

Supplementary Material

Rain-time operation, not rainfall alone, sets wind turbine blade rain-erosion exposure: synchronized disdrometer and SCADA measurements

All analyses use the common window ending 21 July 2026 23:50 local time (the Jiangsu export endpoint). Guangxi contributes 961 QC-matched rain–SCADA intervals (of 967 within-window liquid-rain intervals) and Jiangsu 609 (of 609). Statistics in Tables S1–S3 and Fig. S2 are computed on these common-window intervals.

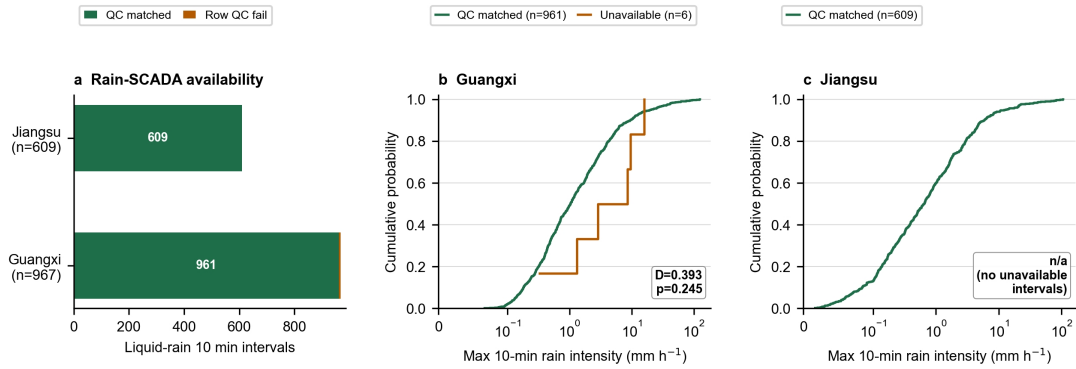


Fig. S1. SCADA availability and Kolmogorov–Smirnov comparison of rain intensity. Farm-median SCADA state against every liquid-rain timestamp in the common window, and a two-sample Kolmogorov–Smirnov (KS) test of 10 min interval-maximum rain intensity between matched and unavailable intervals (Guangxi: $D = 0.393$, $p = 0.245$, $n = 961$ vs 6; Jiangsu: none unavailable, KS test not applicable).

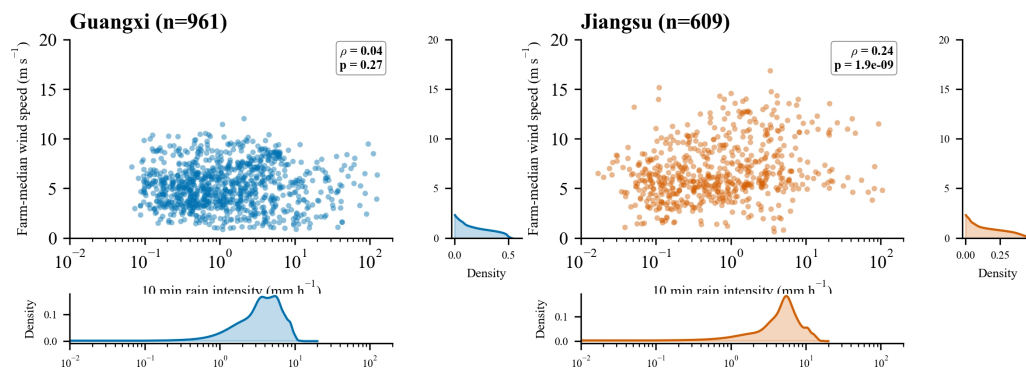


Fig. S2. Joint distribution of rain intensity and farm-median wind speed Scatter with marginal densities of 10 min rain intensity and farm-median wind speed for common-window QC-matched rain intervals (Guangxi $n = 961$; Jiangsu $n = 609$). Spearman $\rho = 0.036$ ($p = 0.271$) in Guangxi and $\rho = 0.240$ ($p = 1.9 \times 10^{-9}$) in Jiangsu.

