rated power ($= P_{row}/P_{rated}$). The normalized mean power is separated into first (turbines H02–H08), second (turbines G01–
 280 G05) and third (turbines F01–F05) rows. For the southerly wind direction, the first row is upstream of the second and third rows.

An unexpected performance pattern occurs in the normalized mean power time series because the second and third rows
 282 consistently outperform the front row (Fig. 5) throughout this time period, even though the second and third rows should be
 impacted by wakes from the first row. This overperformance for the downstream rows occurs in both the observations and
 284 simulations. Further, the normalized mean power of the third row (SCADA = 0.937, WRF = 0.939) is slightly larger than that
 of the second row (SCADA = 0.776, WRF = 0.894). Both the mean power of the third and second rows are larger than that
 286 of the first row (SCADA = 0.621, WRF = 0.629). In percent, the first row is outperformed by the third (SCADA = 51 %, WRF = 51 %) and second (SCADA = 25 %, WRF = 44 %) rows. Although the simulated power of the second row is higher
 288 than that derived from the SCADA, the agreement for the first and third rows is better.

This performance differential was unexpected because the first row is free of wakes for the southerly wind direction and the
 290 second and third rows are likely to experience wake effects. Additionally, because of the gentle or simple terrain, the spatial
 variability of winds was expected to be small. Given these circumstances, the first row was expected to outperform the back
 292 rows. Thus, some physical processes must have induced large spatial variability in the performance of the wind turbines over
 relatively short distances ($\sim 1\text{--}5$ km), unrelated to wakes, and over simple terrain.

294 3.3 Instantaneous wind speed and wakes

This section assesses snapshots of the flow field to describe spatial variations in the mean flow and turbulence structures.
 296 Figure 6 shows the instantaneous wind speed maps at a fixed height of 90 m AGL at 05:00, 05:10 and 05:20 UTC for the
 simulation with the turbines. The flow field over these 20 minutes contains similarities (Fig. 6a–c), such as the higher wind
 298 speed over the second and third rows and lower wind speed over the first row. Nonetheless, temporal variability in the flow field

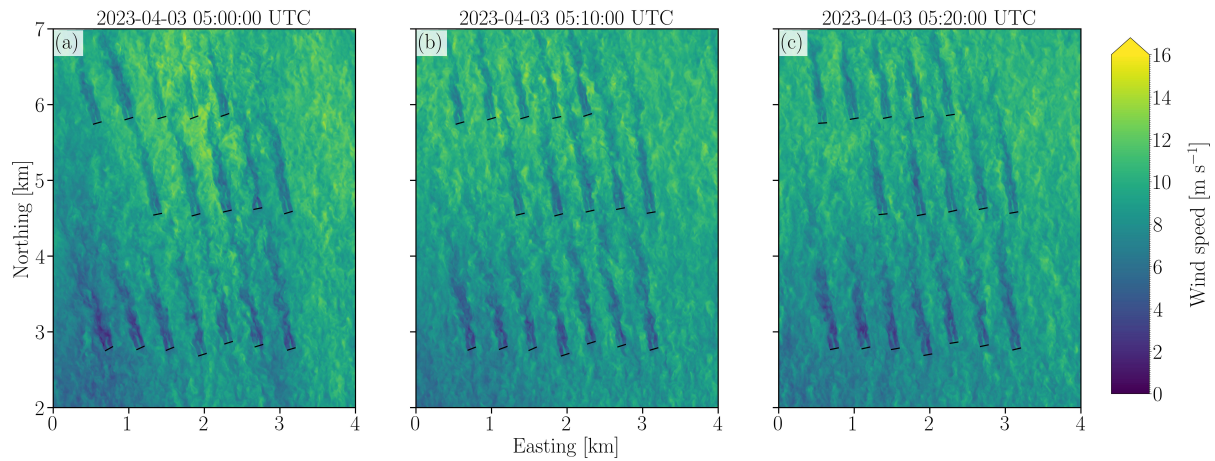


Figure 6. Instantaneous wind speed at 90 m AGL for domain D3 with the turbines at 05:00 (a), 05:10 (b) and 05:20 UTC (c) reveal that temporal fluctuations in the flow field co-exist with a sustained pattern of weaker (stronger) winds upstream (downstream). A video with the complete time window is provided as supplementary material (Radünz, 2024b).

also occurs. At 05:00 UTC, the front row has weaker winds in the westernmost turbines, stronger winds in the center, followed
 300 by another streak of weaker winds in the easternmost turbines. At subsequent times, the spatial variability consists of weaker
 winds in the westernmost turbines and stronger winds in the easternmost turbines. However, despite the temporal variability in
 302 the flow field, the stronger winds over the second and third rows are sustained over time.

Considered in a vertical slice, the flow has three regions with distinct characteristics. Figure 7 shows the instantaneous
 304 wind speed and potential temperature at 04:54 UTC (11:54 LT) in a north-south vertical cross-section that roughly follows
 the streamwise direction, for the simulation with and without turbines. First, a LLJ core region is near 800 m above mean sea
 306 level (AMSL) with very strong winds and weaker turbulence (Fig. 7a–b). At the bottom of the profile, a region with high shear
 and vigorous turbulence exists between the ground level up to about 600 m AMSL. Finally, a layer with coherent turbulence
 308 structures induced by wind shear at the interface between both, which resemble Kelvin-Helmholtz Instabilities (KHIs), as in
 Blumen et al. (2001); Coulter and Doran (2002); Zhou and Chow (2012, 2014); Conrick et al. (2018); Malekmohammadi
 310 et al. (2025) among others. The onset of KHI occurs after the second row, but has a more salient structure near the third row
 (Fig. 7c–d). The vertical entrainment is most visible near the third row and below the LLJ nose by assessing the potential
 312 temperature (Fig. 7c,d). The KHIs are not caused by the turbines because they also occur in the simulation without turbines
 (Fig. 7b,d). However, qualitatively, the amplitude of the KHI appears to be amplified by the presence of the turbines (Fig. 7c).
 314 The enhanced mixing (Blumen et al., 2001; Newsom and Banta, 2003) can transport momentum from the LLJ core downwards
 and accelerate wake recovery.

316 A plausible explanation for the observed KHI formation in our investigation is the low-level wind deceleration induced by
 the terrain (Blumen et al., 2001; Newsom and Banta, 2003). As later shown in Figs. 8b and 10b, the terrain slows down the
 318 upstream wind at King Plains, enhancing the wind shear. This increased wind shear can destabilize the flow and trigger KHIs.

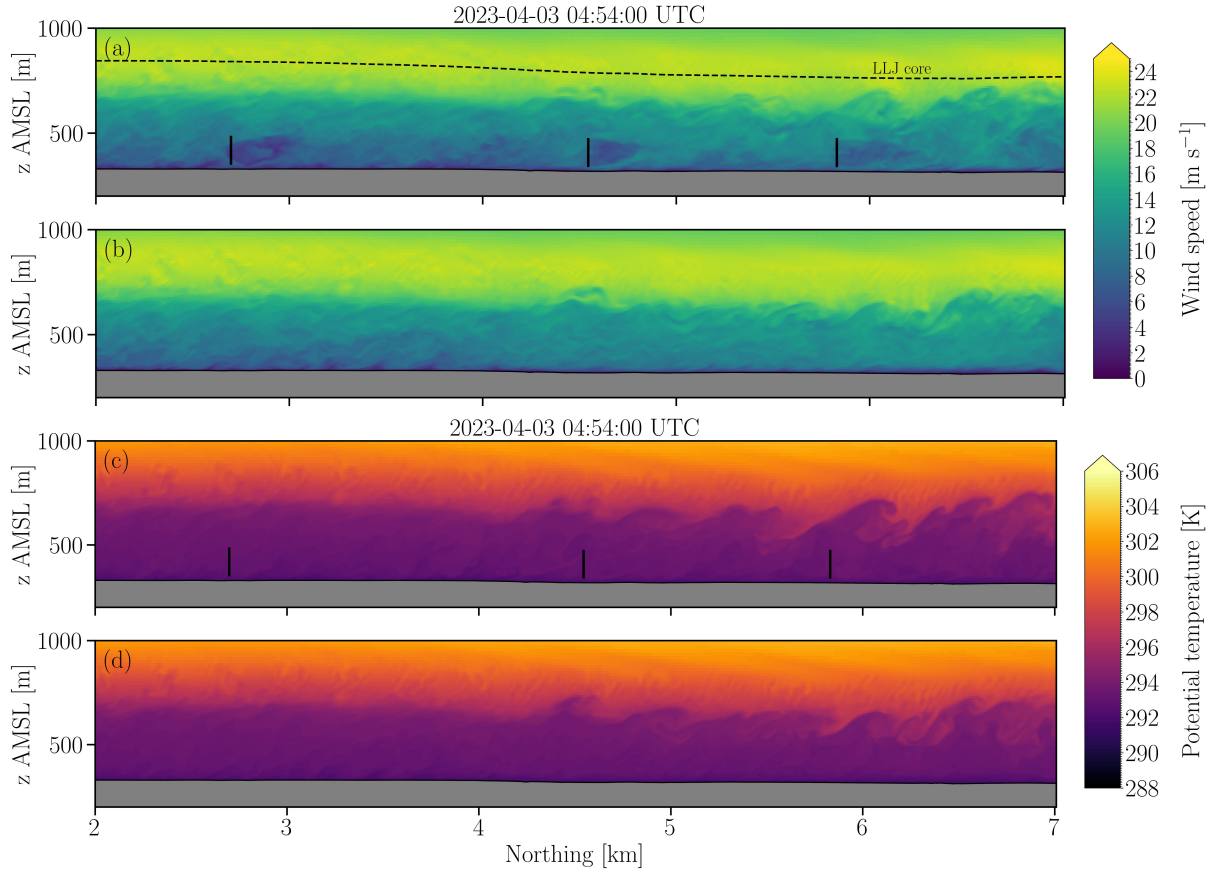


Figure 7. Vertical cross-sections in the south-north direction of wind speed (a, b) and potential temperature (c, d) for the simulation with (a, c) and without turbines (b, d). Videos with the complete time series of wind speed (Radünz, 2024d) and potential temperature (Radünz, 2024c) are provided as supplementary material.

