



Effect of atmospheric stability transition on wind-turbine wake dynamics

Dachuan Feng^{1,3}, Wen Zhang², Minping Wan², and Simon J. Watson³

¹College of Automotive and Energy, Tongji University, 201804 Shanghai, China

²Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, 518055 Shenzhen, China

³Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, Netherlands

Correspondence: Simon J. Watson (S.J.Watson@tudelft.nl)

Abstract. The diurnal transition of the atmospheric boundary layer from thermally stable to unstable stratification subjects wind turbines to rapidly evolving inflow, yet the wake dynamics during this non-equilibrium period remain poorly characterized. Here we use measurement-assimilated large-eddy simulation to reconstruct the boundary-layer evolution observed on 26 September 2023 at the King Plains wind farm during the American WAKE experimeNt (AWAKEN) field campaign, and we analyze the resulting turbine wake and power production across three regimes identified during the transition: stable, transitional, and unstable. As the boundary layer becomes increasingly unstable, the hub-height turbulence intensity increases by roughly an order of magnitude compared to stable night-time conditions and the characteristic length scale of atmospheric motion grows from a few rotor diameters to the full boundary-layer depth. Resolvent analysis, applied around the time-averaged wake in each regime, show that the dominant wake-turbulence mechanism shifts from a single low-rank, shear-driven coherent structure under stable stratification to a higher-rank, buoyancy-driven state under unstable stratification, with the transitional regime exhibiting hybrid behavior. The array-averaged power, its variability, and its spectral content change significantly over a period of a few hours, demonstrating that steady-state stability classifications do not adequately represent the dynamics of the diurnal cycle.

1 Introduction

Wind turbines operate within the lowest few hundred metres of the atmosphere, where the vertical profiles of wind speed, wind direction, and turbulence intensity are strongly modulated by the thermal stratification of the atmospheric boundary layer. Under stable conditions, typically prevailing at night, reduced vertical mixing produces strong wind shear across the rotor plane, suppressed turbulence levels, and persistent wake deficits that propagate far downstream. Conversely, convective conditions during the daytime promote vigorous turbulent mixing, more uniform velocity profiles, and rapid wake recovery. The correlation between atmospheric stability and wake behaviour has been established through field observations, wind tunnel experiments, and numerical simulations over the past two decades, and stability is now recognized as one of the most important meteorological variables governing wind farm efficiency.



Large-eddy simulation (LES) has emerged as the primary computational tool for investigating the three-dimensional, unsteady structure of wind turbine wakes under varying atmospheric conditions. Numerous LES studies have examined wind turbine wakes separately under stable, neutral, and convective boundary layers, revealing distinct wake characteristics in each regime. Abkar and Porté-Agel (2015) found that the growth rate of wind turbine wakes under convective conditions is approximately 2.4 times larger than under stable conditions, attributing this to enhanced turbulent mixing driven by buoyancy production. Xie and Archer (2017) systematically studied single-turbine and wind-farm wakes across three stability regimes and showed that wake expansion is predominantly lateral under stable stratification but vertical under unstable conditions, with the Coriolis-induced wind veering producing significant wake deformation that challenges commonly assumed Gaussian self-similarity profiles. Du et al. (2021) further decoupled atmospheric stability from turbulence intensity and demonstrated that even at identical hub-height turbulence levels, stability independently regulates wake recovery by redistributing turbulent kinetic energy among directional components and altering the spatial scales of atmospheric motion. More recently, Wang et al. (2025) employed proper orthogonal decomposition (POD) and spectral proper orthogonal decomposition (SPOD) techniques to show that the dominant mechanism of wake meandering transitions from passive modulation by large-scale inflow structures under convective conditions to active development driven by internal shear layer instabilities under stable stratification. Complementing these numerical studies, nacelle-lidar field observations by Menken and Wildmann (2026) confirm that wind veer and the shear exponent, both closely tied to atmospheric stability, correlate strongly with lateral wake-center deflection, vertical wake skewness, and near-wake length, providing field-scale validation for the stability-dependent wake deformation predicted by LES.

While these studies have substantially advanced our understanding of wake behaviour under canonical, quasi-steady stability regimes, real atmospheric conditions rarely conform to such steady-state representations. Driven by the diurnal cycle of solar radiation, the atmospheric boundary layer (ABL) undergoes continuous transitions between stable and convective states, especially at inland sites, with particularly rapid changes during the morning and evening. The morning transition, in which a shallow, stably stratified nocturnal layer evolves into a deep, well-mixed convective layer within a few hours, is of special significance for wind energy: the nocturnal low-level jet, the sign of the surface heat flux (and thus the thermal stratification), and the turbulence structure all change simultaneously. Tian et al. (2020) demonstrated through LES of an idealized diurnal cycle that the rotor-layer wind shear exponent can vary from as low as 0.05 under convective conditions to as high as 0.5 under stable conditions, with hub-height turbulence intensity differing by a factor of two to three and average power output differing by approximately 24.4% between daytime and nighttime.

Several studies have since examined wake behavior during stability transitions directly. An early study by Lee and Lundquist (2017) combined coordinated lidar and meteorological-tower observations with mesoscale WRF wind-farm-parameterization simulations to characterize wake evolution during the evening transition, showing that the wake-induced turbulence enhancement and velocity deficit become increasingly confined to the rotor layer and more persistent as the boundary layer restabilizes; however, their mesoscale parameterization could not resolve the three-dimensional, turbulence-scale wake structure that a turbine-resolving LES provides. Tian et al. (2020) demonstrated through LES of an idealized diurnal cycle that the rotor-layer wind shear exponent can vary from as low as 0.05 under convective conditions to as high as 0.5 under stable conditions, with



hub-height turbulence intensity differing by a factor of two to three and average power output differing by approximately 24.4% between daytime and nighttime. Xiao et al. (2025) conducted a comprehensive 24-hour LES of an eight-turbine farm coupled to a one-dimensional soil heat-conduction model, revealing enhanced nighttime ground warming downwind of the farm and a power-production anomaly in which downstream turbines generated more power than upstream ones during the morning transition. Idealized diurnal-cycle simulations nonetheless remain limited by their smooth, sinusoidal thermal forcing, constant geostrophic wind, and horizontally homogeneous initial and boundary conditions, none of which capture the intermittent, site-specific character of real transitions; they also require several diurnal cycles of spin-up, and, as Xiao et al. (2025) noted, remain sensitive to numerical resolution, particularly under stable nighttime stratification.

These considerations motivate an alternative, measurement-assimilated approach, in which observational data from meteorological instruments are used to constrain the LES toward the realistic, evolving atmospheric state observed during a specific transition event, rather than an idealized approximation of one. By ingesting observed profiles of wind speed, wind direction, and temperature, it is possible to reproduce the height and strength of the low-level jet, the intensity of the surface inversion, and the rate of convective boundary-layer growth actually experienced by the turbines, while eliminating the need for multi-day spin-up and enabling direct comparison with concurrent power, lidar, or meteorological tower measurements. The morning stable-to-unstable transition is especially well suited to this approach: it is inherently transient and non-equilibrium, so that the wake reflects the history of preceding conditions as well as the instantaneous atmospheric state; it involves the coexistence of features from both stability regimes, such as a residual low-level jet alongside a growing convective internal boundary layer; and it is when some of the most operationally significant phenomena occur, including rapid changes in wind direction that challenge turbine yaw control, and the anomalous power production patterns identified by Xiao et al. (2025).

In this study, we employ measurement-assimilated (Allaerts et al., 2023; Quon, 2024; Feng et al., 2026) LES to characterize wind turbine wake flow during the transition from thermally stable to unstable stratification at a utility-scale wind farm, analyzing the wake structure, velocity deficit recovery, turbulence characteristics, and power production as functions of the evolving stability conditions. By grounding the simulation in observed atmospheric conditions rather than idealized forcing, we aim to bridge the fundamental understanding of wake–stability interactions established through canonical studies with the complex, site-specific reality of wind farm operation during one of the most dynamically active periods of the diurnal cycle.

The remainder of the paper is organized as follows. We introduce the AWAKEN field campaign, the target transition event, and the measurement-assimilated LES setup, together with the resolvent-analysis post-processing method, in Sect. 2. We then analyze the identification of the three stability regimes and their effects on wake turbulence generation, wake recovery, and turbine power production in Sect. 3. Finally, we present our conclusions in Sect. 4.

