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Drop size distribution evolution through convective storm life-cycles and a site-specific Z–R relationship for radar QPE over Kolkata, Eastern India

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ABSTRACT

This study documents the evolution of drop size distribution (DSD) parameters through the life-cycle of convective storms over Kolkata, eastern India, using coordinated observations from almost collocated (approximately 12 km apart) a Joss–Waldvogel RD-80 disdrometer (22.65°N, 88.43°E) and the Kolkata S-band Doppler Weather Radar (DWR) (22.57°N, 88.35°E). Nine storm events spanning four seasons (pre-monsoon, monsoon, post-monsoon, and winter) between October 2024 and April 2026 provide 1210 phase-classified 1-minute DSD records. The mass-weighted mean diameter D_m increases systematically from 1.56 mm (developing phase) through 2.37 mm (mature) to 1.91 mm (dissipating), tracing a characteristic loop in D_m – N_w space. Phase-specific Z–R relationships are derived but an F-test demonstrates they are not statistically separable from the pooled regression [$F(4, 1204) = 1.68, p = 0.152$]. Accordingly, a single site-specific relation $Z = 959R^{1.62}$ ($R^2 = 0.882, n = 1210$) is recommended for operational QPE. The 4-year climatological Z–R from 138,420 rain records is $Z = 870R^{1.59}$ ($R^2 = 0.830$). Radar–disdrometer comparison (36 matched pairs, 4 events, 3 seasons) reveals a systematic calibration bias of -10.0 dBZ ($r = 0.643$) with seasonal variation from -5.1 dBZ (winter) to -11.6 dBZ (pre-monsoon). Quasi-vertical profiles show bright-band height varying from 3.2 km (winter) to 5.8 km (post-monsoon). A QPE demonstration against 15-minute gauge data on 16 April 2026 shows that the site-specific Z–R reduces rainfall estimation error from +239% (Marshall–Palmer) to +21%. Combined with a companion study on Severe Cyclonic Storm Remal (Karmakar et al., submitted; $Z = 218R^{1.38}$), these results establish that operational QPE over Kolkata requires a two-regime approach. These results provide the first combined radar–disdrometer characterisation of storm-scale precipitation microphysics from the Gangetic West Bengal plains.

Keywords: drop size distribution; Z–R relationship; radar calibration; quantitative precipitation estimation; disdrometer; convective storms; eastern India

1. Introduction

The drop size distribution (DSD) governs the relationship between radar reflectivity factor Z ($\text{mm}^6 \text{ m}^{-3}$) and rain rate R (mm h^{-1}), and is therefore central to radar-based quantitative precipitation estimation (QPE). DSD variability encodes information about precipitation formation processes—collision–coalescence growth, drop breakup, evaporation, and size-sorting—and directly impacts radar rainfall retrieval, satellite precipitation algorithms, and the microphysics parameterisation in numerical weather prediction models (Rosenfeld and Ulbrich 2003; Bringi and Chandrasekar 2001).

The power-law $Z = aR^b$ has been used operationally since Marshall and Palmer (1948) proposed $Z = 200R^{1.6}$ for mid-latitude stratiform rain. However, the coefficients a and b vary with precipitation type, geographic location, season, and storm life-cycle stage (Tokay and Short 1996; Ulbrich and Atlas 2007). In tropical continental environments, convective precipitation typically produces broader DSDs with larger mass-weighted mean diameter (D_m) and lower normalised intercept (N_0) than stratiform rain, as demonstrated by Bringi et al. (2003) across multiple climate regimes. Thompson et al. (2015) extended this framework to show that DSD parameters evolve systematically through the storm life-cycle, but documentation from the Indian subcontinent remains sparse.

Over India, DSD studies include the foundational work of Narayana Rao et al. (2001, 2009) at Gadanki, who derived convective/stratiform Z – R relationships for southern India. Chakravarty and Raj (2013) characterised DSD variability at Pune during the Indian Summer Monsoon. More recently, Kumar et al. (2022, 2025) documented DSD characteristics over the Western Ghats, and Sreekanth et al. (2021) analysed Z – R relationships at a tropical coastal site. Over Kolkata, Maitra and Chakravarty (2009) derived Z – R from limited disdrometer data, and Rakshit et al. (2024) examined the physical phenomena that govern raindrop size distribution and cloud characteristics across the diverse climatic regions of the Indian subcontinent and uses Disdrometer data (DSD) over Kolkata, Bhopal, Desalpar, and Kavaratti Island during the monsoon season. Konwar et al. (2014) demonstrated the role of aerosols in modulating warm-rain depth over peninsular India.

