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WIND ENERGY SCIENCE DISCUSSIONS

Review on Near-Surface Meteorological Variations Induced by Wind Turbines

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Abstract. This review synthesizes more than two decades of research on near-surface meteorological variations induced by wind turbines and wind farms, combining evidence from field measurement campaigns, satellite observations, mesoscale and microscale simulations. Across these different approaches, the literature shows that wind turbines influence the atmospheric boundary layer through blockage effects, momentum extraction, turbulence generation, and rotor-induced vertical motions. Near-surface meteorological responses are strongly controlled by atmospheric stability. Under stable nighttime conditions, wind turbines generally induce near-surface warming, reduced relative humidity, modifications of turbulence characteristics, and changes in sensible and latent heat fluxes. In contrast, effects during unstable daytime conditions are typically weaker and may even exhibit slight cooling. Through their influence on surface moisture and turbulent exchanges, wind turbines can also enhance evaporation. These microclimatic modifications may subsequently have an impact on ecosystems, with some studies reporting impacts on vegetation activity and crop productivity. However, the magnitude and even the sign of these responses remain highly variable across sites. Wind farm size, layout, topography, atmospheric conditions and surface characteristics further modulate the spatial extent and intensity of the observed effects through cumulative wake interactions and flow redistribution processes. Overall, the meteorological perturbations induced by wind turbines are generally small relative to the natural variability of the atmospheric boundary layer, although locally significant effects can occur under favorable atmospheric conditions. Their persistence, cumulative effects within large wind farms, and continued growth in turbine size and installed capacity warrant further observational and modeling efforts to improve understanding of turbine–atmosphere–surface interactions.

1 Introduction

The energy sector remains one of the largest contributors to anthropogenic greenhouse gas emissions (Lee et al., 2023), making the transition toward low-carbon energy systems a major global challenge to limit global warming and mitigate climate change. Among the various renewable energy sources, wind energy has emerged as a key technology and is increasingly adopted by many countries as part of their energy transition strategies. Global installed wind capacity has grown rapidly over the past decades, surpassing 1 TW in 2023 with annual additions exceeding 100 GW per year according to the International Energy Agency. This expansion has been associated with a continuous increase in turbine dimensions, with modern wind turbines (WT) frequently exceeding total heights of 200 m alongside with the development of increasingly large wind farms (WF) both

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onshore and offshore (Veers et al., 2019). While wind energy is widely regarded as a low-carbon and environmentally beneficial technology, the rapid deployment of wind turbines has raised concerns regarding their potential environmental impacts. These include noise emissions (Pedersen and Persson Waye, 2007), visual and light pollution (Wolsink, 2007), as well as ecological effects on wildlife, particularly birds and bats (Kunz et al., 2007; Thaxter et al., 2017). Beyond these aspects, another question has progressively emerged within the scientific community: the potential influence of wind turbines on atmospheric processes and local meteorology.

This question was first explicitly raised in the early 2000s through two pioneering studies published almost simultaneously. Baidya Roy et al. (2004) investigated the impact of wind turbines on meteorology, while Keith et al. (2004) explored their potential influence on climate. Using large-scale numerical modeling approaches, these studies highlighted the existence of measurable, atmospheric variations induced by wind farms. These early works laid the foundation for a new research field dedicated to understanding how wind farms can modify the atmosphere.

As shown in Fig. 1, research activity on this topic has expanded considerably since the 2010s, supported by the development and diversification of measurements and numerical investigation methods. Satellite-based analyses (Zhou et al., 2012), in situ measurement campaigns within wind farms (Smith et al., 2013; Rajewski et al., 2013), and small-scale numerical simulations (Lu and Porté-Agel, 2011; Xie and Archer, 2017) have all contributed to improving our understanding of these phenomena. These different approaches have been applied to a wide range of configurations, including onshore and offshore wind farms, various turbine size, diverse atmospheric conditions and stability.

In an opinion article, Armstrong et al. (2014) identified wind turbine-induced microclimatic changes as an emerging research field and emphasized the limited understanding of their implications for land-atmosphere interactions, ecosystem functioning, and surface energy exchanges. At that time, the scarcity of in situ observations and the limited spatial resolution of available numerical models strongly constrained the interpretation of turbine-induced atmospheric variations. Over the last decade, however, the multiplication of studies and methodologies used to assess wind turbine impacts has considerably expanded our knowledge of this topic. In this context, a review of current knowledge on near-surface meteorological variations induced by wind turbines is needed.

The evaluation and quantification of these meteorological effects have become increasingly important for several reasons. From an environmental standpoint, understanding near-surface atmospheric variations is essential to assess potential impacts on vegetation, agricultural crops, ecosystems, and wildlife in the vicinity of wind farms. From a meteorological perspective, the cumulative effects of large-scale wind farm deployments raise the question of whether wind turbines should be represented in future operational weather models. Finally, from an industrial perspective, these atmospheric modifications may influence turbine-turbine and farm-farm interactions by influencing wake development, thereby affecting wind farm performance and power production.

In this work, we choose to focus specifically on near-surface variations, where the potential impacts on human activities and ecosystems are the most significant. This region is also the most extensively documented in the literature, due to the relative ease of conducting in situ measurements and satellite-based observations. The objective of this paper is to provide an overview of the current state of knowledge regarding near ground meteorological variations induced by wind turbines. The

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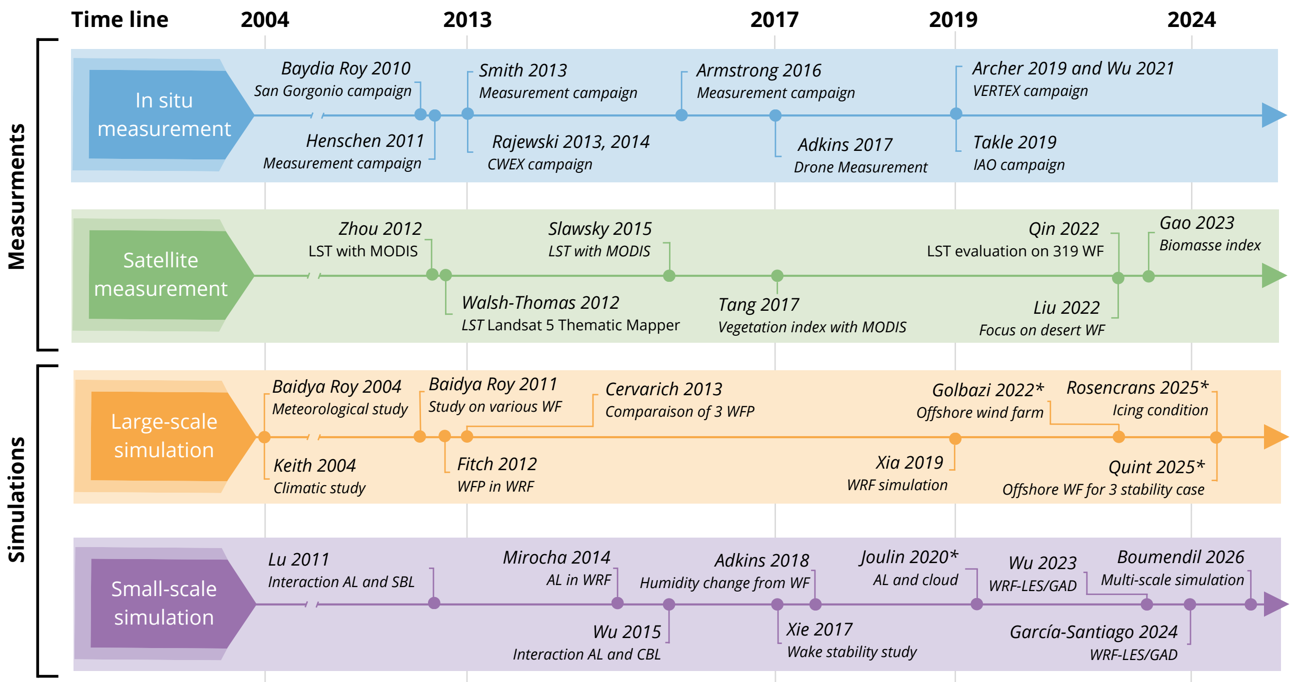

Figure 1. Historic time line on meteorological variations induced by wind turbines studies. Asterisks indicate studies performed in offshore conditions. (WF: Wind Farm, WT: Wind Turbine, LST: Land Surface Temperature, WFP: Wind Farm Parametrization,SBL: Stable Boundary Layer, CBL: Convective Boundary Layer, LES: Large Eddy Simulation, MODIS: Moderate Resolution Imaging Spectroradiometerv, AL: Actuator Line, GAD: Generalized Actuator Disk, WRF: Weather Research and Forecasting model)

paper is written with the objective of providing readers an overview of the main concepts, methodologies, and results currently available in the literature. In this sense, particular attention is given to presenting the different approaches, their historical development and their respective limitations.

The paper is organized as follows. First, we present the main experimental and numerical methodologies used to investigate wind turbine-induced meteorological variations. We then examine each atmospheric variable individually, analyzing their dependence to atmospheric or wind turbine characteristics.

2 Experimental Approaches

Experimental methods include both in situ measurements conducted within or near wind farms and remote sensing observations derived from satellite data. These approaches provide direct evidence of atmospheric or surface modifications but are either constrained by spatial and temporal coverage, or methodologies uncertainties.

Each of these approaches provides complementary insights into the mechanisms governing wind turbine-induced meteorological variations, while also presenting specific limitations. In the following sections, we detail the different methodologies used in the literature and discuss their respective strengths, weaknesses, and inherent constraints.

2.1 In Situ Measurement Campaigns

Although the first temperature measurements near wind farms were collected as early as 1989 at the San Gorgonio site in California (Baidya Roy and Traiteur, 2010), the CWEX (Crop/Wind-energy Experiment) program (Rajewski et al., 2013), initiated in 2010 in Iowa, can be considered the pioneering large-scale in situ study specifically dedicated to wind farm-atmosphere interactions. It was the first extensive field campaign to deploy dense networks of stations and remote sensing instruments upstream, within, and downstream of a part of a wind farm in order to quantify the interactions between wind turbines and the microclimate of agricultural areas. Almost simultaneously, Smith et al. (2013) conducted a similar study in a wind farm composed of approximately 300 turbines in Indiana (map of the measurement setup on Fig. 2). This time the methodology relied on two meteorological towers positioned at opposite side of the wind farm to compare the upstream and downstream flow modified by the wind farm. Concurrently with the early phases of the CWEX campaign, a team of students from Purdue University carried out a case study in the Meadow Lake wind farm in Indiana (Henschen et al., 2011), providing one of the first documented in situ observations of the influence of large wind farms on local microclimatic conditions. Clusters of meteorological instruments separated by more than 4.5 km were deployed across the site to characterize meteorological variations at the scale of a wind farm.

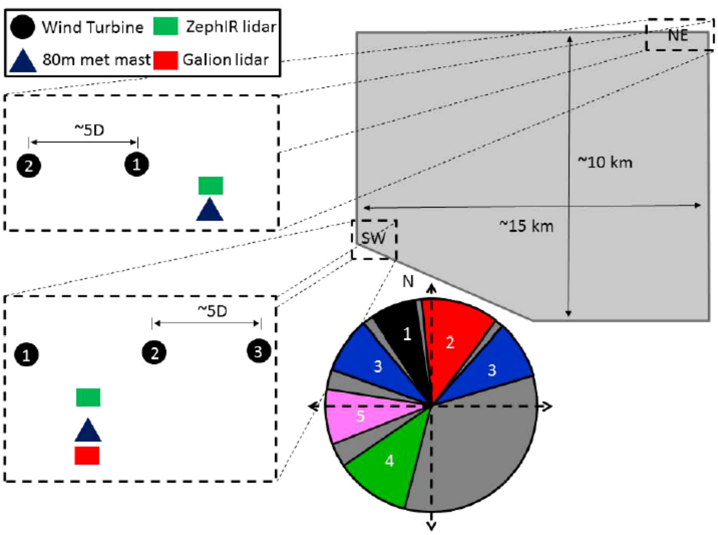

Figure 2. Experimental setup of Smith et al. (2013). The farm (in grey) consists of an approximately 300 onshore turbines located over flat terrain in the U.S. Midwest. Wind-direction sectors were defined to distinguish free-stream conditions (1), direct turbine wakes (3 & 5), and wind-farm wakes (4 & 2) (figure from Smith et al. (2013) in accordance with the Creative Commons Attribution 3.0 License).

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Subsequently, several additional measurement campaigns covering a wide range of spatial scales were conducted. Armstrong et al. (2016) investigated the Black Law wind farm in Scotland using a dense network of tens of ground sensors deployed over a large area to study impacts on a peatland ecosystem. At the opposite, the VERTEX (Vertical Enhanced Mixing) campaign Archer et al. (2019) focused on microscale processes around a single isolated 2MW turbine in Delaware using 15 surface flux stations and two scanning lidars. This high-resolution approach was complemented by the work of Adkins and Sescu (2017), who used drones to map in three dimensions the near wake and humidity profiles behind a single turbine. The IAO (Iowa Atmospheric Observatory) campaign (Takle et al., 2019), conducted in a nearby location of CWEX, focusing the study on vertical change using two meteorological towers.

With the exception of IAO, which was conducted close to the CWEX site, each measurement campaign took place in a distinct environmental and topographic context, with significant differences in turbine size, wind farm configuration, surface characteristics, and climate. Most campaigns were carried out over agricultural landscapes dominated by crops such as corn, soybean, or sugar beet fields (CWEX, IAO, Smith et al. (2013), and Adkins and Sescu (2017)). However, other studies investigated very different environments, such as a blanket bog ecosystem surrounded by conifer forests and grasslands (Armstrong et al., 2016), a coastal marsh environment near an urban area for the VERTEX campaign, or the San Gorgonio site located in a desert within a retention basin in California (Baidya Roy and Traiteur, 2010). This diversity of surface types, roughness conditions, climates, and seasons complicates direct comparisons between studies and are likely to contributes to the variability, and sometimes inconsistencies, of meteorological change reported by the studies.

