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Research Progress on the Impact of Wind Farms on Climate and EcologyPin Zhang ^{a,b,c}, XiaoQing Gao ^{a*}, Yi Han ^d, Jiang Ying ^{a,b,c}, ZhiMin Yang ^{a,b,c}

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Abstract

To mitigate global warming, we must accelerate the development of renewable energy. Wind energy has grown rapidly worldwide recently because of its abundance and environmental benefits. As wind power expands, the climatic and ecological impacts of large-scale wind farms demand urgent attention. This study reviews wind farm impacts at local, regional, and global scales, emphasizing climate responses. It also examines ecological effects during both construction and operation, focusing on soil, hydrology, and biota. Wind farms alter surface fluxes, wind speed, and temperature by extracting atmospheric kinetic energy, increasing surface roughness, modifying boundary-layer stability, and intensifying rotor-wake turbulence. These processes further shift precipitation and cloud cover. Ecologically, construction and operation disrupt bird habitats, raise bird and bat mortality, generate noise, and affect soil carbon cycling and vegetation growth. Offshore projects can weaken hurricane winds and storm surges and reduce ocean-to-atmosphere heat flux, yet construction may harm benthic organisms and algal communities. Overall, this study clarifies how wind energy development interacts with climate and ecosystems. It calls for coordinated development and provides evidence to guide an environmentally friendly energy system in China, supporting high-quality economic and social development.

Keywords: Renewable energy; Climate change; Wind energy development; Wind farms; Climatic and environmental effects

1. Introduction

Fossil fuel combustion is a primary driver of the global rise in carbon dioxide. To achieve sustainable development, societies need to transition their energy systems toward renewable sources. Wind energy offers major advantages: it is abundant, renewable, and produces electricity without pollution (Zhu *et al.*, 2025). The wind power industry has expanded rapidly worldwide. From 2020 to 2050, renewable capacity is projected to increase tenfold, with wind contributing a large share (Zhang *et al.*, 2024). China's wind sector is also advancing quickly. By the end of 2024, grid-connected capacity reached 520 GW. Expanding wind power reduces greenhouse gas emissions and helps mitigate global warming. At the same time, large-scale wind farms alter land surface characteristics and impact climate and ecosystems (Zhao *et al.*, 2025). These impacts are especially critical in developing countries and ecologically fragile regions where wind energy continues to grow. Understanding the environmental and climatic effects of wind farm expansion is therefore essential for sustainable energy development.

As populations grow and modernization advances, energy demand continues to rise. Developing renewable energy presents an effective strategy for sustaining economic growth and mitigating global warming (Zhuo *et al.*, 2023). At the same time, large-scale wind deployment can bring non-negligible climatic and ecological impacts during construction and operation. We must clarify how wind turbines

operate and how they influence climate and ecosystems. Wind-tunnel experiments and CFD simulate blade-flow interactions and turbine operating principles (Sanderse *et al.*, 2011). They can quantify turbine-driven changes in friction velocity and momentum, but they cannot represent atmospheric boundary-layer processes. They also struggle to reproduce wake evolution under realistic winds, so they capture climate responses only to a limited extent (Zhang *et al.*, 2012). Early studies of wind farm climate effects relied on field observations. These methods face high costs, limited quality, and poor spatiotemporal coverage. Satellite data cover large areas at lower cost and with easier access. With stronger computing power and lower costs, numerical modeling now plays a central role in assessing wind farm impacts (Xia *et al.*, 2015). As wind farm scale increases, atmospheric models allow simulation of their influence at regional and even global levels.

Wind farms affect the climate system at local, regional, and global scales. They alter meteorological variables, regulate atmospheric circulation, and shift the energy balance, while also triggering ecological responses and human feedback. Turbine operation slows wind speed and increases turbulent kinetic energy. Large-scale deployment raises surface temperatures, with stronger nighttime warming up to 0.7 °C and larger summer than winter signals (Dai *et al.*, 2015). Acting as momentum sinks, wind farms change regional pressure and wind fields, which in turn influence precipitation (Junxia *et al.*, 2019). By reshaping surface microclimates, wind farm construction and operation modify land surface conditions, causing local warming and reduced evapotranspiration. These shifts can suppress vegetation growth and propagate through the carbon cycle, lowering carbon sequestration; the maximum relative reduction can reach up to 50% (Wu *et al.*, 2023).

Assuming an average wind speed of 7.0 m/s and a mean wind power density of 325 W/m² in China, a mainstream 4.5 MW wind turbine with a capacity factor of 33.2% can generate approximately 12,996 MWh of electricity. Producing the same amount of energy from fossil fuels such as coal or natural gas would, on average, release 6,847 tons of CO₂ into the atmosphere. Thus, wind turbines serve as an effective alternative to fossil fuels by substantially reducing carbon emissions (Abdullah-Al-Mahbub and Islam, 2024). Wind-energy expansion in developing countries and ecologically fragile regions has also drawn growing attention because of its associated climatic and environmental impacts (Zhu *et al.*, 2021). This paper reviews the literature on the climatic and ecological impacts of wind farms and presents a systematic overview of research methods, with a focus on different spatial scales. It highlights the effects of wind farms on global, regional, and local climates and examines ecological effects during construction and operation. Finally, it offers recommendations to guide future wind power development and inform policies that support sustainable energy transitions.

