



Impact of Wind Turbines on Near-Surface Microclimate and Soil Moisture Under Different Stability Regimes

Sampath Buddhika Wijerathna Weerappulli Hewage^{1,2} · Luise Wanner¹ · Matthias Mauder¹

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Abstract

The widespread deployment of wind-energy systems locally alters near-surface turbulent transport processes of energy, affecting temperatures and soil moisture. This study, for the first time, systematically investigates the influence of wind turbines on micro-meteorological conditions using large-eddy simulations across a range of atmospheric stability regimes. Simulations were conducted with and without wind turbines to systematically quantify differences in air temperature, surface temperature, sensible heat flux, latent heat flux, and soil moisture. The results show that turbine effects are strongly influenced by atmospheric stability. Under daytime strongly unstable conditions, turbines induced 0.06 K of modest air temperature cooling and reduced sensible heat flux by 6.97 W m^{-2} . In contrast, strongly stable night-time conditions exhibited pronounced air temperature warming of 0.695 K, widespread increases in surface temperature of 0.76 K, and enhanced soil moisture depletion of around $2.09 \times 10^{-3}\%$ (v/v). The latent heat flux generally increased in unstable regimes, but our result shows an enhancement also under strongly stable conditions, which is 1.72 W m^{-2} , consistent with an average higher reduction of soil moisture. The results show the friction velocity at 4 m increased by up to 0.073 m s^{-1} under stable conditions, but showed slight reductions (around 0.029 m s^{-1}) under strongly unstable conditions. The findings highlight that stability transitions, particularly from strongly stable to unstable states, play a critical role in shaping surface warming, energy fluxes, and soil moisture responses. These insights provide a basis for assessing potential agricultural implications of wind energy development.

Keywords Atmospheric stability · Boundary layer · Microclimate · Turbulence · Wind energy

✉ Sampath Buddhika Wijerathna Weerappulli Hewage
sampath.weerappulli@mailbox.tu-dresden.de

¹ Institute of Hydrology and Meteorology, Dresden University of Technology, 01737 Tharandt, Saxony, Germany

² Boysen-TU Dresden-Research Training Group, Dresden University of Technology, 01187 Dresden, Saxony, Germany

1 Introduction

Human activities, particularly the emission of greenhouse gases (GHG), most notably CO₂, are the primary drivers of global warming (IPCC 2023). It is estimated that energy production accounts for approximately three-quarters of global GHG emissions (IEA 2024). To combat human-caused climate change and achieve carbon neutrality by 2050, as outlined in the European Green Deal, it is crucial to shift energy production toward sustainable and renewable sources. The global demand for renewable energy continues to rise in response to growing concerns over climate change, energy security, and environmental degradation (IEA 2021). As a result, interest in wind energy has peaked as a viable alternative to fossil fuels, leading to a growing number of wind energy projects that contribute to national development (GWEC 2024). In 2023, onshore wind energy saw a record-high number of new installations, adding 100 GW (GWEC 2024).

As wind farms increasingly occupy rural and agricultural landscapes, there is a pressing need to understand their interactions with local atmospheric and land surface processes. Because of this, scientists began research on the effects of renewable energy expansion in various aspects, including social, environmental, and economic. According to research conducted by the US Department of Agriculture, it was found that more than 90% of onshore wind turbines were sited on agricultural lands in the USA (Maguire 2024). As wind farms increasingly occupy rural and agricultural landscapes, there is a pressing need to understand their interactions with local atmospheric and land surface processes.

Previous agricultural studies have shown that farmers have been using ventilators to protect crops during extreme cold Periods (Brooks et al. 1961; Battany 2012) to mix the warm air aloft with the cold air near the surface, thereby reducing frost damage by increasing near-surface temperature. A wind turbine (WT) in the middle of an agricultural land can have the same effect during colder nights and help to reduce the adverse effects of extremely low temperatures to some extent. It reduces the wind velocity at the hub height due to momentum extraction (Emeis and Frandsen 1993; Baidya Roy et al. 2004), and once the turbine begins to rotate, it generates additional turbulence that enhances vertical mixing of momentum, heat, and scalars at the hub height, leading to changes in near-surface heat fluxes (Baidya Roy et al. 2004; Zhang et al. 2013a). Although these effects may appear small on average, even subtle shifts in microclimatic conditions can influence plant growth, frost risks, and soil water retention factors critical to sustainable agricultural productivity (Chmielewski and Rötzer 2001; Lobell and Field 2007).

For this reason, scientists also started research on the effect of wind farms on local meteorological conditions (Baidya Roy et al. 2004; Zhou et al. 2012; Abkar and Porté-Agel 2015; Sharma et al. 2017; Siedersleben et al. 2018; Zhang et al. 2024). Field campaign data showed that the near-surface air temperature increases during the night and early morning hours, whereas a cooling effect occurs during the daytime in the presence of WTs (Ivanova and Nadyozhina 2000; Baidya Roy and Traiteur 2010). It also indicates that the direction of the change in heat fluxes is mainly associated with atmospheric stability, which primarily depends on the lapse rate at the time of day (Baidya Roy and Traiteur 2010). To explore these effects, researchers have adopted a range of methodological approaches. Comparison of field measurement data (Baidya Roy and Traiteur 2010), wind tunnel experiments (Zhang et al. 2013b; Tian et al. 2017), and analysis of satellite data (Zhang et al. 2024) are a few approaches. Traditional field measurements offer valuable insights, but are inherently limited as the variability of natural conditions makes it difficult to isolate the specific influence of wind farms on meteorological variables.

Several previous studies have reported temperature changes associated with wind farm operation. Armstrong et al. (2016), using high-resolution measurements from a wind farm in Scotland, observed that turbine operation increased near-surface air temperature by approximately 0.18 °C during nighttime, and also elevated air, surface, and soil temperatures across the diurnal cycle. Qin et al. (2022) analysed Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data and found an average nighttime warming of 0.10 °C across the entire wind farm area, with 61% of the sites exhibiting warming of up to 0.36 °C. Their study also highlighted that the magnitude of the effect depends strongly on the size of the wind farm. Zhou et al. (2012), based on long-term satellite observations and numerical simulations, reported a significant nighttime surface warming trend of 0.72 °C per decade over large wind farms in Texas. More recently, Han et al. (2025) assessed land-surface temperatures and vegetation dynamics using remote sensing data, showing that wind farms increased nighttime land-surface temperatures by 0.20 °C and decreased daytime temperatures by 0.11 °C, with pronounced seasonal variability during daytime conditions. Field observations sometimes report only weak or location-specific impacts of wind farms on near-surface air temperature. For instance, Moravec et al. (2018) found no systematic differences in air temperature after turbine installation based on measurements at a wind park in the Czech Republic. At one station, they even observed a slight daytime warming rather than the expected cooling, which the authors attributed to natural turbulence generated by the surrounding mountainous terrain. Similarly, Baidya Roy and Traiteur (2010) described such cases as “low-impact wind farms”, where the influence of turbines is comparatively small because background boundary-layer turbulence is already high due to natural conditions. These findings raise an important question: Is additional turbulence from turbines beneficial, detrimental, or significant enough to meaningfully influence near-surface processes? For example, nocturnal warming induced by turbine-driven mixing could reduce the risk of frost damage, offering potential benefits for agriculture in frost-prone regions. Moreover, enhanced turbulence and modified surface–atmosphere exchange may increase evapotranspiration, thereby contributing to increased soil moisture depletion. These processes are not limited to thermal effects but also directly influence land–atmosphere coupling through changes in evapotranspiration and surface moisture exchange. Field evidence from the Crop Wind Energy Experiment (CWEX) demonstrated that wind farms can modify near-surface latent heat fluxes and moisture transport within agricultural landscapes, indicating measurable impacts on evapotranspiration dynamics in addition to temperature changes (Rajewski et al. 2013). Similarly, modeling studies have shown that turbine-induced turbulence can alter surface energy partitioning between sensible and latent heat fluxes, thereby influencing soil moisture availability (Baidya Roy and Traiteur 2010). These findings highlight the importance of explicitly considering hydrological responses when assessing wind farm impacts in agricultural environments.

In light of the above findings, a series of large-eddy simulations (LES) was carried out to systematically investigate the influence of wind-turbine-induced turbulence on the microclimate, thereby extending the current understanding presented in the literature. LES provides valuable insights into these effects in a controlled and reproducible manner. With advancements in computational capabilities, LES has become an important tool in modern scientific research related to meteorology, addressing various topics (Keith et al. 2004; Calaf et al. 2010; Witha et al. 2014; Andersen et al. 2015). In this study, we use a LES model to compare a flat, homogeneous terrain under two scenarios: with wind turbines (WWT) and without wind turbines (WOWT), based on different atmospheric stabilities. LES offers a valuable advantage over field measurements by allowing comparisons between scenarios without being affected by long-term changes such as global warming and the limited availability of field measurements. It allows us to systematically simulate different atmospheric stability conditions and

isolate the effects of specific factors. Field observations often make it difficult to compare identical stability scenarios due to naturally varying conditions. In contrast, LES enables controlled comparisons between scenarios with and without a wind farm, while holding all other factors constant.

The primary objective of this work is to systematically assess the impact of wind turbines on the local atmosphere under various atmospheric stabilities, focusing on the turbulent flow field, surface energy partitioning, and coupled heat and moisture fluxes, and the resulting effects on near-surface temperature and soil moisture. To address this objective, a set of idealized LES is performed and analysed to systematically compare different scenarios with and without wind turbines.

2 Methods and LES Setup

In this study, we compared different atmospheric stabilities with and without wind turbines on flat, homogeneous terrain using the PALM-LES system (Maronga et al. 2020). Moreover, PALM provides an integrated wind-turbine model (Witha et al. 2014) and land surface model (LSM) (Gehrke et al. 2021) and is therefore an excellent tool to address the objectives of this study.

2.1 Large Eddy Simulation Setup

This experiment was based on LES and was conducted with the LES model PALM release 24.04 (Raasch and Franke 2011; Maronga et al. 2020). The turbulence recycling method was used to reduce the domain size and computation time (Gryschka et al. 2008; Gronemeier et al. 2017; Maronga et al. 2019). With this method, the existing turbulence generated due to shear and convection can be transferred back to the start of the domain before it is disturbed by wind turbines. So, the wind can be assumed to be coming from a far distance, even with a rather small inflow area in the domain. By employing this approach, we were able to substantially decrease the computational cost of the simulations, making efficient use of the allocated high-performance computing resources.

To identify initial conditions that yield the aforementioned stability conditions, various combinations of net radiation, temperature profiles, and wind speeds were simulated with a small domain measuring $(l_x, l_y, l_z) = (500 \text{ m}, 500 \text{ m}, 1500 \text{ m})$. Based on these results, initial conditions were chosen to result in the nine targeted stability regimes. Following that, a series of LES simulations on a larger domain measuring $(l_x, l_y, l_z) = (6800 \text{ m}, 1600 \text{ m}, 2000 \text{ m})$ were conducted with an 8 m cubical grid resolution, featuring a 2-h precursor run followed by another 4.5 h of simulation. The domain size of the precursor run was also smaller, measuring $(l_x, l_y, l_z) = (2000 \text{ m}, 1600 \text{ m}, 2000 \text{ m})$. The purpose of the precursor run was to allow time for system stabilization and to create a realistic temperature and wind profile at the beginning of the main simulation based on the prescribed values, depending on the stability condition, as in Table 2. This run also included cyclic boundary conditions for all four edges to mimic an effectively infinite domain during the initial 2 h of simulation. Fixed date and time features were utilized to prevent changes in stability conditions throughout the simulation. This ensured that time remained constant and the solar angle did not vary over the 4.5-h simulation period. Otherwise, simulating the same stability condition could be more challenging, as it does not remain consistent for extended periods during the day. Prescribed initial profiles were established at the start of the precursor run, and during the

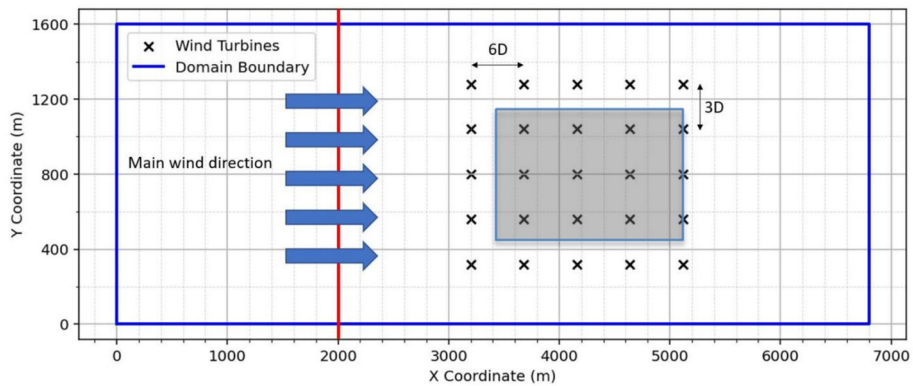


Fig. 1 Wind farm layout considered. The red line shows the line of turbulence recycling. D is the rotor diameter. The shaded gray region represents the spatial domain over which averaging was performed for the analysis

simulation, these profiles were adjusted based on the defined parameters, stabilizing after the simulation's spin-up time. At the end of the precursor run, all stable profiles were saved and used as initial profiles for the main simulations. In the main simulation, the length of 2000 m from the start of the domain along the x direction was defined as the recycling region, as marked on Fig. 1. In this approach, a two-dimensional cross-section of the turbulent flow field is extracted from this downstream location and reintroduced at the inflow boundary. This method ensures a fully developed turbulent inflow for the main simulation while maintaining computational efficiency. To ensure that the effect of the wind turbines does not affect the recycled two-dimensional inflow wind, it was located 15 times the rotor diameter away from the beginning of the wind farm. The downstream fetch of approximately 21 rotor diameters may not be sufficient to capture full wake recovery, particularly under stable stratification where wake persistence is enhanced (Lu and Porté-Agel 2011). Therefore, the present results should be interpreted as representative of the developing flow regime within the wind farm rather than equilibrium or fully developed conditions. However, the analysis is confined to the interior region of the wind farm, which is sufficiently distant from the outflow boundary to minimize potential boundary effects.

The land surface model (LSM) in PALM solves the surface energy balance using a resistance-based parameterization for turbulent fluxes, coupled with a multilayer soil scheme. The temporal evolution of the surface temperature is governed by the surface energy balance, as expressed in Eq. 1, where C_0 and T_0 are the heat capacity and radiative temperature of the surface skin layer, respectively. R_n , H_{surf} , LE_{surf} , and GHF are the net radiation, sensible heat flux, latent heat flux, and ground (soil) heat flux at the surface, respectively (Maronga et al. 2020).