Depending on the experimental setup and the objectives of the campaign, the impact of wind turbines is assessed using different methodologies. The most commonly used approach consists in comparing atmospheric conditions upstream and downstream of the wind farm or turbine on variables such as temperature or humidity (Rajewski et al., 2013; Smith et al., 2013; Adkins and Sescu, 2017; Henschen et al., 2011; Lundquist et al., 2026). The San Gorgonio experiment followed that methodology. However, the presence of aquifer-recharging ponds within wind turbines, located in an arid environment, introduced additional complications for interpreting evaporation and temperature changes, as highlighted by Archer et al. (2019). This extreme case highlight the difficulty of separating wind turbine effects from natural atmospheric heterogeneity and temporal variability. To reduce these biases, the CWEX campaign relied on statistical analyses over long observational periods combined with statistical bias-correction techniques. Similarly, Rajewski et al. (2014) and Armstrong et al. (2016) used turbine maintenance or shutdown periods to compare atmospheric conditions during operational and non-operational phases of the wind farm. Diurnal and seasonal signals were removed by calculating departures relative to the instantaneous mean conditions over the entire site. More recently, numerical simulations of the AWAKEN field campaign (Moriarty et al., 2024) over a wind farm located in complex terrain showed that terrain-induced effects often dominate the near-surface thermal signal, particularly under strong wind conditions (Lundquist et al., 2026). These results further emphasize that upstream–downstream differences should not be attributed solely to wind turbine operation without carefully accounting for the influence of the surrounding terrain and natural atmospheric variability.

The VERTEX campaign was specifically designed to address these biases and adopted an even more restrictive methodology by placing all sensors downstream of the turbine with the prevailing wind and within a relatively homogeneous environment

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(Archer et al., 2019). Wake and non-wake conditions were measured at identical distances from the turbine and were identified using Doppler lidar observations combined with a wake-detection algorithm. In addition, a Difference-in-Differences (DiD) statistical approach was applied (Wu and Archer, 2021) to correct for natural differences between sensors during reference periods without wake influence, thereby reducing systematic biases associated with local topography or environmental heterogeneity.

The observed meteorological variations are generally analyzed as a function of atmospheric stability, which is itself estimated using various metrics depending on the study. These include the Richardson number (Takle et al., 2019), the Obukhov length (Rajewski et al., 2014), or vertical gradients of temperature, humidity and vapor mixing ratio between the surface and hub height (Smith et al., 2013; Adkins and Sescu, 2017; Baidya Roy, 2011), as well as near-surface temperature lapse rate (Archer et al., 2019).

2.2 Satellite Measurements

The first use of satellite data to investigate wind farm impacts dates back to 2012, with the concomitant studies of Zhou et al. (2012) and Walsh-Thomas et al. (2012). Both studies derived land surface temperature (LST) around WF from measurements of thermal infrared radiation in spectral bands sensitive to surface temperature. Zhou et al. (2012) used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra and Aqua satellites, with a spatial resolution on the order of 1 kilometer and a 1 or 2-day revisit cycle. On the other hand, Walsh-Thomas et al. (2012) relied on the Thematic Mapper sensor aboard the Landsat-5 satellite, which provides a higher spatial resolution on the order of 100 m but with a much lower temporal frequency, due to its 16-day revisit cycle.

As a compromise between spatial coverage and temporal resolution, most subsequent studies have relied on MODIS-derived LST products (Slawsky et al., 2015; Tang et al., 2017). To investigate the potential impact of these meteorological variations on ecosystems, several studies have also used satellite-derived vegetation products. In particular, the leaf area index (LAI), the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), derived from MODIS data, have been used to monitor vegetation dynamics in the vicinity of wind farms. More advanced biophysical variables, such as gross and net primary productivity (Tang et al., 2017), have also been analyzed to assess potential impacts on plant biomass production (Gao et al., 2023).

The spatial scale of satellite-based studies has significantly evolved over time. Early analyses were typically limited to relatively small regions, such as Texas (Zhou et al., 2012), northern Illinois (Slawsky et al., 2015), or the Bashang region in China (Tang et al., 2017). More recent studies have extended these analyses to much larger spatial scales. For instance, Gao et al. (2023) analyzed more than 2 400 wind farms in China, representing over 100 000 turbines, while Liu et al. (2022) considered wind farm datasets across both China and the United States.

Two main methodological strategies are generally used to quantify wind farm impacts on LST. The first consists in comparing LST before and after wind farm construction (Zhou et al., 2012; Slawsky et al., 2015). In this case, particular care must be taken to remove interannual climate variability (e.g., warmer or colder years). This is often achieved by subtracting the regional mean temperature from each pixel, thereby isolating local anomalies associated with wind farms. The results of this approach

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in the study by Slawsky et al. (2015) are shown in Figure 3, where LST differences between the pre and post-construction periods reveal a nighttime warming signal consistent with the wind turbine layout, with no significant daytime signal. The second approach consists in comparing areas containing wind turbines with nearby control areas without turbines, in order to isolate the wind farm signal from natural variability (Tang et al., 2017; Zhou et al., 2012).

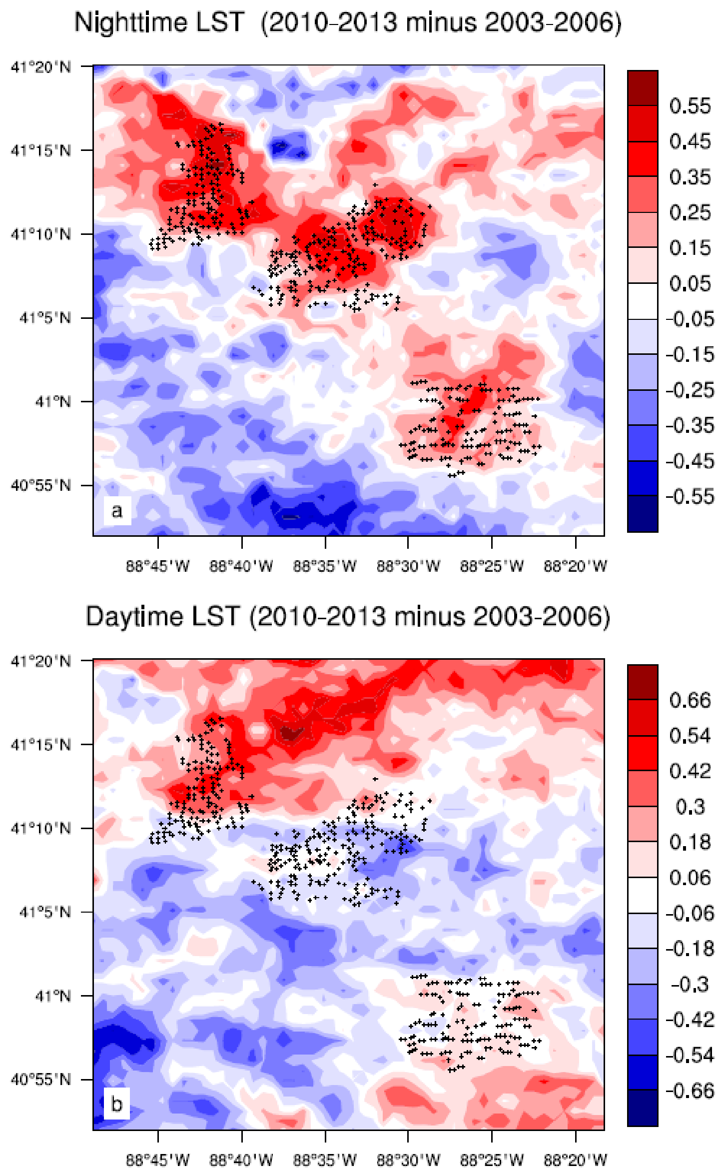

Figure 3. Annual mean MODIS LST differences between 2010-2013 (post-turbine construction) and 2003-2006 (pre-turbine construction) at (a) night and (b) daytime. Pixels with + represent individuals wind turbine (figure from (Slawsky et al., 2015) in accordance with the Creative Commons Attribution 4.0 License).

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Several factors must be carefully considered when applying these methods. First, wind direction and wind speed play a crucial role, as temperature anomalies are often advected downwind of wind farms, leading to elongated spatial patterns of LST variations (Tang et al., 2017). Second, topographic effects such as elevation and slope can significantly influence surface temperature and must be accounted for to avoid attributing natural local variations to wind turbine effects (Zhou et al., 2013; Liu et al., 2023).

Satellites provide global spatial coverage at regular temporal intervals (with limitations related to cloud cover) and therefore offer a powerful tool to monitor and detect the impacts of wind farms. As these observing systems are already operational, they provide available data without the need to deploy dedicated measurement instruments. In addition, satellite archives often include data acquired prior to wind farm construction, allowing for the isolation of wind farm-induced signals from pre-existing environmental conditions. However, it should be noted that satellite observations provide LST, which corresponds to a radiometric measurement of the surface temperature. This quantity differs from near-surface air temperature (typically measured at 2 m height), which is more commonly used in other observational and modeling studies.

3 Numerical Approaches

Numerical simulations provide a complementary approach to observational studies for investigating wind farm-atmosphere interactions. Unlike field measurements, numerical models allow the analysis of wind turbine impacts under a wide range of atmospheric conditions, spatial scales, and wind farm configurations, including scenarios that cannot easily be explored experimentally. Over the past two decades, wind turbine–atmosphere interactions have been investigated using a wide range of numerical approaches, from weather and climate models to high-resolution large-eddy simulations to address distinct scientific questions. Their utilization has been closely linked to the development in wind turbine parameterizations. In this section, we start by presenting the different wind turbine parameterizations then the main numerical methodologies used in the literature to study meteorological variations induced by wind turbines.

3.1 Wind Turbine and Wind Farms Parameterizations

The various wind turbine and wind farm parameterizations mainly differ in their level of physical complexity and representation. The earliest approaches represented wind farms implicitly through modifications of surface properties, such as an increase in roughness length. Over time, more advanced parameterizations were developed to explicitly account for turbine-induced drag and wake generation within the atmospheric flow, from simplified momentum-sink schemes to high-fidelity actuator-based methods.

3.1.1 Implicit Wind Farm Parameterizations

The most rudimentary way to model wind turbines is to increase the ground roughness length z_0. The wind turbine is then considered as a simple obstacle that disturbs the wind profile from the ground (Ivanova and Nadyozhina, 2000). The turbine wakes is not explicitly represented, and the main challenge lies in determining an appropriate equivalent roughness associated

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with the wind farm (Baidya Roy et al., 2004; Fitch et al., 2012). A slightly more advanced version of this approach was proposed by Keith et al. (2004), who introduced an explicit drag scheme applied over the first atmospheric layers of the model. Although these methods are computationally inexpensive and suitable for climate-scale simulations, they are unable to reproduce the turbine wake as wind turbines extract energy around hub height and not near the surface (Fitch et al., 2012; Archer et al., 2020).

3.1.2 Subgrid Explicit Wind Farm Parameterizations

To improve the representation of wind farm effects in mesoscale atmospheric models, a broad range of explicit wind farm parameterizations (WFP) has progressively been developed. The review of Fischereit et al. (2022) identified at least ten different explicit wind farm parameterizations developed between 2004 and 2018, highlighting the diversity to represent turbine and wake effect. In these approaches, wind turbines are represented as elevated momentum sinks within atmospheric grid cells, while turbulence generation is either prescribed explicitly or generated indirectly through the atmospheric flow response to shear flow from the wind farm wake.

The first WFP was introduced by Baidya Roy et al. (2004). Turbines are treated as elevated momentum sinks combined with sources of turbulent kinetic energy (TKE) using a constant power coefficient C_p and constant TKE source term. This approach was later improved by prescribing wind-speed-dependent C_p (Baidya Roy, 2011). A major advance came with the Fitch parameterization (Fitch et al., 2012), in which both the thrust and power coefficients (C_t and C_p) vary with wind speed, enabling a more realistic representation of turbine drag, energy extraction, and wake-generated turbulence, with $C_{TKE} = C_t - C_p$.

The widespread adoption of the Fitch parameterization is largely explained by its integration into the WRF v3.3 (Weather Research and Forecasting), making it one of the standard approaches for mesoscale wind farm simulations. Within WRF, the Fitch parameterization is coupled with the Mellor Yamada Nakanishi Niino level-2.5 (MYNN2) planetary boundary layer scheme (PBL). However, turbine-generated TKE was originally not advected, causing turbulence to remain artificially confined to wind-farm grid cells (Fitch et al., 2012; Archer et al., 2020). Although TKE advection was introduced in WRF v3.5, a coding error in later versions prevented its proper updated until it was identified and corrected by Archer et al. (2020). After correction, turbulence levels were found to be overestimated compared with Large-Eddy Simulations (LES), leading the authors to recommend reducing the C_{TKE} coefficient. The two issues identified by Archer et al. (2020) partly compensated for each other likely explaining why the issue remained unnoticed for several years. Consequently, studies using the Fitch parameterization between WRF v3.6 and v4.2 should be interpreted with caution, including some studies examined in the present review (Xia et al., 2017, 2019; Lee and Lundquist, 2017; Siedersleben et al., 2018).

Despite its widespread use, Fitch is not the only explicit wind farm parameterization available. The Explicit Wake Parameterization proposed by Volker et al. (2015) also represents turbines as momentum sinks but differs by generating turbulence through wake-induced shear within the PBL scheme rather than prescribing TKE explicitly. This approach generally produces a more gradual wake recovery and has proven particularly relevant for offshore and long-range wake studies (Hasager et al., 2017). Recent work has shown that the choice of parameterization can significantly affect simulated wake recovery and boundary-layer characteristics (Quint et al., 2025). Consequently, the necessity of explicitly prescribing turbine-generated TKE remains debated, and the widespread use of the Fitch scheme does not necessarily imply that it provides the most appropriate representation of wind farm effects (Fischereit et al., 2022).

3.1.3 Actuator Approaches

Actuator models are based on body-force approaches in which the aerodynamic effects of wind turbines are represented through distributed forces applied to the flow. Actuator approaches rely on an explicit representation of the turbine rotor distributed over multiple grid points in both horizontal and vertical directions. Typically, the ratio between turbine diameter and mesh resolution, $D/\Delta x$, ranges between 10 and 20, enabling a substantially more detailed representation of wake structures and turbulence generation while maintaining computational costs significantly lower than fully resolved blade simulations. Depending on the required level of fidelity and available computational resources, several actuator formulations have been developed and are briefly introduced below.