Eastern India, particularly the Gangetic West Bengal plains, experiences intense convective activity across all four seasons: nor'wester thunderstorms in the pre-monsoon, mesoscale convective systems during the monsoon, post-monsoon cyclonic disturbances, and embedded convection in winter western disturbances. A companion study (Karmakar et al., submitted) documents the distinct DSD characteristics and Z – R relationship ($Z = 218R^{1.38}$) during Severe Cyclonic Storm Remal (2024) over Kolkata using the same radar–disdrometer infrastructure.

However, the microphysical evolution of DSD through the life-cycle of local convective storms—and the derivation of a general-purpose site-specific Z–R for non-cyclonic precipitation—remains undocumented.

This study addresses this gap using a 4-year disdrometer record (March 2022–April 2026) coordinated with S-band DWR observations. The objectives are to: (1) document DSD evolution through the developing, mature, and dissipating phases of convective storms across four seasons; (2) derive a site-specific Z–R relationship and test whether phase-specific Z–R relations offer statistically significant improvement; (3) quantify the radar–disdrometer reflectivity bias and its seasonal dependence; (4) examine bright-band structure using quasi-vertical profiles; and (5) demonstrate QPE improvement over the Marshall–Palmer default.

2. Data and methods

2.1. Study area and instrumentation

2.1.1. S-band DWR. The IMD Kolkata S-band DWR (SELEX-SI, 10.4 cm wavelength) is located at 22.57°N, 88.35°E, 74 m ASL. The radar operates in single-polarisation mode with 1.0° beamwidth, performing PPI scans at 0.2° elevation (500 km range, 2 km resolution, ~10-minute cycle) and volume scans comprising six elevations (0.2°, 2.1°, 4.8°, 8.5°, 13.7°, 21.0°) at 1 km resolution, 250 km range.

2.1.2. Joss–Waldvogel RD-80 disdrometer. A Distromet RD-80 impact-type disdrometer (Joss and Waldvogel 1967) is installed at Dumdum (22.65°N, 88.43°E), 12.1 km from the radar at a bearing of 42.7°. The instrument measures drops across 20 diameter channels from 0.3 to 5.3 mm, with a 50 cm² sampling area and 30-second integration time.

2.2. DSD parameter computation

The number concentration $N(D_i)$ for each bin i is calculated as $N(D_i) = \frac{n_i}{(A \cdot v(D_i) \cdot \Delta t \cdot \Delta D_i)}$, where $A = 50 \text{ cm}^2$, $v(D) = 9.65 - 10.3 \exp(-0.6D) \text{ m s}^{-1}$ (Atlas et al. 1973), and Δt is the integration interval. The mass-weighted mean diameter $D_m = \frac{\sum N(D) D^4 \Delta D}{\sum N(D) D^3 \Delta D}$. The normalised

intercept N_w follows Testud et al. (2001): $N_w = \frac{\left(\frac{4^4}{\pi}\right)(10^3 \times \text{LWC})}{(D_m)^4}$.

2.3. Data quality control

For the disdrometer, records with fewer than 10 total drops, rain rate $R < 0.1 \text{ mm h}^{-1}$, or integration time anomalies are excluded. The continuous record spans March 2022 to April

2026, providing 3,909,304 raw records of which 138,420 qualify as rain minutes ($R > 0.1 \text{ mm h}^{-1}$). For the radar, the operational clutter filter (IIR Doppler filter at PRF = 300 Hz) removes ground clutter, and reflectivity values below -10 dBZ or above 70 dBZ are flagged. A calibration bias of -10.0 dBZ was established by systematic comparison of 36 radar–disdrometer matched pairs (see Section 3.4).

2.4. Event selection and phase classification

Nine precipitation events spanning four seasons were selected based on concurrent disdrometer rain and identifiable convective structure in radar imagery (Table 1). Storm life-cycle phases are classified using the 1-minute rain-rate time series: a mature window of $\pm 15\%$ of episode duration (minimum ± 5 minutes) is centred on the peak R , with earlier records classified as developing and later as dissipating. Multi-episode events are partitioned at 30-minute rain gaps. This classification reflects the storm’s transit over the instrument rather than intrinsic maturity at the convective core, as discussed in Section 4.1. The procedure yields 1210 phase-classified records: 212 developing, 317 mature, and 681 dissipating.