When defining the land-surface parameters, the soil type was designated as medium fine, and the surface type was classified as vegetation. Furthermore, the vegetation type was identified as crops and mixed farming, as the goal is to primarily simulate the effects on crops. The key land surface parameters used in the simulations are summarized in Table 1. In the radiation model, a constant radiation scheme was adopted, with values determined based on the simulated stability condition.

$$\frac{dT_0}{dt} C_0 = R_n - H_{surf} - LE_{surf} - GHF, \quad (1)$$

Table 1 Prescribed parameters in the land surface model

Parameter	Value
Minimum canopy resistance	180 s m^{-1}
Leaf area index	$3 \text{ m}^2 \text{ m}^{-2}$
Longwave albedo	0.28
Shortwave albedo	0.09
Field capacity	$0.383 \text{ m}^3 \text{ m}^{-3}$
Wilting point	$0.133 \text{ m}^3 \text{ m}^{-3}$
Roughness length for momentum	0.1 m
Roughness length for heat	0.0001 m
Emissivity	0.95

We ran ensemble simulations for each setup. In each simulation, different random perturbations were generated, which changed the turbulence initially and produced different results. For unstable conditions, after conducting ten ensemble simulations and averaging the results, a more uniform pattern emerged, reflecting the wind turbine's influence on ground-level conditions. For neutral and stable conditions, five ensemble runs were conducted. The reason was that the standard deviation of variables did not change significantly after four ensembles. All the data for the analysis were taken from the ensemble-averaged output data. The main simulation had Dirichlet boundary conditions on the left-hand side of the domain, where the main wind was arriving, which caused non-cyclic boundary conditions. Otherwise, cyclic boundary conditions would introduce the effect of an infinitely long wind farm. However, cross-wind direction boundary conditions remained cyclic as required by Dirichlet boundary conditions. Since the predominant wind direction in the simulation is from left to right, as required by the wind turbine model (WTM) in PALM-LES, slight directional deviations occur under stable conditions due to boundary-layer processes such as Ekman turning. As a result, minor lateral variability in the wake structure can develop. However, the use of cyclic boundary conditions in the crosswind direction ensures continuity of the flow field and avoids artificial reflection effects at the lateral boundaries. Above 1000 m from the ground, vertical grid stretching was used to reduce the number of grid cells in the vertical direction.

To evaluate the results, the unstable and stable atmospheric conditions were divided into three subcategories: strongly, moderately, and weakly unstable, and strongly, moderately, and weakly stable. Together with the three (near-)neutral cases, this leads to nine different combinations shown in Table 2.

The stability condition represents strongly unstable (SU), moderately unstable (MU), weakly unstable (WU), near-neutral to unstable (NN-U), neutral (N), near-neutral to stable (NN-S), weakly stable (WS), moderately stable (MS), and strongly stable (SS). U_g (geostrophic wind speed), θ_0 (surface potential temperature), q (total water mixing ratio), T_s (soil temperature), m_s (soil moisture), R (net radiation), T_D (Soil temperature at 2.93 m below surface), Lt (local time, i.e., UTC + 2 h).

2.2 Wind Turbine Model Setup

Following an extensive literature review, the dimensions of the simulated wind farm were chosen as illustrated in Fig. 1. The wind-farm configuration consists of 25 wind turbines

Table 2 Values of prescribed parameters based on stability condition

Stability condition	U_g (m s ⁻¹)	θ_0 (K)	q (kg kg ⁻¹)	T_s at 0.001 m (K)	m_s at 0.001 m (m ³ m ⁻³)	R (W m ⁻²)	T_D (K)	Lt
SU	5	294.50	0.0080	310.00	0.20	660	293.00	1200
MU	10	294.15	0.0055	294.15	0.22	350	293.00	1000
WU	10	295.15	0.0060	298.15	0.22	264	283.15	0910
NN-U	10	284.95	0.0018	286.95	0.26	150	283.15	0830
N	15	274.15	0.0006	272.15	0.25	50	282.15	0800
NN-S	10	274.15	0.0006	272.15	0.25	20	282.15	0800
WS	10	274.15	0.0006	272.15	0.25	10	282.15	0800
MS	10	274.15	0.0006	272.15	0.25	− 5	282.15	0600
SS	5	274.15	0.0006	273.15	0.25	− 25	282.15	0400

arranged in a 5×5 layout. Such configurations are commonly used in LES studies to represent developing wind-farm flow regimes (Calaf et al. 2010; Stevens et al. 2016; Singh and Alam 2023). For the simulations, we employed the NM80 wind turbine model from the *DANAERO MW II* project (Troldborg et al. 2013), a project conducted by the Denmark Technical University (DTU). This turbine features a rotor diameter of 80 m (38.8 m long blade with 1.24 m hub radius), and a hub height of 57 m, making it representative of utility-scale onshore wind turbines (Potentier et al. 2021). Based on findings from previous studies aimed at optimizing wind-farm performance, the spacing between turbines was determined to maximize power output while minimizing wake interference. Specifically, the longitudinal (along-wind) distance between turbines was set to six times the rotor diameter (6D), which is 480 m, in line with recommendations for minimizing wake losses and enhancing energy yield. The lateral (crosswind) spacing was set to three times the rotor diameter (3D), which is 240 m, to balance land-use efficiency with aerodynamic performance. This layout provides a realistic and representative configuration for simulating turbine-induced flow structures and their interactions with the land surface under various atmospheric stability conditions (Milborrow 1980; Stevens et al. 2016; Tian et al. 2018; Ali et al. 2018).

The starting coordinate of the wind farm is 3200 m from the inflow boundary (West) and 320 m from the South boundary. An aligned arrangement was selected instead of the scattered arrangement because the effect of the wake of the previous wind turbine is higher when the aligned arrangement is used (Tian et al. 2018).

In addition to the geometric configuration, the aerodynamic interaction between the wind turbines and the flow is represented using the actuator disk model with rotation (ADM-R) implemented in PALM. In this approach, turbine-induced forces are not prescribed through a fixed thrust coefficient (C_t) but are computed dynamically based on blade-element principles. The model utilizes detailed blade geometry, including chord length and twist distribution, together with airfoil-specific lift and drag coefficients as functions of the angle of attack. The resulting forces act on the flow field and generate velocity deficits, shear layers, and turbulence in the rotor region. These features are explicitly resolved by the LES, while smaller-scale features, such as tip vortices, are partially represented through the subgrid-scale model. Furthermore, the turbine model includes active control mechanisms such as generator speed control, blade pitch control, and yaw control, allowing the turbine to adapt to local flow

conditions. As a result, the thrust coefficient and power extraction evolve dynamically in response to the instantaneous wind field. This ensures a physically consistent representation of turbine-induced momentum extraction, wake generation, and turbulence production across the different atmospheric stability regimes considered in this study. A comprehensive description of the wind turbine model is available in Maronga et al (2020).

2.3 Data Analysis and Diagnostic Definitions

For the systematic analysis, ensemble-averaged values of the simulation results were considered. Table 3 presents the 30-min averaged output values for the one step preceding the last time step of the simulations for the scenarios WOWT and WWT. To assess sensitivity to the selected 30-min averaging period, additional diagnostics were evaluated over five consecutive 30-min windows during the final two hours of simulation for representative strongly unstable, moderately stable, and strongly stable conditions. Key turbine-induced anomalies remained consistent in sign and similar in magnitude across windows, indicating that the selected averaging period captures a quasi-stationary response for the variables analysed. Table 4 summarizes the parameters, expressed as differences between the WWT and WOWT scenarios. To obtain the spatial mean of the 30-min averaged values, we considered the area within the wind farm (shown in gray in Fig. 1), which represents the region influenced by the turbines. The Obukhov length (L), turbulent kinetic energy (TKE), and boundary layer height (z_i) were calculated over the entire model domain. The results highlight how the presence of turbines can lead to very different outcomes depending on the stability of the atmosphere. These cases provide valuable insights into how the presence of wind turbines affects state variables and energy fluxes near the surface.

Table 3 Output values without the wind turbines scenario

Stability condition	L range (m)	L (m)	u_* at 4 m (m s^{-1})	LE_{surf} at 4 m (W m^{-2})	H_{surf} at 4 m (W m^{-2})	T_a at 2 m ($^{\circ}\text{C}$)	θ_{2m} (K)	z_i (m)
SU	$-100 < L < 0$	-20.76	0.417	338.52	284.76	27.77	299.81	843
MU	$-150 < L < -100$	-127.94	0.537	205.73	106.07	25.00	297.01	615
WU	$-200 < L < -150$	-178.43	0.507	176.33	67.31	25.41	297.48	477
NN-U	$-500 < L < -200$	-304.00	0.441	105.94	27.34	14.21	286.32	342
N	$ L > 500$	-2251.47	0.516	33.55	5.50	2.19	274.31	828
NN-S	$200 < L < 500$	413.10	0.322	22.65	-7.52	1.55	273.66	444
WS	$100 < L < 200$	199.96	0.288	19.07	-11.06	1.24	273.35	436
MS	$50 < L < 100$	51.01	0.191	12.43	-13.03	0.53	272.65	364
SS	$0 < L < 50$	10.04	0.104	5.15	-8.64	-1.24	270.90	92

For the stability conditions, refer to Table 2. L (Obukhov length), LE_{surf} (Surface latent heat flux), H_{surf} (Surface sensible heat flux), T_a (Air temperature), θ_{2m} (potential temperature at 2 m), z_i (Boundary layer height), u_* (friction velocity). To get the detailed statistics, refer to the appendices

Table 4 Overview of the parameters investigated, presented as differences (denoted by Δ) between the mean value of the wind turbine (WWT) and no-wind turbine (WOWT) scenarios

Stability condition	ΔTKE at 60 m ($m^2 s^{-2}$)	ΔU at 60 m ($m s^{-1}$)	Δu_* at 4 m ($m s^{-1}$)	ΔLE_{surf} at 4 m ($W m^{-2}$)	ΔH_{surf} at 4 m ($W m^{-2}$)	ΔT_a at 2 m ($^{\circ}C$)	ΔT_{surf} (K)	ΔT_s at 0.001 m (K)	$\Delta m_s \times 10^{-3}$ at 0.001 m % (v/v)
SU	0.04	- 0.62	- 0.029	5.08	- 6.97	- 0.064	0.368	0.171	- 11.26
MU	0.14	- 0.75	- 0.024	0.49	- 1.08	0.001	0.140	0.012	- 0.22
WU	0.15	- 0.74	- 0.023	0.15	- 0.60	0.009	0.099	0.019	- 0.00
NN-U	0.20	- 0.82	- 0.026	- 0.58	0.14	0.011	0.115	0.018	0.59
N	0.18	- 0.84	- 0.030	- 0.23	0.10	0.004	0.004	0.004	0.43
NN-S	0.27	- 1.17	- 0.035	- 0.50	0.57	- 0.002	- 0.019	- 0.002	0.03
WS	0.34	- 1.30	- 0.027	- 0.38	0.52	0.003	- 0.047	0.000	0.03
MS	0.70	- 2.02	- 0.002	0.06	- 0.33	0.095	0.045	0.029	- 0.64
SS	0.45	- 0.57	0.073	1.72	- 6.25	0.695	0.760	0.290	- 2.09

For the stability conditions, refer to Table 2. TKE (Turbulent kinetic energy), U (Horizontal wind speed), LE_{surf} (Surface latent heat flux), H_{surf} (surface sensible heat flux), T_a (air temperature), T_{surf} (surface temperature), T_s (soil temperature), m_s (soil moisture), u_* (friction velocity). To get the detailed statistics, refer to the appendices

In this study, z_i is diagnosed using a stability-dependent approach, reflecting the fundamentally different turbulence-production mechanisms in convective and stable atmospheric regimes. From SU to NN-U (convective-dominated) conditions, z_i is defined as the height at which the vertically resolved kinematic sensible heat flux ($w'\theta'$) approaches zero, consistent with the decay of buoyancy-driven turbulence in convective boundary layers. The flux profile was extracted from the LES output and averaged over model levels, and the zero-crossing height was determined using linear interpolation between adjacent vertical levels.

For neutral and stable conditions, where sensible heat flux remains negative throughout the boundary layer and does not provide a clear diagnostic transition, z_i is determined using the bulk Richardson number method, defined as,

$$Ri_b(z) = \frac{g}{\theta_{v,ref}} \frac{[\theta_v(z) - \theta_{v,ref}](z - z_{ref})}{[u(z) - u_{ref}]^2 + [v(z) - v_{ref}]^2}, \quad (2)$$

where θ_v is virtual potential temperature, z_{ref} is a reference height within the surface layer (20 m in this study), and $Ri_b = 0.25$ is used as the critical threshold for dynamically defining the boundary layer top. The final boundary layer height is identified as the first height at which this threshold is exceeded and remains persistently above the critical value with height. This combined approach ensures physically consistent diagnosis of z_i across the full spectrum of atmospheric stability, from strongly unstable to strongly stable conditions.

Different atmospheric stabilities were chosen to cover a broad spectrum of scenarios, ranging from strongly unstable to strongly stable atmospheric conditions. Stability conditions were distinguished based on the Obukhov length L as indicated by Eq. 3, at the first grid point above the surface:

$$L = -\frac{u_*^3}{\kappa \frac{g}{\theta_v} \overline{w'\theta'}}, \quad (3)$$

with:

$$u_* = \sqrt[4]{\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2}, \quad (4)$$

where u_* is the friction velocity (Eq. 4), κ is the von Kármán constant (0.4), g is the gravitational acceleration, $\overline{w'\theta'}$ is the kinematic sensible heat flux, u' , v' , and w' are the turbulent fluctuations of the streamwise, cross-stream, and vertical velocity components, and the over-bar denotes a temporal and spatial average. The relationship between the kinematic sensible heat flux and the energetic sensible heat flux is described by:

$$\overline{w'\theta'} = \frac{H}{\rho c_p}, \quad (5)$$

where H is the sensible heat flux, ρ is the density of air, and c_p is the heat capacity for constant pressure.