2 Methodology

We performed measurement-assimilated large-eddy simulations of the morning boundary-layer transition observed on 26 September 2023 at the King Plains wind farm in the American WAKE experimeNt (AWAKEN) field campaign. This sec-

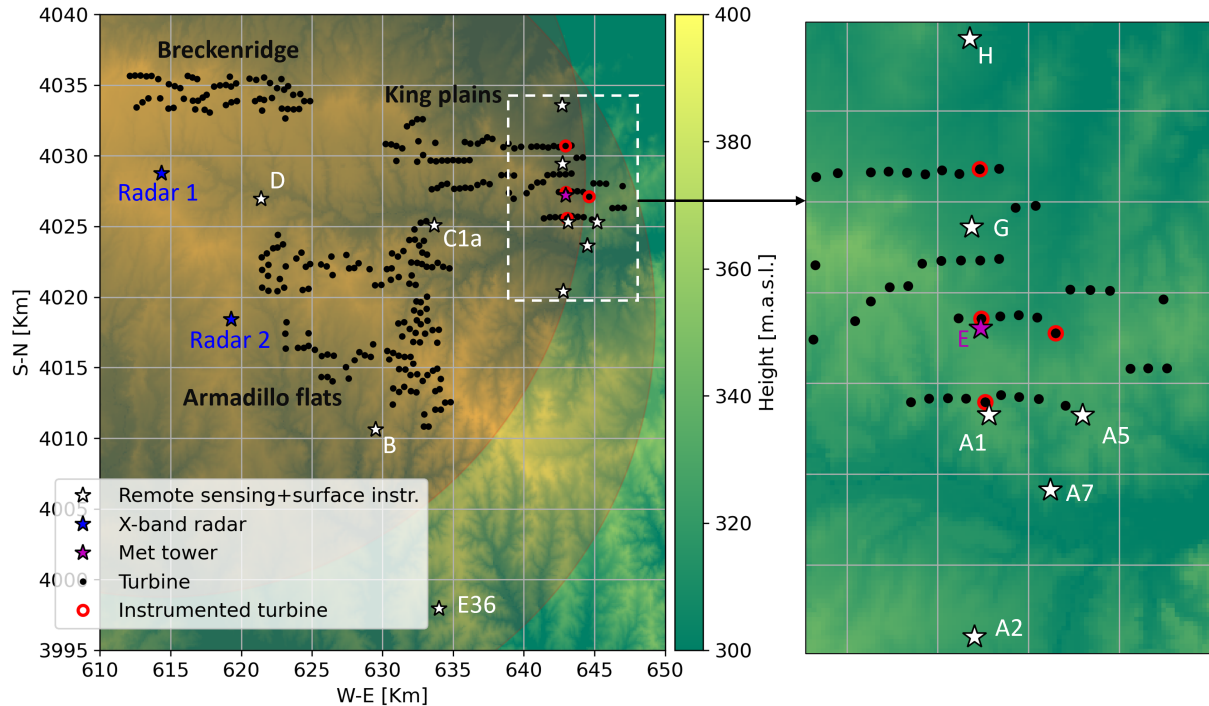


Figure 1. Layout of the AWAKEN sites (Moriarty et al., 2024). Black dots represent wind turbines and black dots with red circles represent the AWAKEN instrumented turbines. Orange partial circles on the left represent the range of the X-band radars.

tion describes the field campaign and the associated observational data, the assimilation strategy for the atmospheric flow, the simulation setup of the turbine flow, and the resolvent-analysis method used to analyze the wake dynamics.

2.1 The AWAKEN field campaign and target transition event

AWAKEN is a large-scale field campaign designed to deliver detailed, co-located observations of wind farm–atmosphere interactions, with the overarching goal of advancing understanding of wind-farm physics and improving operational performance (Moriarty et al., 2024). The campaign instruments several wind farms in the Southern Great Plains of Oklahoma, a region well known for the frequent occurrence of nocturnal low-level jets (LLJs) and strong diurnal cycles. For the present study, we focus on the morning transition of 26 September 2023, during which the boundary layer evolved from a stably stratified nocturnal state, featuring a pronounced LLJ at rotor-layer heights, to a fully convective state by the early afternoon. This event was selected because (i) the vertical extent of the LLJ and the associated shear span the rotor swept area of a utility-scale turbine, (ii) the transition is well captured by the continuous lidar profiling, and (iii) and (iii) the wind direction remained sufficiently steady to permit the use of observations at met mast site A1 as a single-point inflow reference for simulations of downstream wind turbines.

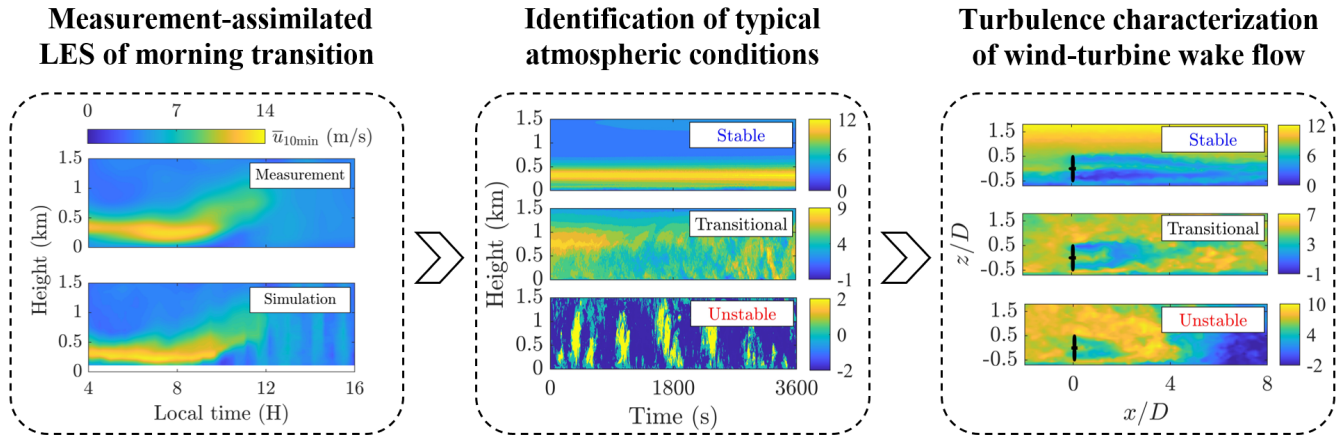


Figure 2. Schematic of turbine simulation under various thermal stability conditions.

A measurement-assimilated LES framework is developed to drive a simulation of a single wind turbine and a row of three identical wind turbines with a realistic representation of the evolving atmospheric state, as shown in Fig. 2. The approach
 105 couples the mesoscale-to-microscale capabilities of SOWFA (Simulator for Wind Farm Applications; Churchfield et al., 2012) with the high spatio-temporal resolution of the AWAKEN lidar measurements. The simulation is carried out in two sequential stages: (i) an inflow simulation, which assimilates the lidar observations to reconstruct the full three-dimensional turbulent boundary-layer state experienced by the turbine(s); and (ii) a turbine simulation, which models the wake flow under the assimilated inflow using an actuator-disk-with-rotation (ADMW) representation of the rotor. These two stages are described in the
 110 following sub-sections.

2.2 Measurement-assimilated large-eddy simulation

In the first stage, the inflow simulation solves the spatially filtered incompressible Navier–Stokes equations for mass and momentum together with a transport equation for potential temperature. The momentum equation contains two additional source terms. The first accounts for mesoscale forcing and is computed using the indirect profile assimilation method of Allaerts
 115 et al. (2020). This technique continuously adjusts the body force so that the horizontally averaged LES solution reproduces the observed time–height profile of wind speed and wind direction, thereby ensuring that the simulated boundary-layer structure, including the height and strength of the LLJ and the depth of the convective internal boundary layer, faithfully reflects the conditions experienced by the turbines during the target event. Missing observations close to the ground are reconstructed using a natural-neighbour interpolation technique (Allaerts et al., 2023) prior to assimilation. The second source term in the
 120 momentum equation accounts for the Coriolis force due to planetary rotation.

The thermodynamic state is prescribed by specifying an initial potential-temperature profile that captures the surface-based nocturnal inversion, a residual near-neutral layer aloft, and a capping inversion at approximately 1250 m, in agreement with the vertical distribution of wind speed shown in Fig. 3. The subsequent evolution of the temperature field is then advanced by the



LES, forced at the surface by a time-dependent heat-flux boundary condition that drives the transition from stable to unstable stratification. Subgrid-scale effects are parameterized using the standard one-equation turbulent kinetic energy (TKE) model of Deardorff (1980).

The computational domain is a rectangular channel of dimensions $3000 \times 3000 \times 1500$ m in the streamwise, spanwise, and vertical directions, respectively, discretized on a uniform grid of $300 \times 300 \times 150$ cells. A slip-wall condition with zero velocity gradient is imposed at the top boundary; the bottom boundary employs a local-similarity logarithmic wall model (Moeng, 1984; Feng et al., 2024a) to account for viscous and subgrid-scale stresses, with an effective aerodynamic roughness of 0.1 m representative of the flat onshore terrain at the King Plains site. Periodic conditions are applied at the lateral boundaries, consistent with the horizontally homogeneous assimilation target. The inflow simulation is integrated over the full diurnal window of interest (04:00–16:00 local time), with the first hour allocated to spin-up. Velocity and potential-temperature slices at the downstream plane of the domain are saved every 0.5 s and serve as the time-varying inflow condition for the subsequent turbine simulation.

Figure 3 compares the simulated and measured time–height histories of 10-min-averaged wind speed and virtual potential temperature. The simulation reproduces both the nocturnal LLJ and its breakdown after sunrise (approximately 07:00 local time), as well as the accompanying erosion of the surface-based inversion, confirming that the assimilated inflow provides a realistic representation of the morning transition.