Table S1. Key metrics in the common and full observation windows

Metric	Guangxi (Tengxian)		Jiangsu (Guanyun)	
	Common window (to 21 Jul 2026)	Full window (to 31 Jul 2026)	Common window (to 21 Jul 2026)	Full window (to 31 Jul 2026)
Valid rain intervals in window (n)	967	1076	609	717
QC-matched rain–SCADA intervals (n, %)	961 (99.38%)	1069 (99.35%)	609 (100.0%)	609 (84.94%)
QC-matched rain duration (h)	160.17	178.17	101.50	101.50
QC-matched liquid rainfall (mm)	508.83	607.53	242.07	242.07
Median wind speed (m s^{-1})	5.11	4.96	6.08	6.08
Median tip-reference speed (m s^{-1})	67.58	66.39	79.17	79.17
Median grid-side active power (kW)	555.1	505.3	1005.9	1005.9
E_{90} , all valid rain intervals	0.1413	0.170	0.0656	0.0712
E_{90} , QC-matched intervals	0.1404	0.169	0.0656	0.0656
E_{SCADA}	0.0251	0.0297	0.0311	0.0311
95% percentile-bootstrap CI	[0.0194, 0.0321]	[0.0230, 0.0373]	[0.0216, 0.0442]	[0.0216, 0.0438]

Note. The common window ends at the Jiangsu SCADA export endpoint (21 July 2026, 23:50 local time); the full window extends the disdrometer record to 31 July 2026. “Valid rain intervals” are all liquid-rain intervals in the stated window; “QC-matched” intervals also have a valid farm-median SCADA state at that same 10 min timestamp; duration, rainfall and median operating variables refer to these. E_{90} uses a fixed 90 m s^{-1} reference tip speed (all-valid or QC-matched); E_{SCADA} uses the observed interval-specific tip-reference speed. CIs are 95% percentile bootstrap intervals (10,000 resamples of QC-matched intervals). The 108 of the 717 Jiangsu intervals beyond the export endpoint cannot be QC-matched, so only the all-valid E_{90} changes there; the small gap between the Jiangsu CI upper bounds (0.0442 vs 0.0438) reflects the shared seeded bootstrap stream (Table 4 note, main text).

Table S2. Mann–Whitney U tests and Cohen’s d for non-rain versus rain-time SCADA state

Site	Variable	Non-rain median	Rain-time median	U	p	Cohen’s d	n (non-rain)	n (rain-time)
Guangxi	Wind speed (m s ⁻¹)	3.663	5.113	2057722	<0.001	-0.802	6830	961
Guangxi	Rotor-speed channel (rpm)	5.988	7.822	2285899	<0.001	-0.454	6830	961
Guangxi	Tip-reference speed (m s ⁻¹)	51.728	67.577	2285899	<0.001	-0.454	6830	961
Guangxi	Grid-side active power (kW)	288.788	555.150	2343063	<0.001	-0.703	6830	961
Jiangsu	Wind speed (m s ⁻¹)	4.639	6.081	1711846	<0.001	-0.748	8772	609
Jiangsu	Rotor-speed channel (rpm)	7.964	9.164	1814856	<0.001	-0.479	8772	609
Jiangsu	Tip-reference speed (m s ⁻¹)	68.804	79.171	1814856	<0.001	-0.479	8772	609
Jiangsu	Grid-side active power (kW)	335.453	1005.946	1743905	<0.001	-0.699	8772	609

Note. Variables are farm-median values over quality-controlled SCADA records in the common window; the non-rain group excludes the QC-matched rain intervals, so the groups are disjoint. Cohen’s d = (mean(non-rain) – mean(rain-time))/pooled SD, so negative values indicate higher rain-time medians. Results describe co-occurrence, not causation.