The Actuator Disk without Rotation (ADNR) consists in representing the wind turbine as a stationary porous disk. The forces exerted by the turbine on the flow are distributed across the rotor disk and are calculated using the thrust coefficient C_t, which depends on wind speed (Jiménez et al., 2010). The resulting force acts only in the direction normal to the rotor plane. As a consequence, this approach neglects tangential forces associated with blade rotation and therefore do not reproduce rotational wake effects, such as the tilting behavior of kinematic stresses (Wu and Porté-Agel, 2011). It has been demonstrated that this model underestimates temperature variations downstream of a wind turbine, particularly at the rotor level and also further downstream (Boumendil et al., 2024) and to the authors' knowledge, it has not been used in other studies investigating the meteorological impacts of wind turbines.

The Actuator Disk with Rotation (ADR), also referred to as the Generalized Actuator Disk (GAD), extends the ADNR framework by explicitly accounting for turbine rotation and blade geometry. In this approach, the rotor disk is discretized, typically using a cylindrical mesh, over which aerodynamic forces are computed. At each time step, local flow conditions, turbine rotational speed, blade pitch angle, and airfoil aerodynamic characteristics are used to estimate the forces applied to the atmospheric flow. The first implementation and validation of the GAD approach in the WRF model was performed by Mirocha et al. (2014). However, as this implementation was not publicly available in WRF, a new GAD parameterization was later developed and validated by Kale et al. (2022). Validation studies have shown that ADR reproduces wake characteristics both qualitatively and quantitatively under a wide range of atmospheric stability conditions. Consequently, this approach has been increasingly used in LES studies of wind farm wakes and atmospheric interactions (Adkins and Sescu, 2018; Haupt et al., 2023; Wu et al., 2023; Kale et al., 2023). The ADR approach has also been implemented and validated in the atmospheric LES model Meso-NH (Boumendil et al., 2024; Lac et al., 2018).

The Actuator Line method (AL) represents the highest level of fidelity among actuator approaches. Originally introduced by Sørensen and Shen (2002), this method differs fundamentally from actuator disk approaches by applying aerodynamic forces along rotating lines representing each turbine blade rather than averaging them over a rotor disk. As a result, AL explicitly accounts for blade rotation, enabling a more realistic representation of turbine-flow interactions and allowing the reproduction of the helical near-wake structure as well as tip and root vortices. Consequently, AL is particularly well suited for

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investigating near-wake physics and turbine-induced turbulence under various atmospheric conditions. However, AL requires both high spatial resolution and sufficiently small time steps to ensure that blade motion remains accurately resolved and does not artificially jump across grid cells (Joulin et al., 2020). The AL model has been implemented and used in several LES atmospheric studies (Lu and Porté-Agel, 2011; Wu and Porté-Agel, 2011; Xie and Archer, 2017; Archer et al., 2020; Joulin et al., 2020).

3.2 Numerical Setup

Now that the different representations of wind turbines and wind farms have been introduced, we provide in this section an overview of their coupling with atmospheric simulations, in order to investigate wind turbine-atmosphere interactions and the resulting meteorological variations. Three main methodologies can be distinguished: mesoscale meteorological simulations relying on WFP such as the Fitch model, microscale LES simulations using actuator approaches, and hybrid multiscale frameworks coupling both methodologies.

3.2.1 Mesoscale Simulations

Mesoscale numerical setups are used to investigate the impact of wind farms at regional scales, ranging from individual wind farms to clusters of farms extending over hundreds of kilometers. Their approach originates from numerical weather prediction and climate modeling in wich wind turbines are treated as subgrid-scale perturbations of the atmospheric boundary layer. Historically, the Regional Atmospheric Modeling System (RAMS) (Cotton et al., 2003) was the first atmospheric model used to investigate wind turbine effects, notably in the pioneering work of Baidya Roy et al. (2004). Since the 2010s, however, the WRF model (Powers et al., 2017) has progressively become the dominant tool in the fiel due to its flexibility, extensive physics parameterizations, active development, and public availability. WRF has been extensively coupled with the Fitch parameterization for mesoscale studies of wind farm impacts (Cervarich et al., 2013; Vautard et al., 2014; Xia et al., 2019; Siedersleben et al., 2018; Rosencrans et al., 2025; Quint et al., 2025).

Mesoscale simulations are typically initialized using large-scale reanalysis and observation-based products, including NARR (Cervarich et al., 2013), NCEP/NCAR (Baidya Roy et al., 2004), ERA5 and ERA-Interim (Bodini et al., 2021; Rosencrans et al., 2025; Baidya Roy and Traiteur, 2010; Hasager et al., 2017). Sometimes complemented by in situ observations from WMO radiosondes (Baidya Roy, 2011) and high-resolution SST analyses from the Danish Meteorological Institute (Hasager et al., 2017).

To ensure physical consistency of the atmosphere, surface fluxes, and turbulence, a precursor period (typically 24 h) is generally applied before the period of interest. Mesoscale models are coupled with parameterizations representing processes such as land–surface exchanges, radiation, cloud microphysics, convection, and atmospheric turbulence. Since turbulence cannot be explicitly resolved at typical grid spacings, PBL schemes are used. Wind farms are represented through wind farm parameterizations, generally applied at resolutions of order 1 km, where one or several turbines may occupy a single grid cell (Fitch et al., 2012).

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To achieve this resolution while maintaining realistic large-scale forcing, most studies employ nested domains, typically with two (Rosencrans et al., 2025; Quint et al., 2025) or three (Baidya Roy et al., 2004; Baidya Roy, 2011; Cervarich et al., 2013) domains in two-way nesting interactions (see numerical setup of Rosencrans et al. (2025) on Fig. 4) with outer domains of 1000–2000 km and inner domains of 100–250 km. Vertical resolution is refined near the surface and within the rotor layer to properly capture wake dynamics, since insufficient vertical resolution has been shown to significantly affect turbine–atmosphere interactions, wake evolution, and power production (Golbazi et al., 2022; Lee and Lundquist, 2017).

Despite their efficiency, WFP have intrinsic limitations (Fischereit et al., 2022). They generally assume horizontally homogeneous flow within grid cells, neglect intra-cell wake interactions, and their results remain highly sensitive to resolution. In addition, the representation of turbine-induced TKE remains uncertain and can strongly affect wake development (Fitch et al., 2012; Volker et al., 2015). Finally, validation is often limited by the scarcity of long-term and large scale observational datasets in wind farm environments.

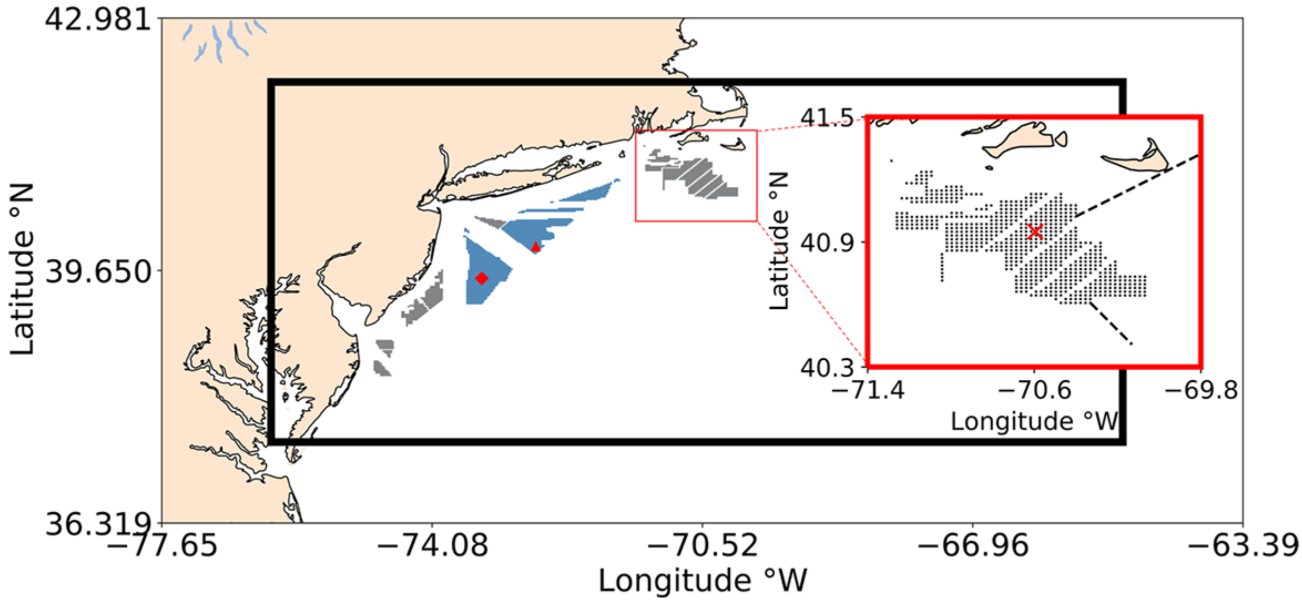

Figure 4. Numerical setup used by Rosencrans et al. (2025) for an offshore wind farm case study. The simulations employ two nested WRF domains with horizontal resolutions of 6 and 2 km. Wind farm effects are represented using the parameterization of Fitch et al. (2012). Each dot represents a wind turbine (figure from Rosencrans et al. (2025) in accordance with the Creative Commons Attribution 4.0 License).

3.2.2 Micro-Scale or LES Simulation

Large-Eddy Simulations (LES) are widely used to explicitly resolve the largest turbulent structures of the atmospheric boundary layer and to investigate wind turbine wakes at fine spatial scales. In contrast to mesoscale models, LES allows a more detailed representation of individual wake interactions and are typically use for small group of wind turbines (Xie and Archer, 2017;

Wu et al., 2023; Lu and Porté-Agel, 2011), though they can extend to entire wind farms (Joulin et al., 2020; Adkins and Sescu, 2018).

Atmospheric inflow conditions are typically generated using idealized profiles or precursor simulations, prescribing wind speed, temperature stratification, ABL height, surface fluxes, and geostrophic forcing (Mirocha et al., 2014; Kale et al., 2022; Wu et al., 2023; Adkins and Sescu, 2018). The surface roughness is chosen depending on the simulation: $z_0 = 0.016$ m to reproduce an offshore environment (Xie and Archer, 2017), $z_0 = 0.05$ m for a smooth landscape (Rajewski et al., 2014), or $z_0 = 0.1$ m (Lu and Porté-Agel, 2011) for an environment with low vegetation. Atmospheric stability is commonly controlled through surface heat fluxes (Mirocha et al., 2014; Xie and Archer, 2017; Lu and Porté-Agel, 2011, 2015) or by specifying the surface temperature (Kale et al., 2022).

Due to their high computational cost, LES domains are generally limited in size. Typical configurations include a single wind turbine or small wind farm, with streamwise extents of 10–30 rotor diameters (D) for isolated turbines (Lu and Porté-Agel, 2011; Wu and Porté-Agel, 2011; Xie and Archer, 2017) and up to 60 D for wind farms (Xie and Archer, 2017; Wu et al., 2023; Joulin et al., 2020) (see numerical setup of Joulin et al. (2020) on Fig. 5). Domain widths are typically 5–10 D, while the vertical extent is set to capture the full boundary layer depth, often extending several times the boundary layer height (Lu and Porté-Agel, 2011). Grid resolutions are typically chosen such that $D/\Delta x \approx 10 - 20$, with finer vertical spacing within the rotor layer (Xie and Archer, 2017; Mirocha et al., 2014; Wu et al., 2023; Joulin et al., 2020).

Despite their ability to reproduce individual turbine wakes at relatively low computational cost compare to blade-resolved simulations, actuator-based approaches models coupled with LES simulation also present several limitations. Their accuracy strongly depends on the quality of the tabulated blade aerodynamic data, and they cannot explicitly resolve near-blade flow features such as surface boundary layers, flow separation, stall phenomena, or blade-tip vortices, although the latter can be partially captured by actuator-line models operated at sufficiently fine grid resolutions (Lu and Porté-Agel, 2011; Porté-Agel et al., 2020). In addition, their results are sensitive to numerical choices, particularly the smearing width used to distribute aerodynamic forces onto the computational grid (Kale et al., 2022; Lu and Porté-Agel, 2011; Wu and Porté-Agel, 2011). An additional challenge concerns the representation of stable atmospheric boundary layers, which remain highly sensitive to subgrid-scale parameterizations and spatial resolution (Xie and Archer, 2015; Kale et al., 2022). Moreover, while idealized surface forcing and homogeneous inflow conditions are well suited for investigating canonical atmospheric and wake processes, they depart from the complexity of real atmospheric conditions and may therefore limit the realism of simulated near-surface meteorological variations and wake evolution (Wu et al., 2023; Boumendil et al., 2024).

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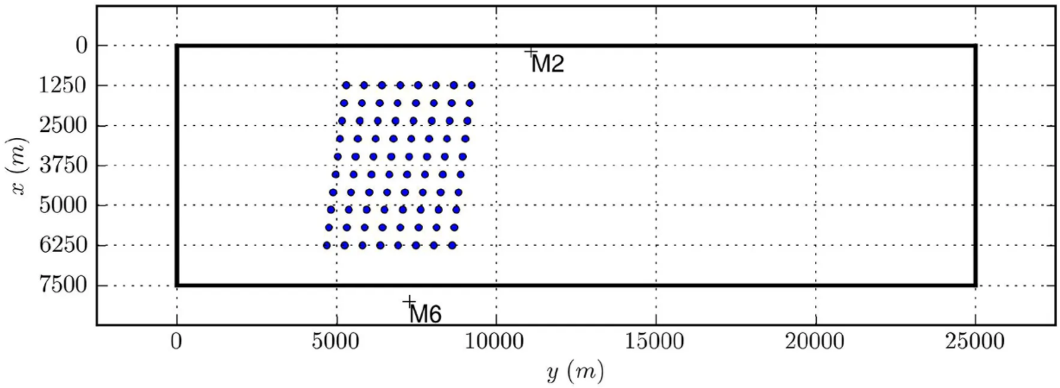

Figure 5. Dimensions of the computational domain (black box) and layout of the simulated wind farm used in the microscale LES simulations of Joulin et al. (2020). The simulations employ a horizontal grid resolution of 5 m (figure from Joulin et al. (2020) in accordance with the Creative Commons Attribution 4.0 License).