Table 5 summarizes the surface sensible heat flux H_{surf} , the surface latent heat flux LE_{surf} , and the Bowen ratio (β), which quantifies the partitioning of available energy between sensible and latent heat fluxes in the WOWT and WWT scenarios. The Bowen ratio is defined as,

$$\beta = \frac{H_{surf}}{LE_{surf}}. \quad (6)$$

Table 5 Spatially averaged surface energy balance components over the wind-farm region shown in Fig. 1

Stability condition		GHF in (W m^{-2})	H_{surf} in (W m^{-2})	LE_{surf} in (W m^{-2})	β
SU	WOWT	36.72	284.76	338.52	0.84
	WWT	38.62	277.78	343.60	0.81
MU	WOWT	38.20	106.07	205.73	0.52
	WWT	38.79	104.99	206.22	0.51
WU	WOWT	20.36	67.31	176.33	0.38
	WWT	20.81	66.71	176.48	0.38
NN-U	WOWT	16.72	27.34	105.94	0.26
	WWT	17.17	27.48	105.36	0.26
N	WOWT	10.94	5.50	33.55	0.16
	WWT	11.07	5.60	33.33	0.17
NN-S	WOWT	4.87	− 7.52	22.65	− 0.33
	WWT	4.80	− 6.95	22.15	− 0.31
WS	WOWT	1.99	− 11.06	19.07	− 0.58
	WWT	1.85	− 10.53	18.69	− 0.56
MS	WOWT	− 4.40	− 13.03	12.43	− 1.05
	WWT	− 4.14	− 13.36	12.49	− 1.07
SS	WOWT	− 21.51	− 8.64	5.15	− 1.68
	WWT	− 16.99	− 14.89	6.88	− 2.17

Including ground heat flux (GHF), surface sensible heat flux (H_{surf}), surface latent heat flux (LE_{surf}), and Bowen ratio (β), for simulations with wind turbines (WWT) and without wind turbines (WOWT) under different atmospheric stability regimes. Net radiation values and corresponding stability classifications are listed in Table 2

The results show a reduction in the Bowen ratio in the WWT scenario under both strongly unstable and strongly stable conditions, indicating a shift toward enhanced latent heat flux relative to sensible heat flux.

We followed the definition of L provided by Gryning et al. (2007) and Van Wijk et al. (1990) to define the stability conditions using L as in Table 3. Although a formulation using virtual potential temperature flux would more completely account for moisture effects on buoyancy, the sensible heat flux formulation was adopted consistently for all simulations and serves here as a stability classification metric.

3 Results

3.1 Overview of Stability Regimes

3.2 Friction Velocity

Friction velocity (u_*) provides a direct measure of the near-surface turbulent momentum flux and serves as a key indicator of turbulence generation within the atmospheric surface layer. It represents the intensity of turbulent mixing close to the surface and is therefore a crucial parameter for understanding surface-atmosphere interactions. Figure 2 presents the

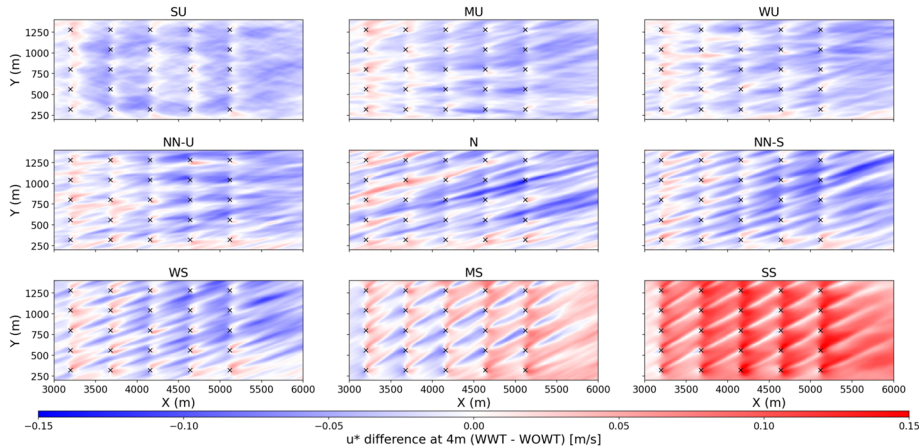


Fig. 2 u_* differences at 4 m height (xy-plane) between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with 'x'. Plot titles correspond to Table 2

spatial distribution of u_* differences at 4m between the WWT and reference WOWT scenarios for each stability condition. The results clearly indicate that increases in u_* concentrated around the wind turbine locations in all the stability conditions. Under unstable and neutral conditions, until the WS scenario, it shows the reduction of u_* in the wake region behind the wind turbines. In contrast, under stable conditions (MS and SS), the influence of the increased u_* extends over a broader region, suggesting that the mechanically generated turbulence more effectively disrupts the stable stratification and enhances momentum exchange across the entire wind farm area. Table 4 shows the average difference of u_* between the WWT and WOWT scenarios. The SU scenario shows the average reduction of 0.029 m s^{-1} . This reduction implies that, in the reference case, turbulence levels are already high due to buoyancy-driven mixing, leaving limited potential for additional enhancement by turbine-induced effects. As atmospheric stability increases, the difference in u_* becomes more pronounced, reflecting the growing importance of mechanical turbulence generated by the turbines. In the SS scenario, u_* increases on average by 0.073 m s^{-1} , indicating that wind turbines substantially enhance turbulent momentum flux in otherwise weakly turbulent and stratified conditions. This demonstrates the turbine's significant effect in promoting mixing and momentum transport near the surface, particularly during stable periods when natural turbulence is suppressed.

3.3 Air Temperature

Figure 3 shows the difference in T_a at 2 m height between the WWT and WOWT simulations. The results indicate that stability conditions directly influence air temperature. Under SU conditions, the average response is a cooling of 0.064 K (see Table 4), with localized regions exhibiting differences greater than 0.2 K (Appendix 2). Overall, 84% of the analyzed area experienced cooling, although small regions of localized warming were also observed, particularly on the upwind side of the wind farm. In contrast, the SS condition produced pronounced warming, with a mean increase of 0.695 K and localized maxima exceeding 1 K , with 100% of the analysed area experiencing warming. The MS condition also showed

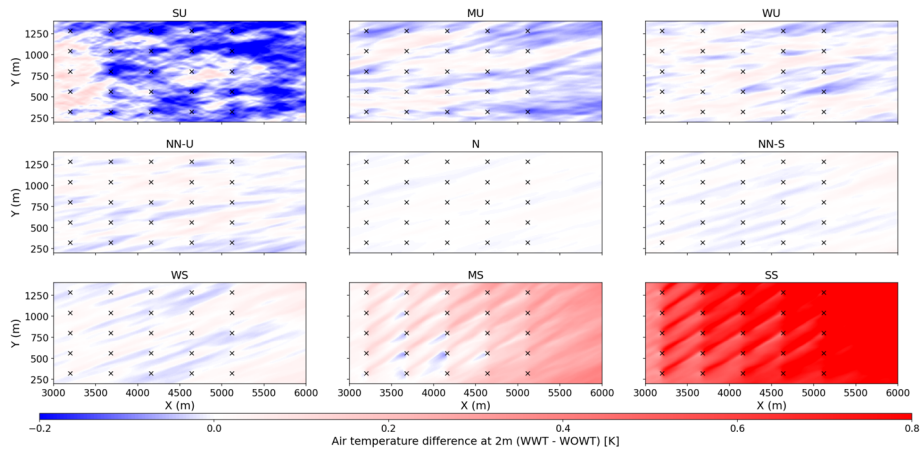


Fig. 3 Air temperature differences at 2 m height (xy-plane) after 30 min between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with ‘x’. Plot titles correspond to Table 2

warming, with an average increase of 0.095 K, and 93.2% of the analysed area was affected by warming. Neutral and near-neutral cases show only minor differences (< 0.05 K), with no clear spatial structure. Overall, the strongest responses are observed under SS and SU, while other stability conditions show weaker but spatially heterogeneous signals.

3.4 Surface Temperature

Figure 4 illustrates the differences in T_{surf} between WWT and WOWT simulations. The results indicate that, across most stability conditions, the presence of turbines generally leads

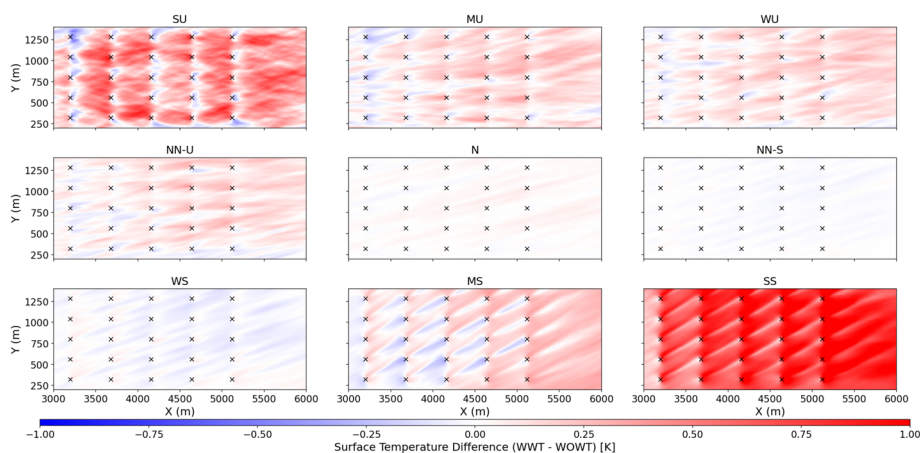


Fig. 4 Surface temperature differences (xy-plane) after 30 min between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with ‘x’. Plot titles correspond to Table 2

to an increase in T_{surf} . Even under neutral conditions, a slight warming of 0.004 K is observed (Table 3). Only the NN-S and WS scenarios exhibit marginal cooling, with decreases of 0.019 K and 0.047 K, respectively. In contrast, SU conditions result in a mean warming of 0.368 K, although the warming is not spatially uniform across the wind farm area. The strongest response in average value difference is found under SS conditions, where T_{surf} increased by 0.76 K (see Table 4). The maximum and minimum differences between WWT and WOWT were found to be 1.18 K and 0.064 K, respectively, indicating that the entire averaged area experienced an increase in T_{surf} (see Appendix 3). By comparison, in the SU scenario, the warming is confined to specific regions, and localized cooling can even be observed directly beneath the turbines.

3.5 Surface Sensible Heat Flux

Figure 5 shows the differences in H_{surf} between WWT and WOWT simulations under various stability conditions. Clear distinctions emerge across all regimes. H_{surf} exhibits a response opposite to that of T_{surf} . Under SU conditions, turbines induce a pronounced reduction in H_{surf} within the wind farm, with local anomalies exceeding -10 W m^{-2} , particularly in wake regions (see Appendix 4). The spatial average across the farm indicates a reduction of -6.97 W m^{-2} (Table 4). In contrast, MU and WU conditions show weaker and more spatially heterogeneous differences, with both positive and negative anomalies, although the average change remains negative. N and NN-U conditions exhibit minimal H_{surf} differences, suggesting negligible turbine effects under well-mixed boundary layers. By contrast, NN-S and WS stratifications reveal enhanced H_{surf} over large parts of the wind-farm area, with positive differences in average values exceeding 0.5 W m^{-2} . In contrast, the MS case shows a slight average reduction of -0.33 W m^{-2} , though the pattern remains spatially variable. A strong negative signal again occurs under SS conditions, where H_{surf} is consistently reduced across the farm, with a mean decrease of -6.25 W m^{-2} . This systematic reduction highlights suppressed turbulent mixing and diminished upward heat transport within stable nocturnal

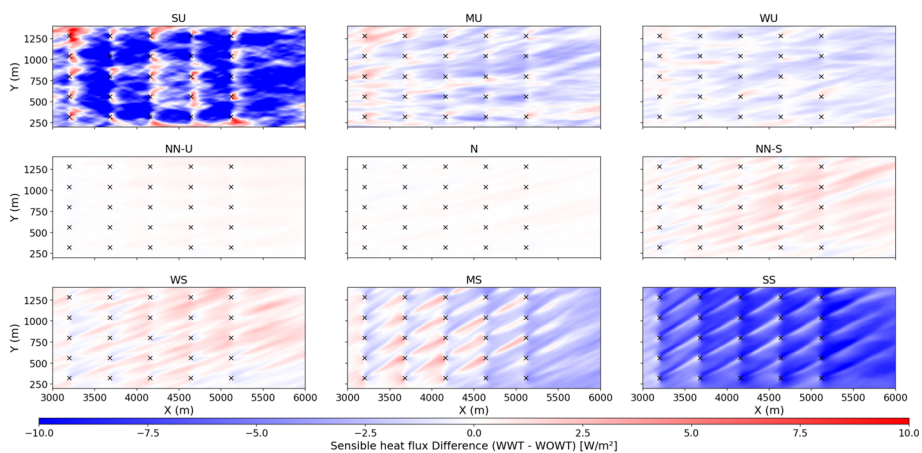


Fig. 5 Sensible heat flux differences at 4 m height (xy-plane) between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with 'x'. Plot titles correspond to Table 2

boundary layers. Overall, these results demonstrate that turbine-induced H_{surf} changes are strongly stability-dependent, with enhanced H_{surf} under weak stability but suppressed H_{surf} under stronger stability and convective conditions.

3.6 Soil Moisture

Figure 6 presents the differences in surface soil moisture (0.001 m top layer) between simulations with and without wind turbines across the considered stability conditions. As the results represent 30-min averages, the volumetric variations are relatively small. However, consistent patterns can be identified. Under SU conditions, soil moisture reduction is most pronounced, with a mean decrease of $1.13 \times 10^{-2}\%$ (v/v) (Table 4). The reduction is spatially heterogeneous, with the wake regions behind the turbines exhibiting the strongest signal showing maximum reduction of $1.69 \times 10^{-2}\%$ (v/v) (see Appendix 5), whereas areas directly beneath the turbines show comparatively weaker reductions. Moreover, the downwind turbine rows experience more pronounced effects than the first row, highlighting the cumulative influence of wake interactions. In contrast, all unstable scenarios (SU, MU, WU) exhibit reductions in soil moisture, with the magnitude of the decrease intensifying with increasing atmospheric instability. NN-U, N, NN-S, and WS conditions display positive soil moisture differences in the presence of turbines, resulting in higher moisture depletion in the scenario without a wind farm. The MS case reveals both localized increases and decreases, but overall indicates a net increase. Under the SS scenario, a consistent reduction in soil moisture is again observed, with an average decrease of $2.09 \times 10^{-3}\%$ (v/v). Although this change is small in absolute magnitude, it represents a systematic response across the wind farm and corresponds to approximately 18.6% of the reduction observed under strongly unstable conditions, indicating that turbine-induced effects remain non-negligible even under stable stratification. These results emphasize the sensitivity of surface soil moisture to turbine-induced modifications of surface fluxes and highlight the importance of extending the analysis to diurnal cycles to capture longer-term impacts on soil water dynamics. To further interpret the surface patterns,

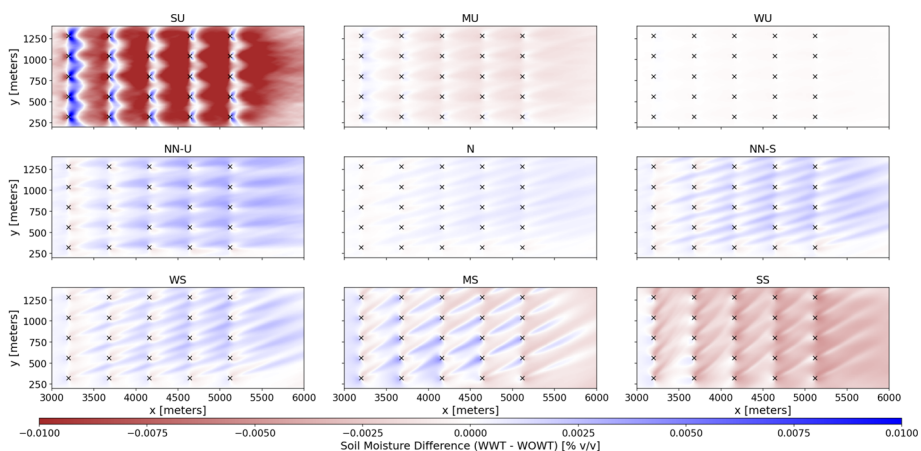


Fig. 6 Soil moisture differences at 0.001 m depth (xy-plane) after 30 min between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with 'x'. Plot titles correspond to Table 2

Fig. 11 presents vertical profiles of the soil moisture difference (WWT–WOWT) within the upper 0.3 m of the soil column. The results show that the strongest differences are confined to the near-surface layers, with the magnitude of the signal decreasing with depth. However, the presence of a coherent signal below the surface indicates that the turbine-induced modifications to surface fluxes are not limited to the immediate surface, but propagate downward through the soil column via land–atmosphere coupling and vertical soil moisture transport.