Table S3. Sensitivity of the number of rain intervals to event-flag rule, diameter lower bound and logger-intensity threshold

Site	Sensitivity family	Rule	Diameter lower bound (mm)	Logger intensity threshold (mm h ⁻¹)	Rain 10 min intervals
Guangxi	Event flag / completeness	Spectrum liquid positive	0.20	0	967
Guangxi	Event flag / completeness	Logger rain positive	0.20	0	967
Guangxi	Event flag / completeness	Both positive	0.20	0	967
Guangxi	Event flag / completeness	Two records + spectrum positive	0.20	0	967
Guangxi	Diameter lower bound	Spectrum liquid positive	0.20	0	967
Guangxi	Diameter lower bound	Spectrum liquid positive	0.57	0	965
Guangxi	Diameter lower bound	Spectrum liquid positive	0.69	0	953
Guangxi	Diameter lower bound	Spectrum liquid positive	0.82	0	913
Guangxi	Logger intensity threshold	Logger intensity > threshold	0.20	0.00	967
Guangxi	Logger intensity threshold	Logger intensity > threshold	0.20	0.05	967
Guangxi	Logger intensity threshold	Logger intensity > threshold	0.20	0.10	947
Jiangsu	Event flag / completeness	Spectrum liquid positive	0.20	0	609
Jiangsu	Event flag / completeness	Logger rain positive	0.20	0	609
Jiangsu	Event flag / completeness	Both positive	0.20	0	609
Jiangsu	Event flag / completeness	Two records + spectrum positive	0.20	0	609
Jiangsu	Diameter lower bound	Spectrum liquid positive	0.20	0	609
Jiangsu	Diameter lower bound	Spectrum liquid positive	0.57	0	604
Jiangsu	Diameter lower bound	Spectrum liquid positive	0.69	0	585
Jiangsu	Diameter lower bound	Spectrum liquid positive	0.82	0	557
Jiangsu	Logger intensity threshold	Logger intensity > threshold	0.20	0.00	609
Jiangsu	Logger intensity threshold	Logger intensity > threshold	0.20	0.05	589
Jiangsu	Logger intensity threshold	Logger intensity > threshold	0.20	0.10	530

Note. The default configuration (0.20 mm diameter lower bound, spectrum-liquid-positive event rule, no logger-intensity threshold) gives 967 intervals in Guangxi and 609 in Jiangsu within the common window. Each family varies one parameter at a time on the common-window 10 min rain records.

Table S4. Parameters, symbols and sources of the observed-period exposure framework

Category	Parameter/symbol	Meaning	Value	Source
Instrument	Sampling beam	Effective measurement area	54 cm ² (180 mm × 30 mm)	Section 2.3
	Count matrix	Diameter × fall-velocity joint counts	32 × 32 (1024 channels)	Sections 2.1, 2.3
	Diameter domain	Liquid raindrop diameter range	0.20–8.00 mm (class centers 0.312–7.500 mm)	Sections 2.4, 2.5
	Time resolution	Spectrum accumulation and SCADA alignment	10 min (left-closed intervals)	Section 2.5
	Installation height	Disdrometer height above ground	15 m (Guangxi) / 10 m (Jiangsu)	Section 2.1
	Hub height	Turbine hub height at each farm	100/110 m (Guangxi); 155 m dominant, few 140/145 m (Jiangsu)	Section 2.1
Rainfall	Liquid-rain criterion	Reconstructed 10 min liquid depth	> 0 (independent of rain-intensity flag)	Section 2.5
	Accumulator jump	Record-level increment anomaly threshold	> 10 mm per 5 min (single case: Jiangsu 87.46 mm on 26 May 2026 09:40, 0.031 mm h ⁻¹)	Section 2.4
Reference rotor	D _{rot}	Common reference rotor diameter	165 m (GW165 platform, 4 MW class)	Section 2.6
	Drivetrain	Direct-drive PMSG 1:1 (no gearbox conversion)	Speed channel equals rotor speed	Section 2.6
	U _{tip} pair	Median rain-time speed → tip-reference speed	7.82 rpm → 67.58 m s ⁻¹ ; 9.16 rpm → 79.17 m s ⁻¹ ($\pi \cdot D_{\text{rot}} \cdot n / 60$ self-consistent)	Section 3.4
	Common-speed baseline	Fixed tip speed for E ₉₀	90 m s ⁻¹	Section 2.6
SCADA screening	Completeness threshold	Record-level completeness lower bound	≥ 0.90	Section 2.5
	Reporting quorum	Minimum reporting share for farm median	≥ 80% (Guangxi ≥ 30/37; Jiangsu ≥ 20/25; consistent with the 29-turbine counter-example)	Section 2.5
	Aggregation	Farm operating-state definition	Median over reporting turbines per timestamp	Section 2.5
	Common window	Comparable analysis period	Through Jiangsu export endpoint 21 July 2026 23:50	Section 2.5
	QC-matched intervals	Rain–SCADA matched sample	961/967 (99.38%, Guangxi); 609/609 (100%, Jiangsu)	Sections 2.5, 3.4
Model and	v _t (D _i)	Terminal-velocity	Gunn–Kinzer-type liquid	Section