2 Research methods for climatic and ecological effects of wind farms

As wind farms expand, research increasingly examines turbulence, wake effects, and climatic ecological responses both within farms and across scales between neighboring farms. Because farm size and the simulation domain vary, studies must adopt scale-specific methodologies. In recent years, researchers have investigated these impacts using in situ measurements, satellite remote sensing, and numerical modeling. Table 1 summarizes the methodologies applied to multi-scale analyses of wind farm effects.

2.1 In situ observations

Field observations capture wind resources and turbine operating parameters within wind farms, directly reflecting turbine impacts. Field observations provide direct meteorological data and clearly show changes in local meteorological variables, making them a key method for studying the impacts of wind farms on local climate. Yet they are scarce, costly, and vulnerable to interference, which reduces data quality and spatial representativeness.

2.2 Satellite remote sensing

Satellite remote sensing offers an efficient alternative, allowing researchers to quantify wind farm impacts over large areas and track long-term changes in environmental parameters before and after development (Liu *et al.*, 2018). MODIS and Landsat retrieve land surface temperature, vegetation indices, and surface albedo, and thus characterize surface thermal conditions and their spatiotemporal

variation (Xingyue *et al.*, 2022). By contrast, Synthetic aperture radar (SAR) retrieves sea surface roughness to detect downstream wind speed deficits, enhanced turbulence, and wake extent. It mainly supports offshore wind farm research and wake monitoring, and it also provides supplementary observations under cloudy or nighttime conditions (Christiansen and Hasager, 2005).

2.3 Numerical simulations

Both in situ observations and satellite remote sensing provide essential datasets and validation for numerical simulations, but they have limitations. Advances in computing have made numerical modeling a key tool for assessing wind farm climate effects. Computational fluid dynamics (CFD) analyzes blade aerodynamics and supports turbine parameterization, site selection, and short-term power forecasting, making it a key method for simulating turbine flow fields (van der Laan *et al.*, 2017). CFD methods include Direct Numerical Simulation (DNS), Reynolds-Averaged Navier-Stokes (RANS), and Large Eddy Simulation (LES). DNS resolves turbulence faithfully but suits only low-Reynolds-number flows. RANS averages high-Reynolds-number turbulence, cutting cost but missing fine structure (Ma *et al.*, 2022). LES bridges the gap by modeling individual turbines within large farms, resolving vertical transport of kinetic energy and heat/moisture fluxes, and quantifying turbine impacts within and downstream of farms (Calaf *et al.*, 2011; Lu and Porté-Agel, 2011). LES captures wake effects and boundary-layer interactions well but is computationally intensive (Porté-Agel *et al.*, 2014).

The Weather Research and Forecasting (WRF) model is widely applied in mesoscale numerical simulations, providing the capacity to represent realistic atmospheric physical processes, and has become an important tool for investigating the climatic impacts of wind farms. Modeling each turbine is crucial to capture boundary layer interactions. Since turbine wake effects occur at subgrid scales, they cannot be directly resolved and must therefore be parameterized (Ma *et al.*, 2022). Keith *et al.* (2004) modeled turbines by increasing surface roughness or turbulent kinetic energy (TKE). However, this approach tends to overestimate sensible heat fluxes, leading to exaggerated temperature changes, and fails to reproduce the complex turbulence induced by turbines (Fitch *et al.*, 2013). Fitch (2016) added turbine drag coefficients to WRF and treated wind farms as momentum sinks and TKE sources. This scheme allowed WRF to represent turbine effects and markedly improved model performance.

The Regional Atmospheric Modeling System (RAMS), another mesoscale model, can also be used to simulate the climatic impacts of wind farms. RAMS employs a subgrid-scale rotor parameterization scheme, in which turbine rotors are represented as momentum sinks and TKE sources, enabling the simulation of wind farm - boundary layer interactions (Baidya Roy, 2011). At the global scale, climate effects of wind farms are commonly investigated using general circulation models (GCMs) and the Community Atmosphere Model version 5 (CAM5). In GCMs, turbine effects are described by adding a drag term to the surface momentum flux, which is combined with simulated wind speed to estimate the large-scale wind power limit (Miller and Kleidon, 2016). In CAM5, wind farms are represented as elevated momentum sinks, while turbulence is enhanced to capture the mixing effects of turbine blades (Fitch, 2015).