2.5. Radar–disdrometer matching

Volume scan reflectivity at the disdrometer location is extracted from the lowest elevation sweep (0.2°) using an azimuth window of $\pm 5^\circ$ around 42.7° and a range window of ± 1 range gate around 12.1 km . At this range, the beam centre is $\sim 51 \text{ m AGL}$, the 3-dB beamwidth spans 212 m , and the lower beam edge extends to $\sim -55 \text{ m}$ (below the surface), introducing a potential ground clutter contribution discussed in Section 4.3. Temporal matching uses a ± 2.5 -minute window.

2.6. Z–R derivation and statistical testing

Power-law Z–R relationships are derived by OLS regression in log–log space: $\log_{10} Z = b \cdot \log_{10} R + \log_{10} a$. An F-test compares the residual sum of squares of three separate phase regressions against the pooled regression to test whether phase-specific Z–R relations offer statistically significant improvement (Neter et al. 1996).

Table 1 Summary of storm events. † PPI only. ‡ Volume scans but no concurrent disdrometer rain. * QPE demonstration event.

Event	Season	IST	PPI	Vol	DSD	Rmax	Zmax
03 Oct 2024†	Post-mon.	13:40–16:40	13	–	131	19.1	54.3
11 Oct 2024‡	Post-mon.	12:40–15:00	9	10	9	23.8	57.7
21 Dec 2024	Winter	10:30–12:40	8	8	121	4.6	42.4
26 May 2025‡	Pre-mon.	10:20–14:40	6	15	261	92.1	60.9
25 Jun 2025‡	Monsoon	–	–	7	–	–	–
07 Jul 2025†	Monsoon	06:40–09:10	9	–	97	1.8	39.8
19 Jul 2025†	Monsoon	09:50–13:10	15	–	145	47.6	62.2
25 Jul 2025	Monsoon	05:00–08:00	–	4	87	89.1	62.0
01 Sep 2025	Monsoon	21:30–00:00	–	12	87	79.7	62.9
08–09 Apr 2026	Pre-mon.	18:30–10:40	72	72	272	57.9	58.9
16 Apr 2026*	Pre-mon.	07:00–09:00	–	12	–	–	60.5

3. Results

3.1. DSD parameter evolution

Figure 2 presents the temporal evolution of R , Z , D_m , and $\log_{10}N_e$ for all nine events. During the developing phase, the DSD is characterised by small drops ($D_m = 1.56 \pm 0.84$ mm) with high concentration ($\log_{10}N_e = 3.18 \pm 0.75$). As the mature core passes overhead, D_m increases to 2.37 ± 1.08 mm ($\log_{10}N_e = 3.34 \pm 0.78$), reflecting efficient collision–coalescence. During dissipation, D_m decreases to 1.91 ± 0.96 mm as size-sorting allows preferential fallout of large drops.

This D_m trajectory ($1.56 \rightarrow 2.37 \rightarrow 1.91$ mm) traces a characteristic loop in D_m – $\log_{10}N_e$ space (Fig. 4), consistent with Bringi et al. (2003) but documented here for the first time for continental tropical convection over the Gangetic plains.

PPI Reflectivity (dBZ) — 08-09 April 2026 (Pre-monsoon)
72 scans over ~12 hours

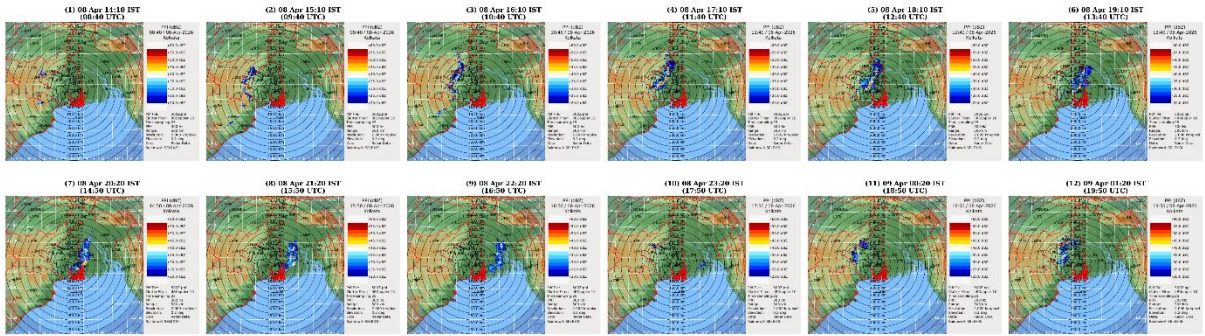


Fig. 1a. PPI reflectivity (dBZ) — 08–09 April 2026 (pre-monsoon). Twelve representative scans from 72 available.