Category	Parameter/symbol	Meaning	Value	Source
material		relation	terminal-velocity relation	2.3
	$H_{i,k}$	Equivalent water layer per diameter class	$H_{i,k} = (R_{i,k}/1000) \cdot (U_{tip,k}/v_t(D_i))$	Section 2.7
	$H_{100}(D_i)$, $m(D_i)$	Reference-coating threshold and speed exponent	Bech et al. fits (commercial polyurethane topcoat on glass-fibre epoxy; validity domain = test domain)	Section 2.7
	E_{90}	Common-speed normalized exposure (matched window)	0.1404/0.0656 (all-valid common window 0.1413/0.0656; Guangxi extended record 0.170; Jiangsu full-window all-valid 0.0712)	Sections 3.3, 3.5; Table 4
	E_{SCADA}	Operation-coupled normalized exposure (matched window)	0.0251/0.0311 (Guangxi extended window: 0.0297)	Sections 2.7, 3.5; Table 4
	Bootstrap	Interval uncertainty quantification	10,000 percentile resamples (QC-matched 10 min intervals, shared seed stream)	Section 3.5; Fig. 7
Statistics	Mann–Whitney U	Rain-time vs non-rain distribution comparison	All 8 comparisons $p < 0.001$	Section 3.4; Table S2
	Kolmogorov–Smirnov (KS) test (within window)	Excluded-interval rain-intensity test (Guangxi)	$D = 0.393$, $p = 0.245$ (matched $n = 961$ vs unavailable $n = 6$)	Section 2.5; Fig. S1
	Kolmogorov–Smirnov (KS) test (beyond window, Jiangsu)	Post-endpoint intervals (sensitivity disclosure)	$D = 0.191$, $p = 0.002$ (108 post-endpoint rain intervals, 22.18 mm, without SCADA)	Section 2.5; Fig. S1
Key observations	Reconstructed/accumulated rainfall; closure	Spectrum reconstruction vs instrument accumulation	611.74/264.25 mm; 582.27/257.68 mm; closure 105.06%/102.55%	Section 3.1
	Window rainfall	Rainfall input within common window (QC-matched intervals)	508.83/242.07 mm (ratio 2.1)	Section 3.5; Table 4
	Drop-size distribution (DSD) statistics	Drop-size distribution characteristics	D_m 2.07/1.96; $D_{50,rain}$ 1.73/1.67; $D_{90,rain}$ 3.28/3.09 mm	Section 3.1
	Rain-time operating state	Median rain-time operating parameters	Tip speed 67.58/79.17 m s ⁻¹ ; rotor speed 7.82/9.16 rpm; power 555.1/1005.9 kW; >100 kW share 76.68%/88.22%	Section 3.4; Table S2
Model and material	$V_{imp,i,k}$	Relative impact speed per diameter class	$V_{imp,i,k} = \sqrt{U_{tip,k}^2 + v_t(D_i)^2}$ (Eq. 6)	Section 2.7
Model and	$H_{crit,i,k}$	Allowed-	$H_{crit,i,k} = H_{100}(D_i) /$	Section

Category	Parameter/symbol	Meaning	Value	Source
material		impingement (critical) water layer per diameter class	$V_{\text{imp},i,k^m(D_i)}$ (Eq. 7)	2.7

Note. Parameters, symbols, thresholds and key results of the exposure framework, with the main-text section where each is defined. E_{90} and E_{SCADA} refer to the common-window matched period; scope differences are in the Table 4 note of the main text.