3.7 Latent Heat Flux

Figure 7 shows the differences in LE_{surf} between simulations with and without wind turbines. A pronounced increase is evident in the wake region under SU conditions, with an average enhancement of 5.08 W m^{-2} . MU and WU scenarios also exhibit positive anomalies, although the increases are comparatively smaller. In contrast, NN-U, N, NN-S, and WS cases display only minor fluctuations, tending slightly toward reductions. The MS condition yields a small average increase of 0.06 W m^{-2} , whereas the SS case shows a more distinct rise of 1.72 W m^{-2} . This increase in LE_{surf} during stable nighttime conditions is consistent with the observed reduction in soil moisture (see Fig. 6 and Table 3). Since LE_{surf} represents the energy associated with evapotranspiration, these findings suggest that turbine-induced turbulence can enhance evapotranspiration at night, thereby contributing to soil moisture depletion. Overall, the variations in LE_{surf} closely mirror those of soil moisture, but in the opposite direction, and the T_{surf} in the same direction, reflecting the coupling between surface energy fluxes and soil hydrology.

These results highlight that even modest changes in LE_{surf} driven by turbine-induced turbulence may alter surface water availability, particularly during nighttime stable conditions. Such effects could have implications for crop water stress, land–atmosphere feedbacks, and long-term assessments of wind farm impacts on agroecosystems.

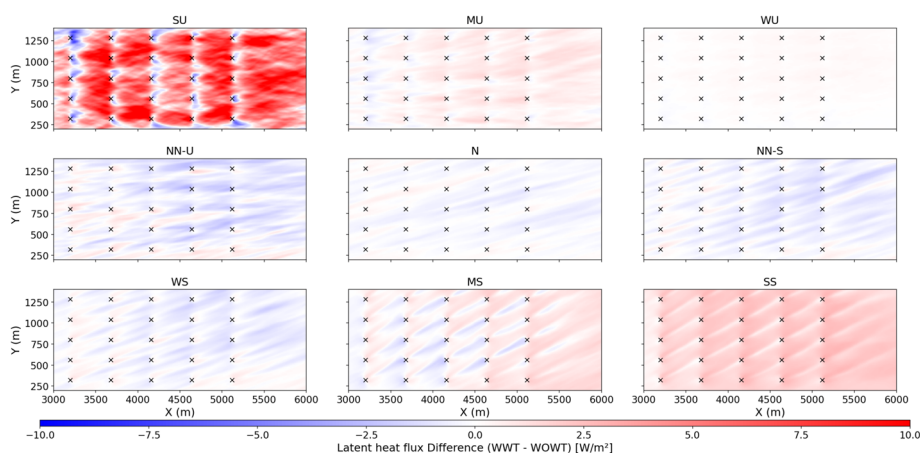


Fig. 7 Latent heat flux differences at 4 m height (xy-plane) between with wind turbines and without wind turbines for all stability conditions. The plots show only the wind farm area; wind turbine locations are marked with ‘x’. Plot titles correspond to Table 2

3.8 Variation of Thermal and Turbulent Characteristics Across Stability Regimes

Figure 8 presents the vertical profiles of potential temperature, providing critical insights into the atmosphere's static stability under varying conditions, from SU to SS. Near the surface, the gradient of the potential temperature profile ($\partial\theta/\partial z$) serves as a direct indicator of atmospheric stability. Stable atmospheric conditions (SS and MS) lead to the greatest alteration in the vertical potential temperature profiles. In contrast, profiles corresponding to other stability regimes, both with and without wind farm effects, display nearly overlapping curves.

The vertical profiles of horizontal wind speed U (Fig. 9) also provide important insight into surface flux responses. Turbines induce a clear reduction of wind speed at hub height and in the wake, consistent with momentum extraction. Interestingly, in strongly stable scenarios,

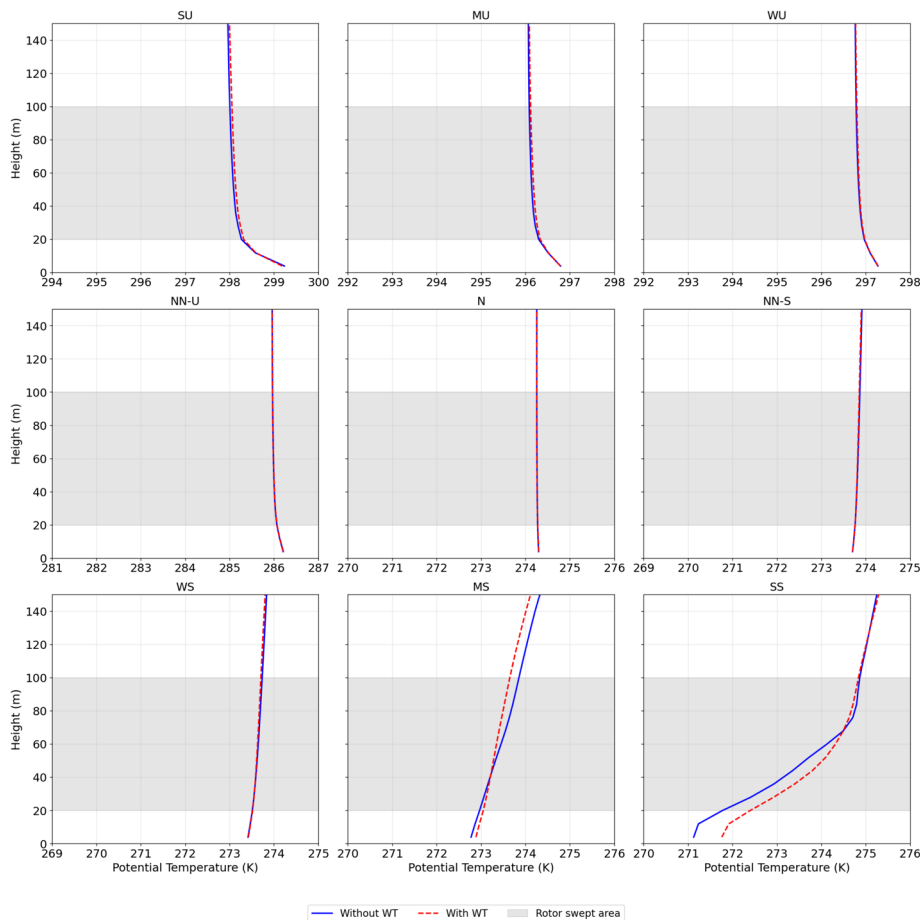


Fig. 8 Vertical profiles of potential temperature (θ), showing mean values averaged over the area defined in Fig. 1. Each profile uses the same axis range to facilitate comparison across stability conditions. The rotor-swept area is shaded in gray. Only the lowest 150 m of the domain is shown. Plot titles correspond to Table 2

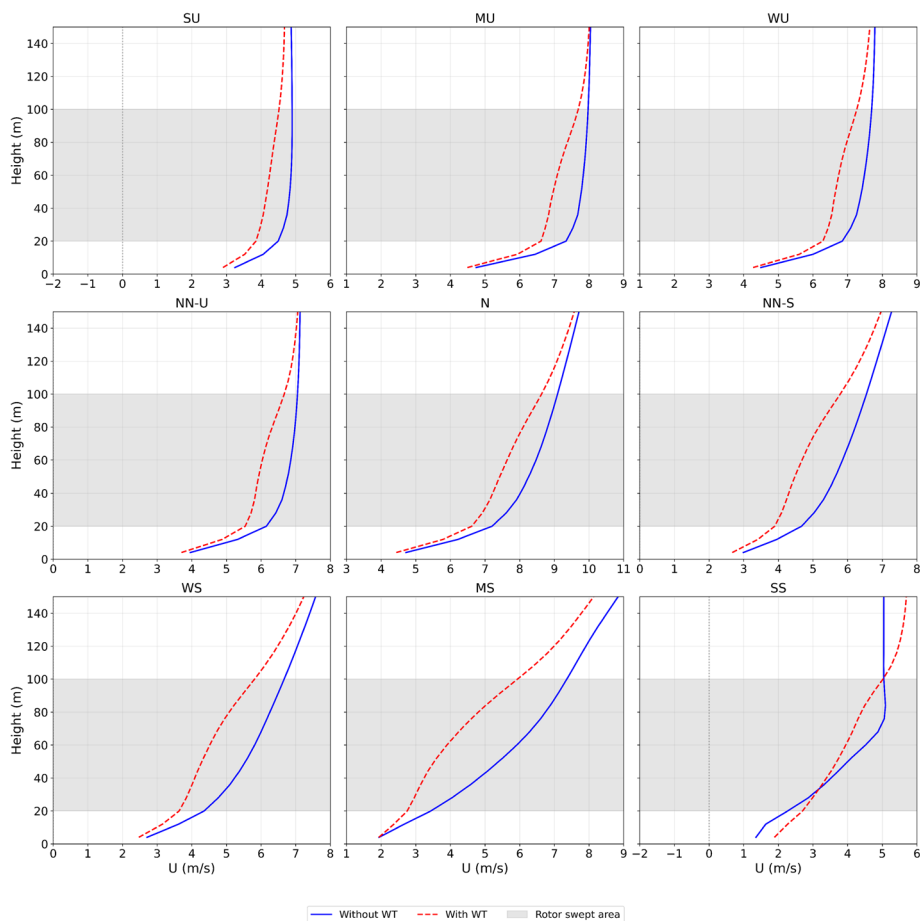


Fig. 9 Vertical profiles of horizontal mean wind speed (U), showing mean values averaged over the area defined in Fig. 1. Each profile uses the same axis range to facilitate comparison across stability conditions. The rotor-swept area is shaded in gray. Only the lowest 150 m of the domain is shown. Plot titles correspond to Table 2

near-surface wind speed is slightly enhanced relative to the no-turbine case. Higher near-surface winds promote turbulent exchange, thereby facilitating upward evapotranspiration (LE). Consequently, the stronger night-time latent heat flux observed in the wake coincides with reductions in soil moisture (Table 4, Fig. 11), reflecting enhanced water loss through increased turbulent transport. Conversely, during unstable conditions, the reduction of near-surface wind speed within the farm likely contributes to the soil moisture decline by limiting moisture replenishment via horizontal advection, while simultaneously enhancing upward fluxes through vertical mixing.

Vertical profiles of water vapor mixing ratio in Fig. 10 further illustrate the impact of wind turbines on moisture redistribution under different stability regimes. Under strongly unstable conditions, the presence of wind turbines leads to an increase in water vapor mixing ratio near the surface as well as at hub height. The enhanced near-surface moisture is consistent with the simulated increase in latent heat flux, while the elevated mixing ratios at hub height

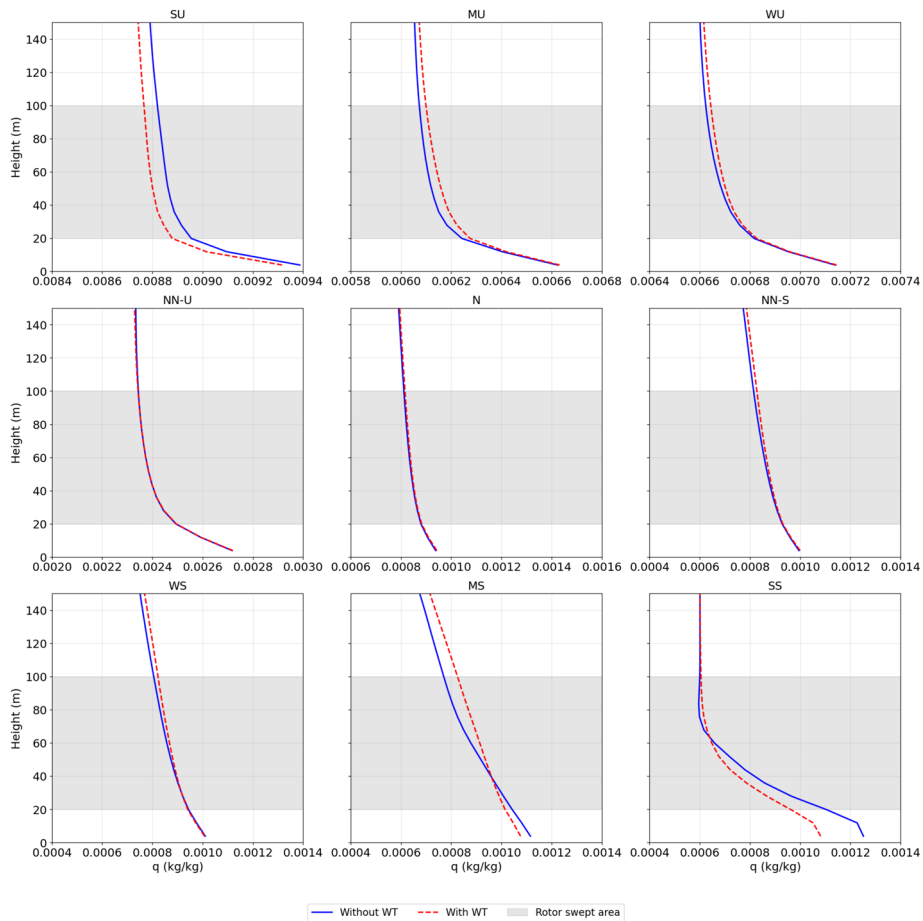


Fig. 10 Vertical profiles of water vapor mixing ratio (q), showing mean values averaged over the area defined in Fig. 1. Each profile uses the same axis range to facilitate comparison across stability conditions. The rotor-swept area is shaded in gray. Only the lowest 150 m of the domain is shown. Plot titles correspond to Table 2

indicate vertical redistribution of water vapor associated with turbine-induced turbulence and wake mixing. In contrast, neutral conditions show only minor differences in the vertical profiles of water vapor mixing ratio between the WWT and WWT scenarios, reflecting the comparatively weak response of surface moisture fluxes. Under strongly stable nocturnal conditions, water vapor mixing ratio increases at hub height but decreases near the surface in the presence of wind turbines, consistent with enhanced mechanical mixing and ventilation of the near-surface layer.