3.2.3 Multiscale Simulations: Hybrid Setups

Investigating wind turbine-atmosphere interactions requires the representation of processes evolving across very different spatial and temporal scales. A new approach consists of coupling mesoscale and microscale simulations within an integrated multiscale modeling chain. These setups generally rely on a mesoscale atmospheric simulation initialized and forced by large-scale meteorological analyses such as ERA5 (Bakhoday-Paskyabi et al., 2022; Wise et al., 2022), IFS (Boumendil et al., 2025), or regional numerical weather prediction models such as AROME (Boumendil et al., 2026). They include atmosphere-surface coupling, turbulence, radiation, microphysics, convection, and cloud parameterizations, while LES formulations are restricted to the innermost high-resolution domains. A sequence of nested domains (typically 4–6) progressively refines the resolution from kilometer scales down to metric LES resolutions (5–30 m) (see Fig. 6). At these scales, wind turbines are represented through actuator-based approaches such as ADR or AL, enabling the representation of wake velocity deficits and rotational effects (Wise et al., 2022). Additional developments, including turbine controllers for rotor speed, blade pitch, and yaw orientation, are often required to represent turbine response to local wind variability (Kale et al., 2023; Wang et al., 2020; Boumendil et al., 2026). Explicit drag formulations for forests and urban areas may also be included to improve near-surface momentum exchanges (Boumendil et al., 2025). Such hybrid frameworks have been widely applied to study wind farm interactions over complex terrain (Kale et al., 2023; Mi et al., 2025; Al Oqaily et al., 2025), offshore conditions (Bakhoday-Paskyabi et al., 2022; Rasheed et al., 2017), and coastal transitions (Maché et al., 2014; Boumendil et al., 2025). To ensure physically consistent LES inflow conditions, synthetic turbulence generation methods are usely employed to accelerate the development of turbulent structures at domain boundaries (Kale et al., 2023; Mi et al., 2025; Wise et al., 2022; Wang et al., 2020; Bakhoday-Paskyabi et al., 2022). Although reproducing the exact atmospheric state of a given location and day remains challenging, these multi-scale approaches considerably improve the realism of turbine inflow conditions and wake dynamics. However, hybrid setups remain computationally demanding and sensitive to multiple sources of uncertainty. Model performance strongly depends on

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the quality of high-resolution terrain and land-use data, while turbulence representation within the grey zone directly influences boundary layer structure and wake evolution (Wise et al., 2022; Al Oqaily et al., 2025). Stable nocturnal conditions, complex topography, and rapid synoptic transitions remain among the most difficult situations to reproduce accurately. Furthermore, hybrid setups inherit the limitations of microscale models, especially those related to actuator-based turbine modelling.

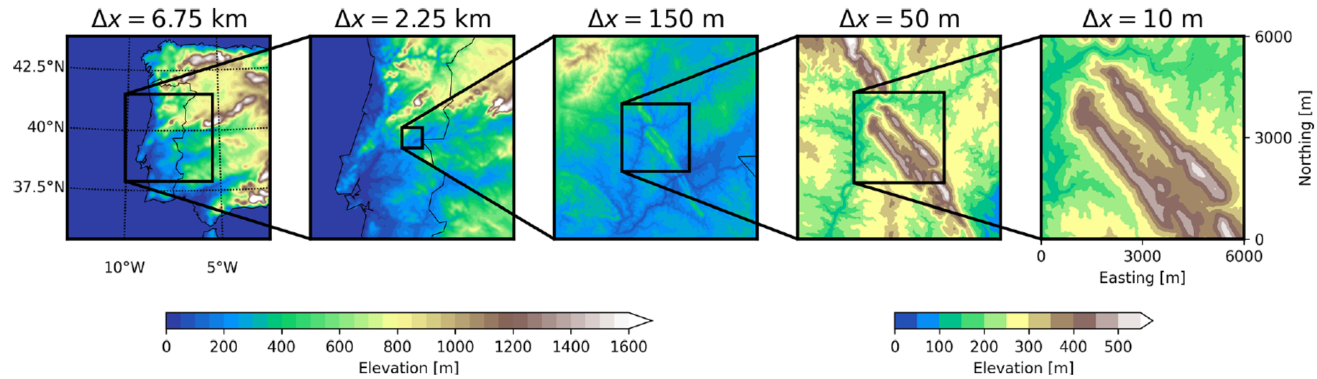

Figure 6. Dynamic multiscale framework used by Wise et al. (2022). The colormap indicates terrain elevation within each nested domain (figure from Wise et al. (2022) in accordance with the Creative Commons Attribution 4.0 License).

4 Meteorological Variations Near the Ground Induced by Wind Turbines

In this section, we analyze the near-surface meteorological variations attributed to wind turbines reported in the literature. The vast majority of studies have focused on onshore wind farms, due to their direct relevance to near-surface impacts on vegetation, crops, and human activities. However, the recent development of offshore wind farms has led to growing research interest in this topic, with several recent studies (Joulin et al., 2020; Golbazi et al., 2022; Rosencrans et al., 2025; Quint et al., 2025). In this review, we consider both onshore and offshore studies, as the mechanisms through which wind turbines induce meteorological variations are broadly similar in both environments. However, marine and terrestrial boundary layers exhibit distinct dynamical and thermodynamical characteristics. Consequently, the resulting meteorological responses may differ between offshore and onshore without invalidating the findings. Each atmospheric variable is reviewed separately in order to compare the results obtained with different methodologies and configuration. We first discuss changes in meteorological properties, such as wind speed, temperature, and humidity, before turning to variations in turbulence and surface fluxes.

For each variable, a summary table compiles the main studies, methodologies and magnitudes of meteorological near surface change. To facilitate the analysis and highlight tendencies across studies, a color code is adopted in the tables: red indicates an increase, whereas blue indicates a decrease. Among the different controlling factors identified in the literature, atmospheric stability consistently emerges as the dominant parameter governing near-surface responses. Consequently, whenever possible, results are organized according to stable and unstable atmospheric conditions. However, this classification remains somewhat

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arbitrary, as not all studies explicitly investigate both stability regimes, use different metrics and thresholds to characterize atmospheric stability or rely simply on a day-night distinction.

In addition, direct quantitative comparison between studies remains challenging because meteorological variations are reported using different metrics, including absolute values, relative percentages, or distinct variables (particularly for humidity). Several studies included in this review do not explicitly focus on near-surface variations, and the reported variations are therefore derived from our interpretation of the figures presented by the authors.

4.1 Variation of Wind Near the Ground

Wind turbines extract kinetic energy from the atmospheric flow and convert it into electricity, generating a velocity deficit downstream of the rotor referred to as a wake. The magnitude and persistence of this wake have been extensively studied due to their importance for wake development, turbine performance, and wind farm energy production. It has been demonstrated that they strongly depend on atmospheric stability and turbulence intensity (Porté-Agel et al., 2020). Under stable atmospheric conditions, wakes tend to remain coherent over longer distances and can exhibit velocity deficits exceeding 40%, whereas enhanced turbulent mixing in unstable conditions promotes a faster wake recovery and weaker deficits (Xie and Archer, 2017; Porté-Agel et al., 2020). Wind speed also plays an important role, with stronger inflow generally leading to larger velocity deficits (Quint et al., 2025). However, turbine-induced flow modifications are not restricted to rotor height and may affect the entire atmospheric column. In addition to altering the height of the ABL (Lu and Porté-Agel, 2011; Wu and Porté-Agel, 2011; Quint et al., 2025), wind turbines can also induce measurable changes below the rotor extending down to the surface.

Near-surface wind variations result from a competition between momentum extraction, turbulence-induced vertical mixing (Baidya Roy et al., 2004; Fitch et al., 2012), and local pressure perturbations (Rajewski et al., 2013). Because these modifications may directly affect surface exchanges, they constitute the main focus of the present review. Numerical simulations of isolated wind turbines generally report an acceleration of wind speed below the rotor in the near wake due to blockage and Venturi effects. LES indicate speed increases between 10 and 20% close to the turbine (Mirocha et al., 2014; Xie and Archer, 2017). This acceleration is generally more pronounced under stable atmospheric conditions where vertical motions that would otherwise allow the flow to pass the obstacle are strongly suppressed (Xie and Archer, 2017) and can be further enhanced with multiple turbine in aligned configurations (see Fig. 7 of García-Santiago et al. (2024)). However, in the case of a single wind turbine, this near-surface acceleration is primarily confined to the near wake and gradually transitions into a velocity deficit a few rotor diameters downstream for all stability regimes. In configurations with consecutive turbines and overlapping wakes, the acceleration effect do no appear for downstream wind turbine under neutral and unstable atmospheric conditions (Xie and Archer, 2017; Wu et al., 2023; García-Santiago et al., 2024) (Fig. 7a,c). Importantly, these results should be interpreted with caution because wind variations are often normalized using the upstream wind speed of the first turbine. Downstream turbines are therefore compared against a progressively wake-modified inflow. Consequently, an apparent absence of relative acceleration near the ground does not necessarily imply that the effect is not present, but rather that local wind speed becomes comparable to the unperturbed wind speed upstream of the first turbine.

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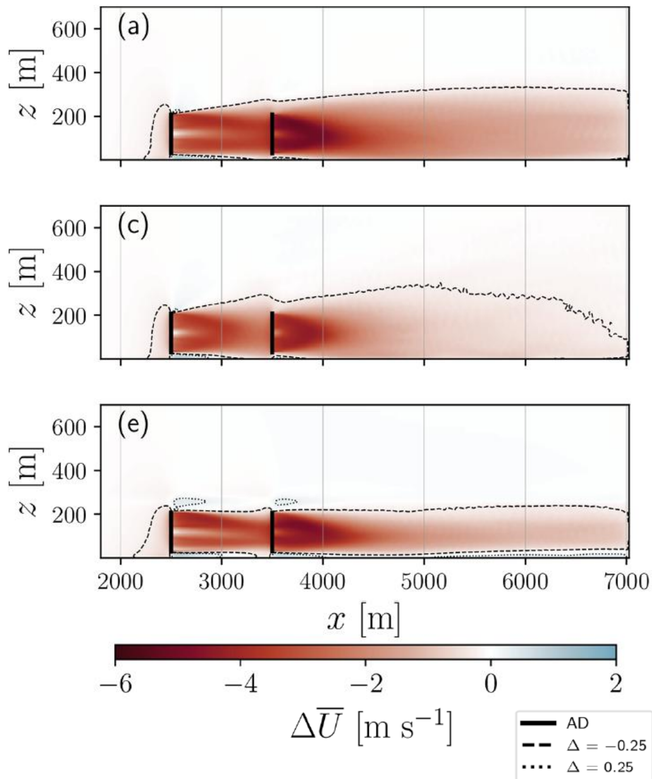

Figure 7. Time-averaged vertical cross section of wind speed through the rotor plane of the differences between a simulations without and with two turbines using LES-ADR under (a) neutral, (c) unstable, and (e) stable ABL. The turbines location is depicted as vertical black lines, and the boundaries of the averaging areas used for the comparison with the PBL simulations are shown in grey. The dashed lines show contours of $\Delta U =$ -0.25 ms^{-1}, and dotted lines show $\Delta U =$ 0.25 ms^{-1} contours (figure from García-Santiago et al. (2024) in accordance with the Creative Commons Attribution 4.0 License).

A clear distinction emerges between stable and unstable atmospheric conditions. During stable conditions, turbine-induced turbulence (Baidya Roy et al., 2004) and vertical movement (Boumendil et al., 2026) enhances vertical mixing and transports higher-momentum air from aloft toward the surface. As a result, several studies report near-surface wind acceleration within and immediately downstream of wind farms. Measurements from the CWEX campaign indicate wind speed increases of approximately 10-20% at 2.5 D downstream of turbines under stable conditions (Rajewski et al., 2013; Takle et al., 2014). Similar results were obtained numerically by Quint et al. (2025) with WFP, who reported wind speed increases reaching +0.32 ms^{-1} and by Bodini et al. (2021) with +10% within wind farms under stable conditions.

By contrast, neutral and unstable atmospheric conditions are generally associated with a near-surface wind deficit. Indeed enhanced ambient turbulence promotes a faster downward expansion of the wake, allowing the rotor-induced velocity deficit to interact more rapidly with the ground. The CWEX campaign reported daytime reductions in near-surface wind speed of around 10% (Rajewski et al., 2013; Takle et al., 2014), while Quint et al. (2025) simulated decreases of up to -0.45 ms^{-1} and -0.82

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ms^{-1} under neutral and unstable conditions, respectively. Measurements from the VERTEX campaign around a single turbine also consistently found a reduction in wind speed near the surface (approximately -20% at 2 m height and 6 D downstream), but independently of atmospheric stability (Archer et al., 2019).