Table S5. Sensitivity of fixed-speed E_{90} and of the compression ratio E_{SCADA}/E_{90} to the reference tip speed (common window, QC-matched intervals)

Reference tip speed (m s^{-1})	E_{90} , Guangxi	E_{SCADA}/E_{90} , Guangxi	E_{90} , Jiangsu	E_{SCADA}/E_{90} , Jiangsu
60	0.0033	7.618	0.0015	20.894
70	0.0131	1.915	0.0060	5.167
75	0.0248	1.014	0.0114	2.720
80	0.0453	0.554	0.0210	1.478
85	0.0808	0.311	0.0376	0.826
90	0.1404	0.179	0.0656	0.474
95	0.2386	0.105	0.1116	0.278
100	0.3971	0.063	0.1860	0.167

Note. E_{90} and E_{SCADA} use the same common-window QC-matched intervals; E_{SCADA} point estimates are 0.0251 (Guangxi) and 0.0311 (Jiangsu). The 90 m s^{-1} row is the fixed reference of the main text (Section 2.6). The steep rise of the ratio at low reference speeds shows that the compression factors are defined against this fixed benchmark, not an arbitrary or rainfall-only reference.

Table S6. Interval- and event-level bootstrap uncertainty of the matched-window exposure indices and their ratio (common window)

Site / resampling level	E_{90} (95% CI)	E_{SCADA} (95% CI)	E_{SCADA}/E_{90} (95% CI)	n
Guangxi, 10-min interval	[0.116, 0.168]	[0.019, 0.032]	[0.140, 0.222]	961
Guangxi, rain event	[0.085, 0.205]	[0.008, 0.054]	[0.066, 0.334]	63
Jiangsu, 10-min interval	[0.049, 0.084]	[0.021, 0.044]	[0.352, 0.611]	609
Jiangsu, rain event	[0.018, 0.128]	[0.005, 0.072]	[0.198, 0.740]	35

Note. 10,000 paired percentile-bootstrap resamples, resampling the same intervals or rain events for E_{90} and E_{SCADA} before forming the ratio. Interval level uses 961/609 intervals, event level the 63/35 events (gaps > 3 h). Both event-level ratio intervals lie below one, supporting within-site compression against the fixed benchmark, but they overlap between sites, so the cross-site ranking and exact magnitudes are not separated.

Table S7. Sensitivity of the matched-window exposure indices to observed versus parameterized (terminal) fall velocity (common window, QC-matched intervals)

Site	E_{90} (terminal)	E_{90} (observed)	E_{SCADA} (terminal)	E_{SCADA} (observed)	E_{SCADA}/E_{90} (terminal $\rightarrow$ observed)
Guangxi	0.1404	0.1698	0.0251	0.0321	0.179 $\rightarrow$ 0.189
Jiangsu	0.0656	0.0875	0.0311	0.0429	0.474 $\rightarrow$ 0.490

Note. Observed: interval-mean fall velocity per diameter class from the raw 32×32 matrices. Terminal: the parameterized relation of Eq. (1). Point changes (E_{90}/E_{SCADA}): +20.9%/+27.7% (Guangxi), +33.4%/+37.9% (Jiangsu). Paired interval-level bootstrap of the observed/terminal ratios (10,000 resamples, seed 20260909): E_{90} [1.14, 1.32] and [1.24, 1.49]; E_{SCADA} [1.13, 1.60] and [1.23, 1.68] (Guangxi, Jiangsu). Compression ratios move by only +5.6% and +3.4%, so the fall-speed treatment does not affect within-site compression or the cross-site ranking.

Table S8. Turbine-level robustness of the rain-time operating state and operation-coupled exposure (common window, QC-matched intervals)

Site	n	Rain-time rotor speed (rpm, per-turbine range)	Farm-median rotor speed (rpm)	Turbine-level E_{SCADA} (range)	Farm-median E_{SCADA}	Turbine-level E_{SCADA}/E_{90} (turbine range)
Guangxi	37	5.50–9.09	7.82	0.0071–0.0579	0.0251	0.05–0.41
Jiangsu	25	8.49–9.35	9.16	0.0264–0.0390	0.0311	0.40–0.59

Note. Per-turbine medians use the common-window rain intervals of turbines passing the per-turbine quality checks; turbine-level E_{SCADA} applies the site rainfall depth to each turbine's own rain-time rotor speed. Every turbine-level E_{SCADA} lies below the site fixed-speed E_{90} (0.140 Guangxi, 0.066 Jiangsu), so compression is not an aggregation artifact.