Conversely, once formed, KHIs can feed back on the mean flow by reducing the wind shear and stratification, potentially impacting the spatial variability in wind speed (Section 4.1). The largest instabilities have length scales ranging from 100 to 200 m. Given that the effective resolution of the numerical model is approximately seven times the grid spacing ($7\Delta x$) (Skamarock, 2004), resolving these instabilities requires a grid finer than 15–30 m. Therefore, the KHI is only resolvable in the innermost domain, D3 ($\Delta x = 5$ m). This constraint is consistent with findings in the KHI literature (Zhou and Chow, 2014; Conrick et al., 2018). Additionally, the influence of microphysics schemes on KHI is examined in detail by (Conrick et al., 2018).

The vertical slices of wind speed and potential temperature reveal that the LLJ core region is displaced vertically (Fig. 7a–d). Near the third row, the distance between the LLJ core region and the turbine rotor is smaller than near the first row. This

328 increase in wind speed associated with the downward displacement of the LLJ agrees with the spatial variability in wind speed
observed in the maps at a fixed height AGL (Fig. 6a–c).

330 3.4 Spatial variability in the mean wind speed and wakes

This section evaluates how the variability in the wind speed and wakes are sustained over time. Thus, the focus is on the
332 behavior of the mean flow. First, we examine the horizontal variability in mean wind speed across different domains for the
simulation without turbines. The wider-scale domain D1 shows considerable spatial variability in wind speeds at 90 m AGL
334 (Fig. 8a). Domain D2 exhibits more detailed flow patterns (Fig. 8b), which includes an area with strong acceleration to the
south of domain D3 (Northing at about -10 km), followed by deceleration over the southern edge of the domain D3 (Northing
336 at about 0 km) and acceleration over the northern edge of the domain D3 (Northing at about 7 km). This pattern of acceleration-
deceleration-acceleration manifests across the whole of domains D1 and D2 due to terrain effects. At the highest resolution in
338 domain D3 and without turbines (Fig. 8c), the streamwise spatial variability in wind speed is between 6 m s^{-1} in the southwest
and 12 m s^{-1} in the north areas. In these stable conditions, the maximum wind speed does not always occur above the highest
340 elevation, but at a location slightly downstream of that elevation peak. Here, the strongest winds of about 12 m s^{-1} occurred
over the eastern turbines of the third row (F03–F05), which are located at lower ground ($z \sim 320 \text{ m AMSL}$) relative to the H05
342 turbine in the front row ($z \sim 330 \text{ m AMSL}$), as shown in Fig. A1c. Notice that the turbine F01 from the third row is located
at the highest elevation within domain D3 (Fig. 2c), but the winds over the third row are stronger near the turbines sited over
344 lower ground (F03–F05). Thus, the relatively poor performance of the first row relative to the second and third rows is not
driven by the upstream blockage effect (although this is certainly present), but by the terrain-induced spatial variability in wind
346 speed.

Having demonstrated the influence of the terrain-induced spatial variability of winds on farm performance, we assess the
348 variability in the wake effects. To delimit the extent of the wake, the time-averaged hub-height wind speed at a fixed height of
90 m AGL from the simulation without turbines (Fig. 9b) was subtracted from that of the simulation with turbines (Fig. 9a)
350 and the wind speed deficits ($WS_{wt} - WS_{nowt}$) with magnitudes smaller than 1 m s^{-1} were filtered out (Fig. 9c). The 1 m s^{-1}
threshold is adopted because a lower threshold (0.5 m s^{-1}) causes the wakes to merge, which complicates their individual
352 assessment. The wakes from the first and second rows reach the downstream latitudes of the second and third rows, respectively.
The wake centerlines from turbines H06–H08 are not fully aligned with the rotor centerline of the downstream turbines. Thus,
354 the wakes only partially reach the rotors with at least a 1 m s^{-1} deficit. Conversely, the wakes from the second row flow in
between the turbine rotors of the third row. Interestingly, the wakes of the H02 and H03 turbines in the front row are much
356 shorter than the others (H04–H08) in the same row. This variability can be explained by the slower inflow wind speeds for H02
(6.7 m s^{-1}) and H03 (7.1 m s^{-1}) in comparison with the remaining turbines ($7.7\text{--}10.7 \text{ m s}^{-1}$), which at these wind speeds,
358 considering the thrust coefficient variability of this turbine, produce a smaller thrust force (275 and 308 kN, respectively) and
thus a weaker wake (Fig. C1a). The expected thrust of the remaining turbines is between 362 and 380 kN and hence closer to
360 the maximum value of 380 kN in the thrust curve. Another possible explanation for the shorter wake of H02–H03 could be the
relatively stronger wake-added turbulence caused by the higher C_t that can enhance wake recovery (Letizia and Iungo, 2022).

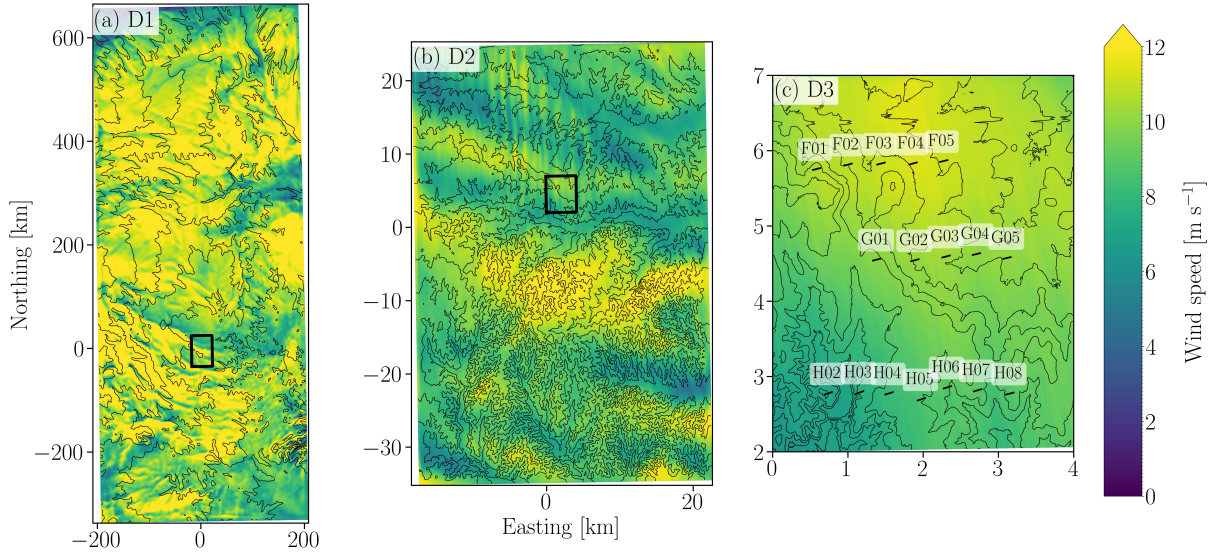


Figure 8. Time-average between 04:50 and 05:25 UTC of wind speed at 90 m AGL for domains D1 (left), D2 (center) and D3 (right) without turbines. The nested domain (black rectangle) and the vertical north-south cross-section (black line) are also illustrated.

Even if the thrust is lower in an absolute sense, H02–H03 ($C_t \sim 0.79$) are expected to have a higher coefficient of thrust (C_t) compared to the other generators in the domain (C_t between 0.42 and 0.79) and based on the C_t vs WS curve (Fig. C1b).

3.5 Vertical displacement and streamwise acceleration of the LLJ

This section analyzes how the interaction between the LLJ and the surrounding terrain leads to the observed horizontal gradients in wind speed. The multiscale influence of the terrain on the flow field is best pictured in north-south transects of wind speed (Fig. 10a–c) and vertical wind velocity (Fig. 10d–f) for domains D1, D2 and D3. The potential temperature isotherms aloft approximate the behavior of the mean flow streamlines and reveal undulations of various scales in the flow field, most clearly in domains D1 and D2. These undulations occur because, during the upslope flow, a low-level deceleration induces an upward component to the wind speed (positive vertical wind velocity) which displaces the LLJ core upwards. Conversely, during the downslope flow, a low-level acceleration occurs in phase with negative (subsiding) vertical wind velocity, and the LLJ core is displaced downwards. The buoyancy restoring forces acting on the initial, terrain-triggered up- and downward motions create and sustain the undulations. The local maximum in wind speed occurs not at the local topographic peaks, but is shifted downstream, typical of stable boundary layers (Baines, 1995). These peaks in acceleration are visible in the D1 domain near –300 (P1), –200 (P2), –60 (P3) and –7 km (P4) (Fig. 10a), the latter being closest to King Plains. In domain D2 (Fig. 10b), both the upstream acceleration near –7 km (P4) and a downstream acceleration near 6 km (P5) are identified, the latter being the responsible for most of the wind speed spatial variability within the farm. Notice that the maximum wind speeds occur near the transition between subsiding and ascending flow (see points P4 and P5 in Fig. 10b and e) because the wind is accelerating