In the second stage, the effect of the wind turbine is incorporated through an additional body-force term in the momentum equations. The turbine is represented by the NREL 5-MW reference model (Jonkman, 2009), a three-bladed horizontal-axis machine with a rotor diameter of $D = 126$ m and a hub height of 90 m. Although the operational turbines at King Plains are General Electric 2.8-MW units, the geometric discrepancies are minor (rotor diameter 127 m vs. 126 m; hub height 88.5 m vs. 90 m), so that the NREL reference model serves as an acceptable proxy for the present preliminary investigation. The cut-in wind speed is 3 m/s.

The rotor forcing is modeled using the actuator-disk method with rotation of Wu and Porté-Agel (2011), which has been demonstrated to yield good agreement with both wind tunnel measurements and high-fidelity simulations in the far-wake region that governs wind-farm-scale flow (Yuan et al., 2023; Stevens et al., 2018). The effects of the nacelle and tower are neglected. For this single-turbine preliminary study, the rotor is operated at a constant rotational speed of 9 rpm; a fully controlled rotor will be considered in future work addressing the full King Plains array.

The turbine is placed $5D$ downstream of the inflow boundary. The assimilated inflow slices from Sect. 2.2 are imposed at the upstream boundary, and a Rayleigh damping layer is applied near the outflow to suppress spurious wave reflections. The remaining boundary conditions (top, bottom, and lateral) are identical to those of the precursor simulation. Flow-field statistics and turbine power are collected over a subdomain spanning $-2 \leq x/D \leq 8$, $-2 \leq y/D \leq 2$, and $-0.7 \leq z/D \leq 2$, with the origin placed at the rotor hub center and x , y , and z denoting the streamwise, spanwise, and vertical coordinates, respectively.

Throughout the paper, instantaneous streamwise, spanwise, and vertical velocity components are denoted by u , v and w , while their time-averaged counterparts are denoted by U , V and W . Time averaging is performed over one-hour windows



centred on each of the three stability regimes defined below, corresponding to statistically quasi-stationary segments of the evolving boundary layer.

160 2.3 Resolvent analysis

To identify the linear mechanisms responsible for the energetic coherent structures observed in the wake under each stability regime, we perform resolvent analysis around the corresponding time-averaged wake flow, following the framework developed for wind-turbine far wakes by Feng et al. (2024b). The formulation is summarized here, and the reader is referred to Feng et al. (2024b) for a complete description and validation.

165 Applying the Reynolds decomposition $\mathbf{q} = [\mathbf{u}^T, p]^T = \mathbf{Q} + \mathbf{q}'$, where $\mathbf{u} = [u_x, u_r, u_\theta]^T$ is the velocity vector, p the density-normalized pressure, and $\mathbf{Q}$ and $\mathbf{q}'$ the time-mean and fluctuating components, respectively, the incompressible Navier–Stokes equations governing the fluctuations can be written as

$$\nabla \cdot \mathbf{u}' = 0, \quad (1)$$

$$\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{u}' + (\mathbf{u}' \cdot \nabla) \mathbf{U} = -\nabla p' + \nabla \cdot [\nu_{\text{eff}} (\nabla \mathbf{u}' + \nabla \mathbf{u}'^T)] + \mathbf{f}, \quad (2)$$

170 where $\mathbf{f} = [f_x, f_r, f_\theta]^T$ is an external forcing that represents the nonlinear fluctuation–fluctuation interactions, and $\nu_{\text{eff}} = \nu + \nu_t$ is the effective viscosity composed of the molecular viscosity ν and an eddy viscosity ν_t that models the dissipative action of the unresolved small-scale turbulence on the energetic structures. Although Eq. (2) is linear in $\mathbf{q}'$, the effect of the nonlinear term is retained through the combined action of the forcing $\mathbf{f}$ and the eddy-viscosity term.

Equations (1) and (2) can be written compactly as

$$175 \quad \mathbf{M} \frac{\partial \mathbf{q}'}{\partial t} + \mathbf{A} \mathbf{q}' = \mathbf{B} \mathbf{f}, \quad (3)$$

with

$$\mathbf{M} = \begin{bmatrix} \mathbf{I} & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \mathcal{L} & \nabla(\cdot) \\ \nabla \cdot (\cdot) & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{I} \\ 0 \end{bmatrix}, \quad (4)$$

where $\mathbf{I}$ is the identity operator and $\mathcal{L} = \mathbf{U} \cdot \nabla(\cdot) + (\cdot) \cdot \nabla \mathbf{U} - \nabla \cdot [\nu_{\text{eff}} (\nabla(\cdot) + \nabla(\cdot)^T)]$ is the linearized Navier–Stokes operator built from the regime-specific mean flow $\mathbf{U}$ and eddy viscosity ν_t .

180 Following the common practice in engineering wake models, the mean wake of each regime is approximated as axisymmetric, and the analysis is restricted to the vertical plane passing through the rotor center. The fluctuating variables $\mathbf{q}' = [u'_x, u'_r, u'_\theta, p']^T$ and the forcing $\mathbf{f} = [f_x, f_r, f_\theta]^T$ are then expanded in a Fourier basis in the azimuthal direction and time,

$$\mathbf{q}'(x, r, \theta, t) = \sum_m \sum_\omega \hat{\mathbf{q}}_{m\omega}(x, r) e^{i(m\theta - \omega t)}, \quad (5)$$

$$\mathbf{f}(x, r, \theta, t) = \sum_m \sum_\omega \hat{\mathbf{f}}_{m\omega}(x, r) e^{i(m\theta - \omega t)}, \quad (6)$$



185 where m is the integer azimuthal wavenumber and ω is the angular frequency. Substituting Eqs. (5)–(6) into Eq. (3) yields the input–output relation

$$(-i\omega\mathbf{M} + \mathbf{A}_m)\hat{\mathbf{q}}_{m\omega} = \mathbf{B}\hat{\mathbf{f}}_{m\omega}, \quad \hat{\mathbf{y}}_{m\omega} = \mathbf{C}\hat{\mathbf{q}}_{m\omega}, \quad (7)$$

where $\mathbf{A}_m$ is the frequency-independent linearized operator at azimuthal wavenumber m and $\mathbf{C} = [\mathbf{I} \ 0]$ extracts the velocity output. Eliminating $\hat{\mathbf{q}}_{m\omega}$ gives $\hat{\mathbf{y}}_{m\omega} = \mathbf{H}_{m\omega}\hat{\mathbf{f}}_{m\omega}$, where

$$190 \quad \mathbf{H}_{m\omega} = \mathbf{C}(-i\omega\mathbf{M} + \mathbf{A}_m)^{-1}\mathbf{B} \quad (8)$$

is the resolvent operator. Its singular value decomposition $\mathbf{H}_{m\omega} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^*$ ($*$ denotes conjugate transpose) provides a set of forcing modes $\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \dots]$ and response modes $\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, \dots]$, ranked by the amplitude gains $\mathbf{\Sigma} = \text{diag}(\sigma_1, \sigma_2, \dots)$ with $\sigma_1 \geq \sigma_2 \geq \dots$. A large separation σ_1/σ_2 (low-rank behavior) indicates that a single coherent structure dominates the response, in which case the leading response mode closely resembles the energetic structures educed from the data.

195 Dirichlet conditions $\mathbf{u}' = p' = 0$ are imposed at the inflow and lateral boundaries, and a mixed velocity–pressure condition is applied at the outflow to minimize spurious reflections. The conditions along the turbine centerline depend on the parity of m , following the standard treatment for cylindrical coordinates. The operator is discretized with a second-order central-difference scheme on a uniform grid. The analysis is performed within the range $0.05 \leq St \leq 1$, where $St = fD/\bar{u}_{\text{hub}} = \omega D/(2\pi\bar{u}_{\text{hub}})$, which spans the dominant frequencies of far-wake turbulent kinetic energy (TKE) generation. Consistent with previous studies
 200 of axisymmetric wakes and jets, the optimal gains peak at $|m| = 1$; we therefore focus on the $m = 1$ modes throughout. Grid resolution and domain extent were verified to give converged gain spectra and mode shapes, following the convergence study reported in Feng et al. (2024b).

The eddy viscosity is evaluated separately for each stability regime from the resolved statistics of that regime as

$$\nu_t(x, r) = -\frac{\overline{u'_x u'_r}}{\partial \bar{u}_x / \partial r}, \quad (9)$$

205 i.e., as the ratio of the resolved Reynolds shear stress to the mean shear. Negative values arising from the local breakdown of the gradient-diffusion hypothesis are set to zero, and the field is smoothed with a Savitzky–Golay filter prior to use, as in Feng et al. (2024b). We emphasize that, in the present formulation, the thermal stratification enters the resolvent operator only indirectly, through the regime-specific mean wake $\mathbf{U}$ in Eq. (4) and the regime-specific eddy viscosity ν_t in Eq. (9); no explicit buoyancy term or potential-temperature equation is included in the linearized operator. This incompressible, eddy-viscosity-augmented
 210 formulation is therefore best regarded as a leading-order linear model whose accuracy is expected to be highest under stable and near-neutral conditions and to degrade as buoyancy production becomes dominant. The implications of this approximation are discussed in Sect. 3.2 and in the conclusions.