PPI Reflectivity (dBZ) — 19 July 2025 (Monsoon)

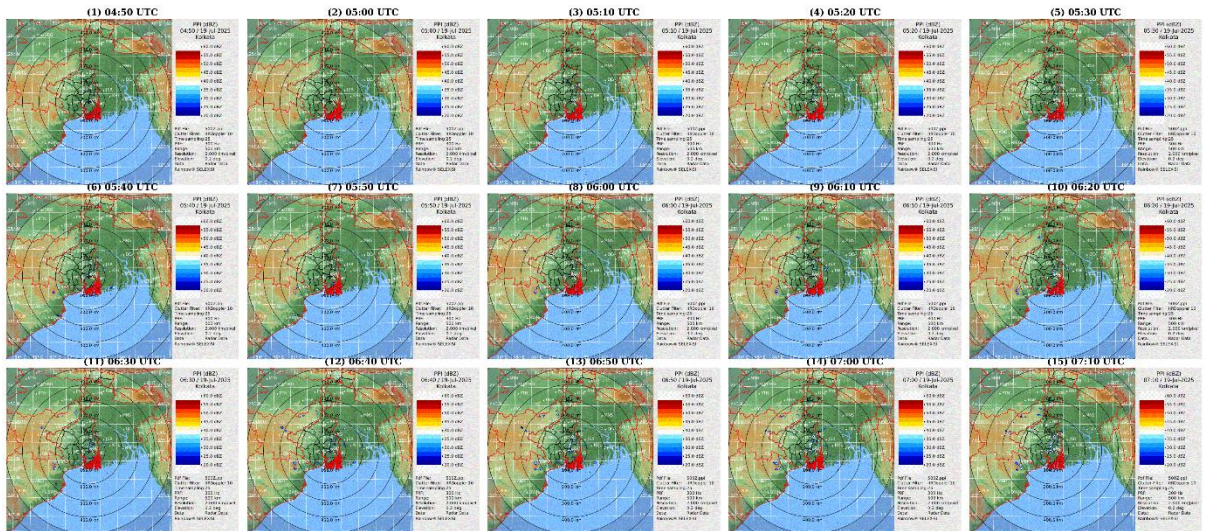


Fig. 1b. PPI reflectivity (dBZ) — 19 July 2025 (monsoon).

PPI Reflectivity (dBZ) – 03 October 2024 (Post-monsoon)

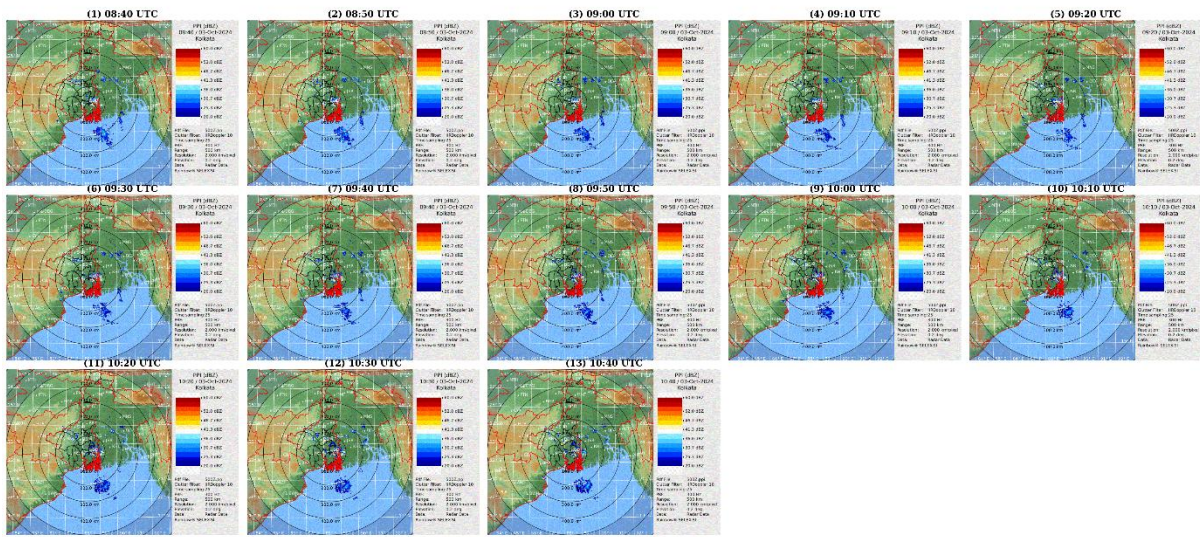


Fig. 1c. PPI reflectivity (dBZ) — 03 October 2024 (post-monsoon).