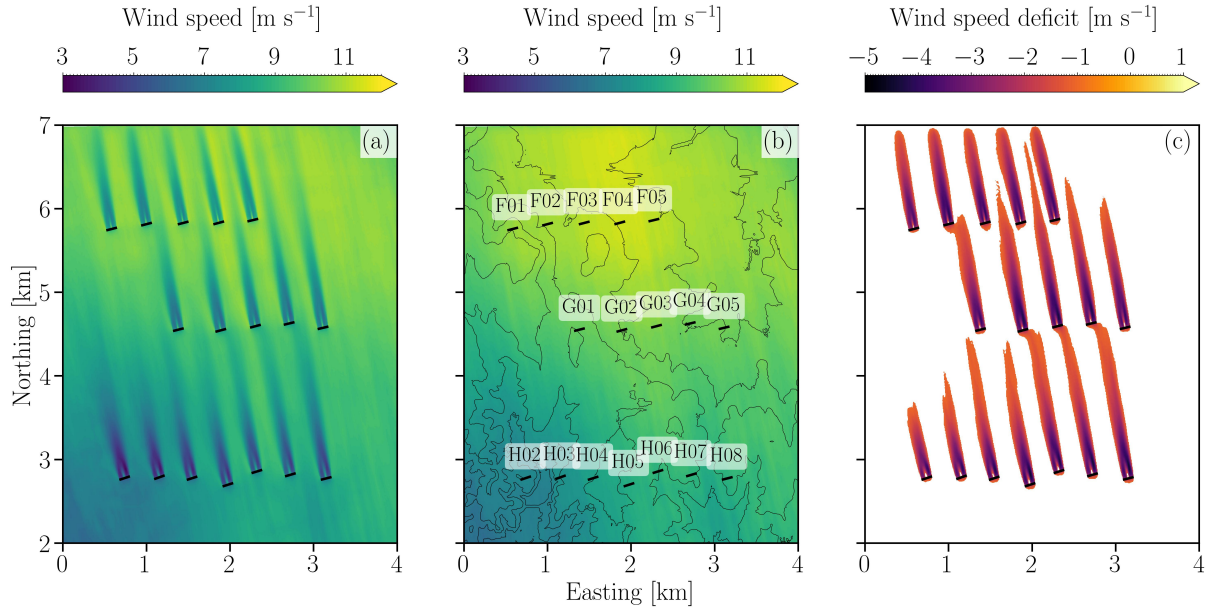


Figure 9. Time-average between 04:50 and 05:25 UTC of wind speed at hub height (90 m AGL) for the simulation with (a) and without (b) the turbines. The normalized wind speed deficit obtained by subtracting and normalizing the latter two indicates the extent of the wake region, considering a threshold of 1 m s^{-1} (c).

during the downslope phase. Even though the flow field undulation appears small in the microscale domain D3 (Fig. 10c), it brings the LLJ core down, closer to turbines in the second and third rows, enough to generate a measurable effect on power.

To better delineate the terrain-induced accelerations, the spatial variability in the wind speed is expressed as the difference from a reference value, which is adopted as being the profile at the first row, fr . Thus, the wind speed difference ($WS - WS_{fr}$) is essentially zero at the first row (Fig. 11a). A closer examination of the finest domain (Fig. 11a) reveals the streamwise wind speed difference that can reach 3 m s^{-1} over a distance of about 3 km downstream, forming a red layer below 300 m AGL. Above the red layer near 500 m AGL, there is a white layer of either positive or negative but small wind speed differences. Finally, near 600 m AGL there is a blue layer where the wind speed difference changes sign. An examination of the wind speed differences at fixed heights AGL (Fig. 11b) reveals positive wind speed differences in the range between 2 and 3 m s^{-1} over the third row of turbines for heights below 300 m AGL.

Thus, three vertical layers with distinct wind speed difference patterns are identified above the second and third rows (Fig. 11a). First, the red layer with strong streamwise acceleration. Second, the white layer with near-zero streamwise acceleration. Third, the blue layer above the LLJ nose with small negative wind speed difference. A plausible hypothesis for this pattern is the combination of vertical displacement and different sign and magnitude of the wind shear. For instance, the downward displacement of the LLJ at a height AGL where the shear is large and positive (such as below the LLJ nose) will lead to streamwise acceleration at that height. However, the downward displacement at a height where the shear is large but

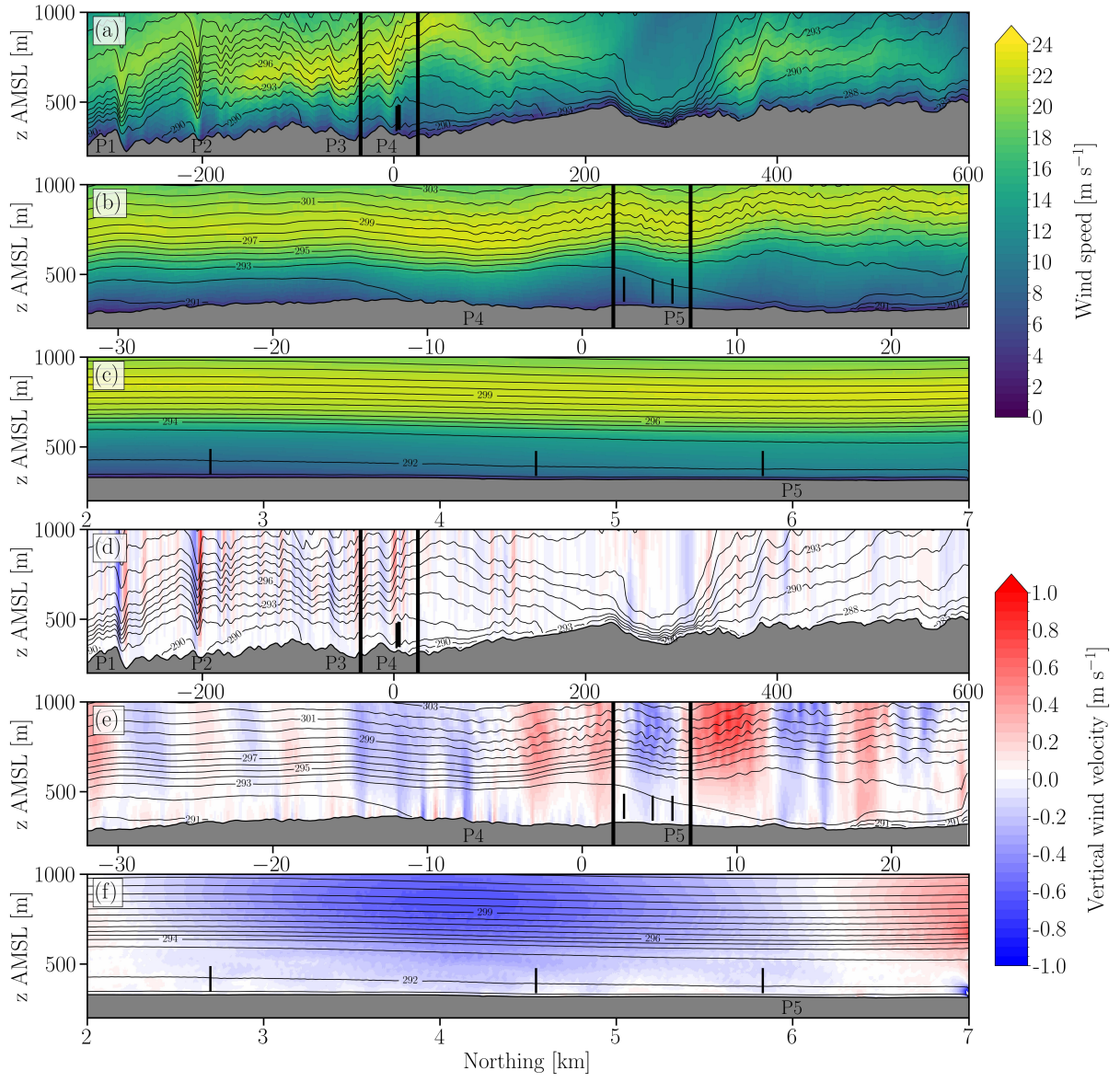


Figure 10. Vertical cross-sections in the south-north direction of wind speed (a–c) and vertical wind velocity (d–f) with potential temperature isocontours for domains D1 (a, d), D2 (b, e) and D3 (c, f). The nested domain (thick black vertical lines) and projected positions of the H05, G02 and F04 turbine rotors (thin black lines) are also shown. The points P1 to P5 mark the local maximums in wind speed induced by the terrain.