Figure 11 presents the vertical profiles of soil moisture differences between the simulations with and without wind turbines for all stability regimes, extending to a depth of 0.3 m. The results indicate that under SU conditions, the reduction in soil moisture is not confined to the immediate surface layer but extends throughout the upper soil column, with a consistent decrease visible down to 0.2 m depth. A similar, though weaker, near-surface reduction is also observed under SS conditions. The weakly unstable scenario doesn't show a noticeable

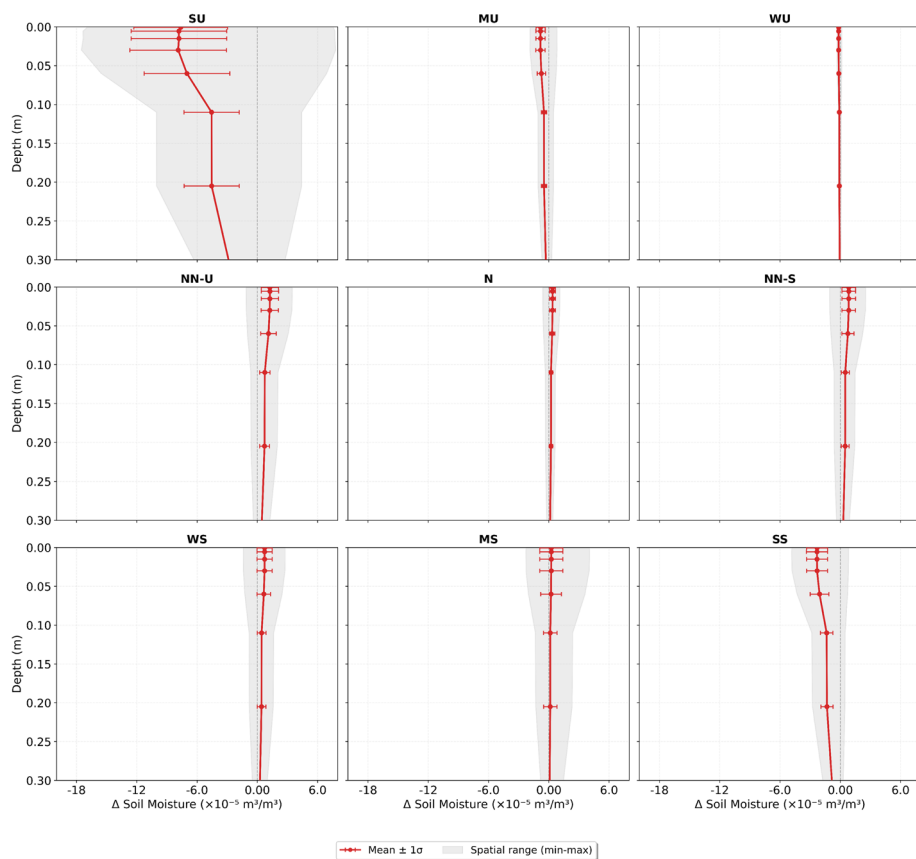


Fig. 11 Vertical profiles of soil moisture difference (WWT-WOWT), within the top 0.3 m of the soil column, spatially averaged over the domain outlined in Fig. 1. Solid red lines with circular markers represent the horizontal mean values, with error bars indicating ± 1 standard deviation (σ) of spatial variability. The grey shaded envelope shows the full spatial range (minimum to maximum) observed across the domain. Plot titles correspond to Table 2

difference in this scale. In contrast, for the remaining stability regimes, the soil moisture profiles for the difference show slightly positive values, indicating wind turbines have reduced the soil moisture depletion. These results suggest that turbine-induced effects on soil moisture exhibit a clear dependence on atmospheric stability, with the most pronounced vertical coherence occurring under strongly unstable conditions.

Figure 12 presents the vertically averaged kinematic sensible heat flux and moisture flux profiles for representative SU, N, and SS conditions. Under SU conditions, both sensible heat and moisture fluxes are substantially enhanced in the WWT simulations compared to the WOWT case throughout the rotor layer and extending above turbine top height. The enhanced upward transport indicates intensified turbulent vertical mixing generated by turbine-induced turbulence under convective stratification. In contrast, the neutral case exhibits very weak scalar fluxes with only minor differences between WWT and WOWT simulations, suggesting that although turbines generate additional turbulence, the absence of strong vertical scalar

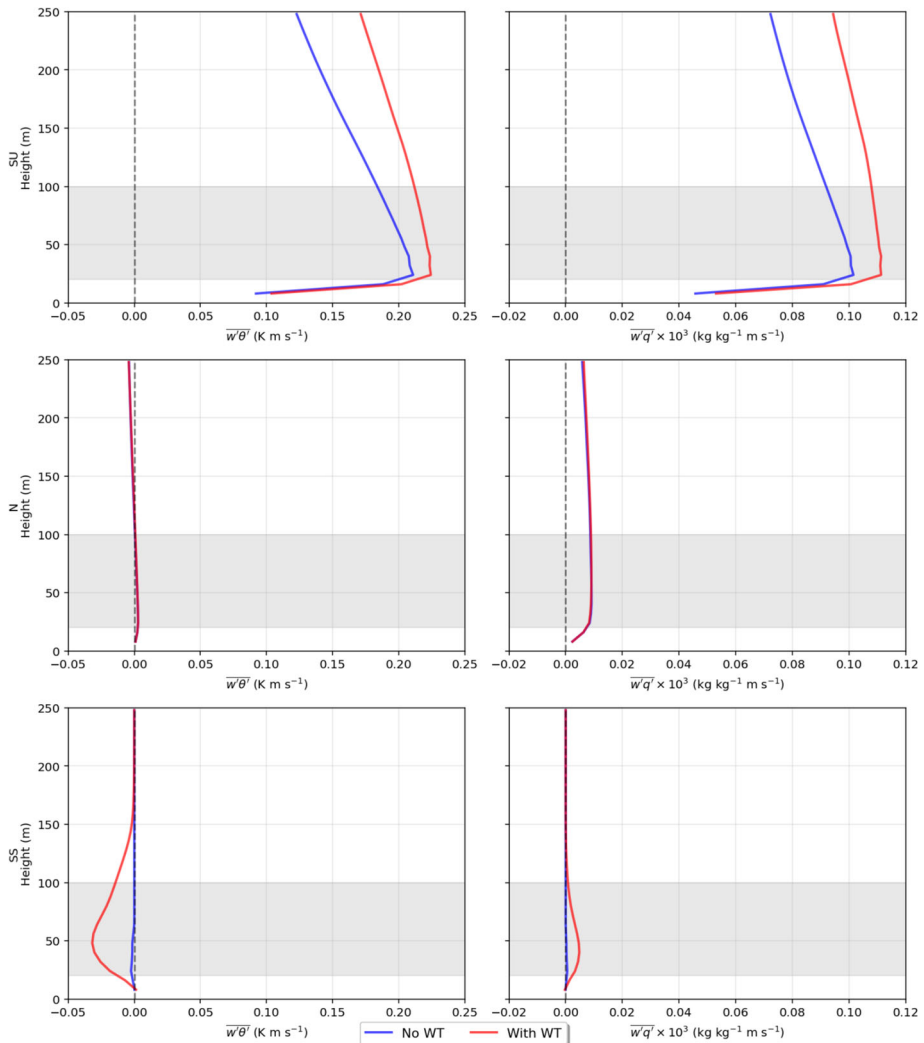


Fig. 12 Vertical profiles of horizontally averaged kinematic sensible heat flux ($\overline{w'\theta'}$, left) and kinematic moisture flux ($\overline{w'q'}$, right) for the SU, N, and SS scenarios in simulations with (WWT) and without wind turbines (WOWT). Profiles are spatially averaged over the wind farm area shown in Fig. 1 and plotted up to 250 m above ground level. The gray shaded region indicates the rotor-swept area

gradients limits the resulting turbulent scalar transport. Under SS conditions, the turbine-induced scalar transport exhibits fundamentally different behavior compared to the unstable regime. While the moisture flux remains positive within the rotor layer, the sensible heat flux becomes strongly negative, indicating enhanced downward transport of warmer air toward the surface. This contrast suggests that turbine-generated turbulence under stable stratification produces differential transport responses for heat and moisture, reflecting the distinct vertical gradients governing each scalar. The strongest perturbations remain confined to the rotor layer

and rapidly decay above approximately 100–150 m, consistent with strong suppression of vertical mixing by stable stratification.

The *TKE* profiles in Fig. 13 further reveal that considerable turbulence is generated even under neutral and near-neutral cases. However, because the vertical θ -gradient is weak in these scenarios, this turbulence does not lead to appreciable warming or cooling. This demonstrates that *TKE* alone is insufficient to explain air temperature responses, but rather, the interplay between turbulence intensity and stratification determines both the sign and magnitude of the impact. The Profile of potential temperature and its gradient, along with the *TKE*, therefore, provide a more reliable diagnostic, as they directly reflect the thermodynamic consequences of vertical displacements. The strong enhancement of *TKE* during stable conditions (Fig. 13) further explains why turbines often produce the most pronounced warming at night, when stable stratification is strongest, and the potential for entrainment of warmer air is greatest.

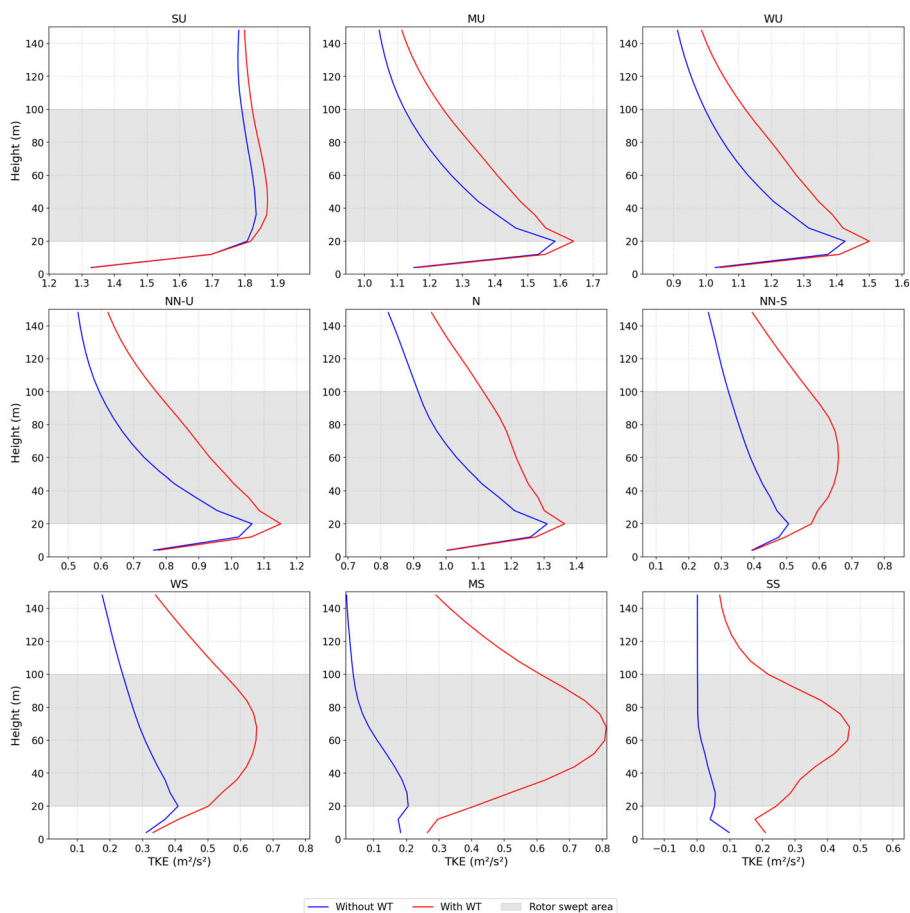


Fig. 13 Vertical profiles of turbulent kinetic energy (*TKE*), showing mean values averaged over the entire domain area. Each profile uses the same axis range to facilitate comparison across stability conditions. The rotor-swept area is shaded in gray. Only the lowest 150 m of the domain is shown. Plot titles correspond to Table 2

Taken together, these diagnostics clarify the interconnected nature of turbine impacts on near-surface climate and surface fluxes. The combination of altered stability, momentum extraction, and turbulence generation explains not only the observed near-surface warming and cooling patterns but also the associated changes in sensible and latent heat fluxes, soil moisture, and surface temperature.

4 Discussion

4.1 Model Validity and Numerical Robustness

To ensure that the results presented here are both robust and internally consistent, an ensemble-based evaluation was performed. For each stability regime, multiple ensemble members were simulated. In the unstable conditions, ten ensemble runs were conducted, while for all other stabilities, convergence was achieved after five ensemble members. Across all cases, change in standard deviation beyond these ensemble numbers was less than 10% of the corresponding ensemble standard deviation, indicating that the simulations had reached statistical stability. Variability analyses were performed for five representative parameters, namely, potential temperature at 2 m, air temperature at 2 m, surface temperature, sensible heat flux at 4 m, and latent heat flux at 4 m. The averaged ensemble spread for these variables was found to be minimal when horizontal averages were considered (see Appendix 9 and Appendix 10 for the ensemble averaged values and standard deviation values for air temperature at 2m and sensible heat flux at 4m for the SU scenario), suggesting that random perturbations introduced in the initial conditions did not lead to divergent behavior. The response of each variable followed the expected physical behavior under the corresponding stability condition, with no unexpected or nonphysical anomalies detected. The relatively large standard deviations associated with some difference fields primarily reflect spatial heterogeneity induced by wake interactions rather than uncertainty of the mean response. Thus, interpretation focuses on coherent spatial patterns, ensemble-averaged anomalies, and temporally persistent signals, rather than on mean differences alone. By specifying the ensemble member number as an integer between 1 and 2000, PALM generates statistically independent realizations of the same simulation setup. While the instantaneous turbulent flow fields of individual ensemble members differ entirely, their mean statistical properties converge toward identical values upon ensemble averaging. This reinforces that the simulated differences between scenarios arise from turbine-induced processes rather than numerical artifacts. All simulations within a given stability class shared identical initial and boundary conditions, differing only by random perturbations applied to the velocity field. Hence, the observed ensemble variability can be confidently attributed to stochastic turbulence generation, not to setup inconsistencies. It is important to acknowledge that the PALM land surface model used in this study does not include freeze–thaw physics. As a result, soil moisture and surface water do not freeze, even when the simulated surface and near-surface air temperatures drop below 0 °C. The model, therefore, continues to permit liquid–water evaporation, leading to non-zero latent heat flux and soil moisture depletion under sub-zero conditions where sublimation or strongly suppressed moisture fluxes would occur in reality. However, our interpretation relies on relative differences between WWT and WOWT simulations, and these differential responses arise from turbulence modification. Therefore, similar turbine-induced changes would be expected under strongly stable conditions with temperatures slightly above freezing, where freeze–thaw processes would not be a factor.