<table>
<tr><th rowspan="3"></th><th rowspan="3">Article</th><th rowspan="3">Type</th><th rowspan="3">Turbines configuration</th><th colspan="4">Wind speed variations near the ground</th></tr>
<tr><th colspan="2">Stable</th><th colspan="2">Unstable</th></tr>
<tr><th>Near wake</th><th>Far wake</th><th>Near wake</th><th>Far wake</th></tr>
<tr><td rowspan="8">Numerical simulation</td><td>Quint et al. 2025*</td><td>WRF, Fitch</td><td>Wind Farm</td><td>+0.32 m/s (inside WF)</td><td>Decrease (outside WF)</td><td>-0.82 m/s (inside WF)</td><td>-0.60 m/s (outside WF)</td></tr>
<tr><td rowspan="2">Xie et al. 2017</td><td rowspan="2">WiTTS, ALM</td><td>Single WT</td><td>+10% (1 D)</td><td>Decrease (5 D)</td><td colspan="2">+10% (1 D)
Not clear (5 D)</td></tr>
<tr><td>2nd WT</td><td colspan="2">+10% (14 D)</td><td colspan="2">No change (14 D)</td></tr>
<tr><td>S. Wu et al. 2023</td><td>WRF, ADR</td><td>Single WT</td><td>+25% (2.5 D)</td><td>-[10;15]% (15 D)</td><td>+10% (2.5 D)</td><td>-[10;15]% (10 D)</td></tr>
<tr><td>Mirocha 2014</td><td>LES, ADR</td><td>Single WT</td><td>+17% (0-3 D)</td><td>-15% (8-10 D)</td><td colspan="2"></td></tr>
<tr><td>García-Santiago et al. 2024</td><td>LES, ADR</td><td>2nd WT</td><td>Increase</td><td>Increase</td><td>Small increase</td><td>Decrease</td></tr>
<tr><td>Golbazi et Archer 2022*</td><td>WRF, Fitch</td><td>Wind Farm</td><td colspan="4">3 summer month average: -0.5 m/s or -10%</td></tr>
<tr><td>Boumendil et al. 2026</td><td>LES, ADR</td><td>Wind Farm</td><td>+ 0.8 m/s (0-3 D)</td><td>Decrease</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Measurement Campaign</td><td>Rajewski et al. 2016</td><td>In situ</td><td>Single line of WT</td><td>+[10;20]% (2.5 D)</td><td>+[20;30]% (17.5 D)</td><td>-10% (2.5 D)</td><td>No change (17.5 D)</td></tr>
<tr><td>Wu and Archer 2021</td><td>In situ</td><td>Single WT</td><td colspan="4">-20% (3 D and 12 D)</td></tr>
</table>

Figure 8. Summary table of near-ground wind variations caused by wind turbines found in the literature. Asterisks indicate studies performed in offshore conditions. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine).

Further downstream, whether a single-turbine wake significantly affects surface wind speed remains less clear. LES simulations suggest that the rotor wake progressively expands downward until it eventually interacts with the surface, a process commonly referred to as *wake touchdown*. According to Wu et al. (2023), touchdown occurs around 15 D under stable conditions, while it happens earlier, at approximately 10 D, under neutral and unstable conditions. Similarly, Mirocha et al. (2014) reported wind speed deficits reaching the surface at around 8–10 D in unstable atmospheres.

Experimental observations remain more contrasted. During daytime unstable conditions, CWEX measurements suggest that isolated wakes generally do not intersect the surface (Rajewski et al., 2013; Takle et al., 2014). Conversely, the VERTEX campaign reported a near-surface wind deficit of approximately 20% at 12 D downstream of a single turbine (Archer et al.,

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2019). In wind farms, overlapping wakes tend to accelerate the touchdown process, such that near-surface impacts may occur only a few rotor diameters downstream.

Figure 8 summarizes the near-surface wind speed variations reported in the literature for both near-wake and far-wake conditions according to the stability. Despite some discrepancies between numerical and experimental studies, several robust tendencies emerge. In the near wake, wind speed often increases below the rotor due to blockage and pressure-induced acceleration. This effect tends to be stronger under stable atmospheric conditions and rapidly weakens under neutral and unstable conditions, particularly in the presence of multiple consecutive turbines and overlapping wakes. Nevertheless, this acceleration generally remains limited in magnitude and spatially confined to the immediate vicinity of the turbine, making its experimental detection particularly challenging. Further downstream, the wake progressively expands and eventually reaches the surface. The distance at which this interaction occurs strongly depends on atmospheric stability: under unstable conditions, enhanced vertical exchanges promote a faster wake expansion toward the surface, whereas in stable atmospheres the touchdown occurs farther downstream.

4.2 Variation of Temperature

Near-surface temperature variations induced by wind turbines are among the most documented and consensual meteorological impacts reported in the literature. Evidence from numerical simulations and field measurements show a strong dependence on atmospheric stability and the diurnal cycle, with near-surface warming generally reported under stable nighttime conditions and weak cooling or negligible effects during unstable daytime conditions.

The most consistently reported signal corresponds to near-surface warming under stable atmospheric conditions. Warming magnitudes generally range from 0.2 K to about 2 K (see table in Fig. 9). The signal is often stronger within large wind farms and in downstream regions where wake interactions accumulate, while progressively decreasing with distance from the turbines (Armstrong et al., 2016; Rajewski et al., 2016). Several studies also suggest that the near-surface thermal inversion is one of the main controlling factors of the temperature variation magnitude, with stronger stratification generally associated with larger temperature changes (Wu and Archer, 2021; Baidya Roy and Traiteur, 2010; Baidya Roy, 2011; Boumendil et al., 2024) (see Fig. 10).

Satellite-based LST measurements indicate temperature responses of similar magnitude. Zhou et al. (2012) and Walsh-Thomas et al. (2012) report nighttime warming signals within wind farms as well as clear differences between pre-construction and post-construction periods (see Fig. 3). Similar LST warming variations withing WF have also been reproduced in LES simulations under stable conditions (Boumendil et al., 2026).

Under unstable daytime conditions, the observed temperature response is generally weaker or negligible. Reported signals range from slight cooling to near-zero effects, and in some cases even weak warming. Compared to the nighttime response, this signal appears less robust and more dependent on local atmospheric conditions (Rajewski et al., 2013; Takle et al., 2014; Wu and Archer, 2021).

Several studies suggest that near-surface temperature changes are also modulated by turbine operating conditions. Baidya Roy and Traiteur (2010); Baidya Roy (2011) and Quint et al. (2025) reported the strongest temperature signals for wind speeds

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	Article	Type	Turbines configuration	Altitude	Temperature variations (K) Stable	Temperature variations (K) Unstable
Numerical simulation	Baidya Roy, Pacala, et al. 2004	RAMS, SMST	Wind Farm	Near-surface air	16-day average: +0.7	
Numerical simulation	Baidya Roy and Traiteur 2010	RAMS, SMST	Wind Farm	Near-surface air	Up to +1.4 Mean +0.4	Up to -0.3
Numerical simulation	Rosencrans et al. 2025*	WRF, Fitch	Wind Farm	Near-surface air	Mean +0.26	-0.041 mean
Numerical simulation	Xie et al. 2017	WiTTS, ALM	Single WT	Near-surface air	No conclusive result	
Numerical simulation	Boumendil et al. 2026	LES, ADR	Wind Farm	Near-surface air	Mean +0.4 Up to +1.6	
Numerical simulation	S. Wu, Archer, and Mirocha 2023	WRF, ADR	Single WT	Near-surface air	+[0.02 ; 0.04]	Negligeable
			3 WT in line		+[0.1 ; 0.13]	Negligeable
Measurement Campaign	Henschen et al. 2011	In situ	Wind Farm	Near-surface air	+2.2	
Measurement Campaign	Rajewski et al. 2013	In situ	Between the wake of 2 WT	9m	Mean +0.32 Up to +1.0	Mean -0.14 Up to -0.75
Measurement Campaign	Rajewski et al. 2016				Up to 0.4	Weak cooling
Measurement Campaign	Smith et al. 2013	In situ	Wind Farm	2m	+[1;1.5] (night)	
Measurement Campaign	Wu and Archer 2021	In situ	Single WT	2m	Up to +0.4 Mean +0.2	Up to -0.2
Measurement Campaign	Smith et al. 2013	In situ	Wind Farm	2m	+[1;1.5] (night)	
Measurement Campaign	Armstrong et al. 2016	In situ	Wind Farm	2m	+0.18 (night)	
Measurement Campaign	Takle et al. 2019	In situ	Wind Farm	5m	Around +0.65	Slight warming
			Single WT		Around +0.25	

	Article	Type	Turbines configuration	Altitude	LST variations (K) Stable	LST variations (K) Instable
Numerical simulation	Lu et al. 2015	LES, ALM	Wind Farm	Land surface		+[0.414 ; 0.650]
Numerical simulation	Boumendil et al. 2026	LES, ADR	Wind Farm	Land surface	+1.6 inside WF -0.7 upstream WF	
Measurement Campaign	Zhou et al. 2012	Satellite, MODIS	Wind Farm	Land surface	+0.458 in winter, +0.724 in summer	
					[0.31;0.70]	Statistically insignificant
Measurement Campaign	Slawsky et al. 2015	Satellite, MODIS	3 Wind Farm	Land surface	+0.39 in winter, +0.18 in summer	
					[0.18;0.39]	No spatial coupling with WT

Figure 9. Summary table of near temperature variations caused by wind turbines. Asterisks indicate studies performed in offshore conditions. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine, SMST: Sink of Momentum and a Source of TKE).

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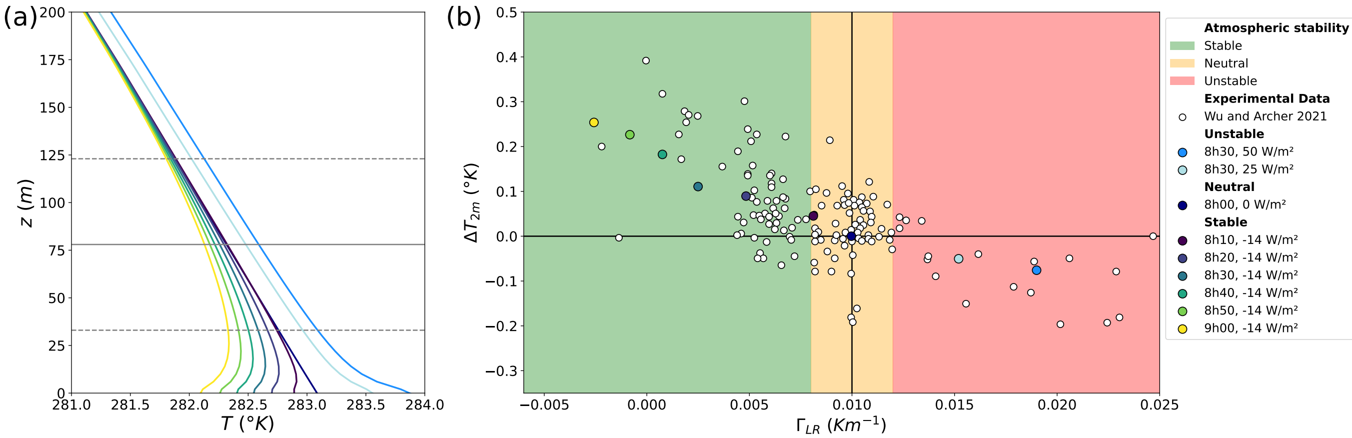

Figure 10. (a) Temperature profile for several stability cases (b) Temperature difference at x = 6D behind the ADR and z = 2m for several stability cases depending on the lower-rotor lapse rate between 10 and 49m Γ_{LR} (Figure from Boumendil et al. (2024) under the Creative Commons Attribution 4.0 License. Measurement data are from Wu and Archer (2021) and are reproduced with permission from Dr. Cristina Archer).

close to 11 ms^{-1}, corresponding approximately to the rated operating regime of many turbines, when the thrust reaches its maximum. This suggests that turbine-induced temperature variations may scale with the intensity of thrust induce by the turbine. Turbine geometry may further influence the near-surface thermal response. Using offshore simulations of next-generation wind turbines with substantially larger hub heights (e.g., the DTU-10MW turbine with a hub height of 150 m), Golbazi et al. (2022) showed that rotor-induced warming may remain elevated and fail to reach the surface. In such configurations, reductions in sensible heat fluxes near the ground can instead dominate (see section 4.5), leading to slight near-surface cooling even under otherwise favorable warming conditions. The magnitude of temperature changes is also influenced by wind farm configuration and downstream distance. Lu and Porté-Agel (2015) show that denser wind-farm layouts show higher surface temperature change. The numerical simulations of Baidya Roy (2011) suggested a characteristic decay distance of about 20 km, independent of wind farm size. Observational studies further suggest that the thermal signal progressively weakens with distance from the nearest turbine (Rajewski et al., 2016) and following a logarithmic decay (Armstrong et al., 2016).

The physical interpretation of these temperature changes has evolved over time. Because the earliest studies on this topic were conducted at relatively large spatial scales (Baidya Roy et al., 2004), these effects were attributed to enhanced vertical mixing driven by turbine-induced TKE. In this framework, wind turbines act as an additional source of turbulence that promotes the exchange of heat between atmospheric layers. This mechanism explain the contrasting diurnal behavior of temperature responses. At night, the boundary layer is typically stably stratified, with warmer air aloft and colder air near the surface. Enhanced turbulent mixing induced by wind turbines therefore redistributes heat vertically, bringing warmer air downward and colder air upward, which results in a near-surface warming (Baidya Roy et al., 2004; Baidya Roy and Traiteur, 2010; Cervarich et al., 2013). During the daytime, however, the boundary layer is already strongly mixed due to surface heating, and the additional contribution of turbine-induced turbulence becomes less significant (Zhou et al., 2012). In some studies, this leads to a weak near-surface cooling, attributed to enhanced vertical mixing induced by wind turbines, which promotes the exchange of warmer near-surface air with cooler air from around hub height.

More recent studies, however, suggest a more complex mechanism. In particular, results from the VERTEX campaign (Archer et al., 2019; Wu and Archer, 2021) and subsequent numerical simulation (Wu et al., 2023) indicate that vertical mixing is not enhanced down to the surface as near ground TKE is rather decreased downstream of wind turbine. Instead, temperature variations near the ground may result from the vertical convergence and divergence of turbulent heat fluxes below the rotor. In this framework, the key mechanism is the redistribution of turbulent heat flux rather than increase turbulent near the surface. The sign of the temperature response then depends on atmospheric stability: downward transport of warmer air in stable conditions leads to warming near the surface, while upward transport in unstable conditions promotes cooling.

Additional processes related to wake dynamics further contribute to the observed temperature structure. The rotation of turbine blades induces a counter-rotating wake, generating organized vertical motions and asymmetries in the flow field in the immediate vicinity of the turbine (Mirocha et al., 2014; Lu and Porté-Agel, 2015; Kale et al., 2022; Wu et al., 2023). These motions can transport air masses vertically, leading to localized warming on one side of the wake and cooling on the other. The resulting anomalies are subsequently transported downstream by advection and progressively spread by turbulent mixing. By comparing actuator simulations with and without wake rotation, Boumendil et al. (2024) were able to isolate and highlight the distinct contributions of wake rotation and flow divergence to the vertical motions and subsequence near ground air temperature anomalies induced by wind turbines (see Fig. 11).