PPI Reflectivity (dBZ) – 21 December 2024 (Winter)

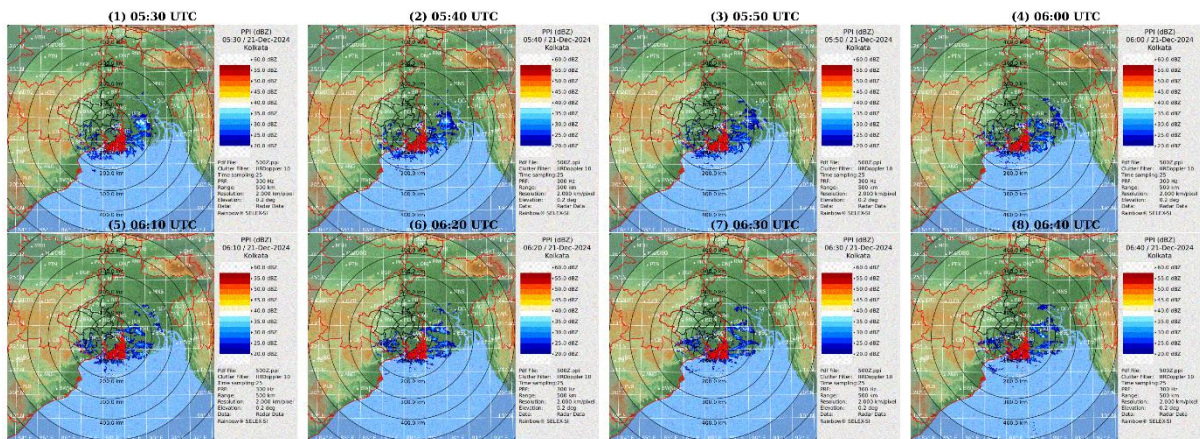


Fig. 1d. PPI reflectivity (dBZ) — 21 December 2024 (winter).