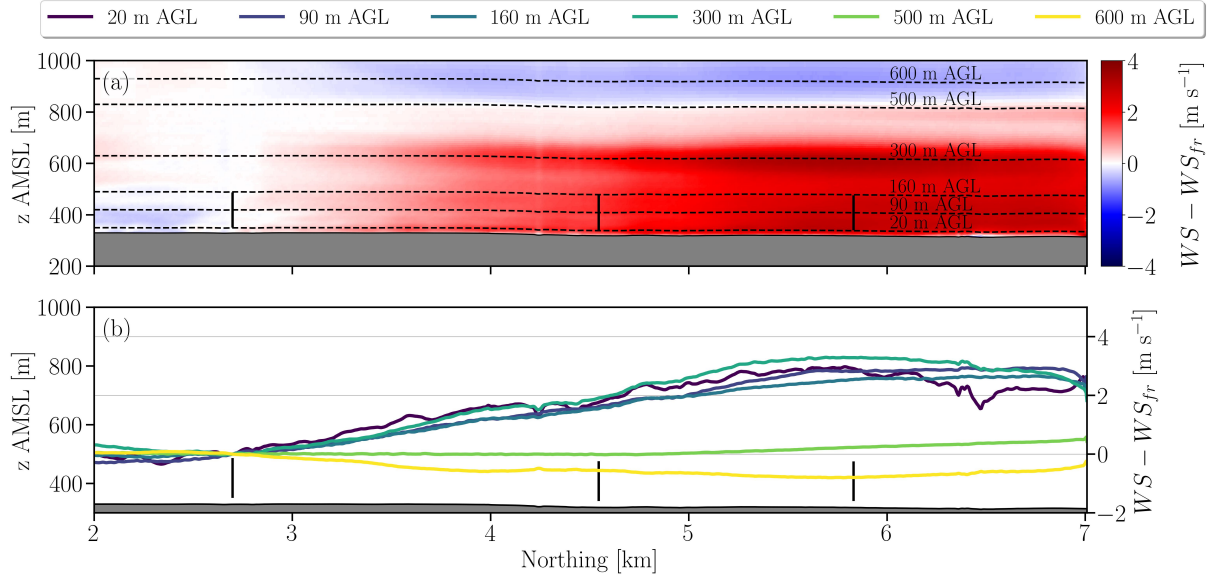


Figure 11. Vertical cross-section of wind speed difference relative to the front row profile ($WS - WS_{fr}$) for domain D3 in the simulation without turbines. The LLJ nose height is also displayed (a). Wind speed difference along terrain-following lines at fixed heights AGL (b). The black vertical lines indicate the projected positions of turbine rotors H05, G02, and F04 onto the vertical plane.

negative (such as above the LLJ nose) will lead to streamwise deceleration at that height. Likewise, if the shear is very small (such as near the LLJ nose) the vertical displacement will produce small changes in wind speed. We will refer to this as the “rigid LLJ displacement” hypothesis. It assumes that the streamlines of the mean flow experience no change in wind speed, but only undulate because of the vertical displacement. Simultaneously, the actual flow acceleration along the streamlines is also quantified. This approach enables assessing the individual contributions of both effects to the overall flow field acceleration at several heights (Fig. 12).

The streamlines are computed based on the bidimensional mean wind field using as starting points the heights between 20 and 600 m AGL near the inlet boundary (Fig. 12a). All streamlines are displaced downward (Δz) downstream of the first row (Fig. 12b). The maximum displacement occurs near the third row at a distance of 6 km and increases with height AGL. The displacement varies between about -15 m (20 m AGL) and -70 m (500 m AGL), and stabilizes between 500 and 600 m AGL. The actual wind speed differences along the streamlines (ΔWS_{str}) are close to 2 m s^{-1} at the lower levels (< 160 m AGL) near the third row (Fig. 12c). At the higher levels near and above the LLJ nose (500 and 600 m AGL), the speed-up along the streamlines is weaker ($< 1 \text{ m s}^{-1}$).

The influence of the vertical displacement of the streamlines on the wind speed difference (ΔWS_{vert}) is now assessed (Fig. 12d). The vertical displacement produces small speed-ups ($\sim 1 \text{ m s}^{-1}$) below 160 m AGL near the third row; a larger speed-up ($\sim 3 \text{ m s}^{-1}$) at 300 m AGL; a small slowdown at 500 m AGL ($> -1 \text{ m s}^{-1}$); and a large slowdown at 600 m AGL ($\sim -2 \text{ m s}^{-1}$). These variations in wind speed difference across streamwise distance and height AGL are explained by the

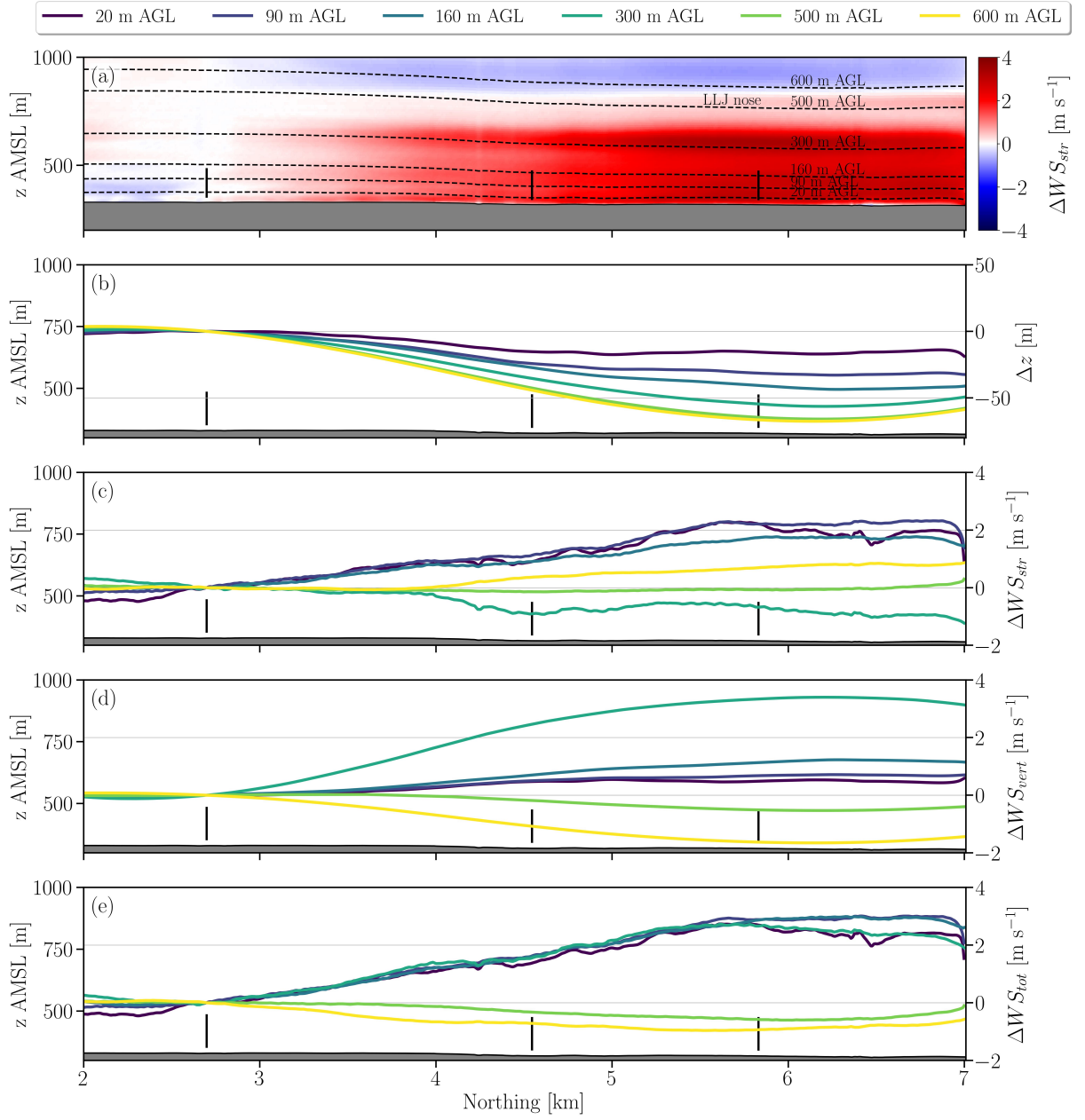


Figure 12. Vertical cross-section of wind speed difference relative to the front row profile ($WS - WS_{fr}$) for domain D3 in the simulation without turbines, with streamlines of the mean flow located between 20 and 600 m AGL near the inlet (a). The remaining subplots show the vertical displacement along the streamlines (Δz , b), actual change in wind speed along the streamlines (ΔWS_{str} , c), estimated change in wind speed caused by the vertical displacement of the LLJ (ΔWS_{vert} , d) and the estimated total change in wind speed of (c) and (d) combined (ΔWS_{tot} , e). The aforementioned variables are relative to the value at the front row. The black vertical lines indicate the projected positions of turbine rotors H05, G02, and F04 onto the vertical plane.

vertical variations in LLJ shear and magnitude of the downward displacement. For instance, at 300 m AGL the simulated wind shear has a local maximum (Fig. 4a) and the downward displacement is relatively large ($\Delta z \sim -50$ m), which creates a large $\Delta W_{S_{vert}}$. Conversely, at 600 m AGL the simulated wind shear is negative (Fig. 4a) and the vertical displacement is even larger ($\Delta z \sim -70$ m), which produces a large slowdown near the third row. Notice that downward displacement near the LLJ at 500 m AGL ($\Delta z \sim -70$ m) is similar to that of 600 m AGL, but the small wind shear (Fig. 4a) leads to a small wind speed difference. Thus far, the rigid LLJ hypothesis is corroborated.

If the conceptual description makes sense, the sum of the effects from the (i) rigid LLJ displacement and (ii) the actual acceleration along the streamlines should produce speed-ups similar to those shown in Fig. 11b. Interestingly, the maximum speed-up along the streamlines ($\Delta W_{S_{str}} \sim 2 \text{ m s}^{-1}$) occurs for the 20, 90 and 160 m AGL streamlines (Fig. 12c). The streamlines higher up at 500 and 600 m AGL attain speed-ups between 0 and 1 m s^{-1} . Thus, the terrain-induced effects are more pronounced at the lowest levels. When the vertical displacement (Fig. 12b) and the acceleration along the streamlines (Fig. 12c) are combined (Fig. 11e), they lead to a maximum speed-up of about 3 m s^{-1} for the streamlines at 20, 90 and 160 m AGL. This combined value of about 3 m s^{-1} is close to the maximum speed-up previously obtained at fixed heights AGL (Fig. 11b). The sum of $\Delta W_{S_{str}}$ and $\Delta W_{S_{vert}}$ also produces values consistent with Fig. 11b for the streamlines at 300, 500 and 600 m AGL.