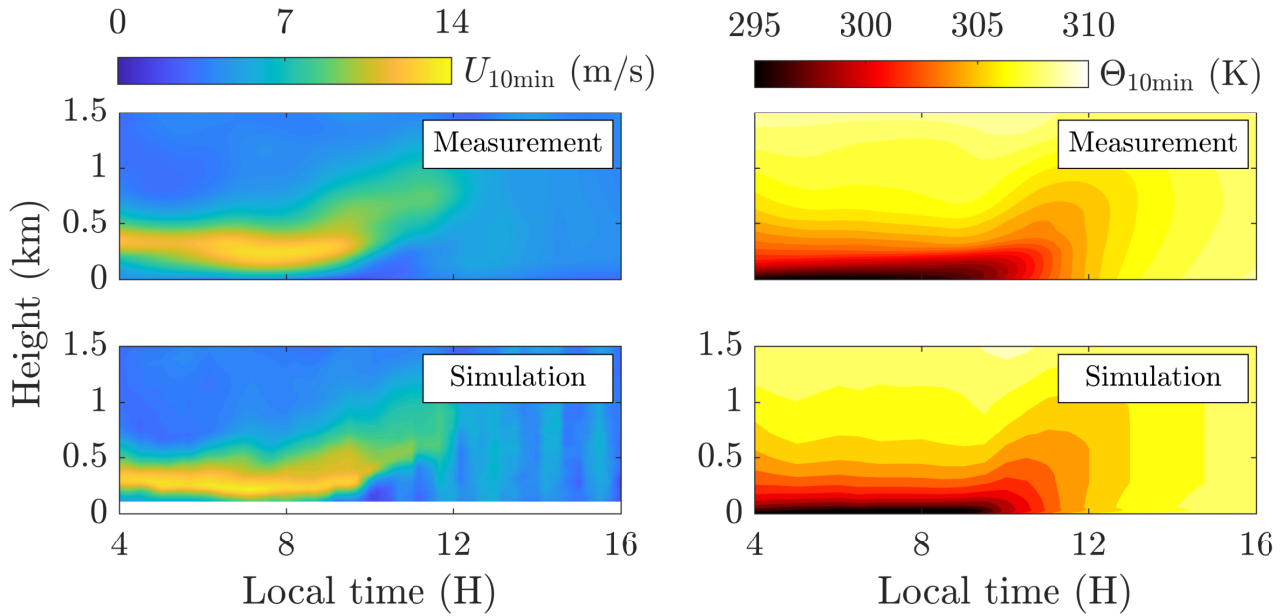


Figure 3. Comparison between simulation (top) and measurement (bottom) of atmospheric flow. Time–height history of 10-min averaged wind speed (left) and virtual potential temperature (right) are shown.

3 Results and discussions

3.1 Identification of three thermally-stratified atmospheric conditions

Figure 3 shows comparisons between simulation (top) and measurement (bottom) for 10-min-averaged wind speed (left) and virtual potential temperature (right). From 04:00 to 16:00 local time, both the simulated and measured wind-speed time–height contours show a low-level jet (LLJ) that forms during the nighttime hours and breaks down after sunrise at approximately 07:00. This period corresponds to the transition from thermally stable to unstable stratification in the virtual potential temperature contours, in which the strong surface-based inversion persisting before sunrise is progressively eroded by the growing convective boundary layer, ultimately producing a well-mixed layer by early afternoon. The close agreement between the simulated and observed time–height histories, in both the wind-speed and temperature fields, indicates that the measurement-assimilated LES faithfully reproduces the site-specific evolution of the boundary layer throughout the morning transition on 26 September 2023.

The left panel of Fig. 4 shows three representative conditions identified during the morning transition of thermal stability: stable (03:00–04:00, top), transitional (09:00–10:00, middle), and unstable (13:00–14:00, bottom). The stable condition features a distinct LLJ region with marginal velocity fluctuations, consistent with the suppression of vertical turbulent mixing under strong stratification. By contrast, the unstable condition exhibits large-scale vertical oscillations owing to the generation of

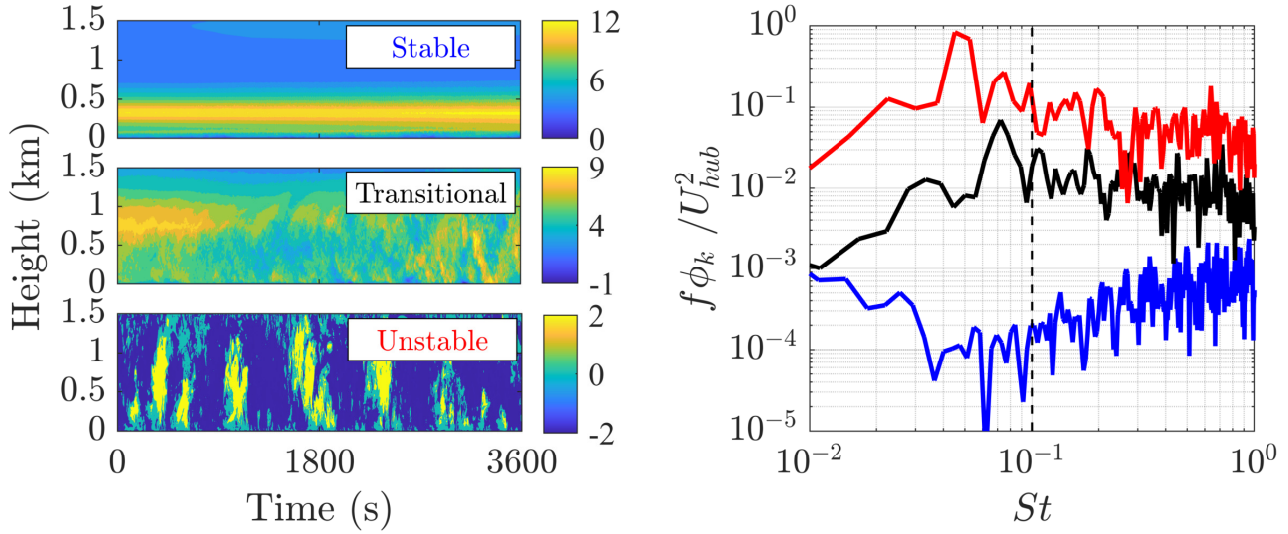


Figure 4. Left: instantaneous atmospheric velocity (in m/s) for stable (u' , top), transitional (u' , middle) and unstable (w' , bottom) conditions. Right: atmospheric turbulent kinetic energy spectra at hub-height for stable (blue line), transitional (black line) and unstable (red line) conditions.

thermal plumes that penetrate deep into the convective boundary layer. During the transition from stable to unstable conditions, the low-level jet dissipates as strong vertical turbulent mixing develops, and the atmospheric flow begins to oscillate vertically on an intermediate spatial scale. The change in characteristic length scale and turbulence level is also evident in the TKE spectra shown in the right panel of Fig. 4. The unstable-condition spectrum (red) exhibits energy levels two to three orders of magnitude higher than the stable-condition spectrum (blue) over the entire Strouhal number range $St = fD/\bar{u}_{hub} \in [0.01, 1]$, with a pronounced peak at $St \approx 0.05$ that reflects the integral time scale of convective plumes. The transitional condition spectrum (black) lies in between the two, with a secondary hump emerging at comparable low frequencies, demonstrating that the convective-type large-scale fluctuations begin to dominate even before the stratification has fully reversed.

Figure 5 statistically quantifies these observations through one-hour-averaged vertical profiles of streamwise velocity $\bar{u}$, virtual potential temperature $\bar{\theta}$ and streamwise turbulence intensity σ_u/U_{hub} . Under stable stratification (blue lines), the wind-speed profile displays a pronounced LLJ with a nose speed of approximately 13 m/s located near a height of 0.3 km. Above the nose, the velocity decreases with height, producing a strong negative shear across the upper half of the rotor. The corresponding potential temperature profile shows a nearly 10 K surface-based inversion extending up to 1 km, and the turbulence intensity remains below 5% throughout the rotor layer. In the transitional state (black lines), the LLJ has largely dissipated; the velocity profile becomes quasi-monotonic with height, the near-surface inversion is significantly weakened, and turbulence intensity grows to 15–25% within the rotor swept area. Under unstable stratification (red lines), the mean velocity profile is even more uniform, the potential temperature is nearly constant with height (indicating a well-mixed convective layer), and the turbulence

