Microclimatic impacts of wind farm: Reduced diurnal temperature range

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Dear Editor,

China currently leads the wind energy deployment, contributing to 43% of the global installed capacity in 2023. According to the World Wind Energy Association (WWEA), the cumulative installed wind energy capacity in China increased from 0.4 gigawatts in 2001 to 441 gigawatts by 2023 (wwindea.org). Wind farms produce clean energy to reduce reliance on fossil fuels and their associated emissions. However, the wake turbulence generated by turbine blades alter heat gradients in the atmospheric boundary layer, thereby affecting the regional land surface temperature (LST).[1] With China's easily developable wind and solar sites nearing saturation, renewable energy deployment is extending into remote high-altitude regions like the Tibetan Plateau.[2] The Tibetan Plateau hosts abundant wind energy resources but is characterized by ecologically fragile and highly climate-sensitive environments.[3] Its unique atmospheric boundary layer, shaped by intense solar radiation and high surface elevation, differs fundamentally from that of low-altitude regions. These distinctive conditions likely give rise to region-specific climatic and ecological responses to wind farm operations.[4] Therefore, understanding the potential impacts of wind farms on LST is crucial before proceeding with large-scale deployment on the Tibetan Plateau in the coming decades.

To address this scientific question, we evaluated the impact of a wind farm on LST in the Qaidam Basin (see Datasets, Figure S1), one of the most wind-rich regions in the Tibetan Plateau, where wind farm construction is rapidly expanding. In previous studies, the LST effects of wind farms are typically quantified by comparing long-term trends between wind farm areas and reference sites across pre- and post-construction periods.[1,5] However, a key characteristic of wind farm impacts is their intermittency, as climate effects primarily occur during turbine operation. In fact, Supervisory Control and Data Acquisition (SCADA) records indicate that approximately half of the data points correspond to periods with low capacity factors (Figure S2). Consequently, methods that average over both operational and idle periods likely underestimate the instantaneous and peak magnitudes of these effects. In this study, we provide a more robust method to evaluate the wind farm impacts on LST, which considers the turbine operational periods and capacity factor. The operational period refers to the time during which the wind farm is actively generating electricity, and the capacity factor is calculated as the output power and the rated power of turbines, which could represent the turbulence strength created by the wind farm. These key variables may determine the magnitude of the wind farm impacts on LST, however, they are usually ignored in previous studies due to data limitation.[5] In this study, we integrated LST observations from the MODIS (Moderate-resolution Imaging Spectroradiometer) Aqua and Terra satellites to assess the impact of wind farms on LST (ΔLST) based on their operational status (see Methods). Using capacity factors obtained from the wind farm's SCADA system, we examined whether the magnitude of the impacts increased with higher capacity factors. By incorporating wind direction and air temperature data collected at multi-levels in boundary layer from local meteorological stations, we further explored the underlying mechanisms driving the ΔLST patterns by the wind farm.

SPATIAL PATTERNS OF THE IMPACTS OF WIND FARM ON LST

We analyzed the spatial patterns of ΔLST under high operational conditions, defined by capacity factors exceeding 0.5, along with the prevailing wind direction. The results revealed markedly different impacts on LST between daytime and nighttime. During the day, the wind farm induced a cooling effect of approximately 3°C within the central region (Figure 1A), whereas at night, it led to a warming effect of around 0.4°C in the same area (Figure 1B). Interestingly, the magnitude of the wind farm's impact on LST along the downwind direction was not uniform. The strongest effects were observed within 0–2 kilometers downwind, with a cooling of about 4°C during the day and a warming of 1.3°C at night. Furthermore, both the cooling and warming effects diminished significantly beyond 5 kilometers downwind. The results indicate that the wind farm reduced regional diurnal temperature range on the Tibetan Plateau, reaching up to -5°C in the most affected downwind area. Compared with methods that ignore operational status, incorporating capacity factor data reveals substantially stronger LST changes—typically several times greater than the ΔLST derived from pre- and post-construction averaging (Figure S3).

IMPACTS OF WIND FRAM ON LST UNDER DIFFERENT OPERATIONAL LEVELS

The use of capacity factor data enables a more detailed assessment of ΔLST variability under different wind farm operating levels. The results showed that the wind farm's daytime cooling and nighttime warming effects both intensified with increasing capacity factor. Notably, the most pronounced ΔLST trends were observed within the 0-2 km downwind area, reaching -0.38°C per 0.1 increase in capacity factor ($p < 0.05$) during the daytime (Figure 1C), and 0.35°C per 0.1 increase in capacity factor ($p < 0.05$) during the nighttime (Figure 1D). In the 0-2 km downwind area, when the wind farm operates at a very high level (capacity factor > 0.8), the impact on diurnal temperature range can reach approximately -8°C, with about 4°C of cooling during the day and a similar magnitude of warming at night. Beyond the 5 km downwind area, these ΔLST trends became statistically insignificant. These findings offer new evidence that the impact of wind farms on LST varies with capacity factor, which primarily modulates the intensity of turbine-induced wake turbulence.

DRIVING PROCESSES OF THE IMPACTS OF WIND FARM ON LST

To elucidate the contrasting daytime and nighttime impacts of wind farms on LST, we examined atmospheric boundary layer stability, a key factor governing ΔLST.[6] The stability of the atmospheric boundary layer depends on the relationship between the environmental lapse rate (γ, the rate of temperature changes with altitude in the ambient atmosphere) and the dry and moist adiabatic lapse rates. When the environmental lapse rate is higher than the dry adiabatic lapse rate ($\gamma > \gamma_d$), the atmospheric stratification is considered absolutely unstable. Conversely, when the environmental lapse rate is lower than the moist adiabatic lapse rate ($\gamma < \gamma_m$), depending on temperature and humidity, the atmospheric stratification is deemed absolutely stable. Wind farm operation enhances turbulence kinetic energy and reduces wake zone wind speed. Through turbulence-driven vertical mixing, it modifies land surface temperature (Figure S4). Whether this process results in surface warming or cooling depends on the stability of the atmospheric boundary layer.[7]

Based on observational lapse rates of air temperature from a nearby meteorological tower, we found that the boundary layer was unstable during the MODIS daytime observation periods (10:30 AM for Terra and 1:30 PM for Aqua), with measured lapse rates of 1.55°C 100 m^{-1} and 2.07°C 100 m^{-1}, respectively—both significantly higher than the dry adiabatic lapse rate (0.98°C 100 m^{-1}) (Figure 1E). An unstable boundary layer is usually character-

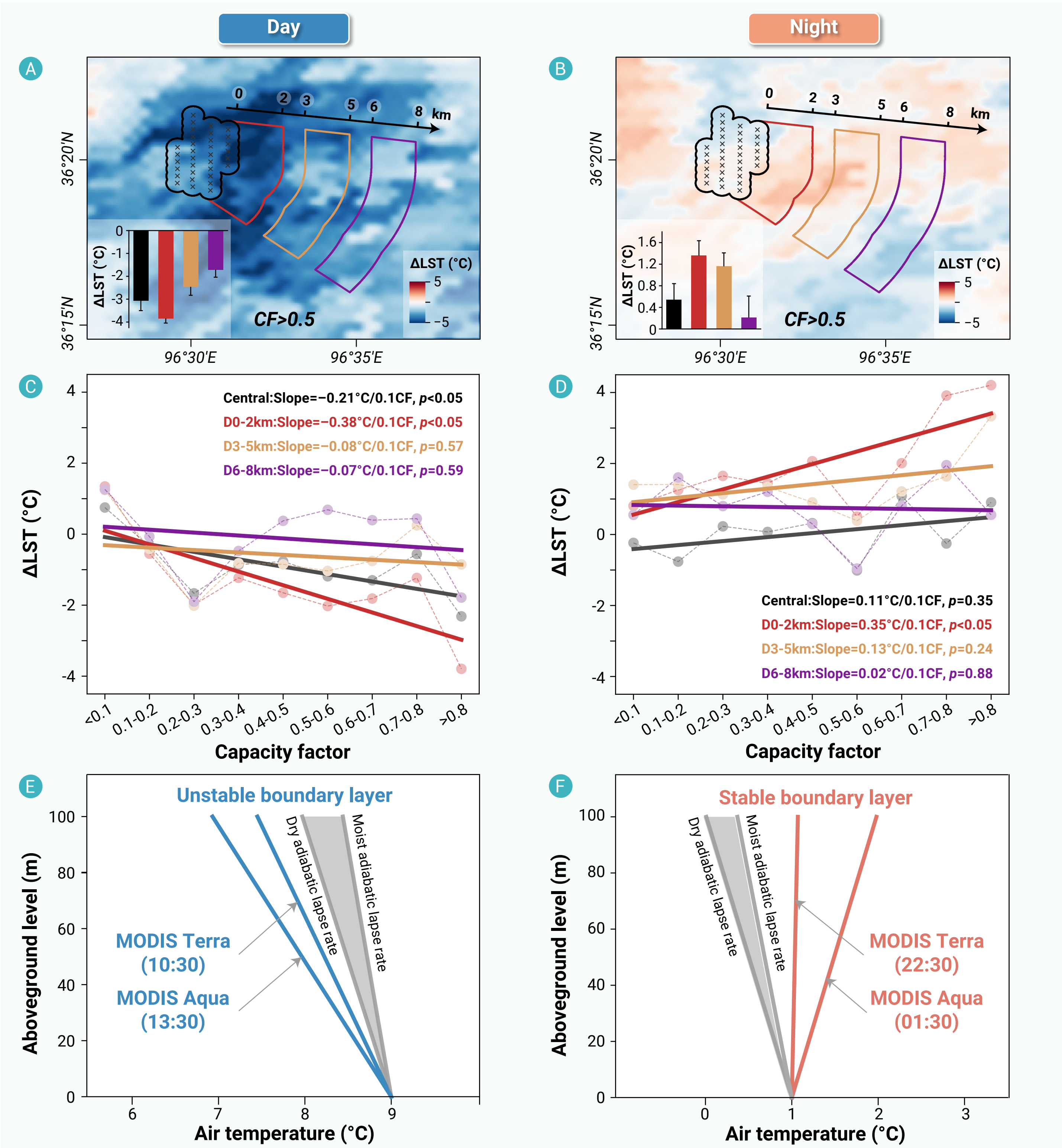

Figure 1. The observed impacts and underlying mechanisms of wind farm effects on land surface temperature A and B, spatial distribution of ΔLST (impacts of wind farm on land surface temperature) during the daytime and nighttime under high operational conditions, defined by capacity factors exceeding 0.5, along with the prevailing wind direction. The insets in A and B represent the averaged ΔLST in the wind farm and downwind areas. C and D, changes and trends of averaged ΔLST in the wind farm and downwind areas with increasing capacity factor levels during the daytime and nighttime. In C and D, Central, D0-2km, D3-5km, and D6-8km represent central area of the wind farm and the downwind areas at distances of 0-2, 3-5, and 6-8 kilometers, respectively. E and F, day and night lapse rates recorded by the meteorological tower adjacent to the wind farm. The plots compare the theoretical dry adiabatic lapse rate, the moist adiabatic lapse rate, and the observed lapse rates from the meteorological tower during daytime and nighttime.

ized by a decrease in air temperature with increasing height above the ground. The turbine-induced wake turbulence can alter vertical heat distribution in the atmospheric boundary layer, bringing cooler air from higher layer down to the near surface and ultimately reducing near-surface temperatures. In contrast, a stable boundary layer was observed during the MODIS nighttime observation periods (10:30 PM for Terra and 1:30 AM for Aqua), with lapse rates of -0.07°C 100 m^{-1} and -0.98°C 100 m^{-1}, respectively—both significantly lower than the saturated adiabatic lapse rate (0.63°C 100 m^{-1}) (Figure 1F). A stable boundary layer is usually characterized by increasing temperature with height above the ground. This inversion structure inhibits vertical mixing, causing colder air to be trapped near the surface while warmer air remains aloft in the upper layer. Operating wind turbines can transport warmer air from the upper layer down to the near surface, thereby increasing near-surface temperatures. From a seasonal perspective, higher daytime lapse rates during spring and summer correspond to stronger cooling, while lower nighttime lapse rates in autumn and winter amplify the warming effect (Figure S5). These observed evidences can deepen our understanding of the physical processes underlying the ΔLST, and also provide a robust benchmark for wind energy modules in the Weather Research and Forecasting (WRF) model.[8]

IMPLICATION AND FUTURE WORK

Our results demonstrate that large wind farms can significantly influence local LST, producing opposite effects during the day and night, and ultimately reducing the diurnal temperature range. Our methodology underscores the value of integrating long-term satellite observations and meteorological data with detailed wind farm records (e.g., operational periods and capacity factors) to more accurately understand the mechanisms of ΔLST by turbine-induced weak turbulence (Figure S6). These findings underscore the need to integrate wind farms' regional climatic effects into the initial planning of wind energy projects, offering a valuable reference for assessing ecological impacts in the climate-sensitive ecosystems of the Tibetan Plateau. Given the substantial differences in assessment outcomes when capacity factor data are incorporated, we emphasize the need for openly accessible capacity factor data from a broader range of wind farms on the Tibetan Plateau and other ecologically sensitive regions. Such data are critical for improving models such as WRF and for accurately evaluating climate effects to inform environmentally responsible wind farm planning.

In supporting China's "dual carbon" goals of peaking emissions and achieving carbon neutrality, it is essential that wind power growth in these frontier areas proceeds in a way that safeguards the Tibetan Plateau's delicate environment. Future research should leverage coupled climate–ecosystem models to explore the broader impacts of large-scale wind development on the plateau's climate and ecology.[9] High-resolution regional simulations (for example, using WRF model with wind energy modules) can examine how turbine arrays interact with atmospheric boundary-layer stability and permafrost processes, enabling scenario testing to optimize site selection and farm design for minimal environmental footprint.[10] Such forward-looking analyses will be essential for guiding the sustainable expansion of renewable energy in the Tibetan Plateau region. By marrying ambitious clean energy deployment with rigorous environmental stewardship, large-scale wind development can contribute to national climate targets while preserving the stability of ecosystems and permafrost in the "Third Pole" region for generations to come.

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AUTHOR CONTRIBUTIONS

D. Wu designed the study, D. Wu and N. Liu drafted the paper, N. Liu and Y. Zhou performed the analyses. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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