The present study employed realistic turbine specifications corresponding to the NM80 model from the *DANAERO MW II* project conducted by DTU, ensuring physical fidelity in the turbine–atmosphere interaction. Land surface characteristics were also derived from literature-based parameters. Vegetation and soil properties were defined according to PALM’s inbuilt parameterizations for “crops and mixed farming” and “medium fine soil,” which determine the roughness length, albedo, canopy resistance, leaf area index, and hydraulic properties (e.g., field capacity, saturation moisture, and hydraulic conductivity). PALM itself has been extensively validated in previous studies for its representation of boundary-layer turbulence, surface–atmosphere exchanges, and turbine wake dynamics (Witha et al. 2014; Gehrke et al. 2021; Wanner et al. 2022; Radović et al. 2024). The present simulations further confirmed its physical realism. The instantaneous outputs of the horizontal wind velocity field clearly demonstrated wake generation, shear-layer formation, and turbulence structures consistent with theoretical expectations and laboratory observations. Although the present study was based on idealized simulations using PALM, and do not allow for direct validation against site-specific measurements, the ability of the LES framework to resolve the dominant turbulent transport processes provides confidence that the key mechanisms governing turbine–atmosphere interactions are realistically captured. The results provide physically consistent insights into how wind turbines modify near-surface thermal and hydrological conditions under different atmospheric stabilities.

4.2 Limitations and Applicability to Real-World Conditions

Although the present simulations provide physically consistent insights into turbine–atmosphere interactions, their transferability to real-world conditions is constrained by several idealizations. The simulations assumed horizontally homogeneous terrain, uniform vegetation cover, constant net radiation during the simulated period, and a fixed atmospheric stability maintained over 4.5 h without diurnal evolution. Such stationary conditions do not occur in nature, where continuously changing boundary-layer dynamics, varying land cover, and heterogeneous terrain can amplify or attenuate the turbine-induced effects. In particular, the use of constant stability conditions allows for the isolation of specific physical mechanisms, but it also limits the direct interpretation of the results in a time-evolving atmospheric context. Despite these simplifications, the simulations remain valuable for understanding fundamental cause-and-effect relationships. The idealized framework enables us to isolate the influence of stability on turbine–atmosphere coupling, which is often difficult to discern from field data due to confounding variability. Thus, the findings can be qualitatively extended to real-world scenarios, under daytime unstable conditions, wind farms may locally reduce T_a due to enhanced mixing of cooler air, whereas during stable nights, they can increase T_a through downward mixing of warmer air and momentum. However, it should be emphasized that the present analysis is based on 30-min mean responses under idealized, quasi-stationary stability regimes. While the diagnosed temperature and flux perturbations are physically meaningful at this timescale, their evolution over longer periods remains uncertain. If such turbine-induced modifications persist over several consecutive hours, they may accumulate and lead to substantial changes in near-surface temperature, surface energy partitioning, and soil moisture. As a result, implications for soil moisture evolution, surface energy partitioning, and agricultural productivity should be interpreted with caution. While the present study identifies robust process-level responses, a quantitative assessment of cumulative impacts requires simulations with time-varying atmospheric forcing over diurnal and longer timescales. Conversely, continued surface warming during stable nighttime

conditions could progressively weaken stratification, eventually transitioning the boundary layer toward near-neutral conditions, under which turbine-induced mixing would be less effective. Similarly, during daytime unstable conditions, enhanced mixing may alter the efficiency of convective heat transport in a non-linear manner as the boundary layer evolves. These potential feedbacks cannot be resolved within the present framework and highlight the necessity of extending future simulations to full diurnal cycles. Only diurnal simulations can capture the temporal interplay between turbine-induced turbulence, boundary-layer stability transitions, and cumulative land-surface responses. Under stable conditions, the observed lateral asymmetry of the wakes is primarily associated with wind veer resulting from Ekman turning, where the combined effects of Coriolis forcing and surface friction lead to a vertical rotation of the mean wind direction. This induces a systematic lateral deflection of turbine wakes and modifies the local inflow conditions experienced by downstream turbines. The strength of this asymmetry increases with atmospheric stability, consistent with boundary-layer theory. While these effects introduce spatial variability in the wake structure, the use of spatial averaging allows us to isolate the bulk response of the wind farm without obscuring the underlying physical mechanisms.

The responses observed in our simulations (see Tables 3 and 4), namely the reduction in T_a and H_{surf} , and the increase in LE_{surf} under strongly unstable conditions, as well as the enhanced near-surface wind speed and warming of T_{surf} , T_a under strongly stable conditions, are consistent with previous studies, despite methodological differences. For instance, Baidya Roy and Traiteur (2010) and Baidya Roy (2011) employed mesoscale modeling with turbine-rotor parameterizations to investigate the impact of large wind farms on near-surface temperature, humidity, and surface fluxes. They found that during stable conditions, wind-farm-induced turbulence enhanced vertical mixing and produced local nighttime warming, with the magnitude of flux changes depending on atmospheric stability. Rajewski et al. (2013), through the Crop Wind Energy Experiment (CWEX) in Iowa, used eddy-covariance measurements within and around a large onshore wind farm and observed altered heat and momentum fluxes in the turbine wake region. Smith et al. (2013) analyzed meteorological data from two 80 m masts at a large wind farm in the U.S. Midwest and found that while the vertical potential temperature gradient was not strongly affected during daytime, it was significantly reduced at night, accompanied by a measurable near-surface (2.5 m) temperature increase. Using satellite observations, Zhou et al. (2012) detected a significant surface warming trend of about 0.72 K per decade over wind farms in west-central Texas, while Xia et al. (2016) similarly reported an increase of 0.31–0.70 °C in nighttime surface temperature after wind farm installation, with no noticeable daytime effect. While the above studies differ from ours in domain, method, and scale, the consistency of the directional responses of sensible heat flux, latent heat flux, surface warming, Air temperature, and enhanced near-surface wind supports the robustness of our LES results. This agreement suggests that PALM adequately represents the dominant physical mechanisms, turbine-induced turbulence, momentum extraction, and the resulting modification of surface energy partitioning.

The chosen grid resolution (8 m) allows the dominant wake structures and shear layers generated by the turbines to be resolved. However, it may be insufficient to fully capture smaller turbulent scales, particularly under strongly stable conditions where turbulence is inherently suppressed. A grid-sensitivity analysis performed with a refined resolution of 4 m showed negligible differences in mean surface fluxes and temperatures, while variability increased due to enhanced resolution of turbulent fluctuations. This indicates that the primary turbine-induced transport processes are robust with respect to grid resolution, although small-scale turbulence remains partially represented by the subgrid-scale model. This limitation is

consistent with findings from LES intercomparison studies (Beare et al. 2006) and should be considered when interpreting higher-order turbulence statistics.

4.3 Physical Mechanisms Governing Stability-Dependent Wind Turbine Effects

The interaction between wind turbines and the atmospheric boundary layer modifies the surface energy balance in a manner that strongly depends on background stability. Under strongly unstable conditions (see Tables 3 and 4), the presence of wind turbines leads to a reduction in near-surface horizontal wind speed (Fig. 9) and u_* (Fig. 2), indicating weakened surface-layer shear production, while turbine-generated turbulence within and above the rotor layer continues to enhance vertical scalar redistribution under buoyancy-dominated conditions. Vertical profiles of water vapor mixing ratio (Fig. 10) reveal an increase near the surface as well as at hub height in the WWT scenario, suggesting enhanced vertical redistribution of moisture. Turbine-induced turbulence promotes the downward transport of relatively cooler and drier air from aloft, which mixes with the warmer and moister air near the surface. While this increases the turbulent removal of water vapor, the near-surface specific humidity does not decrease because evaporation is not moisture-limited under these conditions and the land surface acts as a sufficiently large moisture reservoir. This can be explained by the increased removal of soil moisture in the WWT scenario. In contrast, the near-surface air temperature responds more strongly to the enhanced turbulent exchange, leading to more efficient cooling of air due to the limited surface energy supply. As a result, latent heat flux increases while sensible heat flux decreases (see Table 5), despite only modest changes in mean near-surface humidity.

The counterintuitive coexistence of surface warming and cooling of 2 m air temperature can be interpreted through changes in aerodynamic resistance and surface energy partitioning. The reduction in friction velocity in the WWT case implies increased aerodynamic resistance and weaker surface-atmosphere coupling, which reduces the efficiency of sensible heat transfer from the surface and contributes to surface warming. At the same time, turbine-induced mixing enhances downward transport of cooler air from aloft, resulting in lower near-surface air temperature. This decoupling is further supported by the increase in ground heat flux and the reduction in Bowen ratio (Table 5), indicating increased heat storage at the surface and a shift in available energy partitioning toward latent heat flux. A similar coexistence of surface warming and near-surface air cooling has also been reported by Lu and Porté-Agel (2015), who attributed this behavior to turbine-induced modifications of turbulent transport and land-atmosphere exchange, lending additional support to the physical plausibility of this response. Under moderately unstable conditions, this response becomes much weaker, as stronger background shear maintains more effective surface-atmosphere coupling and suppresses the aerodynamic decoupling observed under strongly unstable conditions. The apparent non-monotonic sign changes across stability classes should not be interpreted as erratic behavior, but rather as reflecting competing physical mechanisms whose relative importance changes with atmospheric stability. Under strongly unstable conditions, buoyancy dominates and turbine effects primarily modify convective transport and energy partitioning, whereas under stable conditions mechanically generated mixing dominates and alters inversion strength, moisture gradients, and momentum transport. In transitional regimes, neither mechanism fully dominates, which can lead to weaker or even opposing responses. This behavior also reflects that the background flow itself does not vary monotonically across stability classes, as indicated by the non-monotonic variations in friction velocity and boundary

layer height (Table 3). Such responses are therefore an expected feature of stability-dependent turbine–surface interactions rather than evidence of numerical inconsistency.

The vertical soil moisture difference profiles (See Fig. 11) provide additional insight into the physical consistency of the simulated response. While the strongest differences occur in the uppermost soil layers, the presence of a coherent signal extending to lower levels under strongly unstable conditions indicates that the observed changes are not limited to the surface. They reflect adjustments in the coupled soil–vegetation–atmosphere system driven by turbine-induced modifications of turbulent exchange and surface fluxes. It should be noted, however, that the simulation period is relatively short and does not allow deeper soil layers to reach hydrological equilibrium. Therefore, the results should be interpreted as short-term responses of the upper soil column rather than long-term changes in root-zone soil moisture. The PALM land surface model represents vertical soil moisture transport through its soil parameterization, enabling the propagation of near-surface changes into deeper layers. Under strongly stable nocturnal conditions (see Tables 3 and 4), wind turbines induce distinct modifications to the surface energy balance through enhanced turbulent mixing. The wind turbine-induced turbulence enhances downward mixing of warmer but drier air from hub height into the surface layer, weakening the near-surface temperature inversion. Despite the increase in u_* (Fig. 2), the simulations show an at time—negative H_{surf} across the entire wind farm area (Fig. 5), with H_{surf} becoming more negative by approximately 6.25 W m^{-2} on average in the WWT scenario (Table 4). This reduction in H_{surf} arises from an increased near-surface temperature gradient as T_a increases relative to T_{surf} . Consequently, LE_{surf} increases compared to the no-turbine case, driven by enhanced turbulent exchange, elevated surface temperature, and the downward mixing of drier air, which together strengthen the surface–air moisture gradient. Higher air temperatures further increase saturation vapor pressure at the surface, reinforcing evaporative fluxes. The simultaneous reduction in H_{surf} and increase in LE_{surf} thus reflect differential responses of thermal and moisture gradients to turbine-induced mixing. The streamwise evolution shown in the figures in Appendix 11–14 highlights that the reported bulk anomalies are influenced by the finite extent of the simulated 5×5 turbine array. The strongest responses generally occur after the flow has interacted with several turbine rows, reflecting the growth of an internal boundary layer and the cumulative adjustment of momentum and scalar transport within the wind farm. Consequently, the domain-averaged values presented in the tables should be interpreted as integrated responses over a developing array rather than as representative of fully developed deep-array conditions described in the literature (e.g., Calaf et al. 2010, 2011; VerHulst and Meneveau 2014). This distinction is particularly relevant because many agricultural wind farms consist of finite turbine arrays where entrance effects remain important and may substantially influence the local microclimatic response.

The vertical scalar flux profiles further support the physical interpretation of the turbine-induced transport mechanisms. Under strongly unstable conditions, both kinematic sensible heat flux and moisture flux remain positive throughout the rotor layer and are enhanced in the WWT simulations relative to the WOWT case, indicating intensified upward turbulent transport driven by turbine-enhanced mixing. In contrast, under strongly stable conditions, the turbine-induced response differs fundamentally between heat and moisture transport. The kinematic sensible heat flux becomes substantially more negative within the rotor layer, while the moisture flux remains positive and increases relative to the WOWT case. This behavior indicates enhanced downward transport of warmer air together with enhanced upward transport of moisture from the surface, consistent with turbulence-induced weakening of the nocturnal inversion and enhanced evaporation. These contrasting responses highlight the

competing roles of turbine-generated turbulence, background stratification, and reduced near-surface momentum exchange. A similar competition between enhanced turbulent mixing and reduced surface exchange efficiency was described by Calaf et al. (2011), who identified a delicate balance between opposing mechanisms controlling scalar transport in wind-farm boundary layers. While their simulations considered neutral stratification, the present results demonstrate that this balance becomes strongly stability dependent under convective and stable atmospheric conditions.