Thus, both the (i) vertical displacement of the LLJ and the (ii) acceleration along the streamlines are important to the spatial variability in wind speed. The difference is that whereas (i) occurs at all heights and is dependent on wind shear, (ii) exerts most of its influence close to the ground. At 20 m AGL, about 18 % of the total speed-up is caused by the vertical displacement, the rest being associated with acceleration along the streamlines. This ratio increases higher up at 90 m AGL (23 %) and 160 m AGL (39 %). At 300 m AGL, the vertical displacement is responsible for most of the overall speed-up. Thus, the vertical displacement mechanism becomes more important with height because the vertical displacement also increases (Fig. 12b) and the streamlines accelerate less (Fig. 12c) with height.

4 Discussion

4.1 The role of LLJs in the terrain-induced spatial variability of nocturnal flows

In stable conditions, the low-level wind decelerates upstream of obstacles more than it would in neutral conditions because of the downward buoyancy (Mahrt and Larsen, 1990; Baines, 1995; Hunt et al., 1988) forcing the flow to stay at the same altitude rather than rising over the obstacles. Likewise, the flow accelerates more in the lee, and this combination enhances the spatial variability in wind speed. The Nh/U parameter is commonly used in the literature to describe stratified flows over topography (Baines, 1995; Sauer et al., 2016; Fernando et al., 2019). Here, $N = \sqrt{\frac{g}{T_v} \frac{\Delta \theta_v}{\Delta z}}$ is the Brunt-Vaisälä frequency, g is the gravity acceleration, T_v is the virtual temperature, $\Delta \theta_v$ and Δz are the difference in potential temperature and height between two vertical levels, respectively. Then, h is the characteristic height of the topographic feature and U is the wind speed. This behavior of stratified flows over terrain occurs, to a lesser or greater extent, in any SBL, with LLJs representing a particular case. This section explores how LLJs contribute to larger spatial variations compared to regular SBLs.

One key factor in this enhanced spatial variability is the high wind shear characteristic of LLJs. In Section 3.5, we identified a mechanism whereby wind shear combined with downward displacement of the mean flow streamlines causes wind turbines downstream to experience stronger winds than those upstream (Fig. 12a). Combining the magnitude of the downward displacement with a reference LLJ wind speed profile at the first row, which we denoted as the “rigid LLJ hypothesis”, we demonstrated that part of the spatial variability in wind speed is caused by the vertical variations in wind shear and the vertical displacement of streamlines. For instance, below the LLJ nose where the wind shear is high and positive (Fig. 4a), the downward displacement leads to a streamwise speed-up (the red layer in Fig. 12a, heights below 300 m AGL in Fig. 12d). Conversely, near the LLJ nose the shear is near zero, so that the downward displacement produces very small speed-ups (the white layer in Fig. 12a, at 500 m AGL in Fig. 12d).

Notice that the vertical displacement of the streamlines in the SBL is an important component for the spatial variability in wind speed. In this regard, the depth of the SBL plays a key role. Idealized numerical simulations revealed that for SBLs with the same wind speed and stratification, the case with a deeper layer produced a stronger acceleration in the lee of the obstacle (Durran, 1986). Thus, the Nh/U parameter was the same, with only a difference in H_{SBL}/h , where H_{SBL} is the depth of the SBL. One interpretation is that the buoyancy force acts over the stratified layer and it being too shallow restrains the magnitude of the acceleration. This feature was discussed in experimental and theoretical works on stratified flow and obstacles (Long, 1955; Baines, 1995). More recently, a field measurement campaign and numerical simulations revealed the evolution of strong downslope flow in the Alaiz mountain (Santos et al., 2020; Peña and Santos, 2021). After the evening transition, the recently formed SBL developed into a LLJ. However, the spatial variability in the wind over the mountain becomes large only later on when the SBL becomes deeper. Then, the wind accelerates down the slope and produces lee waves. A similar process was also described in the Perdigo field campaign, where the maximum wind speed was not at the top of topographic features, but rather further downstream (Fernando et al., 2019). Likewise, a wind farm with two rows of turbines located in complex terrain experienced a similar nocturnal pattern in the wind (Radünz et al., 2021, 2022). On average, very stable conditions dominated in the early nighttime, whereas weakly stable conditions dominated in the late nighttime (Radünz et al., 2021). However, the back rows outperformed the front rows consistently only in the late nighttime. That apparent inconsistency was attributed to the SBL being deeper later on, despite being less stratified (Radünz et al., 2022). One important implication of this fact is that the LLJs later in the nighttime are likely associated with deeper SBLs and more prone to higher spatial variability. Our analysis refers to 5 hours after the evening transition, which allows the SBL to develop a reasonable depth.

The relatively weak winds near the surface, caused by the high wind shear, also could make LLJs more prone to large spatial variability. In Zhou and Chow (2014), multiscale LES were used to investigate cold air pooling and a turbulence intermittency mechanism. The valley was oriented in the east-west direction (similar to ours), whereas the winds were southerly. They discussed that considering the relatively simple terrain (small h) and the relatively high wind speed (high U), the low Nh/U value suggests that the cold air would be swept away from the valley towards the north. However, the valley shelters the cold air from the stronger wind aloft, so that the cold pool remains. This rationale could be adapted to interpret our results. The strong LLJ (nose wind speed $> 20 \text{ m s}^{-1}$) and the simple terrain ($h \sim 10\text{--}50 \text{ m}$) would suggest small terrain-induced effects (low Nh/U). Nonetheless, because of the high shear the wind speed is considerably smaller in the rotor layer (from 6 to

10 m s⁻¹) and the Nh/U parameter is larger. Because of the higher Nh/U , the weaker surface winds are more susceptible to deceleration up the slope, and consequently upper layers of the LLJ are displaced upwards. Conversely, the low-level wind accelerates down the slope and the LLJ moves downwards. This process creates the spatial variability in wind speed (Fig. 11). The flow acceleration along the streamlines, shown to be more pronounced near the ground and weaker higher up, is related to this feature (Fig. 12b). Finally, the temporal evolution of the LLJ typically involves wind intensification, an increase in stable boundary layer depth, and clockwise rotation, a process that is already heterogeneous over the SGP (Smith et al., 2019). Local terrain-induced effects further modify an already heterogeneous process. When considering wind farm performance at larger scales in the SGP, both the large-scale spatiotemporal variability described by Smith et al. (2019) and local terrain influences should be accounted for.

Accounting for the spatial variability of LLJs of different depths is also relevant for turbine loads. Atmospheric stability influences turbine loads by modulating shear and turbulence (Sathe et al., 2013a; Porté-Agel et al., 2020). Strong, high-nose LLJs (Krishnamurthy et al. (2025); Figure 6) can increase axial loads due to enhanced shear (Gadde et al., 2021), while weaker, shallower LLJs may expose turbines to negative shear and reduce loads. Neglecting the spatial variability in wind speed can also bias load predictions in multiscale simulations (Shaler et al., 2024).

Therefore, aspects related to wind shear and SBL depth associated with the LLJ reported here, and with LLJs in general, make it susceptible to terrain-induced accelerations. In that situation, even simple terrain can induce streamwise changes in wind speed capable of significantly impacting wind farm performance patterns.

4.2 Comparison with other physical mechanisms that modulate wind farm performance in stable conditions

This section discusses how the terrain-induced spatial variability in wind speed compares with other physical processes that influence farm performance in stable boundary layers, such as wind farm blockage and wakes. The literature discussion below applies a spatial variability metric that measures the degree of horizontal wind speed variations associated with each process, computed as the amplitude of the wind speed deviation or deficit caused by the process divided by a reference wind speed ($\Delta WS/WS_{ref}$).

The terrain-induced variability in wind speed reported here is about 4 m s⁻¹ over a distance of 5 km, or 50 % for a reference wind speed of 8 m s⁻¹ (Fig. 11). Consequently, the second and third downstream rows of turbines produced between 20 and 50 % more power than the first row (Fig. 5). Based on the Nh/U parameter, given the same inflow wind speed (U) and stratification (N), the more complex terrain (higher h) likely amplifies the magnitude of the flow field variability relative to simpler terrain (Baines, 1995). For instance, when Nh/U increases from 1.56 to 2.84, that produces low-level flow blockage and a more acute acceleration near the lee (Fig. 5.3 in Baines (1995)). At a wind farm built over a plateau with an elevation change of 100–150 m upstream and 160–300 m downstream, a wind speed difference of the order of 3–4 m s⁻¹ was identified between two rows of turbines separated by a distance of about 1 km (Radünz et al., 2021, 2022). That is the same order of variability reported here (~ 4 m s⁻¹ over 5 km) but over a much shorter distance. Not surprisingly, at times the turbines in the back row in that investigation produced twice as much power as those in the front row.