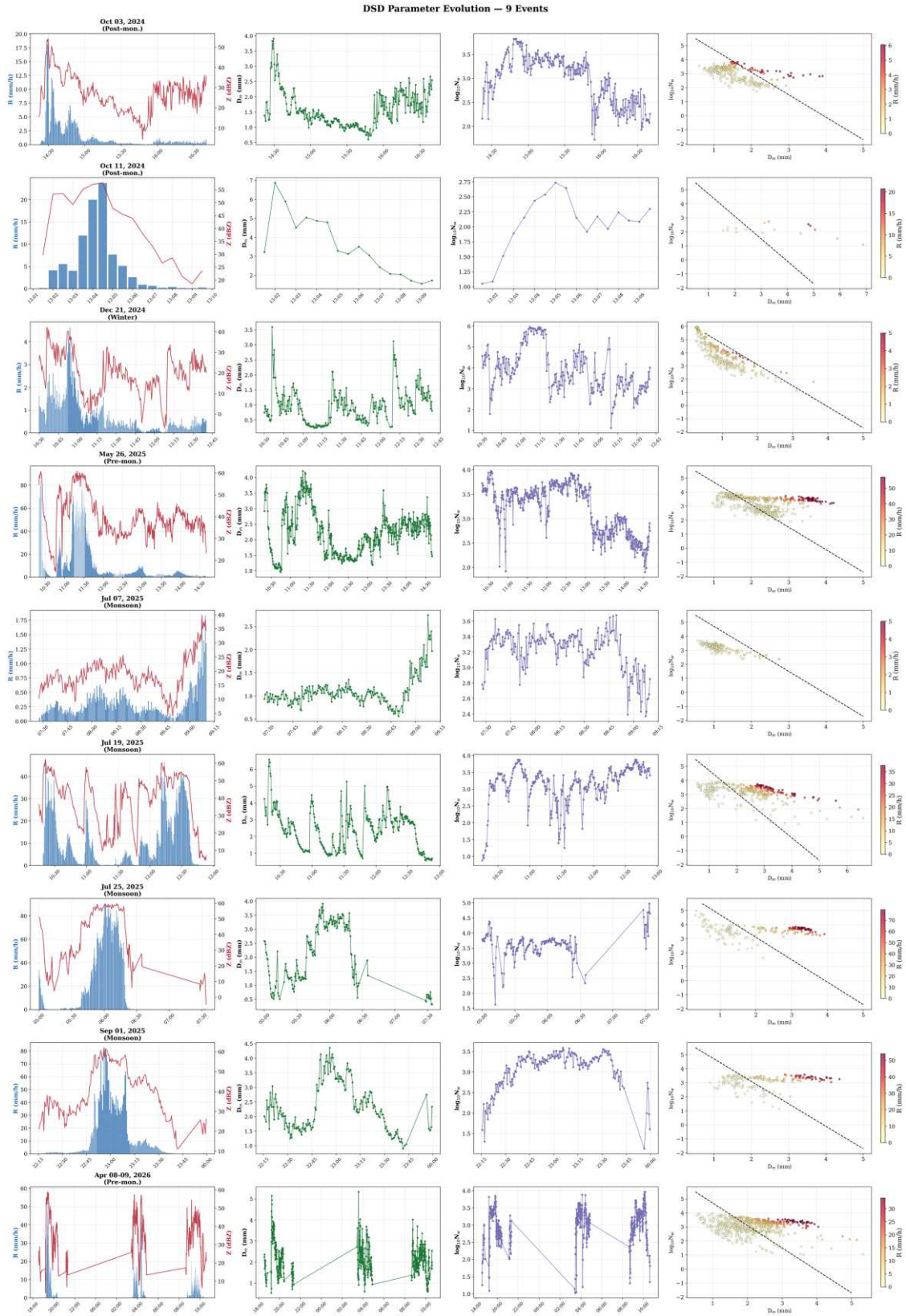


Fig. 2. DSD parameter evolution for nine events. Columns: (a) R and Z ; (b) D_m ; (c) $\log_{10}N_e$; (d) D_m – N_e scatter. Dashed line: Bringi et al. (2003) separation.

3.2. D_m - N_e distribution

The composite D_m - $\log_{10}N_e$ distribution (Fig. 3) shows seasonal stratification. Winter events cluster in the stratiform regime ($D_m < 1.5$ mm, $\log_{10}N_e > 3.5$). Pre-monsoon and monsoon events extend into the deep convective regime, particularly nor'wester events where D_m exceeds 5 mm. When coloured by phase (Fig. 4), developing-phase records occupy the stratiform quadrant, the mature phase extends into the convective regime, and dissipating records occupy intermediate positions (Fig. 5).

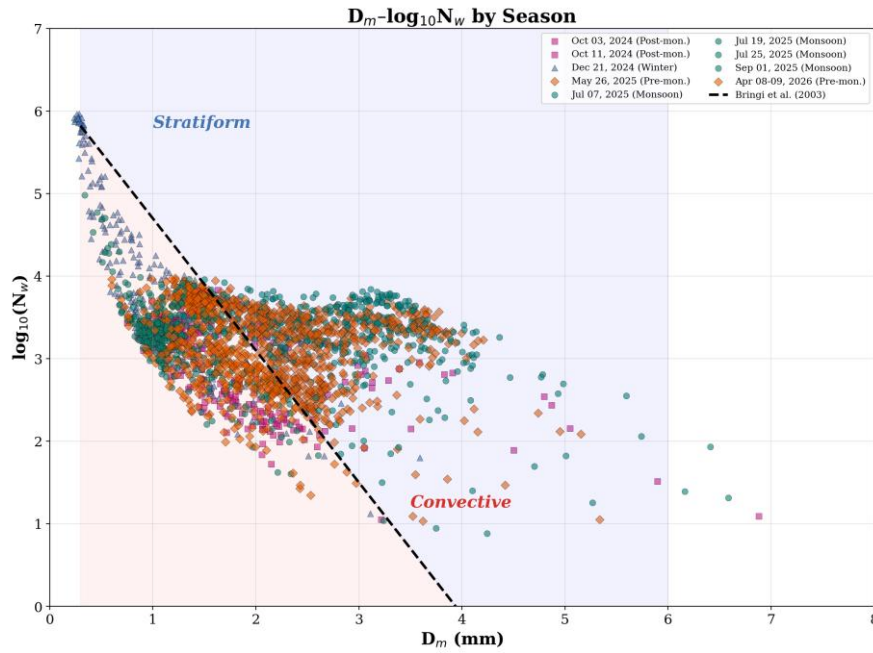


Fig. 3. D_m - $\log_{10}N_e$ by season. Dashed line: Bringi et al. (2003) convective-stratiform separation.