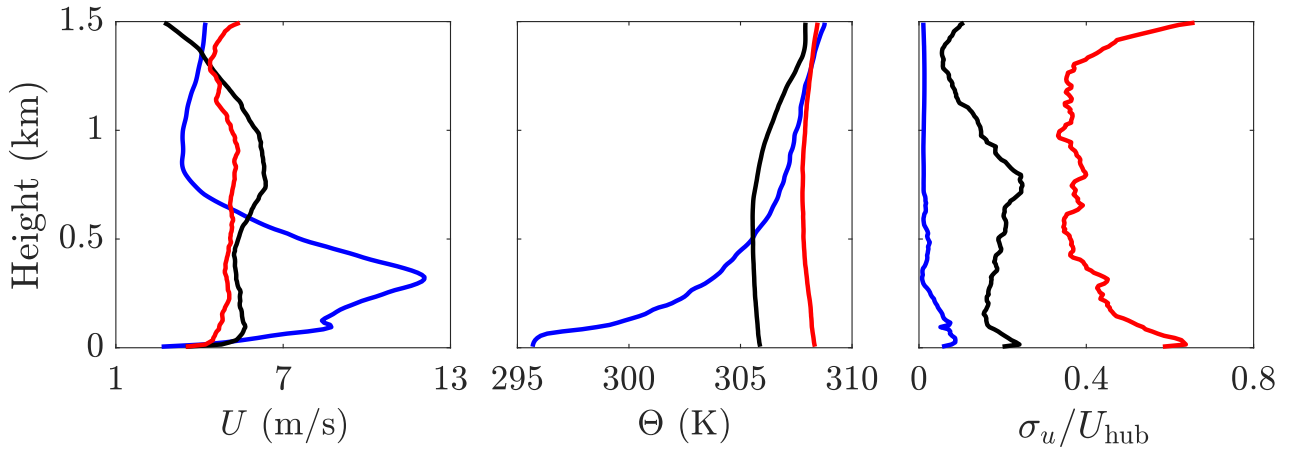


Figure 5. Vertical profiles of one-hour averaged streamwise velocity (left), virtual potential temperature (middle), turbulence intensity (right) for stable (blue lines), transitional (black lines) and unstable (red lines) conditions.

intensity exceeds 60% over most of the rotor. The hub height turbulence intensity thus increases by roughly an order of magnitude from stable to unstable conditions, consistent with the spectral broadening observed in Fig. 4.

Taken together, the atmospheric flow fields identified in Figs. 3–5 define three qualitatively distinct inflow regimes (stable, transitional, and unstable) that will be used in the following subsections to analyze the response of the wind turbine wake and its associated power production.

3.2 Turbulence characteristics of a single turbine wake

Figure 6 (left) shows instantaneous streamwise wake velocities on a vertical plane passing through the rotor center for the three stability conditions. Under stable stratification (top), the wake manifests itself as a narrow, nearly horizontal velocity deficit streak that persists to $x/D \approx 8$ without appreciable vertical expansion. The coherent deficit reflects the combination of weak ambient turbulence and the strong LLJ-induced shear, which inhibits vertical entrainment of high-momentum fluid into the wake core. In the transitional case (middle), the wake is laterally and vertically more irregular: intermittent large-scale structures distort the wake boundary, and the deficit recovers to near free-stream levels by $x/D \approx 8$. Under unstable stratification (bottom), the wake is engulfed by large convective plumes; the deficit is rapidly diluted, with full recovery occurring by $x/D \approx 5 - 6$, and the downstream flow is dominated by ambient buoyant structures rather than by turbine-induced shear.

The right panel of Fig. 6 shows TKE spectra at hub height for the inflow (dotted) and the wake region $x/D \approx 3$ (solid) for the three regimes. Two features are noteworthy. First, the stable-wake spectrum (solid blue) is elevated by roughly an order of magnitude above the stable inflow spectrum (dotted blue) for $St \geq 0.1$, indicating that under stable conditions the turbine itself is the dominant source of wake turbulence; in the absence of ambient large-scale motions, the rotor-generated shear layer produces turbulence locally through Kelvin–Helmholtz-type instabilities. Second, under unstable stratification, the wake and

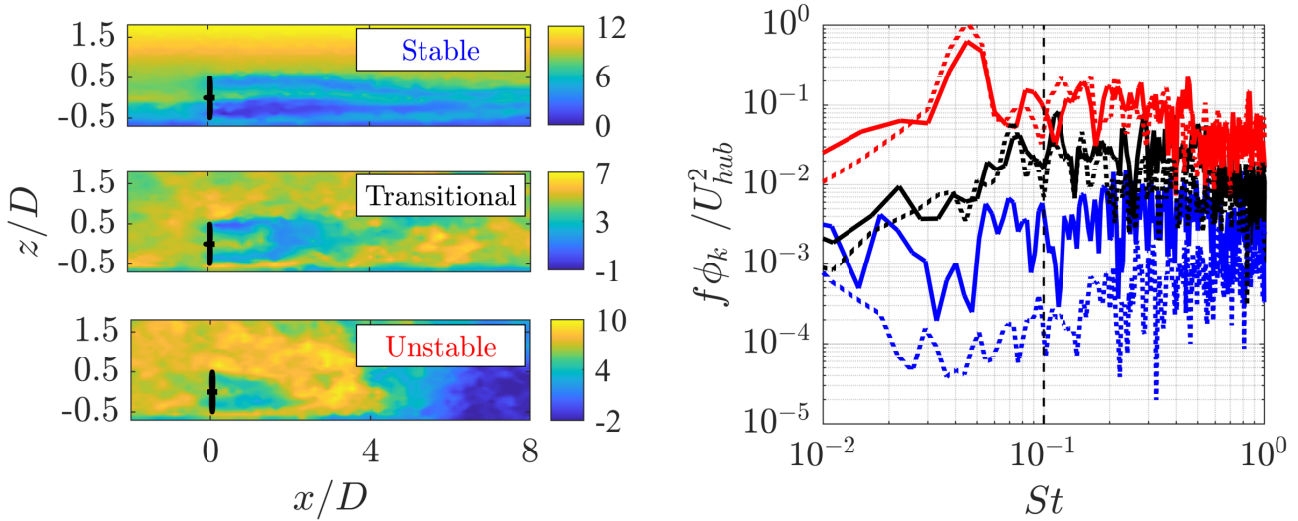


Figure 6. Left: instantaneous wind velocity (in m/s) in a vertical plane through the centre of the rotor for stable (top), transitional (middle) and unstable (bottom) conditions. The vertical axis is relative to the rotor hub. Right: turbulent kinetic energy spectra at hub-height for stable (blue line), transitional (black line) and unstable (red line) conditions. Inflow (dotted lines) and wake (solid lines) spectra are shown.

inflow spectra (red solid and dotted) nearly collapse, with only a modest enhancement at high St . This collapse shows that
 265 the wake inherits its dominant fluctuation energy from the convective ambient flow, and that turbine-generated turbulence is
 dominated by large-scale atmospheric motions. The transitional case (black) is intermediate: the wake spectrum shows a mild
 enhancement over the inflow at intermediate frequencies ($0.1 \leq St \leq 1$) but retains the low frequency imprint of incipient
 convective structures. This behaviour is consistent with the proposition of Wang et al. (2025), who argued that the dominant
 wake-meandering mechanism transitions from internal shear layer instability under stable stratification to passive modulation
 270 by large-scale ambient structures under unstable stratification.

To identify the underlying mechanisms responsible for the energy-containing structures observed in Fig. 6, we apply the
 resolvent analysis described in Sect. 2.3 around the time-averaged wake flow in each stability regime. Figure 7 shows the
 leading resolvent forcing (left) and response (right) modes at $St \approx 0.1$, indicated by the dashed vertical line in the spectra.
 Under stable stratification (top), the forcing mode is tilted in the direction opposite to the mean flow, indicative of the Orr
 275 mechanism that amplifies the inflow perturbations (Feng et al., 2024b; Pickering et al., 2020). The response mode shows
 typical Kelvin–Helmholtz-type structures, which intensify in the downstream region, characteristic of convective-type shear
 instabilities. Under transitional stratification, the Orr-type forcing mode becomes less tilted, and the Kelvin–Helmholtz-type
 response mode extends in the radial direction. Under unstable stratification (bottom), both the forcing and response modes span
 the entire radial domain, indicating that the wake flow is dictated by the ambient plumes rather than shear-instability-induced
 280 structures.

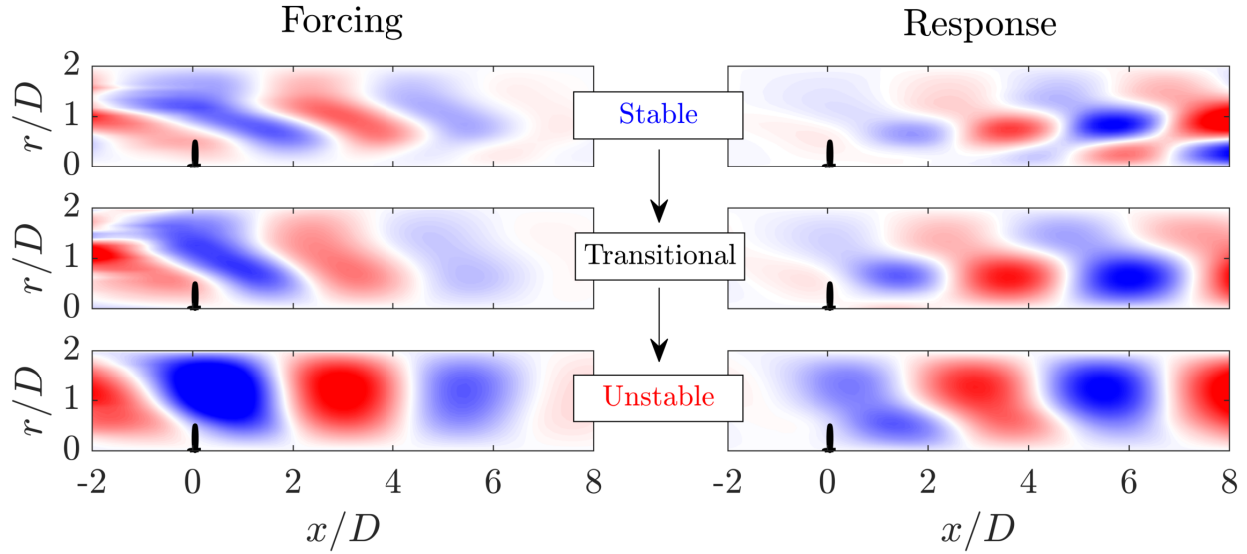


Figure 7. Resolvent forcing (left) and response (right) modes. The vertical axis is the normalized radial component centred on the rotor hub. Three thermal stability conditions are shown: stable (top), transitional (middle) and unstable (bottom).