Table 1 The methodologies applied to multi-scale analyses of wind farm effects

Method		Advantages & Limitations	Key Research Questions	Application Scenarios	
Field Measurements	Meteorological instruments (towers, helicopters, UAVs)	Offers high observational accuracy and temporal resolution, but limited spatial coverage and sensitivity to site placement	Wind speed, wind direction, and operational parameters within wind farms	Local impact studies	
Radar remote sensing	MODIS and Landsat optical/thermal infrared remote sensing; SAR microwave remote sensing	Provides broad spatial coverage and strong spatiotemporal continuity, making it well-suited for long-term change monitoring	Wind resource characteristics and meteorological changes in wind farms	Large-scale, all-weather ground-based observations	
Numerical Simulations	computational fluid dynamics CFD	DNS	Resolves all turbulence scales with the highest fidelity but requires massive computational resources	Flow mechanisms at the microscale	Suitable for laboratory studies, simulations of large wind turbine blade

		RANS	Parametrizes turbulence by averaging and resolves turbine flow with low computational cost	Engineering studies in wind energy	rotation, and small-scale wind turbine or turbine-cluster flow fields, including turbine and wind farm wake effects
		LES	Parametrizes only small-scale turbulence, achieves high accuracy, but demands high computational cost	High-resolution simulations of wind farm flows	
	WRF (mesoscale model)		Wind farm parameterizations at the regional scale and is well suited to simulating wind farm-boundary layer interactions; the results remain sensitive to parameterization schemes, model resolution, and initial and boundary conditions	Wind farm-atmosphere interactions; mesoscale prediction and assessment	Applied to prediction and assessment at wind farm scale, wind base scale, or larger regional (national) wind farm scales
	RAMS (regional model)		Captures regional climate variability and evaluates the impacts of boundary conditions	Interaction between wind farms and the atmospheric boundary layer; effects of wind farms on climatic elements, including wind, temperature, humidity, and pressure	
	Global model GCMs/CAM5		Supports impact assessment at global or continental scales and enables analysis of the feedback of large-scale wind energy development on atmospheric circulation, energy balance, and the climate system		

3. Wind farm impacts on climate

Wind turbines reshape land – atmosphere exchange. They raise surface roughness, intensify rotor-wake turbulence, and adjust atmospheric boundary-layer (ABL) stability. The response depends on ambient wind and on ABL stratification, which varies strongly by day and season (Baidya Roy, 2011; Baidya Roy and Traiteur, 2010). Figure 1 illustrates the mechanism of wind farm climate impacts.

3.1 Local climatic effects of wind farms

The impact of wind farms on local air temperature exhibits diurnal and seasonal variations. Specifically, wind farms induce a diurnal asymmetric effect on temperature, which is determined by the stability of the atmospheric boundary layer. Under stable ABL conditions—typically occurring at night when warmer air overlays cooler near-surface air—wind turbines enhance vertical mixing, transporting warmer air downward and thereby causing nocturnal warming (Smith *et al.*, 2013). Seasonal anomalies in wind farm impacts on surface temperature mainly depend on the difference between turbine-induced turbulent kinetic energy (TKE) and background TKE. In spring, strong convective winds intensify background turbulent kinetic energy (TKE), which can overshadow turbine-induced turbulence and weaken seasonal warming effects (Xia *et al.*, 2015).

Walsh-Thomas *et al.* (2012) employed satellite remote sensing data to examine wind farm-induced temperature changes. They found that wind farms increased surface temperature at night and in the early morning; in summer, the downwind area was on average about 4–8 °C warmer than the upwind area.

Zhou *et al.* (2012b) used Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature (LST) data to assess the effects of large wind farms in west-central Texas. Results showed higher near-surface air temperatures downwind at night and in the early morning, whereas the opposite occurred during the rest of the day. Follow-up analyses identified a nocturnal warming effect of 0.31–0.70 °C, with no significant daytime change. Summer showed stronger nighttime warming than winter, with increases of 0.724 °C per decade and 0.458 °C per decade, respectively. The warming was stronger at 22:30 local time than at 01:30, and turbine locations closely matched the warming pattern within the wind farm (Zhou *et al.*, 2012a). Ma *et al.* (2022) used MODIS satellite remote sensing to assess wind farm-induced changes in land surface temperature in northern Zhangjiakou, Hebei. They reported nighttime warming and daytime cooling in downwind areas. Spring showed the strongest warming, at 0.379 °C/(10a). Summer and autumn showed weaker warming, at 0.206 °C/(10a) and 0.211 °C/(10a), respectively, while winter showed no significant warming.