In Liu and Stevens (2021), a contrasting mechanism for a terrain-induced enhancement in power performance during a LLJ emerged. In the idealized LES simulation, a single wind turbine was positioned downstream of a single hill. The performance enhancement was attributed to the higher momentum entrainment from the LLJ that was caused by the hill wake. We argue that despite this mechanism being possible in other situations, during stable conditions the attached flow tends to minimize hill wakes. Most importantly, the mechanism described by the linear wave theory and towing tank experiments (shallow water equations) is unrelated to turbulent transport, but to modifications experienced by the mean flow (Baines, 1995). The terrain-induced spatial variability in wind for stable boundary layers and LLJs literature (Santos et al., 2020; Peña and Santos, 2021; Radünz et al., 2021, 2022) and the results we report on belong to the latter type (Baines, 1995).

There is consensus that wind turbine (Schepers et al., 2012; Abkar and Porté-Agel, 2015) and farm wakes (Barthelmie and Jensen, 2010; Hansen et al., 2012; Abkar et al., 2016; Lundquist et al., 2018; Krishnamurthy et al., 2025; Porté-Agel et al., 2020) recover slower in stable conditions because of the weaker entrainment of momentum into the wake. Idealized LES studies report wind speed deficits between 20 and 30 % at downstream distances between $8D$ and $12D$ for a single wind turbine (Abkar and Porté-Agel, 2015) and up to 50 % for a wind farm (Abkar et al., 2016) in stable conditions. Our results reveal a wind speed deficit of about 1 m s^{-1} ($\sim 12.5 \%$) over the second and third rows of turbines (Fig. 9). In part, differences can arise from different power curves from turbine models and operating conditions. However, high turbulence levels (Hansen et al., 2012) and veer (Abkar et al., 2016) are known to enhance wake recovery. To some extent, the somewhat weaker wakes reported here could be a byproduct of the relatively high TKE, since this LLJ is strong (Banta, 2008; Klein et al., 2015), and wind veer. Therefore, the terrain-induced spatial variability in wind speed of about 4 m s^{-1} ($\sim 50 \%$) overshadows the variability associated with the wake deficits of our study ($\sim 12.5 \%$) and scales with the deficits associated with idealized simulations of wind farms in stable conditions ($< 50 \%$) (Abkar et al., 2016).

The terrain-induced spatial variability in wind speed acting over different turbines is between 6.7 and 10.7 m s^{-1} and causes a variability in the region of operation of individual turbine power curves (Fig. C1a,b). As a result, turbines H02–H03 experience a smaller thrust force (275 and 308 kN, respectively) than the other turbines (between 362 and 380 kN) (Fig. C1a). This combination of effects is a plausible reason for the spatial variability in the wakes (Fig. 9c) and can have an important outcome for wind farm control, which is considered to be most useful in the stably stratified conditions such as considered here (Fleming et al., 2019). Porté-Agel et al. (2020) discussed two aspects that modulate wind farm wakes and performance. The first is the diurnal cycle and its modulation of stability, turbulence, shear and veer, discussed in the previous paragraph. The second is the presence of terrain induces a non-zero streamwise pressure gradient, vertical displacement of the wake center, and flow separation. Based on our work, it can be added that the interplay between terrain and stability, particularly in the case of LLJs (Section 4.1), is an important source of wind farm wake variability, even for simple terrain. It was pointed out that challenges in complex terrain (associated with the spatial variability of winds) should be addressed in future studies (Meyers et al., 2022). The AWAKEN project site was selected owing to the lesser terrain complexity and has ongoing wind farm control studies (Moriarty et al., 2024). The existence of spatial variability in wake effects, as revealed by turbines H02 and H03 (Fig. 9c), highlights that accounting for terrain effects, however simple the terrain may be, is important for wind farm control. Some multiscale models, such as AMR-Wind, do not yet consider topographic effects, and how this influence will be

548 considered for model intercomparison and testing the AWAKEN scientific hypotheses is an open problem. Thus, wind farm control strategies will likely be influenced by this terrain-induced variability.

550 Previously, we discussed that the low-level deceleration upstream and acceleration downstream of topographic obstacles displaces the LLJ vertically, and is a source of spatial variability in wind speed (Section 4.1). A similar process occurs when
552 wind farm wakes decelerate the wind speed and the LLJ is displaced vertically (Wu and Porté-Agel, 2017; Larsén and Fischereit, 2021; Krishnamurthy et al., 2025; Quint et al., 2025) even without the presence of terrain. In a numerical investigation
554 of a conventionally-neutral boundary layer, the exit region of the wind farm displayed flow acceleration compared with the entrance region (Wu and Porté-Agel, 2017). Immediately downstream, the flow experienced further acceleration owing to (i) the
556 boundary layer adjustment and (ii) the downward displacement of the stratified free-atmosphere (their Figure 4). Even though a conventionally-neutral boundary layer is different from a SBL, the concept associated with the streamwise acceleration in
558 the exit region and downstream is similar, the release of turbulent stresses induced by the “roughness” of the turbines. Therefore, accounting for and quantifying the terrain-induced and wind-farm-induced spatial variabilities is important for wind farm
560 performance assessments.

The spatial variability associated with terrain, demonstrated here, is an order of magnitude larger than that due to upstream
562 blockage. According to the literature, the blockage effect may produce a maximum slowdown in the wind speed of about 10 % and often below 5 % (Wu and Porté-Agel, 2017; Bleeg et al., 2018; Sebastiani et al., 2021; Schneemann et al., 2021; Sanchez
564 Gomez et al., 2022). Using Reynolds-averaged Navier-Stokes simulations with turbines represented as actuator disks, Bleeg et al. (2018) showed that the blockage effect produced an average slowdown of 3.4 % of the free wind at a distance of two
566 rotor diameters upstream, and an average slowdown of 1.9 % at seven to ten rotor diameters upstream. Another study used multiscale simulations at the same King Plains wind farm during a LLJ episode (Sanchez Gomez et al., 2022). The slowdowns
568 associated with the blockage effect varied between 8 % (0.64 m s^{-1}) and 1 % immediately upstream and $24D$ upstream of the first row of turbines, respectively. At an offshore wind farm during stable conditions and with turbines operating in the
570 high-thrust coefficient regime, the blockage was about 4 % upstream the wind farm (Schneemann et al., 2021). In Wu and Porté-Agel (2017), the maximum blockage $2.5D$ upstream of the first row of turbine was 0.8 to 1.2 % (weak free-atmosphere
572 stratification) and 10 to 11 % (strong free-atmosphere stratification). This means that the spatial variability in wind speed associated with blockage ($\sim 1\text{--}10\%$) is likely one order of magnitude smaller than that of the terrain ($\sim 50\%$).

574 Finally, whereas the farm performance is especially sensitive to wakes and blockage in high thrust coefficient conditions and environmental conditions associated with strong stratification and low TI, the terrain-induced variability can affect performance
576 from cut-in to near-rated wind speeds and during weaker stratification and high TI scenarios. These three effects will also modulate performance differently across different wind speed, direction, stability and turbulence conditions. Also, the terrain
578 complexity further enhances the terrain-induced variability.

5 Conclusions

580 Stratified flows over terrain have always attracted scientific interest from engineers and atmospheric scientists. The flow pat-
582 terns that include lee waves and hydraulic jumps have been observed in controlled laboratory experiments as well as in field
584 campaigns in the natural environment. Advances in wind energy now demand a deeper understanding of the behavior of stable
boundary layers (SBLs) and nocturnal low-level jets (LLJs) as they interact with wind farms and the surrounding landscape.
The scientific literature generally attributes challenges to *complex terrain*, but the results we report suggest that even sites that
do not belong to that category, which we denote *simple terrain*, may experience important terrain-induced spatial variability in
the wind resources.

Using both observations and multiscale numerical simulations of a strong LLJ at the AWAKEN campagin, we show that
588 even simple terrain can induce important accelerations in the flow field. Furthermore, specific attributes of LLJs that may
separate them from regular stable boundary layers when it comes to the terrain-induced spatial variability in wind speed. For a
590 site in simple terrain in stable conditions, the expectation is that the downstream turbines will likely produce less energy than
the upstream turbines because of the wake effects. However, here, results from a realistically-forced multiscale simulation with
592 the WRF-LES-GAD approach were corroborated by the wind farm SCADA data to reveal that turbines in the front row were
actually outperformed by those in the second (SCADA = 25 %, WRF = 44 %) and third (SCADA = 51 %, WRF = 51 %) rows.
594 This performance variability occurred because of terrain-induced spatial variability in wind speeds, which produced stronger
winds over the second and third rows. The relatively simple terrain, combined with certain attributes of the LLJ, induces a
596 streamwise speed-up of up to 4 m s^{-1} over a distance of 5 km. The mechanism underlying this acceleration is related to the
vertical displacement of the LLJ combined with the high positive wind shear below its nose. Near the ground, the wind also
598 decelerates or accelerates along the mean flow streamlines. Higher up, the acceleration along the streamlines is smaller, and
the vertical displacement (undulation) of the streamlines (in response to low-level flow de/acceleration) causes the downstream
600 wind speeds at the same height above ground level (AGL) to increase. Conversely, near the LLJ nose where the wind shear
is near-zero, the vertical displacement produces small variations. Above the LLJ nose, where the wind shear is negative, the
602 downward displacement produces small slowdowns.

The terrain-induced spatial variability in wind speed associated with the LLJ has implications to the wind farm performance
604 and control literature. The aforementioned effect can not only be important at sites with apparently simple terrain, but also scale
with or even overshadow the degree of variability associated with other mechanisms that modulate wind farm performance,
606 such as turbine wakes and wind farm blockage. Wind farm control is regarded as one of the grand challenges in wind energy
science. Thus, the horizontal gradients in wind speed induced by even simple terrain should be accurately represented in the
608 numerical tools that implement farm control.