The resolvent gain spectra in Fig. 8 complement this picture. For each stability condition, the three lowest-rank modes are plotted against St . Under stable stratification (blue), the gain of the leading mode reaches approximately 270 and peaks at $St \approx 0.2$, whereas the second and third modes remain near 100 with no pronounced peak; the gain separation between mode 1 and the subdominant modes is roughly a factor of 2.5, indicating that a single coherent structure dominates the wake response. In the transitional case (black), the leading mode peak gain decreases slightly to about 265 and shifts to lower St , while the second and third mode gains rise substantially compared to the stable case, reducing the rank 1 separation. Under unstable stratification (red), the leading gain decreases further to about 200, and the gap between the three leading modes narrows significantly. The gradual reduction of rank 1 dominance from stable to unstable stratification is consistent with a transition from low-dimensional, shear-driven wake dynamics to higher-dimensional, buoyancy-driven dynamics in which multiple forcing directions are comparably amplified. Practically, this implies that reduced-order models based on a single mode are most justified under stable conditions and progressively less accurate as the boundary layer becomes less stable.

3.3 Power productions of a three-turbine array

To assess how the evolving stability conditions translate into turbine performance, we simulate an array of three in-line turbines (T1, T2, and T3), spaced $5D$ apart, as shown in Fig. 9. Figure 10 shows instantaneous wake contours for the three-turbine array. Under stable stratification (top panel), the wake meandering is stronger for downstream turbines. This is because wake TKE

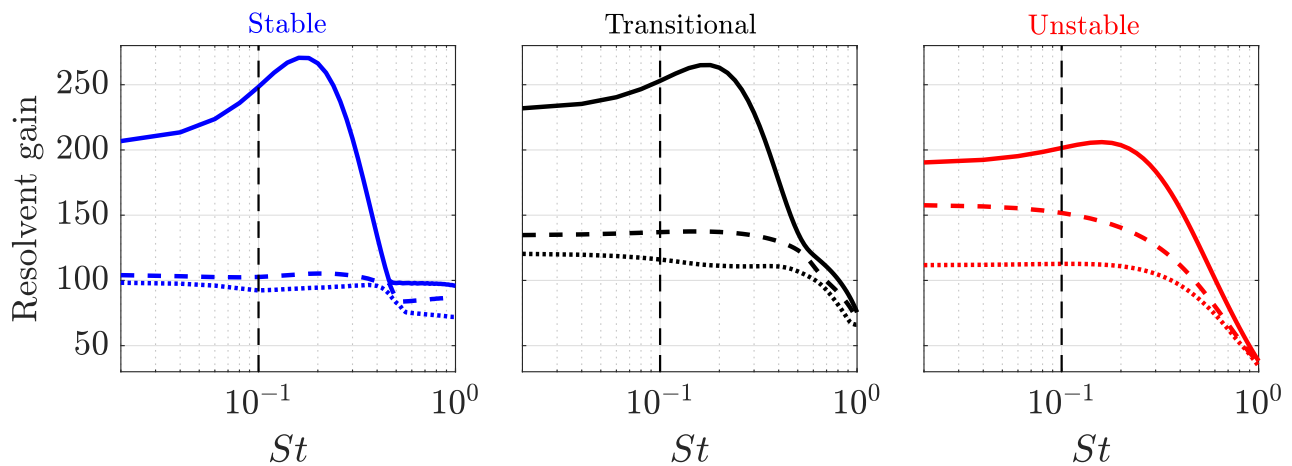


Figure 8. Resolvent gain spectra for stable (blue lines), transitional (black lines) and unstable (red lines) conditions. The lowest three ranks of modes are shown: mode 1 (solid lines), mode 2 (dashed lines) and mode 3 (dotted lines).

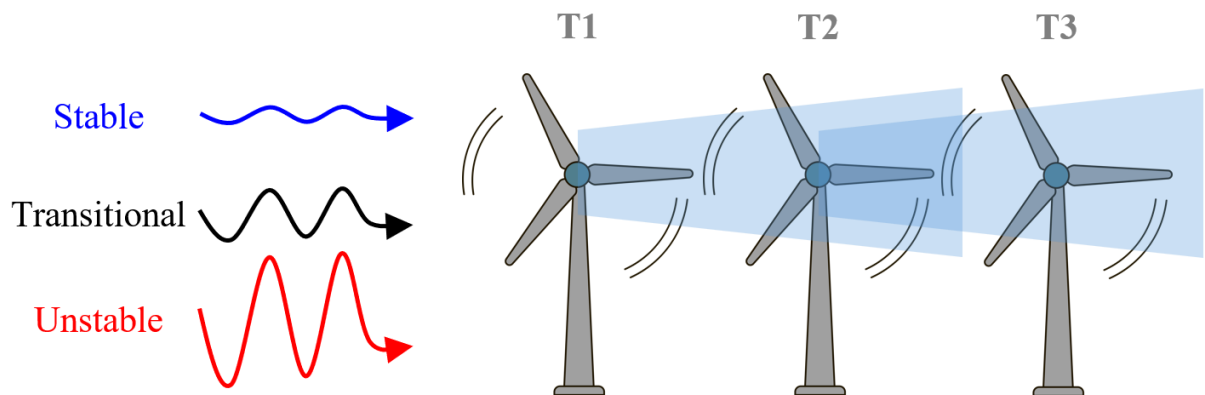


Figure 9. Schematic layout of the three in-line turbines (T1, T2, and T3) used in the array simulation, spaced $5D$ apart.

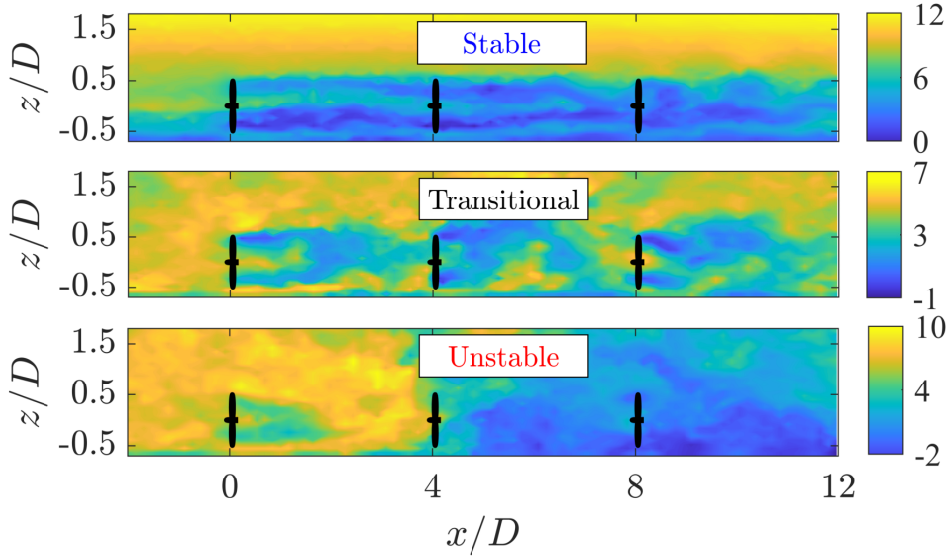


Figure 10. Instantaneous streamwise wind velocity component (in m/s) in a vertical plane through the centre of the rotors for stable (top), transitional (middle) and unstable (bottom) conditions for three-turbine case. The vertical axis is relative to the rotor hub.

is increased through shear instabilities, consistent with the observations in Fig. 6 (blue solid and dashed lines). Wake effects become less pronounced with increasing thermal instability. Under unstable stratification (bottom panel), the wake from the first turbine is just visible, but has dissipated by the time the wind flow has reached the second turbine. The wakes resulting from the second and third turbines are barely noticeable compared with the strongly fluctuating turbulent structures in the background flow.