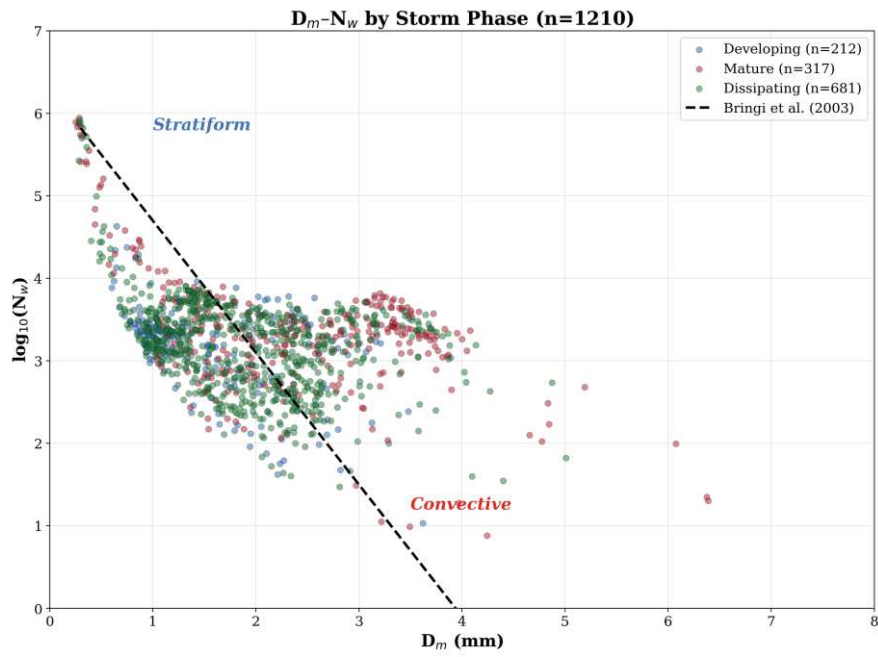


Fig. 4. D_m-N_e by storm phase ($n = 1210$).

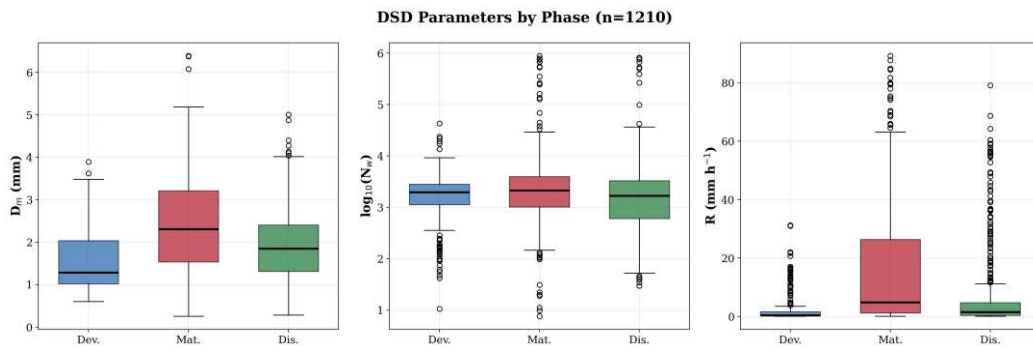


Fig. 5. DSD parameters by phase: (a) D_m , (b) $\log_{10}N_e$, (c) R . Boxes = IQR; line = median.

3.3. Z–R relationships and statistical separability

Phase-specific Z–R relationships are presented in Table 2. Prefactors range from 840 to 1021, all exceeding Marshall–Palmer ($a = 200$). Exponents cluster between 1.60 and 1.66. An F-test comparing three separate phase regressions against a single pooled regression yields $F(4, 1204) = 1.68$, $p = 0.152$, indicating that the phase-specific Z–R are not statistically distinguishable at $\alpha = 0.05$. The overall $Z = 959R^{1.62}$ ($R^2 = 0.882$) is therefore recommended as a single relation for operational QPE. The 4-year climatological $Z = 870R^{1.59}$ ($n = 138,420$) confirms representativeness.

Table 2 Z–R relationships. SE = standard error of b.