The spatial sensible heat flux anomalies within the wind farm exhibit organized wake-aligned streak structures whose magnitude and spatial coherence depend strongly on atmospheric stability (Fig. 5). Under unstable conditions, the anomalies are spatially heterogeneous and concentrated near wake interaction regions, whereas under stable conditions, broader coherent reductions in sensible heat flux emerge across the farm. These patterns are qualitatively consistent with the wind-tunnel experiments of Zhang et al. (2013a), who also reported pronounced spatial heterogeneity of surface heat fluxes associated with turbine wakes. However, unlike the near-neutral conditions considered in their experiments, the present LES suggests that the response of scalar transport to turbine-induced mixing depends strongly on atmospheric stability, which governs whether the resulting anomalies remain localized or produce a coherent domain-scale signal.

Additionally, the observed increase in near-surface wind speed and u_* facilitates the removal of water vapor from the surface layer through advection and increased mixing, further sustaining evaporation throughout the night. The combined effect of these processes suggests a shift in energy partitioning toward latent heat and a reduction in the Bowen ratio since the net radiation remains the same in both WWT and WWT scenarios when the soil moisture depletion is noted. This eventually leads potentially to a greater cumulative soil-moisture depletion beneath the wind farm during stable nighttime conditions (Fig. 6). The spatial heterogeneity of these effects reflects the interplay between turbine-induced turbulence and background convective processes. Beyond implications for crop water availability, turbine-induced modifications of heat and moisture exchange may also influence broader biogeochemical processes, including soil respiration and trace gas emissions such as N_2O , though these processes are beyond the scope of the present study.

Although the present simulations do not capture the full diurnal cycle, these patterns suggest that the cumulative daily effect could be substantial. In prolonged periods without precipitation or irrigation, the presence of wind turbines may therefore reinforce the decline in soil moisture by a few percent, so that critical values such as the wilting point are reached more rapidly. Such persistent drying could have implications for plant development throughout different growth stages, potentially resulting in reduced crop productivity. These patterns emphasize the importance of simulations resolving the complete diurnal cycle, as the interaction between turbine-induced turbulence and background stability evolves substantially between daytime convective and nighttime stable regimes. Therefore, 24-h simulations could capture how these adjustments accumulate and feed back across successive stability states, and are thus required to determine the net daily impact on surface fluxes and soil moisture.

Furthermore, the simulations revealed a mean increase of 0.695 K in air temperature at 2 m after one 30-min averaging interval during strongly stable conditions compared to the WWT scenario (see Table 4). Although this warming may appear modest in magnitude, such a warming over a short averaging period is significant (Mahrt et al. 2020). If sustained or recurrent over several hours, this turbine-induced mixing could lead to a considerable cumulative warming throughout the course of a night. Thus, this effect could mitigate surface cooling and frost formation in agricultural croplands, potentially reducing frost-related

damage of plant tissue. In addition, it may also alter nocturnal boundary-layer stratification, surface energy partitioning, and dew formation processes, with complex feedbacks on local microclimates and ecosystem functioning. However, such feedback would likely not persist in a linear manner throughout the night. As the near-surface layer warms, static stability would progressively weaken, ultimately approaching near-neutral conditions in which turbine-generated turbulence has a much smaller impact on mixing. This suggests that the magnitude and duration of turbine-induced warming are dynamically constrained by the evolving stratification. Overall, the comparison between the SS and SU regimes underscores the dual role of wind turbines in modifying land–atmosphere interactions. They enhance nocturnal latent heat flux and near-surface warming under stable conditions, while modifying convective heat and moisture redistribution during daytime instability. To fully capture all relevant feedback and assess how the warming evolves over a complete diurnal cycle, simulations spanning full diurnal cycles are required. Such simulations are part of ongoing work and will help better constrain the real-world relevance of the identified mechanisms.

The downstream fetch of the domain after the wind farm is approximately 1680 m (~21 rotor diameters), which may not be sufficient for complete wake recovery, particularly under stable conditions where turbulence is suppressed and wake deficits can persist over longer distances, as highlighted by (Lu and Porté-Agel 2011). However, the primary focus of this study is on the flow and surface–atmosphere interactions within the wind farm region itself, rather than on far-wake recovery. Regarding the outflow boundary condition, PALM employs a radiation-type boundary condition designed to minimize artificial reflections of disturbances back into the domain. In the present simulations, no indications of upstream-propagating artifacts or nonphysical flow features were observed in the velocity or turbulence fields within the wind farm region. Furthermore, the analysis is restricted to the interior of the wind farm (as indicated in Fig. 1), which is sufficiently separated from the outflow boundary to reduce potential boundary effects.

These results highlight the importance of considering atmospheric stability when assessing wind farm impacts on the surface energy balance and land-surface processes.

5 Conclusion

This study investigated the impact of wind turbines on near-surface meteorological and land-surface variables using LES under a range of atmospheric stability conditions over a 30-min interval. The results demonstrate that turbine-induced turbulence modifies the surface energy balance and soil–atmosphere interactions in a systematic and stability-dependent manner.

Near-surface air temperature exhibited contrasting responses. The SU conditions were associated with a mean cooling of 0.064 K, while the SS conditions led to pronounced warming of 0.695 K, with almost 100% of the turbine area experiencing positive anomalies (Fig. 3). Surface temperature showed a similar pattern, with general warming across stability regimes. The strongest increase occurred under SS conditions (0.76 K), whereas only marginal cooling was observed in near-neutral to stable scenarios.

Simulated surface fluxes further highlighted the role of turbines in modulating land–atmosphere exchanges. H_{surf} was reduced under unstable conditions, particularly in SU, with an average decrease of -6.97 W m^{-2} , reflecting enhanced mixing and reduced vertical temperature gradients. Conversely, under Neutral and weakly stable regimes (NN-S, WS), H_{surf} often increased. However, SS conditions show a systematic average reduction of 6.25 W m^{-2} ,

reflecting enhanced downward turbulent heat transport. LE_{surf} generally increased, particularly under SU conditions ($+ 5.08 \text{ W m}^{-2}$) and SS conditions ($+ 1.72 \text{ W m}^{-2}$), suggesting turbine-induced enhancement of evapotranspiration. These findings are consistent with the observed reduction in m_s across most unstable regimes, with the strongest decline in SU ($- 1.126 \times 10^{-2}\%$ (v/v)) and then the second strongest decline under SS ($- 2.09 \times 10^{-3}\%$ (v/v)).

Vertical profiles of potential temperature, wind speed, and TKE provided physical explanations for these patterns. Turbines acted as localized sources of turbulence and sinks of momentum, consistent with previous studies (Baidya Roy et al. 2004; Miller & Keith, 2018). Strong vertical gradients of θ under SS conditions facilitated near-surface warming, while limited stratification under neutral cases prevented significant temperature changes despite enhanced TKE . Wind speed profiles revealed reductions at hub height and near the surface, with higher residual near-surface wind under SS conditions, potentially contributing to soil moisture depletion beneath the wind farm.

A key contribution of this work lies in its systematic analysis of wind turbine effects across a broad spectrum of atmospheric stability regimes, ranging from strongly unstable to strongly stable. To our knowledge, this is among the first studies to explicitly link turbine-induced surface responses with the transition between stability conditions to the best of our knowledge, thereby filling a critical gap in the literature. This framework provides a pathway to better understand how diurnal transitions in stability mediate wind farm impacts.

Overall, the findings highlight that, while daytime effects remain modest, nighttime stable conditions exhibit a systematic warming, heat flux changes, and soil moisture reductions. Intricate land–atmosphere feedbacks are at play in response to the presence of wind turbines and could have mixed implications for agriculture, including potential frost mitigation but also enhanced evapotranspiration and soil drying. Future work should therefore extend these simulations to full diurnal cycles, allowing the stability–turbulence feedbacks to evolve naturally, to explore cumulative effects over multiple days. Additionally, the interactions with crop models can be useful to better quantify the agricultural relevance of these land–atmosphere feedbacks.

Appendix 1: Friction velocity

Friction velocity at 4 m average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WWT scenarios for each stability. All values are in m s^{-1} .

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	0.417	0.399	0.434	0.006	0.388	0.352	0.435	0.014	-0.029	-0.070	0.020	0.015
MU	0.537	0.506	0.561	0.008	0.513	0.462	0.564	0.017	-0.024	-0.076	0.028	0.018
WU	0.507	0.485	0.529	0.008	0.485	0.440	0.535	0.015	-0.023	-0.079	0.037	0.018
NN_U	0.441	0.410	0.480	0.011	0.415	0.348	0.476	0.021	-0.026	-0.107	0.046	0.024
N	0.516	0.473	0.550	0.014	0.486	0.414	0.579	0.024	-0.030	-0.132	0.070	0.029
NN_S	0.322	0.293	0.350	0.010	0.287	0.225	0.367	0.023	-0.035	-0.098	0.058	0.025
WS	0.288	0.262	0.309	0.008	0.261	0.207	0.334	0.023	-0.027	-0.088	0.052	0.025
MS	0.191	0.182	0.202	0.003	0.190	0.115	0.256	0.029	-0.002	-0.077	0.067	0.029
SS	0.104	0.098	0.111	0.003	0.177	0.077	0.261	0.031	0.073	-0.026	0.158	0.032

Appendix 2: Air temperature at 2 m

Air temperature at 2 m average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in °C.

Stability condition	WOWT			WWT			Difference					
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	27.767	27.599	27.982	0.058	27.703	27.453	27.884	0.057	− 0.064	− 0.275	0.138	0.068
AMU	24.998	24.941	25.074	0.022	24.999	24.939	25.058	0.019	0.000	− 0.090	0.076	0.026
WU	25.410	25.356	25.464	0.017	25.419	25.356	25.472	0.020	0.009	− 0.084	0.074	0.026
NN_U	14.211	14.174	14.258	0.016	14.221	14.183	14.274	0.015	0.011	− 0.044	0.067	0.018
N	2.190	2.181	2.201	0.004	2.194	2.178	2.209	0.006	0.004	− 0.011	0.022	0.005
NN_S	1.549	1.535	1.560	0.004	1.547	1.531	1.567	0.006	− 0.002	− 0.022	0.025	0.008
WS	1.235	1.217	1.254	0.007	1.238	1.205	1.278	0.014	0.003	− 0.035	0.046	0.016
MS	0.530	0.476	0.575	0.022	0.624	0.452	0.786	0.058	0.095	− 0.072	0.278	0.066
SS	− 1.244	− 1.339	− 1.115	0.064	− 0.550	− 0.886	− 0.211	0.110	0.695	0.329	1.105	0.128

Appendix 3: Surface temperature

Surface temperature average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in K.

Stability condition	WWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	310.126	309.909	310.453	0.085	310.494	309.923	310.974	0.186	0.336	-0.261	0.880	0.205
MU	300.125	300.020	300.344	0.057	300.266	300.019	300.534	0.086	0.112	-0.127	0.381	0.089
WU	299.524	299.455	299.656	0.051	299.623	299.451	299.846	0.070	0.088	-0.175	0.329	0.075
NN_U	287.221	287.125	287.372	0.047	287.336	287.152	287.547	0.070	0.079	-0.131	0.358	0.079
N	274.495	274.449	274.498	0.027	274.498	274.433	274.540	0.020	0.018	-0.039	0.086	0.019
NN_S	273.335	273.308	273.338	0.013	273.316	273.283	273.349	0.014	-0.015	-0.044	0.033	0.012
WS	272.804	272.751	272.812	0.023	272.756	272.678	272.853	0.031	-0.028	-0.112	0.078	0.033
MS	271.612	271.581	271.664	0.020	271.657	271.321	271.936	0.113	0.036	-0.305	0.309	0.116
SS	269.514	269.493	269.614	0.040	270.274	269.648	270.696	0.188	0.727	0.064	1.182	0.195

Appendix 4: Surface sensible heat flux

Surface sensible heat flux average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in W m^{-2} .

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	284.76	277.54	291.08	1.94	277.78	266.62	290.57	4.12	-6.97	-19.38	6.70	4.69
MU	106.07	103.66	107.93	0.62	104.99	101.85	107.79	0.99	-1.08	-4.25	1.90	1.04
WU	67.31	66.31	68.21	0.34	66.71	65.02	68.38	0.54	-0.60	-2.62	1.70	0.63
NN_U	27.34	27.11	27.52	0.09	27.48	27.14	27.72	0.10	0.14	-0.25	0.47	0.13
N	5.50	5.38	5.66	0.06	5.60	5.27	5.84	0.09	0.10	-0.30	0.46	0.11
NN_S	-7.52	-8.09	-6.86	0.20	-6.95	-8.33	-5.68	0.43	0.57	-1.07	1.76	0.48
WS	-11.06	-11.68	-10.33	0.23	-10.53	-12.16	-9.02	0.57	0.52	-1.38	2.19	0.62
MS	-13.03	-13.64	-12.40	0.22	-13.36	-16.42	-9.29	1.32	-0.33	-3.38	3.79	1.35
SS	-8.64	-9.36	-8.16	0.28	-14.89	-18.30	-9.18	1.69	-6.25	-9.90	-0.80	1.72

Appendix 5: Soil moisture

Soil moisture average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in % v/v.

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	19.332117	19.328363	19.331041	0.002465	19.320856	19.311926	19.336805	0.004876	- 0.007626	- 0.016935	0.007592	0.004662
MU	21.601716	21.598637	21.599236	0.002760	21.601497	21.596995	21.599860	0.003397	- 0.000819	- 0.001852	0.000811	0.000457
WU	21.654125	21.651804	21.652190	0.002134	21.654120	21.651503	21.652265	0.002295	- 0.000163	- 0.000337	0.000161	0.000084
NN_U	25.782278	25.784934	25.785577	0.002974	25.782868	25.784165	25.788489	0.003718	0.001245	- 0.001118	0.003472	0.000866
N	24.930276	24.929526	24.929738	0.000630	24.930702	24.929085	24.930735	0.000747	0.000370	- 0.000596	0.001104	0.000292
NN_S	24.951169	24.950850	24.951184	0.000175	24.951203	24.949920	24.953556	0.000951	0.000841	- 0.001056	0.002520	0.000679
WS	24.955165	24.957736	24.958053	0.002722	24.955200	24.956432	24.960685	0.003498	0.000723	- 0.001404	0.002766	0.000754
MS	24.971037	24.969628	24.969848	0.001289	24.970396	24.967515	24.973789	0.001214	0.000245	- 0.002274	0.004044	0.001154
SS	24.983044	24.983445	24.983613	0.000491	24.980955	24.978742	24.984300	0.001066	- 0.002316	- 0.004828	0.000827	0.001049

Appendix 6: Latent heat flux

Latent heat flux average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in W m^{-2} .