Figure 11 presents the instantaneous power time series under each regime. Under stable stratification (blue), turbine T1 operates within a relatively small power band with a mean power of approximately 1.8 MW and low-amplitude, high-frequency fluctuations; however, T2 and T3 produce only approximately 0.6–0.8 MW on average, reflecting the persistence of strong velocity deficits from upstream turbines in the quiescent stable wake. In the unstable case (red), the upstream turbine power drops substantially (approximately 0.5 MW), owing to the lower hub-height mean wind speed, but exhibits large excursions exceeding 2 MW associated with the passage of convective plumes. Notably, the spread in average power production between T1, T2, and T3 is much smaller than in the stable regime, and occasional peaks in T2 and T3 power exceed those of T1 when high-momentum air is advected through the downstream rotors, consistent with the anomaly reported by Xiao et al. (2025) during diurnal transitions. The transitional case (black) displays characteristics of both regimes: a lower mean than the stable case, larger variability than the stable case but less extreme than the unstable case, and a partial erosion of the upstream–downstream power hierarchy.

Figure 12 presents the corresponding premultiplied power spectra $f\phi_P/P_{\text{rated}}^2$ for each turbine. Under stable stratification, the spectrum is broadband and featureless at low St , confirming that power fluctuations are driven primarily by small-scale

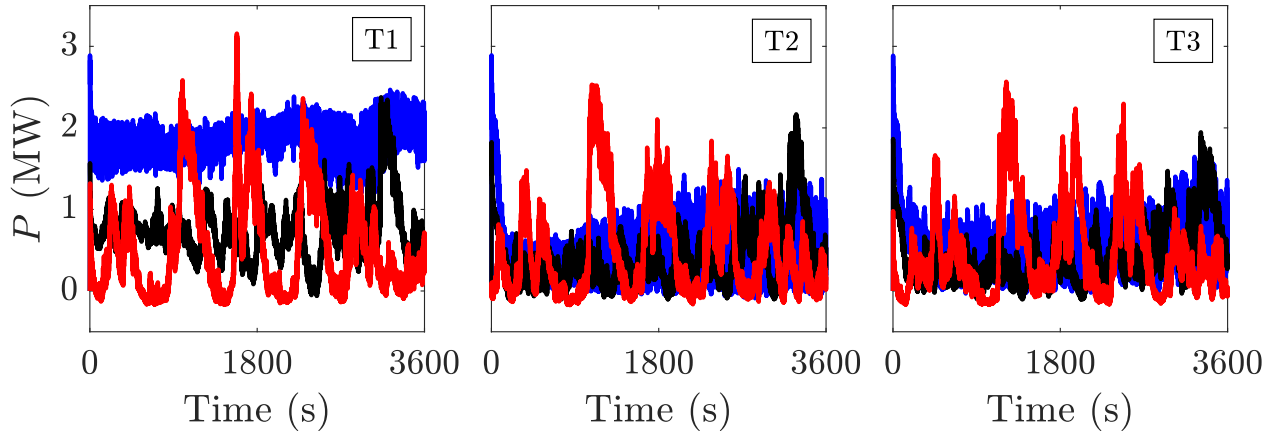


Figure 11. Power time-series for three turbines: T1 (left), T2 (middle) and T3 (right). Red=unstable; black=transitional; blue=stable.

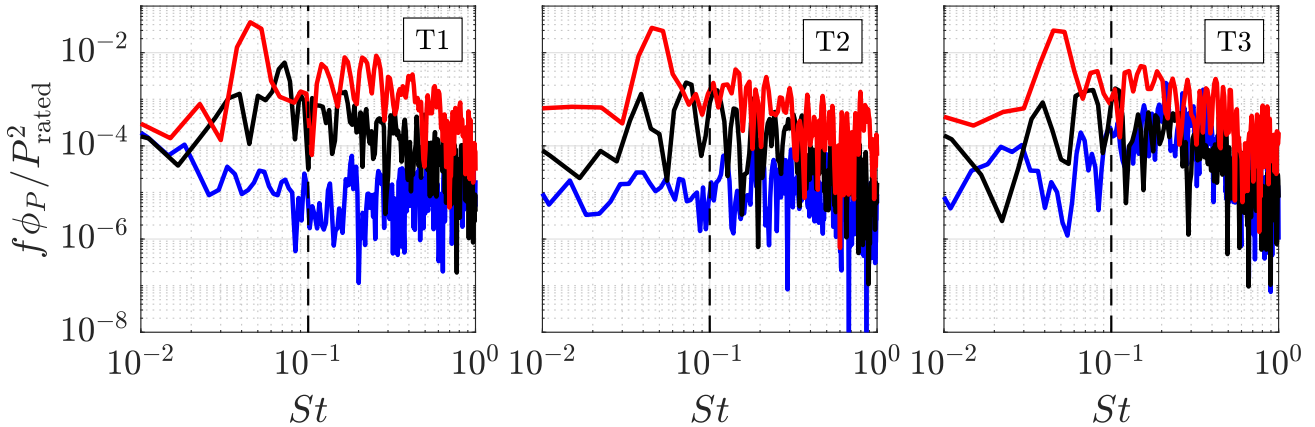


Figure 12. Power spectra for three turbines: T1 (left), T2 (middle) and T3 (right). Red=unstable; black=transitional; blue=stable.

wake turbulence. Under unstable stratification, a distinct peak emerges at $St \approx 0.05$ for all three turbines, corresponding to the
 315 characteristic time scale of the convective plumes identified in Figs. 4 and 5. This peak is roughly two orders of magnitude
 higher than that of the stable case, indicating that convective plumes impose a strong low frequency modulation on turbine
 power that has no counterpart in the stable regime. The transitional spectrum exhibits an intermediate but non-monotonic
 character, with a small low frequency peak at $St \approx 0.1$ that is already indicative of emerging convective structures even though
 the boundary-layer has not yet transitioned to a fully convective state.

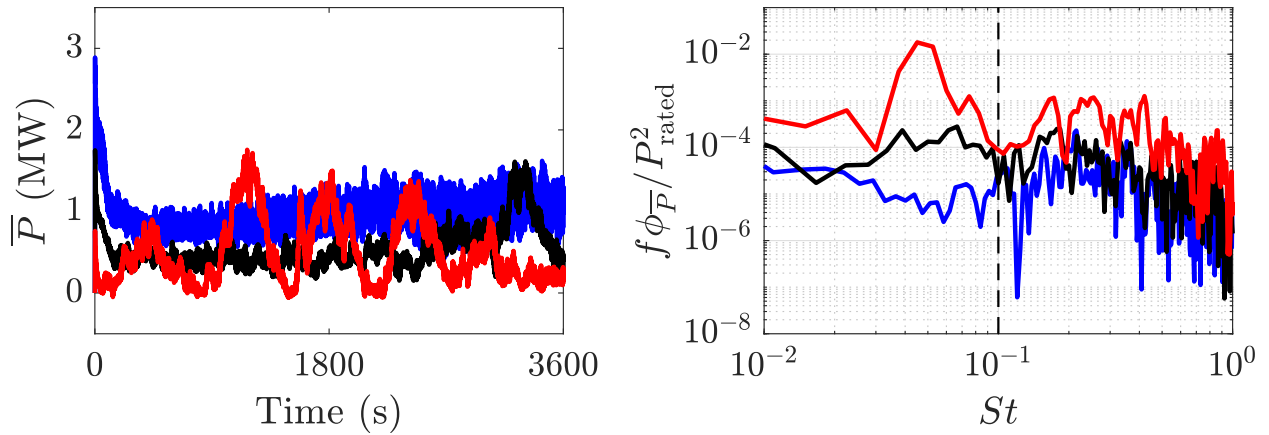


Figure 13. Time-series (left) and spectra (right) for power averaged over three turbines. Red=unstable; black=transitional; blue=stable.

Figure 13 summarizes these observations through the time series and spectra of the three-turbine averaged power $\bar{P}$. In the stable regime, the array-averaged power is nearly constant at approximately 1 MW, reflecting a quasi-steady balance between upstream production and downstream wake losses. In the unstable regime, $\bar{P}$ displays pronounced oscillations with a period of approximately 1000 s and a peak-to-peak amplitude of nearly 2 MW, driven by the coherent arrival of convective plumes. The transitional regime power signal exhibits an intermittent combination of both behaviours, with quiescent periods punctuated by plume-induced power excursions. The averaged power spectra (right panel) confirm this: the stable regime has the lowest magnitude for all St ; the unstable regime exhibits the largest low-frequency content with a clear spectral peak; and the transitional regime lies between the two across the resolved frequency band. These results demonstrate that the diurnal transition is a period of rapidly evolving power statistics in which both the mean power and its variability change by factors of order unity over only a few hours.

4 Conclusions

By simulating turbine flow during the diurnal transition on 26 Sep 2023 at the AWAKEN King Plains site using a measurement-assimilated LES framework, we have characterized how the wake structure, wake turbulence generation mechanisms, and turbine power output evolve as the boundary layer transitions from thermally stable to unstable stratification. Three distinct atmospheric regimes were identified from the simulation: a stable state featuring a well-defined LLJ and suppressed turbulence; a transitional state in which the LLJ dissipates and convective plumes begin to form; and an unstable state dominated by deep convective mixing and a well-mixed potential temperature profile. The hub height turbulence intensity increased by roughly an order of magnitude from the stable to the unstable state, while the characteristic length scale of atmospheric motion grew from a few rotor diameters to the full boundary-layer depth.