Overall, these different explanations highlight the crucial role of the spatial scale at which the flow is studied. Coherent vertical motions within individual turbine wakes, which are explicitly resolved in LES and actuator-based methods, are represented as subgrid-scale TKE in large-scale parameterizations. In this sense, the apparent differences in physical interpretation across studies largely reflect differences in model resolution rather than fundamentally distinct processes.

In summary, numerical and experimental studies based on a wide range of methodologies consistently converge toward the conclusion that both individual wind turbines and wind farms modify near ground air and surface temperature conditions. The strongest effect occurs under stable atmospheric conditions, when the atmosphere is strongly stratified and near-surface warming is generally observed. In contrast, under unstable conditions, the response tends to be much weaker and is characterized by slight cooling or near-zero effects. The magnitude of these temperature variations appears to be primarily controlled by the near-surface thermal inversion, although other factors such as wind speed, turbine characteristics and wind farm configuration may also influence the response.

Finally, it is important to interpret the terms warming and cooling carefully in this context. As emphasized by Takle et al. (2019), these temperature changes should not be understood as net heating or cooling of the system, but rather as anomalies in the near-surface temperature stratification relative to the unperturbed flow.

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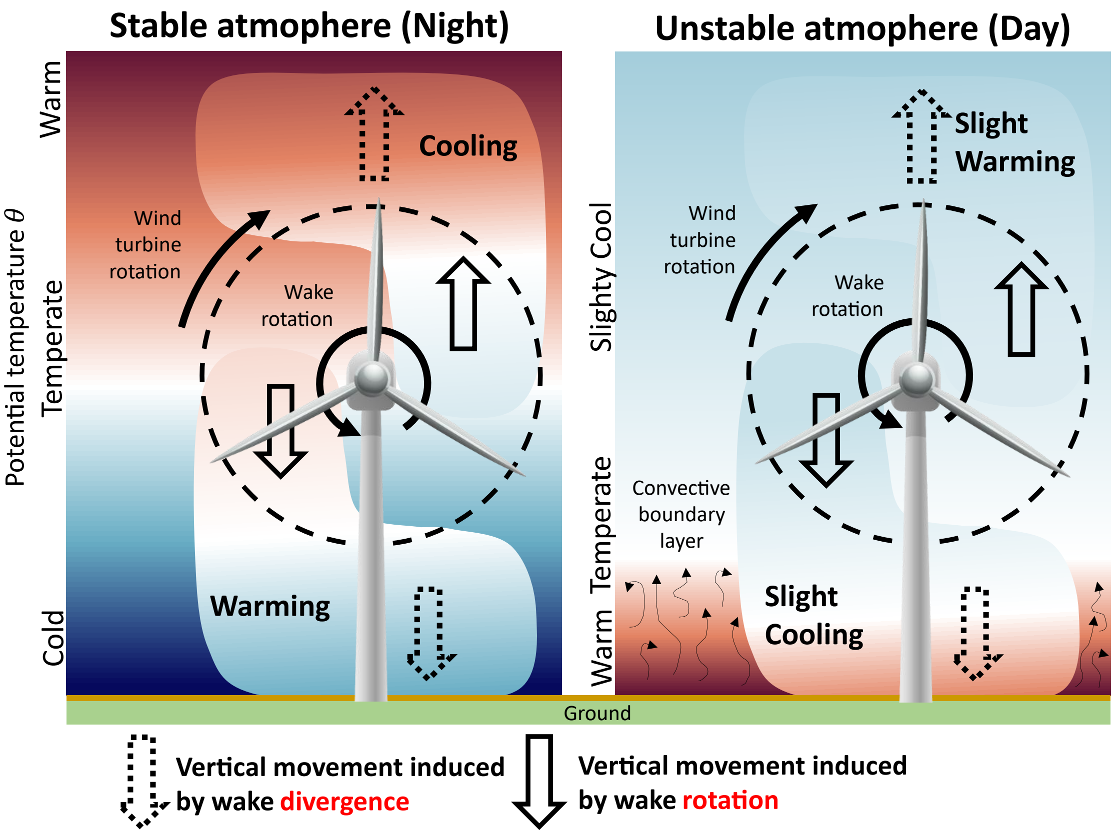

Figure 11. Summary diagram of temperature variations in the wake of a wind turbine for stable and unstable atmosphere (based on the mechanisms describe in Boumendil et al. (2024)).

4.3 Variation of Humidity

Compared to temperature, turbine-induced variations in humidity have received less attention in the literature. A recent review by Adkins and Sescu (2022) overview the humidity modifications induced by wind turbines across the entire atmospheric column. The present review is therefore complementary as it focus on near ground effects. Similarly to temperature, humidity changes arise from turbine-induced vertical mixing and therefore strongly depend on atmospheric humidity stratification. As for temperature humidity variation have been predominantly study in nighttime stable conditions. Under those condition most available studies report a decrease in near-surface relative humidity, whereas little or no signal is found during unstable daytime conditions. One of the most comprehensive investigations combining drone measurements and LES simulations was conducted by Adkins and Sescu (2017, 2018).

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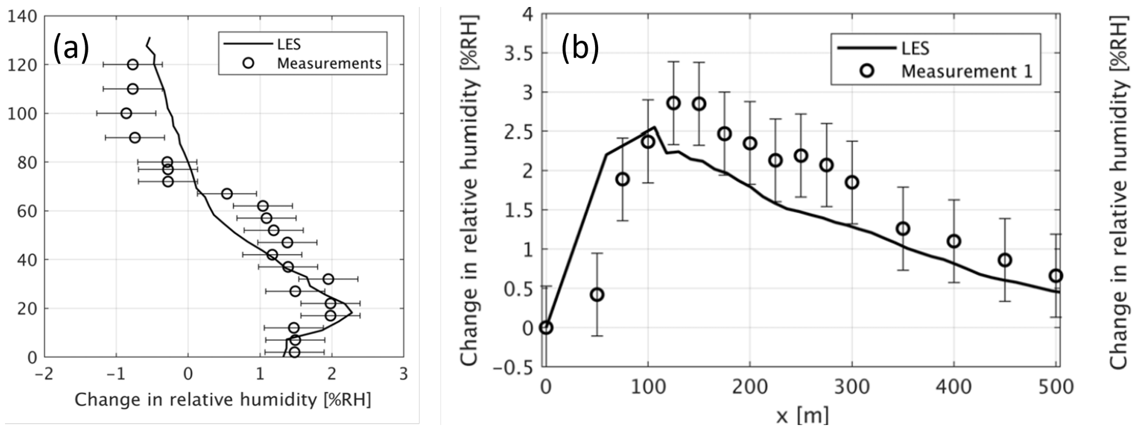

Figure 12. LES and drone measurements changes in relative humidity (upstream minus downstream) (a) as a function of height, at 100 m downstream (b) as a function of downstream distance at the lower turbine tip height. With the convention adopted here, a positive change corresponds to a decrease in humidity (Figure reprinted from Adkins and Sescu (2018) with the permission of John Wiley and Sons).

Their results revealed a drying signal near the surface, with relative humidity reductions of approximately -1.5% (Adkins and Sescu, 2018) in the near wake of a single wind turbine, while humidity increased above hub height (Fig. 12). Similar vertical humidity structures were also reported during the IAO campaign (Takle et al., 2019) and numerical simulations of Boumendil et al. (2025) for stable conditions. These results are consistent with the earlier mesoscale simulations of Baidya Roy et al. (2004), which reported a mean reduction in water vapor mixing ratio of approximately -0.7 g kg^{-1} over a 16-day period, with the strongest effects occurring under stable nighttime conditions.

As for temperature, cumulative within wind farms amplifies humidity changes. For example, in the wake of a single wind turbine, relative humidity might decrease by -1.5% at 2 m above the ground, by -3.5% after 5-6 turbines (Adkins and Sescu, 2018) (Fig. 13), and by -11% after a wind farm with several dozen turbines (Henschen et al., 2011).

Mirroring temperature variations, the sign of near-surface humidity changes appears to depend on the vertical gradient of humidity (Adkins and Sescu, 2017, 2018). Although this gradient is influenced by the diurnal cycle and atmospheric stability, classifying humidity responses solely based on stability is not always relevant. Wind farm-scale simulations by Baidya Roy (2011) showed that for a similar stable atmospheric cases with different mixing ratio lapse rates opposite responses arrised: positive vertical gradients led to increases in near-surface total water mixing ratio r_w, whereas negative gradients resulted in decreases in r_w. Thus, although the distinction between stable and unstable thermal stratification is often useful for interpreting humidity responses, the vertical stratification of atmospheric moisture appears to also play a role. This effect is illustrated by Armstrong et al. (2016), who reported a slight increase in absolute humidity (+0.03 g m^{-3}). However, because air temperature increased simultaneously, relative humidity decreased. As emphasized by Adkins and Sescu (2022), humidity responses are intrinsically coupled with temperature changes: turbine-induced warming increases the saturation vapor pressure, such that the relative humidity may decline even when the absolute amount of atmospheric moisture slightly increases.

In summary, despite the limited number of studies available, several consistent tendencies emerge. Under stable atmospheric conditions and decreasing humidity profile with height, wind turbines generally induce a decrease in near-surface relative

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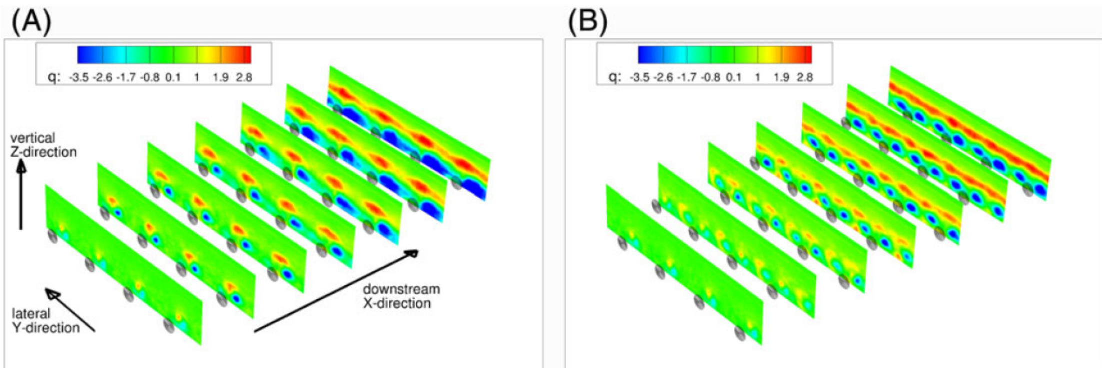

Figure 13. Contour plots of time-averaged relative humidity difference in vertical plane slices at fixed downstream distances: (A), aligned turbine array; (B), staggered array (the legend shows changes in the relative humidity with respect to the upstream level) (figure reprinted from Adkins and Sescu (2018) with the permission of John Wiley and Sons).

humidity, typically ranging between -1 and -2%. Wind farm further amplify these drying signals through wake accumulation effects. In contrast, humidity variations are much weaker or often negligible during unstable daytime conditions, when strong natural convective mixing tends to dominate over turbine-induced effects. Finally, relative and absolute humidity responses should be interpreted jointly, as temperature-induced changes in saturation vapor pressure can significantly modulate apparent humidity variations.

4.4 Variation of Turbulence

The atmospheric boundary layer, where wind turbines operate, is turbulent. The intensity and size of these turbulent structures evolve throughout the day, primarily due to surface forcing (Stull, 1988). Wind turbines interact with this atmospheric turbulence and modify it (Archer et al., 2016; Lu and Porté-Agel, 2011). The rotor area and blade tips are known to be strong sources of turbulence, as the velocity deficit generated by the turbine produces intense shear layers that enhance turbulence production (Chamorro and Porté-Agel, 2009; Porté-Agel et al., 2020; Xie and Archer, 2015).

Under stable conditions, stratification and buoyancy forces tends to inhibit vertical mixing. Studies show that turbine-generated turbulence often remains confined above hub height (see Fig. 15f), rarely reaching the ground (Archer et al., 2019; Wu et al., 2023; García-Santiago et al., 2024; Wu and Archer, 2021). However, other studies investigating the cumulative effects of multiple turbines, either through field measurements (Rajewski et al., 2013) or mesoscale simulations using WFP (Fitch et al., 2012; Bodini et al., 2021), report increased near-surface TKE within and downstream of large wind farms, sometimes extending several kilometers (up to 6 km) beyond the farm boundaries. In these cases, the enhanced turbulence is attributed to the vertical transport of turbulence from the rotor region due to wake accumulation effects.

Under unstable conditions, natural convective mixing dominates the boundary layer dynamics, and the additional turbulence generated by wind turbines is more easily redistributed vertically (Quint et al., 2025). LES simulations by García-Santiago et al.

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	Article	Type	Turbines configuration	Altitude	Humidity an evaporation rate variations: Stable	Humidity an evaporation rate variations: Unstable
Numerical simulation	**Baidya Roy, Pacala, et al. 2004**	RAMS, SMST	Wind Farm	Near-surface air	16-day average: -0,7 g/kg (r_v)	
Numerical simulation	**Boumendil et al. 2025**	LES, ADR	Single WT	2m	-2.3%	-0.19%
Numerical simulation	**Joulin et al. 2020***	LES, AL	Wind Farm	30m	-0.1 g/kg (r_v)	X
Numerical simulation	**Golbazi et Archer 2022***	WRF, Fitch	Wind Farm	Near-surface air	< -0.1 g/kg (r_v)	X
Numerical simulation	**Baidya Roy 2011**	RAMS, SMST	Wind Farm	Near-surface air	Negative mixing ratio: -0.08 g/kg (r_v) Positive mixing ratio: +0.2 g/kg (r_v)	X
Numerical simulation	**Adkins et al. 2018**	LES, ADM-R	Wind Farm	2m	-3.5% (RH)	X
Numerical simulation	**Adkins et al. 2018**	LES, ADM-R	Single WT	2m	-1.5% (RH)	X
Measurement Campaign	**Adkins et al. 2018**	Drone	Single WT	2m	-1.3% (RH)	X
Measurement Campaign	**Henschen et al. 2011**	In situ	Wind Farm	Near-surface air	-11% (RH)	X
Measurement Campaign	**Armstrong et al. 2016**	In situ	Wind Farm	2m	+0.03 g/m³ (AH)	X
Measurement Campaign	**Takle et al. 2019**	In situ	Single WT	20m	[-0.1; -0.2] g/m³ (AH)	Decrease
Measurement Campaign	**Takle et al. 2019**	In situ	Wind Farm	20m	[+0.1 -0.8] g/m³ (AH)	No change

Figure 14. Summary table of near-ground humidity variations caused by wind turbines found in the literature. Asterisks indicate studies performed in offshore conditions. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine, SMST: Sink of Momentum and a Source of TKE, RH: Relative Humidity (%), AH: Absolute Humidity (g/m^3)).