Porté-Agel *et al.* (2014) using large-eddy simulation (LES), investigated interactions between atmospheric boundary-layer turbulence and wind turbines. They showed that turbine-induced rotation enhances vertical heat mixing, leading to near-surface warming of 0.04 K under stable conditions and cooling of 0.025 K under convective conditions, while reducing the magnitude of surface heat fluxes by ~5%. Armstrong *et al.* (2016) reported that at night, turbines raised air temperature by 0.18 °C, increased absolute humidity by 0.03 g/m³, and amplified variability in air, surface, and soil temperature across the diurnal cycle. Calaf *et al.* (2011) demonstrated that turbines increase fluxes within the ABL by ~10%–15% due to added turbulence in wakes but reduce friction velocity and surface fluxes beneath the farm as turbines extract momentum.

3.2 Regional climatic impacts of wind farms

Wind farms affect both local weather and regional climate. Large deployments can shift local temperature by several degrees and cut precipitation by up to 20%. They can also weaken winds and, in some cases, ease dust storms and coastal storm surges (Jacobson *et al.*, 2014; Chang *et al.*, 2016). Turbine blades enhance vertical mixing in the atmosphere, weaken downstream wind speeds, and modify surface sensible and latent heat fluxes. These changes dry the near-surface air and indirectly alter precipitation and cloud cover (Baidya Roy, 2011; Armstrong *et al.*, 2014).

Chang *et al.* (2016) used MODIS land surface temperature (LST) data to assess wind farm effects in Guazhou, northwest China. They observed a pronounced nighttime warming trend in LST over wind farm areas: the strongest warming occurred in summer (up to 0.51 °C/8 years), followed by autumn (0.48 °C/8 years); winter showed the weakest warming (0.38 °C/8 years), and no warming trend appeared in spring. Fiedler and Bukovsky (2011) applied the WRF regional climate model to a large wind farm in the eastern United States. A hypothetical large wind farm increased average warm-season rainfall by 0.3% across two-thirds of the eastern United States, with localized increases of up to 1.0% near farms during the rainy season. In a GCM with explicit turbines, Miller and Kleidon (2016) showed that turbine-induced kinetic-energy extraction can reduce downstream wind speeds by 43% and that the resulting kinetic-energy deficit can be used to constrain the upper bound of sustainable wind power potential.

Baidya Roy and Traiteur (2010) applied RAMS to a 7 × 3 turbine array. They showed that warming mainly reflected land surface properties and time-varying boundary layer conditions. Baidya Roy *et al.* (2004) also used RAMS and investigated large wind farms over summer plains. Wind turbines extracted kinetic energy at a mean rate of 0.8 W/m² and reduced wind speed at hub height. Rotor-induced vertical mixing raised surface temperature by about 0.7 °C, lowered humidity by about 0.7 g/kg, and reduced surface sensible heat flux by 8.4 W/m². Because nocturnal boundary layers remain stable with strong wind shear, the strongest impacts occurred before dawn. Under such conditions, vertical mixing exerts stronger effects than in the well-mixed daytime boundary layer. Baidya Roy and Traiteur (2010) showed that daytime cooling and nocturnal warming both result from turbine-induced vertical mixing. In stable atmospheres, where warm layers overlay cooler near-surface air, mixing transports warm air downward and lifts cooler air upward, leading to surface warming.

Under very large-scale deployment scenarios, modeling studies have shown that regional mean wind speed can decrease by about 43%, indicating that wind energy extraction can feed back on the background wind field at large scales. Wake effects further amplify regional impacts. Turbine wakes reduce wind speed and increase downstream turbulence over 30–60 km. They can raise turbulent kinetic energy by more than 30%. Bodini *et al.* (2021) suggested establishing buffer zones in wind-rich regions to improve

efficiency. Ai *et al.* (2022) applying the WRF model with the Fitch turbine parameterization, found that climate responses depend strongly on land surface type and turbine spatial layout. Farm design shapes turbulence structures and modulates wake effects. Shu *et al.* (2018) used WRF-Fitch for lake regions and showed that sparse hollow-diamond layouts accelerate wake recovery. Wake intensity and spatial extent also depend on farm scale and topography. Flat terrain amplifies wake impacts compared to complex mountainous regions (Alfredsson and Segalini, 2017).

3.3 Impacts of wind farms on global climate

Wind farms alter climate from local to global scales by redistributing energy and moisture vertically and changing surface–atmosphere exchanges. Increased surface roughness shifts global circulation. Dynamical changes affect precipitation, while thermal changes influence temperature. Wind farms increase near-surface drag and add kinetic-energy dissipation P (10–20 TW), but they change the global-mean total surface kinetic-energy dissipation by less than 1%. They produce a negligible global-mean near-surface temperature response, yet regional peak seasonal responses exceed 2 °C. By reducing total atmospheric energy, wind farms modify global surface momentum and surface fluxes (sensible and latent heat), which in turn shift global precipitation and cloud distributions. (Keith *et al.*, 2004). Wind farms exert a significant local impact on wind speed and turbulence, while their influences on temperature, sensible heat, latent heat fluxes, clouds, and precipitation are relatively minor at the regional and global scales. The warming from wind farms is still far weaker than greenhouse gas–driven global warming (Fitch, 2015).