The wake analysis revealed a corresponding transition in the physical mechanisms driving wake turbulence. Under stable stratification, wake fluctuations are generated internally by shear-layer instability of the rotor-induced velocity deficit, and resolvent analysis identified a single low-rank coherent structure that accounts for the bulk of the wake energy. Under unstable stratification, by contrast, the wake passively inherits its fluctuation energy from large-scale convective plumes in the ambient flow, and the resolvent gain spectrum becomes multi-modal with substantially reduced rank 1 dominance. The transitional regime exhibits hybrid characteristics in which incipient convective structures already modulate the wake even before the stratification has fully transitioned to a convective state. These findings demonstrate that reduced order modeling of wakes requires regime-dependent formulations, and that steady-state stability classifications (fully stable or fully convective) do not adequately represent the rich dynamics of the morning transition.

From an operational standpoint, the three-turbine array simulations show that the mean array-averaged power, its temporal variability, and the spectral content of its fluctuations all differ markedly between the three regimes. The stable regime produced the highest mean power under the conditions studied but also the largest upstream–downstream power asymmetry. The unstable regime generated lower mean power but with large convectively driven excursions that occasionally inverted the upstream–downstream hierarchy, consistent with previous observations in idealized diurnal-cycle simulations. The transitional regime exhibited characteristics of both, highlighting the importance of capturing transition dynamics for accurate short-term power forecasting and for turbine load assessment.

The present work represents a preliminary investigation based on a single-turbine high-fidelity simulation and a three-turbine array analysis, and several extensions are natural next steps. First, the resolvent operator explicit buoyancy term and a linearized potential temperature equation, which is expected to improve quantitative accuracy under strongly convective conditions where the present incompressible, eddy-viscosity-based formulation is least justified. Second, the simulation will be extended to the full King Plains turbine layout, and the constant rpm assumption relaxed by coupling to a realistic turbine controller. Third, the predicted wake and power statistics will be validated against concurrent SCADA data and nacelle-mounted lidar observations from the AWAKEN campaign. By grounding the simulation in observed atmospheric conditions rather than in idealized thermal forcing, the measurement-assimilated LES approach demonstrated here provides a promising path toward bridging fundamental wake–stability understanding and the complex, site-specific reality of utility-scale wind farm operation.

Data availability. The atmospheric measurement data used in this paper are open source and can be found at <https://a2e.energy.gov/data>.

Author contributions. DF was responsible for the writing of the original draft, conceptualization, methodology, software, validation, and formal analysis. WZ was responsible for software, validation, and discussion. MW was responsible for resources, supervision, and discussion. SJW was responsible for the writing (review and editing), conceptualization, supervision, project administration, and funding acquisition.



Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work has been partially supported by the MERIDIONAL project, which receives funding from the European
370 Union's Horizon Europe Programme under the grant agreement No. 101084216, by the Fundamental Research Funds for the Central Universities under the grant agreement No. 22120260439.



References

- Abkar, M. and Porté-Agel, F.: Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study, *Physics of Fluids*, 27, 035 104, <https://doi.org/10.1063/1.4913695>, 2015.
- 375 Allaerts, D., Quon, E., Draxl, C., and Churchfield, M.: Development of a time–height profile assimilation technique for large-eddy simulation, *Boundary-Layer Meteorology*, 176, 329–348, 2020.
- Allaerts, D., Quon, E., and Churchfield, M.: Using observational mean-flow data to drive large-eddy simulations of a diurnal cycle at the SWiFT site, *Wind Energy*, 26, 469–492, 2023.
- Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J.: A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics, *Journal of turbulence*, p. N14, 2012.
- 380 Deardorff, J. W.: Stratocumulus-capped mixed layers derived from a three-dimensional model, *Boundary-layer meteorology*, 18, 495–527, 1980.
- Du, B., Ge, M., Zeng, C., Cui, G., and Liu, Y.: Influence of atmospheric stability on wind-turbine wakes with a certain hub-height turbulence intensity, *Physics of Fluids*, 33, 055 111, <https://doi.org/10.1063/5.0050861>, 2021.
- 385 Feng, D., Gupta, V., Li, L. K., and Wan, M.: Parametric study of large-eddy simulation to capture scaling laws of velocity fluctuations in neutral atmospheric boundary layers, *Physics of Fluids*, 36, 2024a.
- Feng, D., Gupta, V., Li, L. K. B., and Wan, M.: Resolvent analysis for predicting energetic structures in the far wake of a wind turbine, *Physics of Fluids*, 36, 085 101, <https://doi.org/10.1063/5.0212389>, 2024b.
- Feng, D., Dangi, N., and Watson, S.: Wind turbine wake dynamics subjected to atmospheric gravity waves: a measurement-driven large-eddy simulation study, *Wind Energy Science*, 11, 395–404, 2026.
- 390 Jonkman, J.: Definition of a 5-MW Reference Wind Turbine for Offshore System Development, National Renewable Energy Laboratory, 2009.
- Lee, J. C. Y. and Lundquist, J. K.: Observing and Simulating Wind-Turbine Wakes During the Evening Transition, *Boundary-Layer Meteorology*, 164, 449–474, <https://doi.org/10.1007/s10546-017-0257-y>, 2017.
- 395 Menken, J. and Wildmann, N.: Impact of atmospheric stability and turbulence on wind turbine wake characteristics: a nacelle lidar study, *Wind Energy Science*, 11, 2783–2800, <https://doi.org/10.5194/wes-11-2783-2026>, 2026.
- Moeng, C.-H.: A large-eddy-simulation model for the study of planetary boundary-layer turbulence, *Journal of the Atmospheric Sciences*, 41, 2052–2062, 1984.
- Moriarty, P., Bodini, N., Letizia, S., Abraham, A., Ashley, T., Bärfuss, K. B., Barthelmie, R. J., Brewer, A., Brugger, P., Feuerle, T., Frère, A., Goldberger, L., Gottschall, J., Hamilton, N., Herges, T., Hirth, B., Hung, L.-Y. L., Iungo, G. V., Ivanov, H., Kaul, C., Kern, S., Klein, P., Krishnamurthy, R., Lampert, A., Lundquist, J. K., Morris, V. R., Newsom, R., Pekour, M., Pichugina, Y., Porté-Agel, F., Pryor, S. C., Scholbrock, A., Schroeder, J., Shartzer, S., Simley, E., Vöhringer, L., Wharton, S., and Zalkind, D.: Overview of preparation for the American WAKE ExperimeNt (AWAKEN), *Journal of Renewable and Sustainable Energy*, 16, 053 306, <https://doi.org/10.1063/5.0141683>, 2024.
- 400 Pickering, E., Rigas, G., Nogueira, P. A., Cavalieri, A. V., Schmidt, O. T., and Colonius, T.: Lift-up, Kelvin–Helmholtz and Orr mechanisms in turbulent jets, *Journal of Fluid Mechanics*, 896, A2, 2020.
- Quon, E.: Measurement-driven large-eddy simulations of a diurnal cycle during a wake-steering field campaign, *Wind Energy Science*, 9, 495–518, 2024.



- Stevens, R. J., Martínez-Tossas, L. A., and Meneveau, C.: Comparison of wind farm large eddy simulations using actuator disk and actuator
 410 line models with wind tunnel experiments, *Renewable Energy*, 116, 470–478, <https://doi.org/10.1016/j.renene.2017.08.072>,
 2018.
- Tian, L., Song, Y., Zhao, N., Shen, W., Wang, T., and Zhu, C.: Numerical investigations into the idealized diurnal cycle of atmospheric boundary layer and its impact on wind turbine's power performance, *Renewable Energy*, 145, 419–427,
<https://doi.org/10.1016/j.renene.2019.05.038>, 2020.
- 415 Wang, Y., Li, Y., Lu, P., Zhao, G., Wang, B., and Zhao, M.: Influence of atmospheric thermal stability on wake meandering of a large-scale
 wind turbine, *Physics of Fluids*, 37, 115 149, <https://doi.org/10.1063/5.0297434>, 2025.
- Wu, Y.-T. and Porté-Agel, F.: Large-eddy simulation of wind-turbine wakes: evaluation of turbine parametrisations, *Boundary-layer meteorology*, 138, 345–366, 2011.
- Xiao, S., Zhu, X., Narasimhan, G., Gayme, D. F., and Meneveau, C.: Wind farm dynamics over a diurnal cycle: Analysis of a
 420 comprehensive large-eddy simulation, web-services accessible dataset, *Journal of Renewable and Sustainable Energy*, 17, 063 301,
<https://doi.org/10.1063/5.0283412>, 2025.
- Xie, S. and Archer, C. L.: A Numerical Study of Wind-Turbine Wakes for Three Atmospheric Stability Conditions, *Boundary-Layer Meteorology*, 165, 87–112, <https://doi.org/10.1007/s10546-017-0259-9>, 2017.
- Yuan, Y., Ma, Q., Yan, S., Zheng, X., Liao, K., Ma, G., Sun, H., and Khayyer, A.: A hybrid method for modelling wake flow of a wind
 425 turbine, *Ocean Engineering*, 281, 114 770, 2023.