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(2024) and Xie and Archer (2017) indicate enhanced near-surface TKE in the wake of both isolated turbines and successive turbine rows (Fig. 15d).

The spatial organization of turbines strongly modulates turbulence variations. In wind farms, overlapping wakes can lead to cumulative effects, significantly enhancing turbulence levels compared to a single turbine case (Wu et al., 2023). This can lead to the formation of an internal boundary layer within the farm, where turbulence becomes more homogeneous but remains elevated (Maché et al., 2014). Wind farm layout also plays a key role: aligned configurations tend to produce stronger and more persistent turbulence due to wake superposition, whereas staggered configurations promote faster wake recovery and reduced peak turbulence intensity (Lu and Porté-Agel, 2011; Adkins and Sescu, 2018).

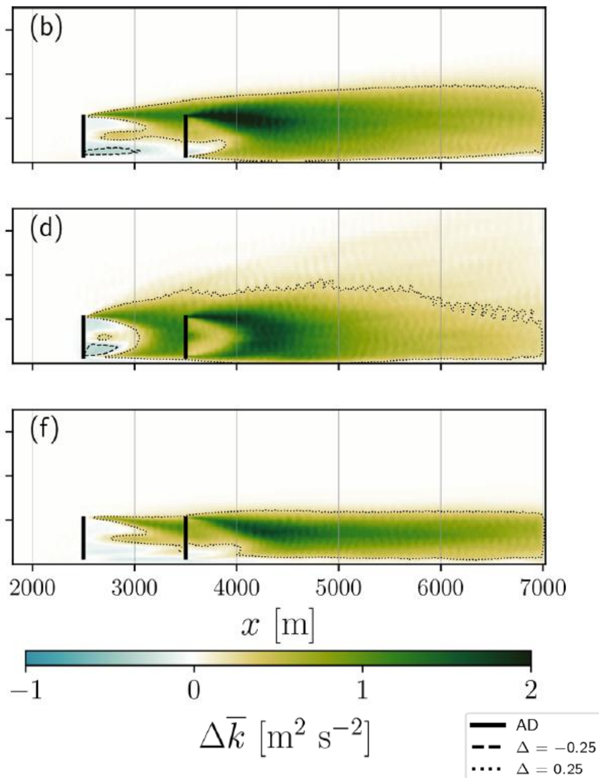

Figure 15. Time-averaged vertical cross section of TKE through the rotor plane of the differences between a simulations without and with two turbines using LES-ADR under (b) neutral, (d) unstable, and (f) stable ABL. The turbines location is depicted as vertical black lines. The dashed lines show contours of Δk = -0.25 m^{2}s^{-2}, and dotted lines show Δk = 0.25 m^{2}s^{-2} contours (figure from García-Santiago et al. (2024) in accordance with the Creative Commons Attribution 4.0 License).

Changes in turbulence characteristics are not limited to TKE and turbulence intensity. They also affect the turbulent transport of momentum, leading to modifications of surface momentum fluxes. Most studies report a reduction in turbulent momentum fluxes near the ground under the wake, consistent with the reduced wind speed and shear (Lu and Porté-Agel, 2011, 2015).

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	Article	Type	Number of wind turbine	Altitude	TKE, TI and u* variations	
					Stable	Unstable
Numerical simulation	Xie et al. 2017	WiTTS, ALM	Single WT	Near-surface air	No change	Increase
	Wu, Archer, and Mirocha 2023	WRF, ADR	Single WT	Near-surface air	Decrease TKE	Small decrease TKE
			Wind Farm		Small decrease TKE	
	García Santiago et al. 2024	LES, ADR	2^{nd} WT	Near-surface air	Small decrease or no change	Small increase
	Boumendil et al. 2025	LES, ADR	Single WT	Near-surface air	Small decrease	Decrease TKE
	Lu et al. 2011	ALM	Wind Farm	Near-surface air	Reduction of u*, TKE, -30% momentum flux	X
Measurement Campaign	Rajewski et al. 2013	In situ	Single WT	6.5 m	Mean TKE at +189%	+20% TKE
			After 2 rows of WT	6.5 m	Average +242% TKE Up to +[400-500]%	
	Rajewski et al. 2014	In situ	1 row of WT	6.5 m	+ [25;50]% in u*	No change
	Archer et al. 2019	In situ	Single WT	3 m (6 D)	In neutral and slightly stable: -25% TKE and -51% of the momentum flux	
	Wu and Archer 2021	In situ	Single WT	3 m (6 D)	Reduction of u* and TKE	

Figure 16. Summary table of near-ground turbulence variations caused by wind turbines found in the literature. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine).

Measurements from the VERTEX campaign confirm significant decreases in near-surface turbulent momentum fluxes under wake conditions across stability regimes (Archer et al., 2019).

Consequently, the friction velocity $u^* = \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2}$ is generally reduced near the surface in the wake of wind turbines (Wu and Archer, 2021; Lu and Porté-Agel, 2015). However, some field observations, such as the CWEX campaign (Rajewski et al., 2013, 2016), report an increase in u^* under stable nighttime conditions in the near wake (around 2.5 D). The apparent discrepancy between the VERTEX and CWEX observations may result from differences in both the spatial scale investigated and the measurement height. While VERTEX primarily examined the wake of a single turbine, CWEX focused on wind-farm environments where cumulative wake effects may enhance turbulence levels. In addition, turbulence measurements were performed at higher elevations during CWEX (8–10 m above ground level) than during VERTEX (3 m) and after which may partly explain the different near-surface responses reported by the two campaigns.

Figure 16 summarizes the variations in TKE, turbulence intensity (TI) and u^* found in the wake of wind turbines near the ground across different studies.

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In summary, wind turbines are strong sources of turbulence in the upper part of their wake, particularly near the blade tips. However, depending on atmospheric stability and the number of turbines, this turbulence does not systematically reach the surface. An important finding from Wu et al. (2023) is that wind speed deficits and turbulence do not behave in the same way. While the velocity deficit can extend to the ground relatively rapidly, often within 8–10 D downstream of a turbine, the turbulence generated by the rotor tends to remain confined aloft. For an isolated wind turbine, there is little evidence of a direct wake "turbulence touchdown" at the surface. As a result, under stable conditions, turbulence intensity, TKE, and momentum fluxes are often reduced near the ground. In contrast, significant influences of turbine-generated turbulence on near-surface turbulence intensity are generally observed only in large wind farms, where wake interactions accumulate, or under unstable atmospheric conditions that favor vertical mixing.

4.5 Variation of Sensible Heat Fluxes

Surface heat fluxes are driven by surface forcing and therefore vary throughout the diurnal cycle. Two main types of surface heat flux can be distinguished: sensible heat flux, associated with the turbulent transfer of heat driven by temperature gradients between the surface and the atmosphere, and latent heat flux, which results from phase changes of water stored in the soil, vegetation or ocean. Variations in near-surface temperature are intrinsically linked to changes in sensible heat flux (Stull, 1988; Quint et al., 2025), while variations in surface moisture are coupled to latent heat flux and evaporation. This section focuses on variations in sensible heat flux, while the following section addresses latent heat flux.

Wind turbines can modify surface heat fluxes through the interplay of two competing mechanisms: enhanced vertical mixing generated by turbine-induced turbulence and changes in near-surface wind speed, which influence the turbulent exchange of heat between the surface and the atmosphere (Xia et al., 2019). It is important to note that the interpretation of sensible heat flux variations induce by wind turbine can be ambiguous due to sign conventions. During daytime we use the convention that the sensible heat flux is typically upward (positive), and that at night it is downward (negative). In the following, flux changes are described in terms of becoming more or less positive during daytime conditions and more or less negative during nighttime conditions. This terminology is adopted to provide a consistent framework for comparison and to avoid misinterpretations, as the sign convention and interpretation of flux variations are not always clearly stated in published studies.

In stable conditions (typically nighttime), several studies suggest that turbine-induced mixing can enhance the downward transport by bringing warmer air from aloft toward the surface, leading to a more negative heat flux (Baidya Roy et al., 2004; Baidya Roy, 2011; Xia et al., 2019). This interpretation is supported by measurements from CWEX, which report localized increases in downward heat flux (more negative, up to $40\ \mathrm{Wm^{-2}}$). However, opposite responses have also been observed. In particular, reduced near-surface wind speed and shear within the wake can weaken turbulent transport, leading instead to a less negative heat flux (Lu and Porté-Agel, 2011; Golbazi et al., 2022; Xia et al., 2019). In unstable daytime conditions, wind turbines tend to reduce the magnitude of the flux, leading to a less positive sensible heat flux (Lu and Porté-Agel, 2015; Quint et al., 2025). This behavior is primarily attributed to reduced wind speed and friction velocity, which decrease the efficiency of turbulent heat transport away from the surface. Some studies suggest that enhanced mixing could instead increase upward fluxes by bringing cooler air downward, but this signal is generally weak compared to ambient convective turbulence.

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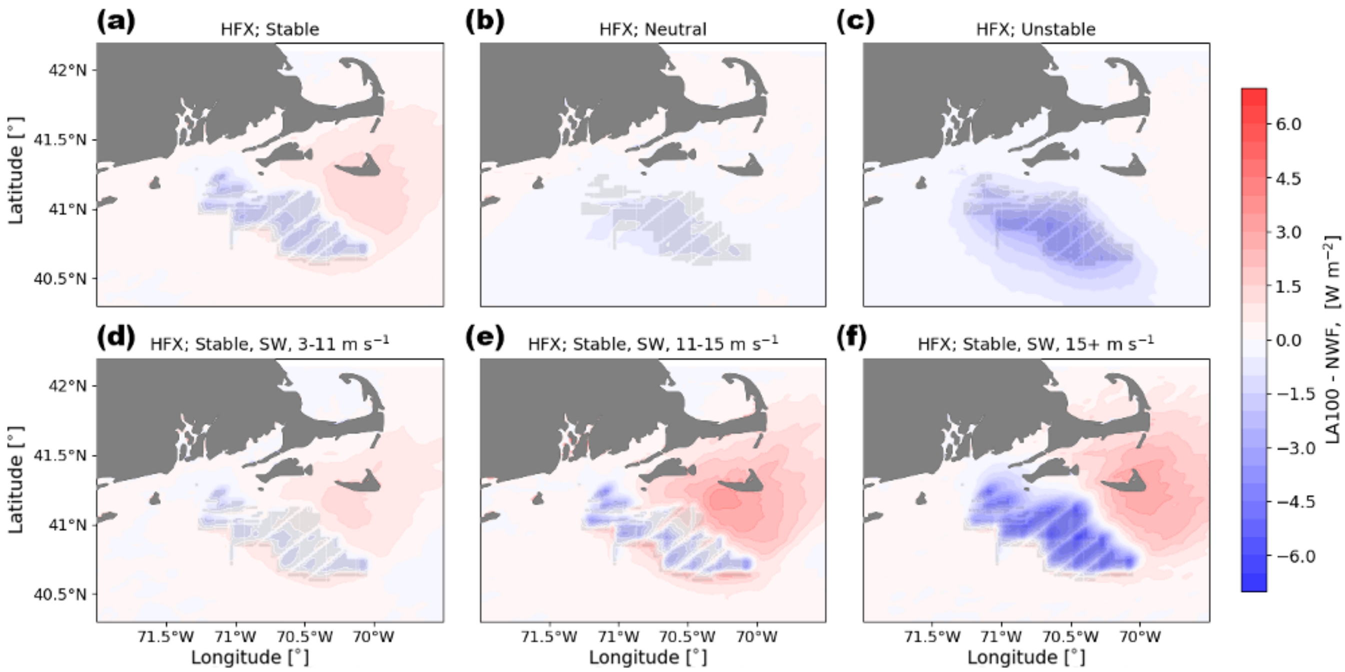

Figure 17. Mean heat flux difference in an offshore wind farm between a simulation with WFP with 100% added TKE and without WFP in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d) 0–3 ms^{-1}, (e) 3–11 ms^{-1}, and (f) 11+ ms^{-1}. Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray (figure from Quint et al. (2025) under the Creative Commons Attribution 4.0 License).

Numerical simulations of offshore wind farms using WRF coupled with wind farm parameterizations (Quint et al., 2025; Golbazi et al., 2022) confirm a general reduction in the magnitude of sensible heat flux within wind farms. These effects are particularly pronounced in stable atmosphere at higher wind speeds (Fig. 17d, e and f).

Overall, despite significant variability across studies and measurement campaigns, a consistent picture emerges: wind turbines tend to reduce the magnitude of near-surface sensible heat fluxes, either by enhancing downward heat transport under stable conditions or by weakening upward transport under unstable conditions. The remaining discrepancies likely reflect differences in measurement height, atmospheric conditions, and the difficulty of accurately measuring highly variable surface fluxes.

4.6 Variation of Evaporation and Latent Heat Flux

Several studies suggest that wind turbines may alter surface evaporation, thereby modifying the associated latent heat flux. One of the first studies on this process, Baidya Roy et al. (2004) reported enhanced evaporation in wind farm wakes under stable conditions, with magnitudes not exceeding 0.2 mm h^{-1}. Baidya Roy (2011) show, however, that the response of the latent heat flux depends on the vertical gradient or lapse rate of the water total mixing ratio. Under stable conditions, the

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	Article	Type	Number of wind turbine	Altitude (Distance)	Heat flux variations: Stable	Heat flux variations: Unstable
Numerical simulation	Baidya Roy, Pacala, et al. 2004	RAMS, SMST	Wind Farm	Near-surface air	Reduction of sensible heat flux in the early morning hours (more negative)	X
Numerical simulation	Quint et al. 2025*	WRF, Fitch	Wind Farm	10 m	More negative Inside the WF Less negative (+1.5 W/m²) downstream the WF	Differences up to around -3 W/m² (less positive)
Numerical simulation	Lu et al. 2011	LES, ALM	Wind Farm	Surface	-15% (less negative)	X
Numerical simulation	Lu et al. 2015	LES, ALM	Wind Farm	Near-surface air	X	Magnitude of the surface heat flux is slightly reduced
Numerical simulation	Golbazi et Archer 2022*	WRF, Fitch	Wind Farm	Near-surface air	Around +1 W/m² on average (less negative) downstream the WF	X
Numerical simulation	S. Wu, Archer, and Mirocha 2023	WRF, ADR	Single WT and WF	Near-surface air	Do not focus on the variations in heat flux, but on convergence and divergence	
Measurement Campaign	Wu and Archer 2021	In situ	Single WT	(3 D) (11 D)	Statistical slight reduction (less negative) Statistical significant reduction (less negative)	No statistical significant change
Measurement Campaign	Rajewski et al. 2013	In situ	Single WT and Wind Farm	6.5 m (17.5 D and 34 D)	Enhanced negative (more negative) Up to 40 W/m²	
Measurement Campaign	Rajewski, et al. 2016	In situ	Single WT and Wind Farm	6.5m (2.5 D, 17.5 D, and 34 D)	Nighttime surface heat flux is higher (more negative)	Increased outgoing heat flux strongly at 34 D (more positive)

Figure 18. Summary table of near-ground heat flux variations caused by wind turbines found in the literature. Asterisks indicate studies performed in offshore conditions. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine).

sign of this gradient can be different, which may result in either an increase or a decrease in latent heat flux depending on the moisture stratification. During daytime, measurements indicate increases in latent heat fluxes of about $+60\ \mathrm{Wm^{-2}}$ (Rajewski et al., 2014) associate with enhanced evaporation rates of 10–15% (1.0–2.0 mm day^{-1}). Similarly, Henschen et al. (2011) observed enhanced evaporation in the wake of a wind farm, with cumulative values of 1.4 mm within the farm and 3.2 mm downstream over a 13-day period, corresponding to a 52% increase. This evaporation increase is consistent with the decrease in relative humidity observed downstream of wind turbines. Based on MODIS satellite observations, Liu et al. (2023) identified evapotranspiration as the primary driver of wind-farm-induced temperature changes during the growing season. They showed that wind turbines may enhance local evapotranspiration under irrigated conditions. In such regions, increased evapotranspiration induces a surface cooling effect that can offset, at least partially, turbine-induced warming.

Several sources suggest that drying of the near-surface air increases the humidity gradient between the surface and the atmosphere (Baidya Roy et al., 2004; Baidya Roy, 2011). This enhanced gradient promotes vapor transport, thereby increasing evapotranspiration rates. Although measurable, these changes are often described as modest compared to sensible heat flux variations, which remain the dominant driver of surface temperature changes (Xia et al., 2019).

Such evaporation increases may have important implications for agricultural crops and ecosystems located within and downstream of wind farms. However, despite these potentially significant impacts, the effects of wind turbines on evaporation remain poorly documented and comparatively understudied, as already highlighted by Armstrong et al. (2014).

4.7 Others Near-Ground Variations

Other surface meteorological variations potentially attributable to wind turbines have been mentioned in the literature.

Rosencrans et al. (2025) examined how wind-farm-induced meteorological modifications may influence ice formation through accretion on ships or offshore wind turbines. On wind turbine blades, ice can significantly reduce electricity production (by up to 80% according to Gao et al. (2023)) and force turbines to shut down for safety reasons. Meteorological changes induced by wind turbines, as discussed previously, can either decrease or favor ice formation depending on atmospheric stability and altitude. According to Rosencrans et al. (2025), only minor changes in icing risk are associated with large offshore wind farms, with reductions of up to 13 hours during the 2019–2020 winter.

Wind turbines have been shown to modify surface CO_2 fluxes in the atmospheric boundary layer, suggesting potential impacts on vegetation activity. During the CWEX campaigns, measurements over a cornfield indicated an increase in daytime CO_2 uptake of 8–12% at approximately 5 D downstream of a turbine, with variations reaching up to 500% depending on wind direction and 200% at night. These variations were found to be potentially linked to changes in latent heat and water vapor fluxes, although a direct causal relationship remains uncertain. However, similar upstream-downstream differences were also observed when turbines were not operating, highlighting the role of the structures themselves as obstacles to surface fluxes. Overall, results suggest that CO_2 flux responses are highly variable and strongly dependent on local flow conditions and measurement context.

Closely related to near-surface moisture processes, dew formation has also received some attention in the literature, as turbine-induced changes in humidity and stability may affect both the occurrence and duration of dew (Adkins and Sescu,

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	Article	Type	Turbines configuration	Altitude	Evaporation rate (mm) and latent heat (W/m^2) flux variations: Stable	Evaporation rate (mm) and latent heat (W/m^2) flux variations: Unstable
Numerical simulation	Baidya Roy, Pacala, et al. 2004	RAMS, SMST	Wind Farm	Near-surface air	Departures < +0.2 mm/hour	
Numerical simulation	Baidya Roy 2011	RAMS, SMST	Wind Farm	Near-surface air	+0.07 W/m^2 -2.2 W/m^2	
Numerical simulation	Golbazi et Archer 2022*	WRF, Fitch	Wind Farm	Near-surface air	-8 W/m^2 (a 15% reduction) of the latent heat flux	
Numerical simulation	Xia et al. 2019	WRF	Wind Farm	Near-surface air	+0.27 W/m^2 inside the WF -0.36 W/m^2 downstream WF	
Measurement Campaign	Henschen et al. 2011	In situ	Wind Farm	Near-surface air	+52% of evaporation over 13 days 1.4 mm inside WF vs 3.2 mm downstream	
Measurement Campaign	Rajewski et al. 2014	In situ	Single WT	Near-surface air		+[10;15]% or 1.0–2.0 mm/day +60 W/m^2 of latent heat flux

Figure 19. Summary table of evaporation and latent heat flux variations caused by wind turbines found in the literature. Asterisks indicate studies performed in offshore conditions. Cells marked with a cross indicate atmospheric stability cases that were not considered in the corresponding study (WF: Wind Farm, WT: Wind Turbine).

2022). A later on study using the CWEX field measurements show that dew duration remains similar measurements stations when both are outside the wake. However, when one station is located in the wake of a turbine, dew duration is systematically reduced downstream, with an average decrease of approximately 120 minutes. This effect suggest a direct influence of wake on near-surface condensation processes.

Under specific saturation conditions (typically in offshore or humid environments) wind turbine wakes may also influence fog and low-cloud formation (Hasager et al., 2013, 2017; Joulin et al., 2020). Wake-induced vertical motions can lift moist air from the surface, which then cools adiabatically and may reach saturation, promoting localized condensation and the formation of wake fog or cloud structures. These effects remain episodic but highlight the ability of turbine wakes to influence phase-change processes in the lower atmosphere.

Satellite observations indicate that wind farms have measurable effect on vegetation growth, with marked reductions in vegetation indices such as NDVI (-14.5%), EVI (-14.8%), and LAI (-8.9%) (Tang et al., 2017). These impacts translate into a decrease in vegetation biomass production within a radius of 1 to 10 km around turbines (Gao et al., 2023). The main identified mechanism is an increase in LST, which reduces soil moisture and intensifies water stress in surrounding vegetation. These negative impacts should however be nuanced, as Liu et al. (2023) show that in well-managed agricultural lands, wind farms

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may locally enhance evapotranspiration processes and have cooling effects on local LSTs during the growing season. Similarly, Slawsky et al. (2015) highlight that in humid and vegetation-rich ecosystems, surface warming can be attenuated due to a larger fraction of available energy being partitioned into latent heat flux through vegetation.

Conversely, the economic analysis of Kaffine (2019) reports a positive relationship between wind farm development and agricultural productivity, suggesting that wind-farm-induced microclimatic changes may contribute to improved growing conditions. Quantitatively, the study estimates that an additional 100 MW of installed wind capacity in an average area leads to an increase in corn yields of approximately 0.5% to 1.5%. This enhancement in crop productivity translates into an estimated local economic benefit exceeding 5 $ per MWh.

5 Conclusions and Discussions

Wind energy is expected to play an increasingly important role in the global energy transition, leading to the continued expansion of wind farms and the deployment of larger turbines both onshore and offshore. In this context, understanding the interactions and modification of wind turbines on the atmospheric boundary layer has become an important scientific question. This review focuses on near-surface meteorological variations induced by wind turbines and synthesizes the findings of experimental and numerical studies published over the past two decades.

Wind turbines affect the structure of the atmospheric boundary layer by enhancing vertical mixing through the combined effects of blockage, momentum extraction, turbulence generation, flow divergence, and rotor-induced vertical motions. This enhanced mixing alters the vertical stratification of the atmosphere and can lead to meteorological anomalies throughout the atmospheric column. Near the surface, wind speed generally increases immediately below the rotor in the near wake due to pressure-gradient effects and transports of higher-momentum air from aloft toward the surface. In the far wake, depending on atmospheric stability and the number of consecutive wind turbines, the velocity deficit can expand and reach the ground. Near ground air and surface temperature show a warming under stable conditions and weak cooling or negligible effects under unstable conditions. Humidity changes are primarily controlled by the water vapor mixing ratio profile and temperature variations, as relative humidity is intrinsically coupled to temperature. This coupling often leads to reduced near-surface relative humidity under stable conditions. Wind turbines can also alter turbulence characteristics, although the response near the ground differs substantially from that observed at rotor height. While turbulence production is enhanced within the rotor region, it remains largely aloft and the surface only with the influence of cumulative wakes effect or under unstable conditions. Changes in sensible and latent heat fluxes have also been reported with a decrease of the sensible heat flux and an increase of the evaporation in stable condition. All these alterations have been shown to inhibit local vegetation growth and productivity, with satellite observations revealing significant declines in different vegetation indices within few kilometers around the wind farm. Opposite effects have also been reported in the literature, which find improved crop productivity linked to wind-farm-induced microclimatic changes, highlighting the strong dependence of wind-farm impacts on climatic conditions and site-specific characteristics

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Results from the literature highlight the dominant role of atmospheric stratification and stability. Most near-surface meteorological effects are strongest under stable conditions, when natural turbulent mixing is weak and turbine-induced perturbations can have a strong relative impact. In contrast, unstable background turbulence attenuates turbine-induced signals. Wind farm size and layout further modulate these effects through wake accumulation processes, which can amplify meteorological perturbations compared with single turbines.

Contradictions remain between some field campaigns, numerical simulations, and parameterized mesoscale studies, particularly regarding turbulence and surface flux responses. These discrepancies likely arise from differences in atmospheric conditions, turbine characteristics, surface properties, wind farm size and layout, as well as from variations in measurement techniques, modeling approaches, and methodologies used to quantify turbine-induced effects.

In addition, several potentially important variables, including evaporation, dew formation and especially ecosystem responses, remain largely unexplored. Yet, these processes may represent some relevant pathways through which wind farms interact with surrounding vegetation and ecosystems, highlighting the need for dedicated observational and modeling studies.

Despite significant advances in numerical modeling capabilities and increasingly ambitious field measurement campaigns, important uncertainties remain. Further work is needed to reconcile observations across scales, identify the effects of individual turbines from the cumulative impacts of entire wind farms, and assess how future generations of taller and larger turbines may induce different near-surface atmospheric variations. Particular attention should be given to the rapid expansion of offshore wind energy, where the deployment of multiple large wind farms raises questions regarding their potential influence on marine atmospheric conditions, air-sea exchanges, fog formation, possible downstream effects on coastal meteorology and hydrodynamical conditions.

The success of recent field campaigns using unmanned aerial systems of Adkins and Sescu (2017) demonstrates the value of detailed wake observations and highlights the need for additional drone measurement campaigns within and downstream large wind farms. As pointed out by Archer et al. (2019) and Golbazi et al. (2022), long-duration and multi-season observational studies are particularly needed to capture the strong seasonal dependence of turbine-atmosphere interactions and to establish the robustness of currently reported signals. Further efforts are also required to better understand the interaction between turbine-generated turbulence and atmospheric turbulence. In particular, the production, transport, and dissipation of turbine-induced TKE remain incompletely understood, especially within large wind farms where wake interactions become dominant. Improving the representation of these processes in wind farm parameterizations remains a key challenge, notably for schemes such as that of Fitch et al. (2012), where the fraction of added TKE remains an important source of uncertainty (Quint et al., 2025).

Finally, future high resolution LES numerical studies would benefit from more realistic representations of atmospheric and surface conditions. The development of multi-scale modeling frameworks, combining weather prediction models with LES, appears particularly promising for capturing the multiscale interactions governing turbine wakes and their impacts on the ABL and surface layer. Such efforts will be essential not only for improving our understanding of turbine-atmosphere interactions but also for supporting the sustainable development of wind energy and its integration into weather, climate, and environmental impact assessments.

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The magnitude of wind-turbine-induced meteorological perturbations reported in the literature remains relatively modest when compared with other anthropogenic surface modifications. This limited amplitude is reflected in the difficulty of isolating turbine-specific signals from background atmospheric variability. In addition, the reported effects often exhibit significant variability in both magnitude and sometimes even sign, suggesting a strong dependence on local conditions. Nevertheless, given the ongoing increase in both turbine size and installed capacity worldwide, these subtle but persistent effects require continued investigation and systematic documentation.

Data availability. The study is based on previously published literature, and all information discussed in the manuscript is available from the cited references.

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