Future work should address how the long term terrain-induced spatial variability in wind speed is influenced by the diurnal
610 cycle. Specifically, work could assess (i) differences between the unstable (typically daytime) and stable (typically nighttime)
conditions, (ii) non-LLJ and LLJ stable cases and (iii) the role of the SBL depth and wind shear in the spatial variability in wind
612 speed. This research direction is important because more statistical significance of unstable and stable boundary layer flows

will enable drawing contrasts on how they modulate spatial variability in wind speed. Furthermore, it can help to elucidate the key parameters that describe the spatial variability in wind speed. One of the main challenges is to distinguish the terrain-induced acceleration effects from other processes that also produce spatial variability in wind speed, such as wind farm wakes, blockage and dynamic events. If successful, however, this inquiry will lead to a deeper understanding of how physical processes in the atmospheric boundary layer influence wind farm flows and performance in the long term. These insights can guide the development of computational frameworks to improve the design and operation of modern wind farms.

Code and data availability. The AWAKEN observations are available online at the Data Archive Portal (DAP) at <https://a2e.energy.gov/>, except for the turbine SCADA data, which is proprietary. Links to the observations used in this paper can be accessed at Letizia and Bodini (2023); Pekour (2023); Shippert and Zhang (2016); Wharton (2023). The WRF-LES-GAD model framework version 4.3 is available at https://github.com/a2e-mmc/WRF/tree/mmc_update_v4.3 (which is not the same version we used). The WRF-LES-GAD model framework version 4.1.5 can be made available upon request. The terrain and land-use data can be downloaded at U.S. Geological Survey. (2020, 2019). The HRRR data can be downloaded from [https://noaa-hrrr-bdp-pds.s3.amazonaws.com/hrrr.202304\[DD\]/conus/hrrr.t\[HH\]z.wrfnatf00.grib2](https://noaa-hrrr-bdp-pds.s3.amazonaws.com/hrrr.202304[DD]/conus/hrrr.t[HH]z.wrfnatf00.grib2), where [DD] should be replaced with the dates of interest, including the spin-up period (i.e., 02 and 03 April 2023), and [HH] with the UTC hour of the analysis. The WRF model setup files for the two simulations can be accessed at Radünz (2024a).

Video supplement. Temporal evolution of streamwise transects of wind speed (Radünz, 2024d) and potential temperature (Radünz, 2024c). Temporal evolution of wind speed maps at 90 m AGL (Radünz, 2024b).

Appendix A: Detailed terrain elevation profiles

Although the terrain might initially appear complex, the elevation variations occur over large horizontal distances. In domain D1 (Fig. A1a), the maximum variation in elevation is approximately 300 m ($\approx 500\text{--}200$ m AMSL) over a horizontal distance of about 900 km. In domain D2 (Fig. A1b), two notable topographic features are evident. The first is a larger feature spanning -30 to 0 km, with a characteristic height (h) of about 60 m ($\approx 360\text{--}300$ m AMSL). The second is a smaller feature spanning 0 to 10 km, with a characteristic height of about 30 m ($\approx 330\text{--}300$ m AMSL).

Within the wind farm area (domain D3; Fig. A1c), elevation variations are even more subtle, with a maximum difference of about 10 m ($\approx 330\text{--}320$ m AMSL) between the first and second/third rows of turbines. Despite this minimal elevation variation, the downstream rows experience stronger winds (Fig. 8c) and higher energy production (Fig. 5).

Appendix B: Turbulence spin-up fetch

Turbulence is considered fully developed when the streamwise changes in the $\overline{w'w'}$ profile become relatively small. Near the inflow boundary (Northing = 0 km), turbulence is virtually absent, as indicated by $\overline{w'w'}$ values near zero at all heights

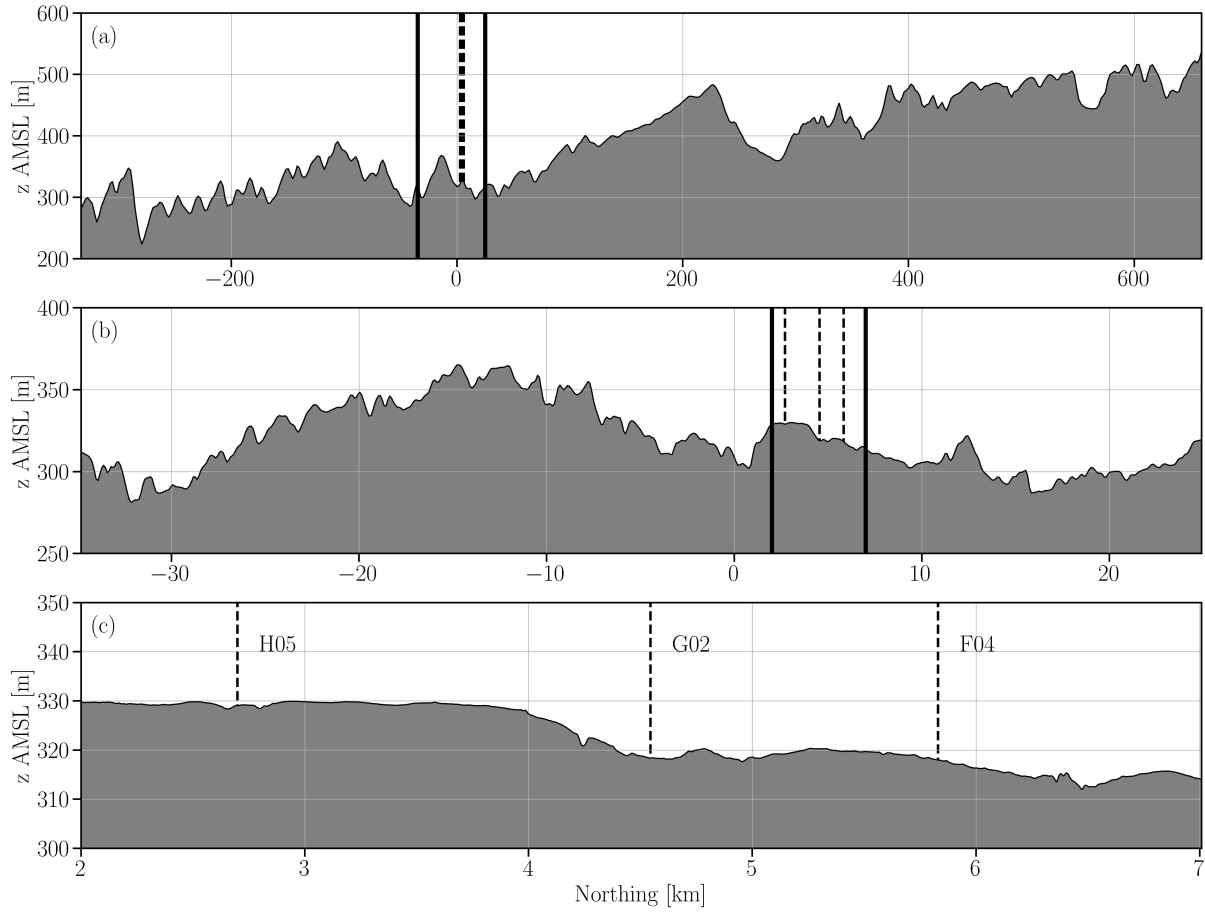


Figure A1. Terrain elevation profiles along a north-south transect for domains D1 (a), D2 (b), and D3 (c). The solid black vertical lines delimit the nested domains, while the dashed vertical lines mark the locations of turbines in the first (H05), second (G02), and third (F04) rows.

(Fig. B1). At Northing 0.5 km, the $\overline{w'w'}$ profile exhibits overexcited turbulence compared to profiles at downstream locations below 100 m AGL. Between Northing 1.5 km and 2 km, the $\overline{w'w'}$ profiles show better agreement, suggesting that turbulence has spun up. The $\overline{w'w'}$ profiles in this region also align closely with those observed at the A1 site, including observational data (Fig. 4e). Consequently, we adopted a 2 km fetch as the spin-up region (Fig. 2c).

Appendix C: Turbine power curves and mean wind speed

The theoretical curves shown in Fig. C1a,b are derived from the OpenFAST implementation, where an IEA reference turbine was scaled to approximate the characteristics of the GE 2.8 MW turbines installed in King Plains (Quon, 2022). Since the detailed specifications of these turbines are proprietary, this scaling provides a representative but not exact model. The GAD

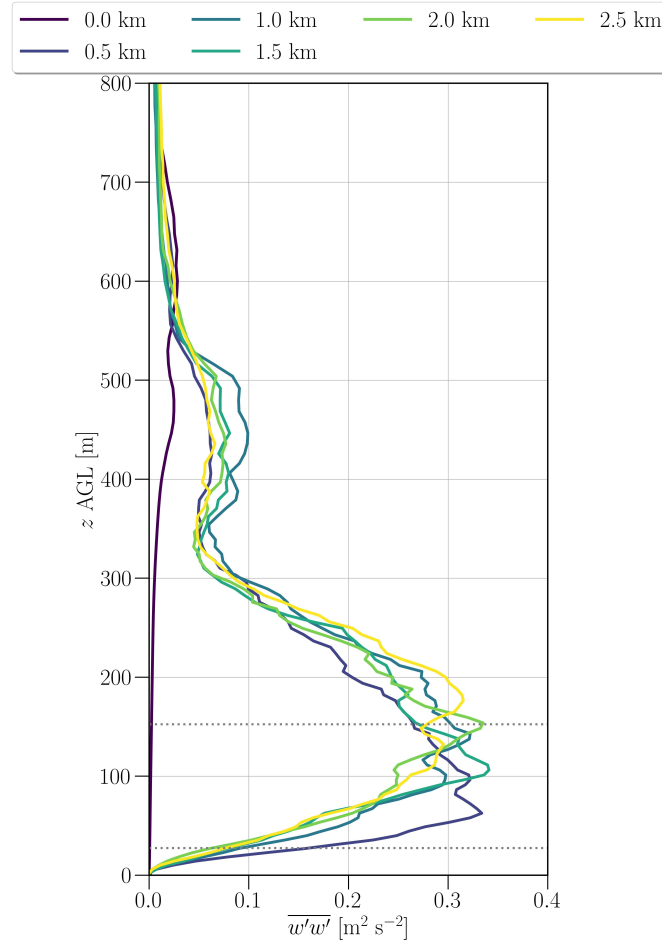


Figure B1. Profiles of vertical wind velocity variance ($\overline{w'w'}$) along a north-south transect at selected distances from the southern boundary inflow. The time average spans the period from 04:50 to 05:25 UTC, with a temporal resolution of 5 s.