Phase	Z–R	R^2	n	SE(b)	F-test
Developing	$Z = 887 R^{1.61}$	0.891	212	0.039	–
Mature	$Z = 840 R^{1.66}$	0.857	317	0.038	–
Dissipating	$Z = 1021 R^{1.60}$	0.868	681	0.024	–
Overall	$Z = 959 R^{1.62}$	0.882	1210	0.017	$p=0.152$
Climatological	$Z = 870 R^{1.59}$	0.830	138,420	0.002	–
M-P	$Z = 200 R^{1.60}$	–	–	–	–

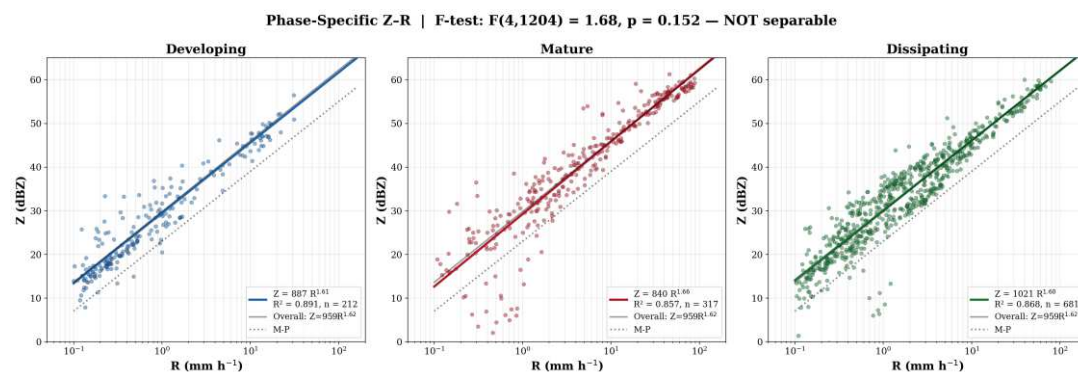


Fig. 6. Phase-specific Z–R scatter. Black solid = overall; dotted = M–P. F-test confirms non-separability.

3.4. Radar–disdrometer reflectivity comparison

Volume scan data from 128 scans yield 36 rain-matched pairs. The radar exhibits a bias of -10.0 dBZ (RMSE = 15.6 dBZ, $r = 0.643$). Seasonal decomposition: winter -5.1 dBZ ($n = 6$), monsoon -10.1 dBZ ($n = 13$, $r = 0.951$), pre-monsoon -11.6 dBZ ($n = 17$).

3.5. Quasi-vertical profiles

QVPs reveal seasonal melting layer variation: 3.2 km (winter), 4.2 km (pre-monsoon), 3.8 – 4.2 km (monsoon), and 5.8 km (post-monsoon). The winter melting layer provides ~ 3 km for coalescence, producing small- D_m DSDs; the post-monsoon melting layer enables ~ 6 km of warm-rain depth.

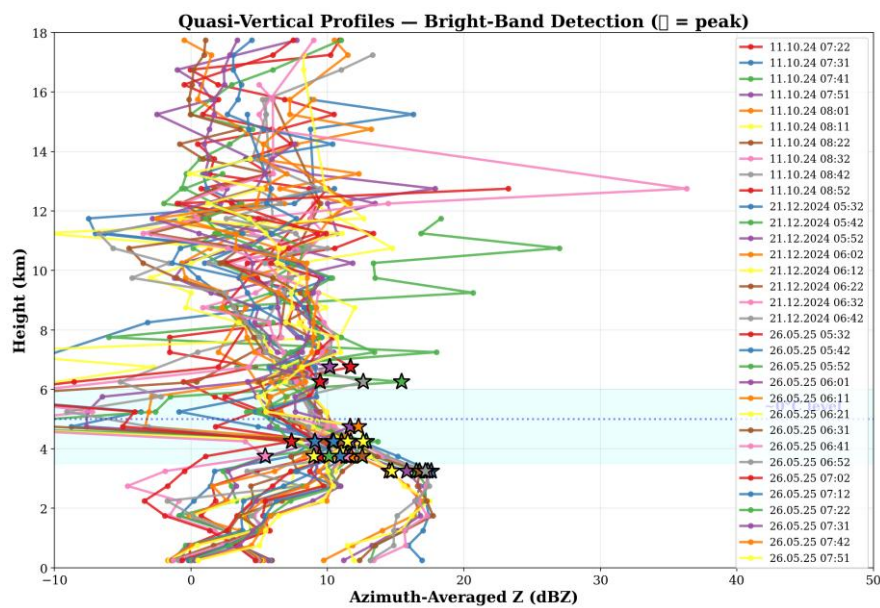


Fig. 7. Quasi-vertical profiles. Stars mark bright-band peaks. Blue shading: $\sim 0^\circ\text{C}$ level.

3.6. QPE demonstration

An independent event on 16 April 2026 (12 volume scans) provides a QPE demonstration at Kolkata (22.53°N , 88.33°E). