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Mesoscale Enhancements in Lightning Density Near Isolated Wind Farms

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Key points

- Isolated wind farms are associated with mesoscale enhancements in lightning density.
- Lightning density near isolated wind farms is elevated within ~ 80 km and decays smoothly with distance.
- The elevated density extends for tens of kilometers, well beyond the expected scale of turbine attachment effects.

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Abstract

Lightning-turbine interactions have primarily been studied at local scales, yet wind farms span tens of kilometers and interact collectively with the lower atmosphere. Using six months (May–October 2025) of Geostationary Lightning Mapper (GLM) observations from GOES-19, we examine whether wind farms are associated with mesoscale differences in lightning density. Lightning within 150 km of isolated wind farms is compared with matched turbine-free control regions selected to have similar background lightning density. Radial profiles of flash and group density are computed for each site and compared using matched-pair differences relative to normalized baselines. Lightning density near isolated wind farms is elevated relative to controls, with isolated-minus-control differences reaching approximately 20–55% of background levels within the innermost ~ 10 km. The enhancement persists over the inner ~ 80 km and decreases smoothly with distance, indicating systematic mesoscale enhancement of lightning density near isolated wind farms.

1 Introduction

Modern wind-power installations represent some of the largest engineered structures interacting with the lower atmosphere. As wind-energy infrastructure has expanded over the past two decades, the growing spatial footprint of wind farms raises a question about their influence on nearby thunderstorms.

Field and laboratory measurements have shown that wind-turbine components become electrically polarized under ambient atmospheric electric fields, leading to enhanced local electric fields and, under some conditions, corona discharge, even in fair weather (Rison et al., 2015; Fontanes et al., 2022). Observational studies further demonstrate that corona discharge from rotating turbine blades can initiate upward leaders under strong vertical electric fields (Montanyà et al., 2014). Statistical analyses of cloud-to-ground lightning indicate that lightning occurrence is significantly enhanced within a few hundred meters of wind turbines (Soula et al., 2019), as in general for tall towers (Kingfield et al., 2017). More recently, Said et al. (2025) showed that the effective lightning collection area of wind turbines scales with blade-tip height.

Together, these studies demonstrate turbine-related lightning effects confined to the immediate vicinity of individual turbines. However, the potential for distributed mesoscale effects associated with the cumulative influence of turbine arrays has not been directly examined. The kilometer-scale array of tall structures comprising a wind farm can perturb the atmospheric boundary layer by increasing turbulent mixing, altering boundary-layer stability and depth, and modifying surface heat fluxes (Lu & Porté-Agel, 2015; Fitch et al., 2012). The collective presence of many turbines therefore raises the possibility that storms passing near wind farms experience altered electrical environments that influence lightning density beyond the immediate vicinity of individual turbines.

Previous studies have not tested this possibility using satellite observations. Here, observations from the Geostationary Lightning Mapper (aboard GOES-19) are used to examine lightning patterns near isolated wind farms. By comparing radial lightning density around isolated wind farms with matched turbine-free control regions, we test whether wind farms are associated with mesoscale differences in lightning density.

2 Data and Methods

The dataset for this study consists of Level-2 GLM flash and group products from GOES-19 (Goodman et al., 2013) spanning 1 May through 31 October 2025. Wind turbine locations are taken from the U.S. Wind Turbine Database version 8.0. Turbines are clustered into wind farms using the DBSCAN algorithm (Ester et al., 1996) with a 10 km neighborhood radius and a minimum cluster size of ten turbines. For each cluster, a con-

vex hull is constructed around the turbine locations and expanded by a 10 km buffer to merge nearby turbine groups and define a contiguous farm footprint. A farm is classified as isolated if every point of its buffered hull lies at least 150 km from any point on the hull of its nearest neighboring farm. This ensures spatial separation between analysis sites.

Six isolated wind farms and six turbine-free control locations were chosen for this analysis. They are distributed across the contiguous United States (Figure 1). Control sites are selected from regions with no utility-scale turbines.

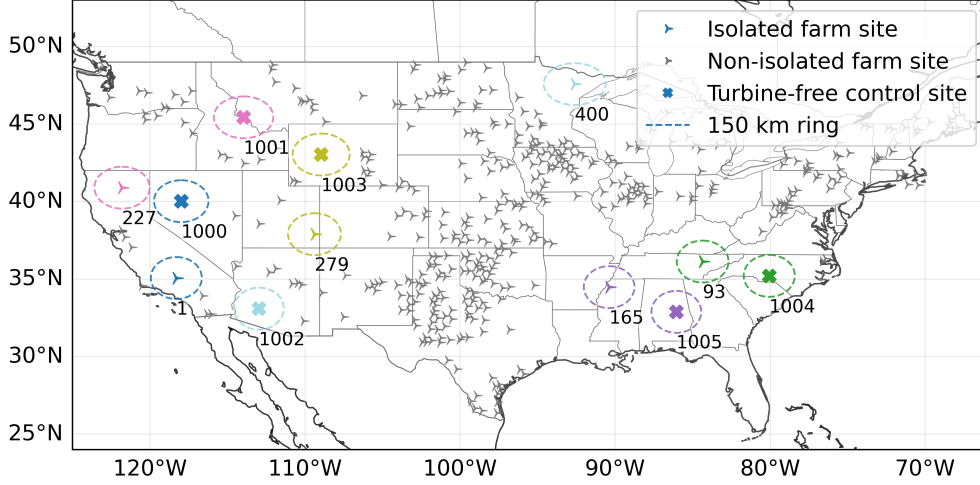


Figure 1. Locations of isolated wind farms and their matched turbine-free control sites colored by matched pairs. Non-isolated wind farms are shown in gray for context. Dashed circles indicate the 150 km analysis domains. Each site has a unique index.

For each site, a circular analysis domain with radius 150 km was subdivided into concentric annuli of width 10 km. Lightning density is computed as the number of flashes or groups per unit area within each annulus (counts per km²). Geometric sampling effects inherent to ring-based analyses are assumed to be similar across isolated and control sites and are greatly reduced when the isolated-minus-control difference is taken.

To control for differences in regional lightning density, each site’s radial density profile is normalized by its own far-field background density, computed from lightning activity observed between 100 and 150 km from the site centroid. The far-field background density is defined as the total number of flashes or groups within this outer region divided by its total area.

Let $\rho(r)$ denote the lightning density (flash or group counts per km²) within each annulus at radius r , and let ρ_{bg} denote the corresponding site-specific far-field background density. A dimensionless normalized density is defined as

$$\rho^*(r) = \frac{\rho(r)}{\rho_{bg}}. \quad (1)$$

Ring densities are computed at the site level and normalized by each site’s far-field background density. Each isolated wind farm is paired one-to-one with a turbine-free control site using a matching procedure that minimizes absolute differences in far-field background density, with each control site used once (Figure 1).

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Matched-pair differences of the normalized densities are computed ring-by-ring as

$$\Delta\rho_i^*(r) = \rho_{\text{iso},i}^*(r) - \rho_{\text{ctl},i}^*(r). \quad (2)$$

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For each annulus, these differences are averaged across the N matched site pairs to obtain the pooled mean difference $\overline{\Delta\rho^*}(r)$ and its associated standard error $\sigma_{\overline{\Delta\rho^*}}(r)$, which reflects variability across site pairs. Standardized effect sizes are then defined as

$$Z(r) = \frac{\overline{\Delta\rho^*}(r)}{\sigma_{\overline{\Delta\rho^*}}(r)}. \quad (3)$$

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In this context, Z quantifies how consistently the isolated-control contrast is observed across independent site pairs: values of $|Z| \approx 1$ indicate that the pooled difference is comparable to inter-site variability, whereas values near or above $|Z| = 2$ indicate a consistent effect across sites rather than one driven by a small number of outliers. All analyses were performed using custom Python software developed for this study, which is available through Zenodo (Reger, 2026).

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3 Results

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Figure 2 shows pooled matched-pair differences ($\overline{\Delta\rho^*}$) in normalized lightning density as a function of distance from isolated wind farms. Both flash and group densities are systematically higher near isolated wind farms than at matched turbine-free control sites. Within the innermost ~ 10 km, isolated-minus-control differences reach approximately 20–55% of the site background density for flashes and groups.

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The density enhancement decreases smoothly with increasing distance from the site centroid. The ± 1 standard error (SE) bands intersect zero at approximately 80 km for both metrics, providing an uncertainty-based estimate of the radial scale over which the enhancement remains distinguishable from background. Standardized effect sizes are close to $Z = 2$ out to ~ 75 km for both metrics, indicating that the enhancement is consistently observed across independent matched-site pairs over those radii. These results demonstrate that on average, lightning density near isolated wind farms is elevated, and the elevation persists over mesoscale distances.

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4 Discussion and Conclusions

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The density profiles provide consistent evidence that lightning patterns differ systematically near isolated wind farms. Storms passing near isolated farms exhibit higher lightning density than storms sampled at matched turbine-free control regions, with enhancements that decay smoothly over tens of kilometers.

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The spatial scale of the observed enhancement differs fundamentally from the turbine-scale effects documented in previous studies. For example, Soula et al. (2019) quantified changes in cloud-to-ground lightning density within 500 m of turbine structures, consistent with local attachment and initiation effects. In contrast, the present analysis identifies systematic lightning density enhancements extending tens of kilometers from isolated wind farms, indicating a phenomenon operating on storm-scale spatial extents. It should be noted that the diameter of all but one wind farm is < 20 km.

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One plausible explanation for the observed mesoscale enhancement is that wind turbines act as preferred lightning initiation sites that tap into extensive, pre-existing storm-scale charge regions (Stolzenburg et al., 1998). Tower-initiated lightning has been observed to initiate at tall structures and subsequently propagate tens of kilometers as flashes develop through large charge reservoirs within storms (Steiger et al., 2024). In this view, turbines focus lightning activity by providing initiation points that preferentially access storm-scale charge. However, the persistence of elevated lightning density

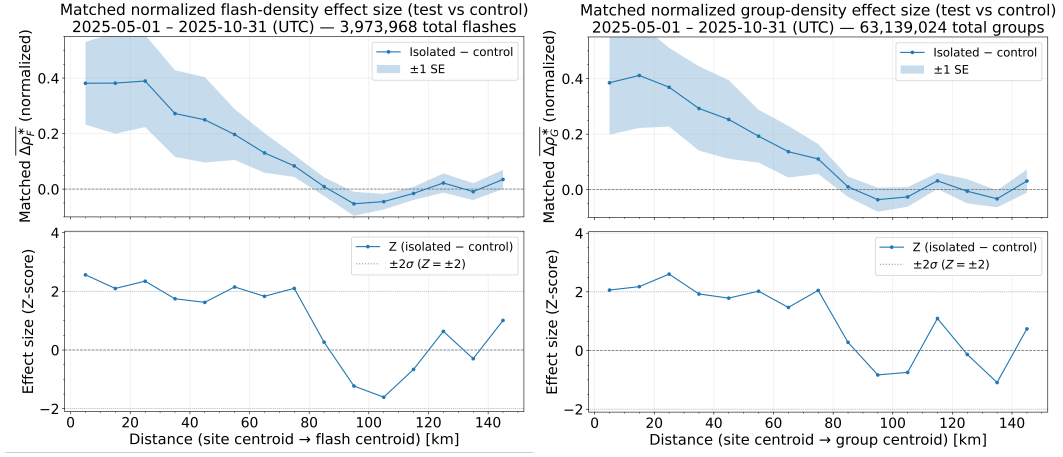


Figure 2. Matched-pair differences in normalized lightning density ($\overline{\Delta\rho^*}$) around isolated wind farms relative to turbine-free control sites for flashes (left) and groups (right). Upper panels show pooled isolated-minus-control differences as a function of distance from the site centroid, with shaded regions denoting ± 1 SE across matched pairs. Lower panels show corresponding standardized effect sizes (Z); dotted lines indicate $Z = \pm 2$.

tens of kilometers away from the wind farm is difficult to reconcile with attachment-based mechanisms alone, which primarily influence where lightning initiates rather than how lightning activity is distributed across storm-scale regions.

A potential alternate pathway involves wind-farm-induced modifications to the atmospheric boundary layer. Wind farms have been shown to alter near-surface turbulence, heat fluxes, and flow structure (Lu & Porté-Agel, 2015). Numerical modeling studies indicate that such modifications can extend tens of kilometers beyond the turbine array (Fitch et al., 2012). Prior work has shown that turbulence can influence lightning density within storms (Bruning & MacGorman, 2013). Together, these results suggest that boundary-layer modifications represent a plausible mechanism that may modulate lightning activity on mesoscale distances. The consistency of elevated lightning density near isolated farms—reflected in Figure 2—indicates that the observed differences are *not* artifacts of regional climatology or site selection.

These results also have implications for lightning risk management and for understanding anthropogenic influences on thunderstorms. For the wind-energy industry, elevated lightning density within tens of kilometers of isolated wind farms suggests that lightning-interaction risk may extend well beyond turbine footprints, with potential relevance for surrounding infrastructure.

The presence of elevated lightning density near multiple isolated farms raises a natural question: to what extent might the combined footprint of many adjacent wind farms influence regional lightning patterns? Addressing this question will require targeted observational and modeling studies, but the present results provide a quantitative foundation for such efforts.

Together, these results demonstrate that wind-farm installations are associated with mesoscale modifications to lightning density detectable from geostationary orbit. The identification of density enhancements near multiple isolated sites highlights the sensitivity of lightning processes to large engineered surface features. Future work combining satellite-based lightning observations with radar, lightning mapping array, and nu-

merical modeling will be required to identify the physical pathways responsible for these mesoscale effects.

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Data Availability

Geostationary Lightning Mapper data were obtained from the NOAA open-data archive on Amazon Web Services (<https://registry.opendata.aws/noaa-goes/>).

Wind farm locations were obtained from the U.S. Wind Turbine Database (USWTDB v8.0; <https://energy.usgs.gov/uswtdb/data/>).

Competing Interests

The authors declare no competing interests.

AI Disclosure

Portions of the text and code used in this study were developed with the assistance of generative AI tools. These tools were used solely for editing, formatting, and coding support. Code validation, scientific analyses, interpretation of results, and conclusions are the responsibility of the authors.

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