approach does not directly use these curves. Instead, it relies on the same turbine rotor speed and pitch control curves, along
650 with the blade aerodynamic properties, that generate the power and thrust curves in OpenFAST. The GAD then computes the
axial and tangential forces acting on the rotor disks, which in turn influence the momentum tendencies (Mirocha et al., 2014;
652 Aitken et al., 2014; Arthur et al., 2020).

The spatial variability in turbine performance is evident in Fig. C1a,b. The wind speed across turbines varies significantly,
654 ranging from approximately 6.7 to 10.7 m s^{-1} , representing a difference of about 4 m s^{-1} . As a result, some turbines in the first
row (H02–H04) operate in Region 2 of the power curve, with generator power values between 1000 and 1500 kW (Fig. C1a).
656 In contrast, turbines in the third row (F01–F05) operate near or at rated capacity (2820 kW).

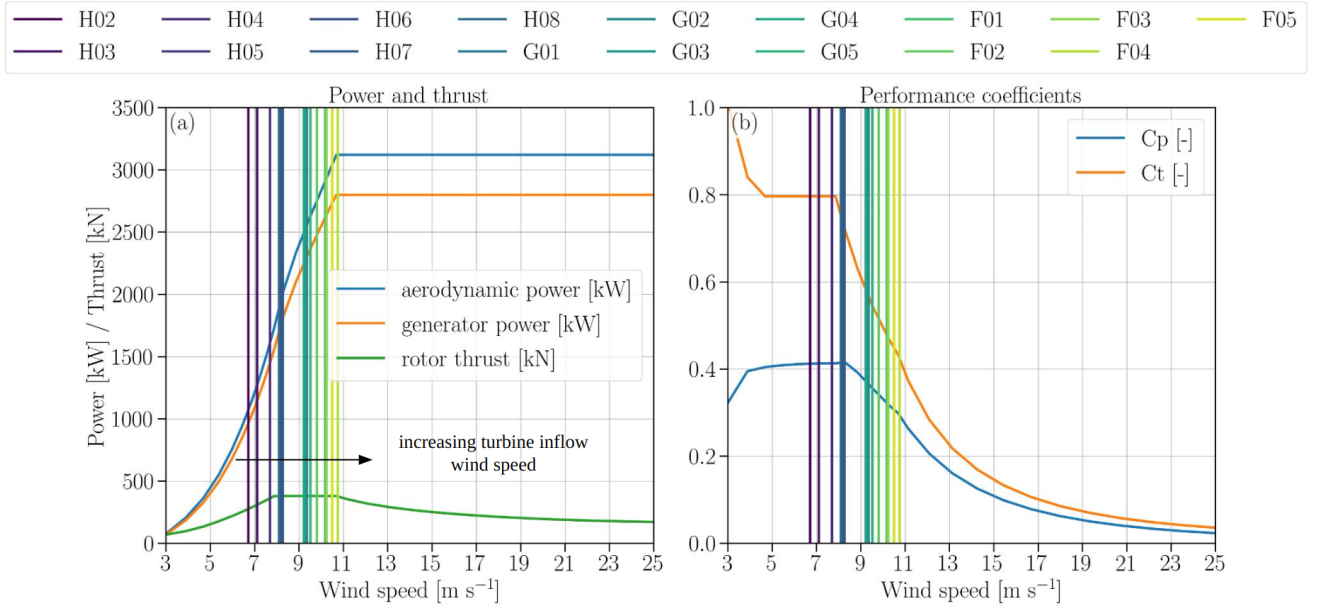


Figure C1. Theoretical aerodynamic, generator power, and rotor thrust curves for the NREL 2.82 MW turbine (Quon, 2022) (a). The power (C_p) and thrust (C_t) coefficient curves (b). The mean wind speed at hub height upstream of the turbines is calculated for the simulation with turbines and is shown as vertical lines.

Variability is also observed in the thrust force (Fig. C1a) and thrust coefficient (C_t) (Fig. C1b). These differences, combined with variations in the mean wind speed that transports wakes downstream, result in complex wind speed and wake fields. This complexity poses challenges for effective wind farm control.

Appendix D: Multiscale simulation flowchart

Fig. D1 illustrates the multiscale simulation framework used in this study. The setup follows a nested domain configuration, with boundary conditions passed down through one-way coupling from the mesoscale to the LES domains. This schematic complements the description provided in Section 2.2, highlighting the sequential activation of domains and the localized application of the CPM (Muñoz-Esparza et al., 2014, 2015; Muñoz-Esparza and Kosovic, 2018) and GAD (Mirocha et al., 2014; Aitken et al., 2014; Arthur et al., 2020) models in D3.

Author contributions. WR, BSC, JKL and NH conceptualized the work. WR carried out the simulations. WR, SL and AA did the data curation and formal analysis. WR did the investigation. WR, ASW, MSG and RKR worked on the simulation methodology. WR prepared the original draft. All authors reviewed and edited the manuscript.

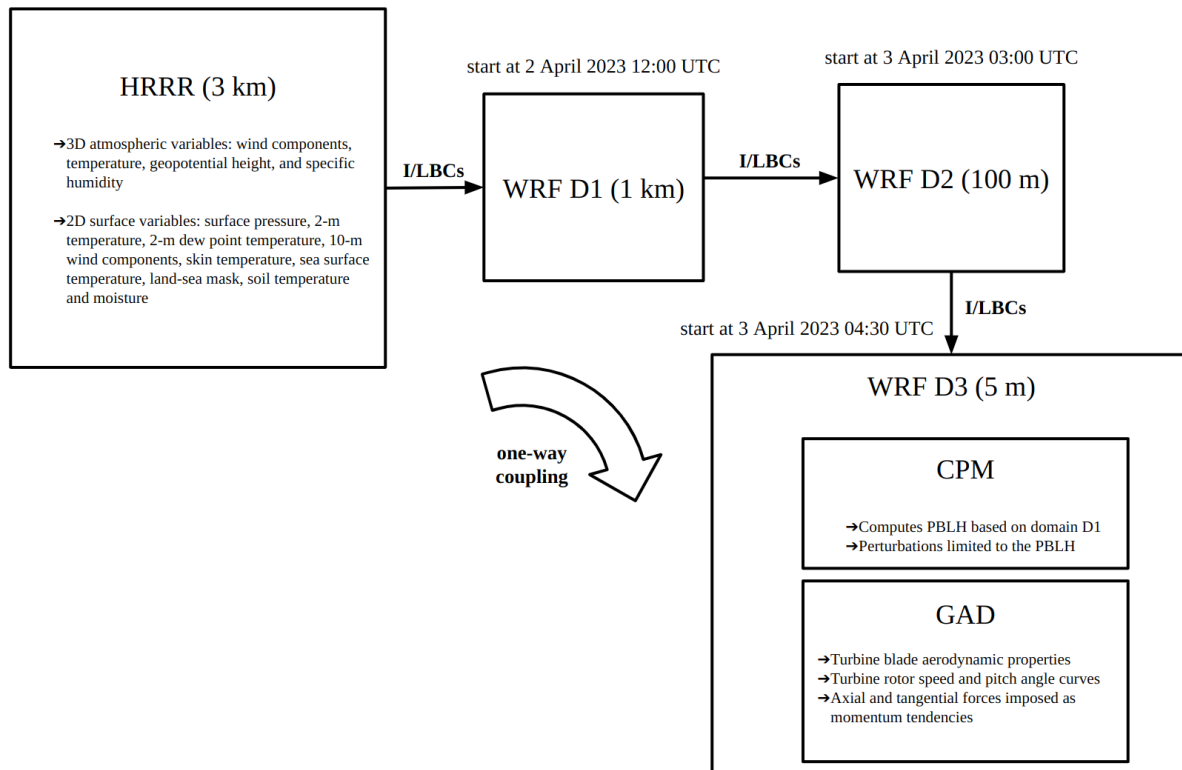


Figure D1. Multiscale simulation flowchart: The HRRR analysis dataset (hourly frequency) provides initial and lateral boundary conditions (I/LBCs) for the mesoscale domain D1 in WRF. The nested LES domains D2 and D3 receive I/LBCs from their respective parent domains (D1 and D2) through one-way coupling, meaning no feedback occurs to the parent domains. To reduce computational cost, the domains are activated sequentially in time. The Cell Perturbation Method (CPM) and Generalized Actuator Disk (GAD) are applied only in the innermost domain D3.

Competing interests. At least one of the (co-)authors is a member of the editorial board of *Wind Energy Science*.

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