Wang and Prinn (2010) used a coupled atmosphere–ocean–land model to test large deployments on land and nearshore seas. By 2100, turbines warmed land by more than 1 °C and cooled oceans by over 1 °C. Turbines increase surface roughness and trigger Rossby waves. These weaken near-surface westerlies, change vertical mixing, and warm the land surface. The warming also alters cloud cover and surface heat fluxes (Kirk-Davidoff and Keith, 2008). On land, roughness is already high. At sea, the added drag generated stronger turbulence, offsetting wind speed loss. This enhanced ocean–atmosphere heat exchange, especially latent heat, produced local cooling across most sites. In some areas, convection and large-scale rainfall changed by more than 10%, but the global mean effect stayed modest (Marvel *et al.*, 2012).

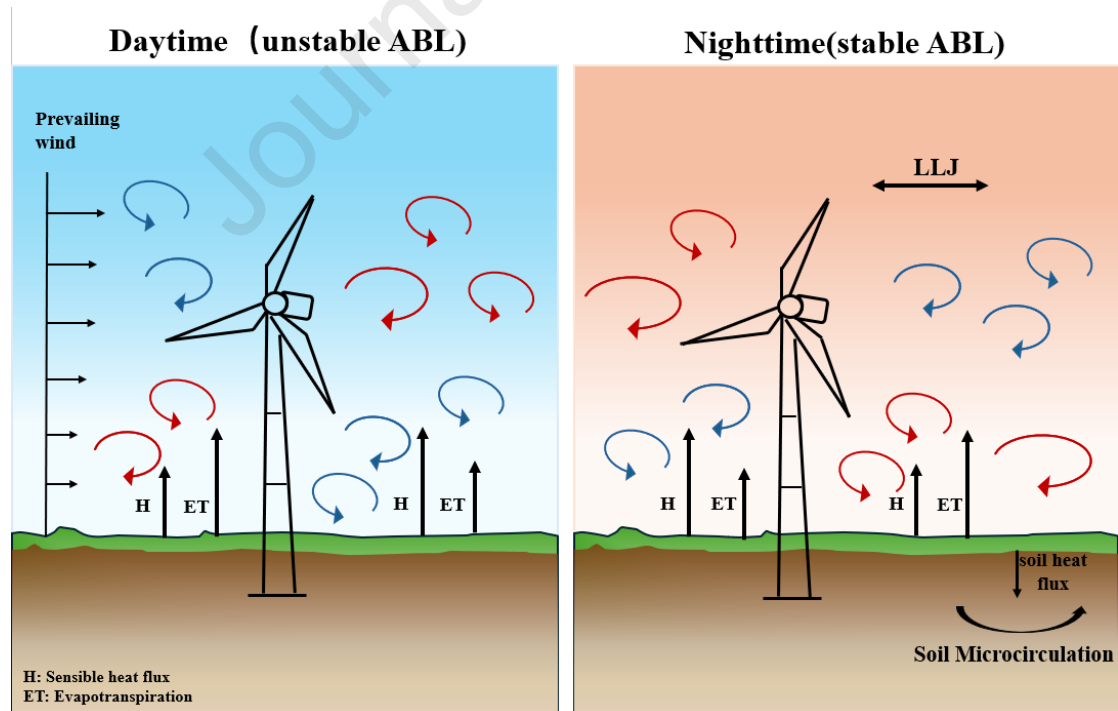


Fig. 1. Schematic of the mechanisms underlying wind-farm impacts on climate

4 Environmental impacts of wind farms

Wind farm development directly alters terrestrial ecosystems through land occupation and engineering construction. During operation, turbines generate noise that disturbs birds and bats. Wake turbulence and local microclimatic changes further affect ecosystem processes. These ecological and environmental impacts show clear stage-specific, compound, and spatially heterogeneous characteristics. Vegetation and soil may respond differently inside and outside wind farms and between upwind and downwind areas. Table 2 summarizes the environmental impacts of wind farms at different development stages.

4.1 Impacts of wind farm construction and operation

The growing demand for wind energy increasingly pressures lands with complex terrain and ecologically fragile regions, raising concerns over the environmental impacts of land-use and land-cover changes induced by wind power development (Miller and Keith, 2018). Building turbine facilities fragments and degrades habitats, making them unsuitable for breeding, foraging, and migration (Voigt *et al.*, 2024).

Onshore wind farm development affects terrestrial ecosystems primarily through land surface disturbance during transport, construction, and installation. Activities such as site leveling, road building, turbine transport, material storage, and transmission line construction alter surface morphology and soil structure, hinder vegetation growth, and may accelerate soil erosion.

During operation, wind farms generate noise pollution, including both mechanical and aerodynamic components. Low-frequency noise from rotating blades can disturb nearby communities and, in severe cases, threaten human health. Noise impacts decrease with distance but remain pronounced within 500 m of turbines, with higher propagation levels at night (van den Berg, 2004). Turbine blades also pose collision risks to birds, increasing mortality rates, reducing population sizes, and threatening biodiversity. Bird mortality correlates positively with hub height and varies geographically, with lower collision risks observed in plains (Loss *et al.*, 2013). Birds may collide with turbine towers, transmission facilities, and rotating turbine blades, resulting in injury or even death (Dai *et al.*, 2015). On the other hand, the construction and development of wind farms damage habitats, which affects the breeding and activities of birds (Bright *et al.*, 2008).

Bats account for a substantial proportion of wind turbine-related fatalities, making wind energy development a leading driver of bat mortality worldwide. Bats exhibit strong behavioral responses to moving objects, leading to high fatality rates within wind farm areas. Mortality increases exponentially with tower height (Voigt *et al.*, 2024). Furthermore, operating turbines generate substantial turbulence and reduce wind speeds downstream, producing wake effects that create unfavorable conditions for bat activity (Leroux *et al.*, 2024).

4.2 Effects of wind farms on vegetation and soil

Wind farm construction and operation influence both climate and ecosystems. By altering land surface properties, wind farms affect local and regional climates, which in turn feed back into ecosystem processes. Onshore wind farm development reshapes surface morphology, disrupts soil structure, reduces fertility, and alters vegetation cover.

Wind farms modify land surface properties and disturb land-atmosphere interactions, thereby affecting surface temperature and vegetation dynamics. Satellite-based studies have quantified vegetation responses to wind farms, highlighting both time lags and spatial heterogeneity. Gao *et al.* (2023) found sharp biomass declines in Chinese wind farm regions. Wu *et al.* (2023) used MODIS Normalized Difference Vegetation Index (NDVI) data from the 2001–2018 growing seasons (June–August) and found 70% of wind farms showed a trend of slowed vegetation growth. This effect intensifies as the wind farm scale expands. In spring, higher nocturnal land surface temperatures (LST) increase soil moisture and insulate against frost, favoring vegetation growth. In contrast, hot and dry summer conditions, combined with nocturnal warming and soil moisture depletion, hinder growth (Ma *et al.*, 2022). Su *et al.* (2024) used satellite remote sensing data to investigate how wind farms affect climate and vegetation in the Inner Mongolia grasslands during the growing season. They found that vegetation inside and outside wind farms follows an "inhibition inside, promotion outside" response pattern. These impacts differ across grassland types: meadow grasslands suffer the strongest inhibition on vegetation growth. Inside

wind farms, nocturnal surface temperature rises, and evapotranspiration falls—these changes inhibit vegetation growth. In contrast, vegetation growth improves in areas outside wind farm regions.

Changes in land surface properties induced by wind farms also affect local and regional climates, which subsequently alter ecosystem processes. Large-scale simulations show that positive albedo–precipitation–vegetation feedbacks in the Sahara increase precipitation by about 0.25 mm/d and vegetation cover by 0.084. Enhanced vegetation growth then further increases rainfall (Li *et al.*, 2018). By altering plant communities and productivity, wind farms indirectly modify soil physicochemical conditions, carbon and nitrogen inputs, and microbial community composition, thereby feeding back to global change (Armstrong *et al.*, 2014). Additionally, nighttime turbine operations increase CO₂ release from soils. Soils then absorb CO₂ during the daytime—this process affects soil carbon stocks (Armstrong *et al.*, 2016).

Table 2 Main impacts of wind farms on the ecological environment

Stage	Main impact sources	Main ecological and environmental impacts
Construction	Site leveling, road construction, equipment transport, and foundation excavation	Surface disturbance, vegetation loss, soil erosion, and habitat fragmentation
Operation	Turbine rotation, wake effects, and noise disturbance	Bird and bat collision mortality, altered microclimate, suppressed vegetation growth, and changed soil moisture
Maintenance	Equipment servicing, road access, wastewater, and solid waste discharge	Increased pollution risk, local habitat disturbance, and reduced ecosystem services

5 Impacts of offshore wind farms on climate and ecology

Offshore wind farm development affects the regional climate and can also play an important role in mitigating extreme weather events. Offshore wind farms can mitigate extreme weather by extracting energy from hurricanes, reducing peak wind speeds, and weakening storm surges. Arrays placed along coastlines not only lower hurricane risks but also generate substantial electricity (Jacobson *et al.*, 2014). Akhtar *et al.* (2022) used a regional climate model to assess near-surface atmospheric and air–sea flux responses to offshore wind farm deployment under the existing layout. Offshore wind farms reduced the mean 10 m wind speed by about 0.52 m/s, with local downstream reductions of about 1 m/s, and lowered air–sea heat fluxes by more than 2.0 W/m². Over the wind farm area, they increased mean precipitation by about 5% and low-cloud cover by about 0.02. They warm the air below hub height as turbulent kinetic energy declines, though the signal remains smaller than interannual variability. WRF simulations show that offshore turbines reduce hub-height wind speed by about 16%, increase turbulent kinetic energy nearly sevenfold, and raise surface wind speed by about 11% through downward momentum transport. Compared with land-based systems, offshore turbines produce stronger wake effects that alter boundary-layer structure (Fitch *et al.*, 2012).

Offshore winds are stronger and more reliable, offering high energy potential with a comparatively smaller environmental footprint (Abdullah-Al-Mahbub and Islam, 2024). Construction of offshore wind farms damages fish and algal habitats and generates intense underwater noise that disrupts benthic metabolism and behavior (Cones *et al.*, 2024). Offshore wind farms create complex ecological trade-offs. They provide shelter for fish but increase turbidity, which disrupts fish activity and degrades algal habitats. By fostering reef-like structures, they also supply food, offer refuge for marine species, and function as no-take zones (Bergström *et al.*, 2013). They also increase turbidity and block sunlight, hindering algal photosynthesis. In some cases, wind farms may enhance local biodiversity and generate spillover effects that benefit nearby ecosystems (Knorrn *et al.*, 2024). Yet turbine platforms can block sunlight, limiting photosynthesis for certain algal species.

Offshore and onshore wind farms alter local to regional wind, temperature, humidity, and fluxes by extracting momentum, reducing wind speed, and enhancing turbulent mixing, but they produce markedly different climatic and ecological responses. Onshore wind farms sit over highly heterogeneous surfaces, where topography, vegetation, soil moisture, and land use create higher background roughness and make climate responses strongly sensitive to terrain and surface cover. Offshore wind farms, by contrast, operate over smoother surfaces with greater heat capacity and stronger air–sea exchange, so they more

readily alter air-sea fluxes and marine boundary-layer structure (Seo *et al.*, 2025). Simulations show that large offshore wind farms can raise sea surface temperature by about 0.3–0.4 °C and destabilize the marine atmospheric boundary layer by enhancing upward heat fluxes. Offshore wakes also last longer than onshore wakes. Under stable stratification, they can extend 50–70 km, reduce the downstream 10 m wind speed by about 1 m/s, and increase regional mean precipitation by about 5% (Akhtar *et al.*, 2022). Ecologically, onshore systems mainly affect vegetation, soils, birds, and bats, whereas offshore systems more strongly affect benthic organisms, fish, seabirds, and marine mammals, and introduce artificial reefs, noise, and electromagnetic-field effects (Watson *et al.*, 2024). Existing evidence shows that offshore wind farms cause mainly negative ecological effects during construction, while operational effects are more mixed, and many ecosystem-service impacts remain poorly constrained.

6 Conclusions and outlook

6.1 Conclusions

This study offers a comprehensive assessment of wind farm impacts on climate and ecosystems. It synthesizes prior findings and introduces new perspectives to analyze effects at local, regional, and global scales. Turbines directly change wind speed and turbulence. By enhancing vertical mixing, wind farms alter surface-atmosphere heat exchange and reshape boundary-layer structure. These shifts modify near-surface meteorology and can cascade to larger scales. The mechanisms of local climatic impacts include (1) turbines converting wind energy into electricity, extracting kinetic energy from the atmosphere, and reducing downstream wind speed, with attenuation effects diminishing with distance. (2) Turbine operation enhances turbulent kinetic energy, modifies sensible and latent heat fluxes, and alters near-surface temperature and humidity. (3) Increased surface roughness and wake-induced disturbances modify turbulent energy and water-vapor transport within the boundary layer.

At larger scales, wind farms affect the climate in several ways: (1) They alter large-scale circulation and reduce atmospheric energy, shifting meridional winds, surface temperature, energy budgets, and radiative balance. (2) They enhance turbulent transport of sensible and latent heat, affecting surface temperature. (3) They heat land by more than 1 °C and cool oceans by over 1 °C, thereby reorganizing global precipitation and cloud distributions, especially low clouds.

Ecological impacts extend to soil, plants, and animals, and vary by project stage: (1) during construction, wind farm development disturbs soil structure, alters landforms, induces erosion, and modifies vegetation distribution. (2) The operation generates noise and increases bird and bat mortality via blade strikes. (3) Maintenance can introduce pollution if wastewater and construction debris are poorly managed.

In sum, wind farms influence climate and ecosystems. Figure 2 summarizes these impacts.

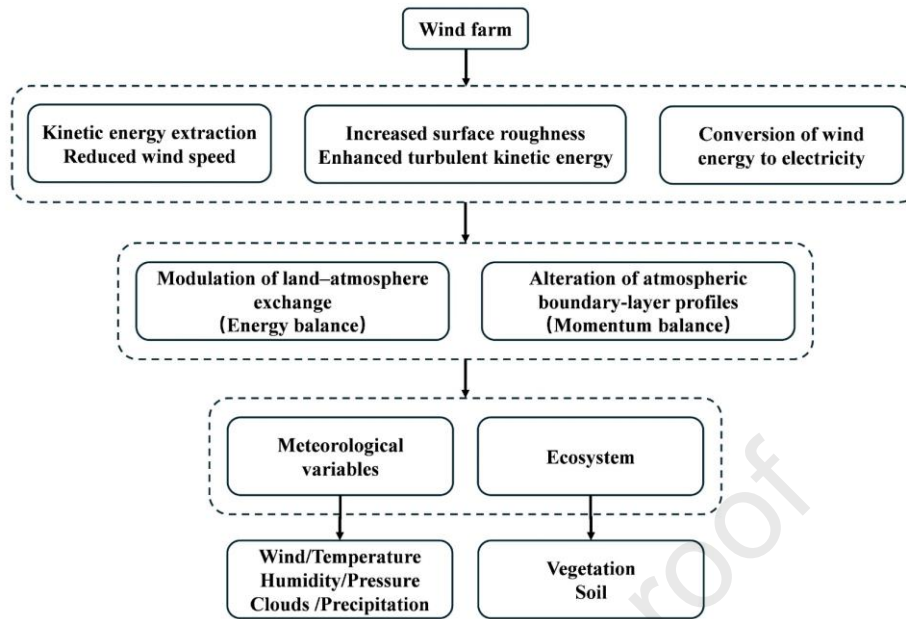


Fig. 2. Mechanisms of wind farm impacts on climate and ecology

6.2 Outlook

On a larger scale, wind farm deployment alters surface characteristics, and turbines may emerge as a major driver of anthropogenic land-use change in the future. Understanding wind farm–atmosphere interactions and evaluating their potential climatic and ecological impacts holds significant societal relevance (Zhou, 2012; Zhou *et al.*, 2012). Previous studies synthesize multi-scale methods to assess wind-farm climate and ecological effects, from local to regional and global scales. These studies broadly agree that wind farms extract momentum and enhance turbulence, which changes atmospheric boundary-layer (ABL) stability. As a result, wind farms reshape land–atmosphere exchange and modify near-surface meteorological conditions. Observations and models often show nighttime warming over wind-farm regions and daytime cooling, with stronger nighttime warming in summer than in winter. Some studies also report increased precipitation. Overall, wind-farm–induced climate perturbations remain far smaller than the warming driven by CO₂ emissions.

First, studies still report clear differences in effect direction, magnitude, and spatial extent. These inconsistencies show that wind farm climate–ecology effects do not remain constant. Surface type, boundary-layer stability, wind farm size and layout, observation period, and methodological scale all shape them. Future research should strengthen quantitative attribution and move from single meteorological responses to integrated climate–ecology assessments. Such work can guide turbine deployment and quantify how wind farms interact with climate and vegetation dynamics, thus supporting both wind energy development and ecological sustainability (Yang *et al.*, 2023).

Second, growing evidence shows that wind farms alter not only local wind, temperature, and humidity, but also evapotranspiration, soil moisture, vegetation growth, and carbon cycling, thereby generating ecological feedbacks. These findings can directly support more targeted wind farm layout optimization and more ecologically sustainable development (Dong *et al.*, 2026). Future studies may focus on developing integrated assessment models to quantify the multi-dimensional impacts of wind farms under diverse climatic contexts. By incorporating sustainability indicators, such models can evaluate environmental, economic, and social benefits, offering a critical tool to decode the complex “green energy–climate–ecosystem” nexus.

The development of renewable energy, including solar and wind, represents an effective strategy for strengthening energy security and reducing greenhouse gas emissions. However, the deployment of renewable energy in climatically and ecologically fragile regions poses significant challenges and requires particular attention to environmental compatibility. Thus, integrated renewable energy

development models should be applied to simulate, assess, and strategically plan the impacts of wind power deployment on local climate and ecosystems, especially in ecologically vulnerable areas. China must accelerate the construction of large-scale wind and photovoltaic bases, capitalizing on the abundant wind and solar resources in northwestern deserts, Gobi, and arid regions. This requires optimizing land use and promoting intensive large-scale renewable energy development. In ecologically sensitive areas of Northwest China, strategies such as establishing shelterbelts, grass planting, and soil stabilization, as well as ecosystem protection and restoration, can help reconcile the expansion of renewable energy with ecological protection.

CRedit authorship contribution statement

XiaoQing Gao: Writing - review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. Yi Han: Writing - review & editing, Project administration, Funding acquisition. Jiang Ying: Writing - Reviewing and Editing. ZhiMin Yang: Writing - Reviewing and Editing. Pin Zhang: Writing - review & editing, Writing - original draft, Resources, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of interests

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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