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	338.52	334.63	342.97	1.21	343.60	334.63	350.85	2.84	5.08	- 4.23	13.05	3.15
MU	205.73	205.11	206.37	0.18	206.22	204.94	207.38	0.41	0.49	- 0.79	1.63	0.40
WU	176.33	176.06	176.59	0.09	176.48	176.09	176.80	0.13	0.15	- 0.16	0.42	0.09
NN_U	105.94	104.67	107.25	0.44	105.36	103.51	106.75	0.56	- 0.58	- 3.08	1.32	0.71
N	33.55	33.14	33.86	0.14	33.33	32.67	34.06	0.22	- 0.23	- 1.15	0.60	0.27
NN_S	22.65	22.12	23.06	0.15	22.15	21.01	23.32	0.38	- 0.50	- 1.56	0.87	0.41
WS	19.07	18.65	19.44	0.14	18.69	17.62	19.81	0.40	- 0.38	- 1.51	0.91	0.42
MS	12.43	12.17	12.68	0.09	12.49	10.33	13.95	0.68	0.06	- 2.05	1.57	0.69
SS	5.15	5.03	5.33	0.07	6.88	5.25	8.00	0.50	1.72	0.01	2.90	0.52

Appendix 7: Horizontal wind speed U at 60 m

Horizontal wind speed U at 60 m average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in m s^{-1} .

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	4.86	4.59	5.11	0.07	4.25	2.92	4.74	0.28	-0.62	-2.04	-0.08	0.30
MU	7.83	7.58	8.03	0.09	7.08	5.78	7.88	0.39	-0.75	-2.01	0.03	0.40
WU	7.48	7.11	7.80	0.13	6.74	5.50	7.57	0.39	-0.74	-1.91	0.19	0.39
NN_U	6.86	6.43	7.18	0.15	6.04	4.49	7.11	0.50	-0.82	-2.48	0.38	0.52
N	8.47	8.15	8.78	0.15	7.64	6.44	8.49	0.40	-0.84	-2.04	0.12	0.42
NN_S	5.85	5.61	6.05	0.08	4.68	3.24	5.87	0.50	-1.17	-2.57	0.10	0.51
WS	5.82	5.63	6.00	0.07	4.52	3.20	5.74	0.52	-1.30	-2.62	-0.09	0.52
MS	5.92	5.77	6.05	0.06	3.90	2.01	5.47	0.66	-2.02	-3.92	-0.54	0.64
SS	4.52	4.47	4.56	0.02	3.95	1.25	5.37	0.93	-0.57	-3.24	0.84	0.93

Appendix 8: Potential temperature at 2 m

Potential temperature average, minimum, maximum, and standard deviation (SD) values, and average, minimum, and maximum values for the difference between WWT and WOWT scenarios for each stability. All values are in K.

Stability condition	WOWT				WWT				Difference			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
SU	299.81	299.62	300.00	0.06	299.70	299.48	299.90	0.06	-0.06	-0.27	0.14	0.07
MU	297.01	296.97	297.11	0.03	297.01	296.97	297.09	0.03	0.00	-0.09	0.08	0.03
WU	297.48	297.39	297.49	0.05	297.48	297.39	297.50	0.04	0.01	-0.08	0.07	0.03
NN_U	286.32	286.25	286.33	0.04	286.32	286.26	286.35	0.03	0.01	-0.04	0.07	0.02
N	274.31	274.30	274.32	0.01	274.32	274.30	274.33	0.01	0.00	-0.01	0.02	0.01
NN_S	273.66	273.65	273.68	0.01	273.66	273.65	273.69	0.01	0.00	-0.02	0.03	0.01
WS	273.35	273.34	273.37	0.01	273.36	273.33	273.40	0.01	0.00	-0.03	0.05	0.02
MS	272.65	272.60	272.70	0.02	272.76	272.58	272.91	0.06	0.09	-0.07	0.28	0.07
SS	270.90	270.79	271.01	0.07	271.56	271.24	271.92	0.11	0.69	0.33	1.10	0.13

Appendix 9: Ensemble average values for air temperature at 2 m in SU scenario

Individual simulations average, minimum, maximum, and standard deviation (SD) values, and ensemble average, minimum, and maximum values for the without wind turbines scenario for strongly unstable scenario. All values are in °C.

Ensemble number	Individual averages				Ensemble averages			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
1	27.74	27.29	28.17	0.13	27.74	27.29	28.17	0.13
2	27.84	27.49	28.46	0.14	27.79	27.48	28.16	0.10
3	27.78	27.35	28.23	0.14	27.78	27.47	28.12	0.09
4	27.76	27.41	28.12	0.13	27.78	27.55	28.05	0.08
5	27.82	27.40	28.29	0.15	27.79	27.58	28.07	0.07
6	27.80	27.39	28.13	0.11	27.79	27.60	28.04	0.07
7	27.65	27.32	28.07	0.14	27.77	27.59	28.00	0.06
8	27.73	27.44	28.37	0.13	27.76	27.58	27.98	0.06
9	27.74	27.44	28.16	0.12	27.76	27.58	27.95	0.06
10	27.82	27.52	28.28	0.14	27.77	27.60	27.98	0.06

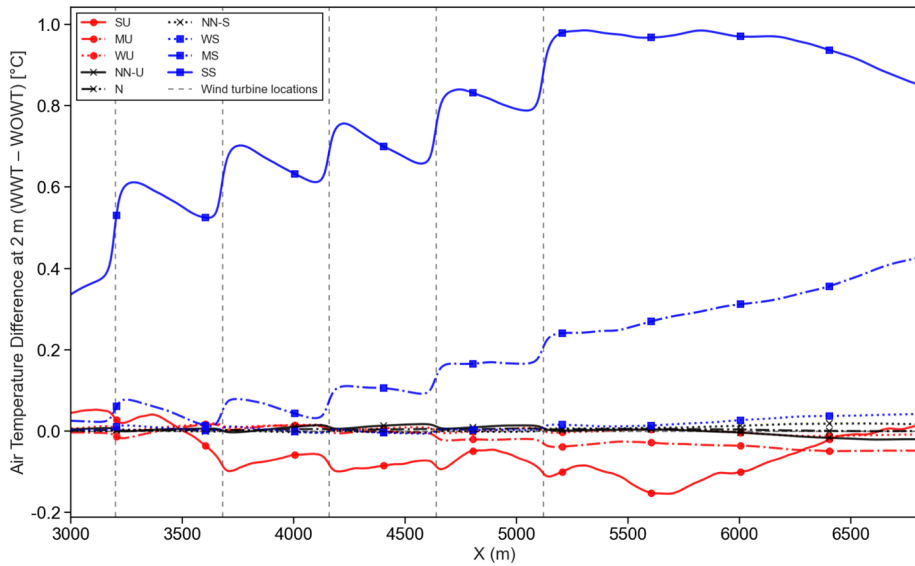
Appendix 10: Ensemble average values for surface sensible heat flux at 4 m in SU scenario

Individual simulations average, minimum, maximum, and standard deviation (SD) values, and ensemble average, minimum, and maximum values for the without wind turbines scenario for strongly unstable scenario. All values are in W m^{-2} .

Ensemble number	WOWT				WWT			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
1	289.59	273.39	307.32	5.62	289.59	273.39	307.32	5.62
2	286.47	262.70	303.28	6.09	288.03	275.12	299.58	3.88
3	290.26	265.81	305.04	6.21	288.77	278.82	297.49	3.12
4	282.17	256.16	308.07	8.01	287.12	277.28	296.36	2.87
5	282.62	256.17	302.06	9.26	286.22	276.39	294.76	2.86
6	283.60	266.21	299.41	5.30	285.78	276.49	293.25	2.64
7	278.23	250.58	302.32	7.18	284.70	275.96	291.71	2.39
8	290.15	262.38	304.27	5.48	285.39	276.60	291.98	2.22
9	279.52	260.80	308.70	7.33	284.73	277.13	291.32	2.05
10	284.95	259.58	299.85	6.43	284.75	277.54	291.08	1.94

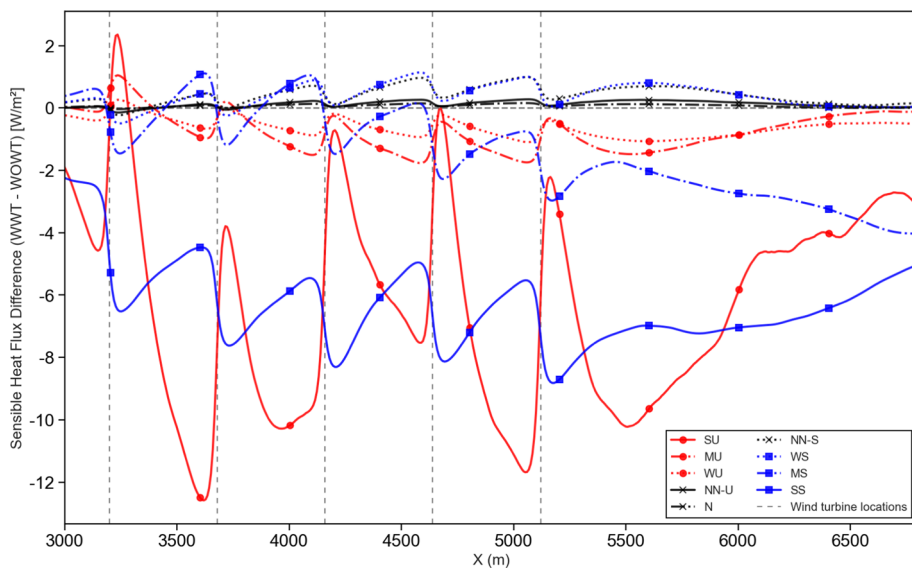
Appendix 11: Streamwise development of the laterally averaged 2 m air temperature difference

Laterally averaged profiles of the 2 m air temperature difference (WWT – WWT) along the streamwise direction, calculated across the wind farm width (320–1280 m), illustrate the downstream adjustment of the surface response under different atmospheric stability conditions.



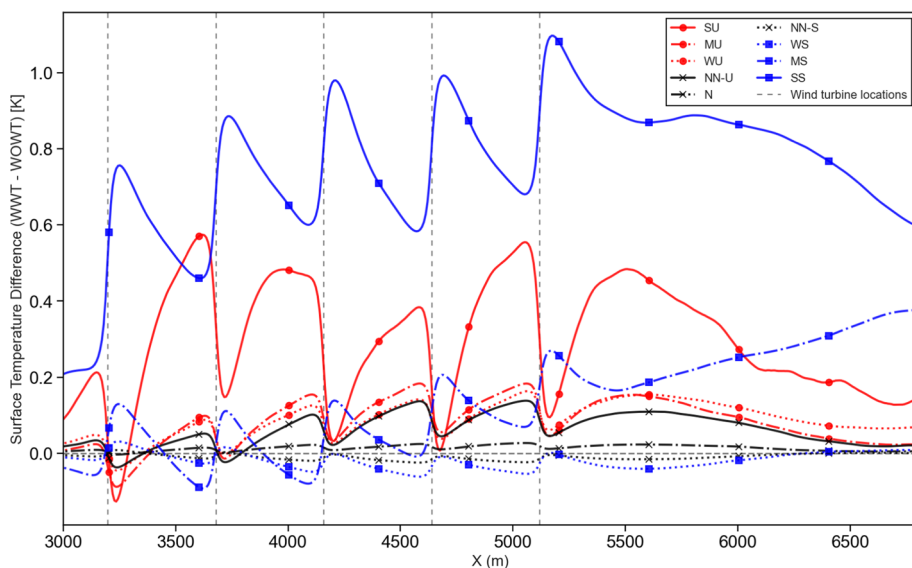
Appendix 12: Streamwise development of the laterally averaged sensible heat flux difference

Laterally averaged profiles of the sensible heat flux difference (WWT – WWT) along the streamwise direction, calculated across the wind farm width (320–1280 m), illustrate the downstream adjustment of the surface response under different atmospheric stability conditions.



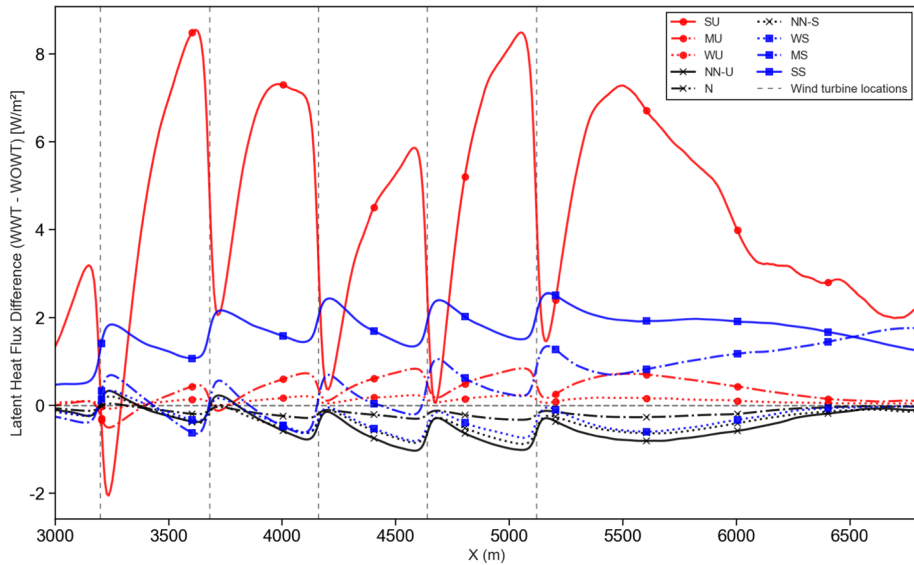
Appendix 13: Streamwise development of the laterally averaged surface temperature difference

Laterally averaged profiles of the surface temperature difference ($WWT - WOWT$) along the streamwise direction, calculated across the wind farm width (320–1280 m), illustrate the downstream adjustment of the surface response under different atmospheric stability conditions.



Appendix 14: Streamwise development of the laterally averaged latent heat flux difference

Laterally averaged profiles of the surface temperature difference (WWT – WOWT) along the streamwise direction, calculated across the wind farm width (320–1280 m), illustrate the downstream adjustment of the surface response under different atmospheric stability conditions.



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Author Contribution S.W. wrote the main manuscript text, the analysis and interpretation of the results, and prepared the figures. All authors contributed to the conception and design of the LES experiments, the development of the LES methodology, and the critical revision of the manuscript.

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Data Availability The data used in this study were generated using large-eddy simulations with the PALM model. Due to the large volume of the simulation output and storage constraints on the high-performance computing system, the datasets are not publicly available but can be made available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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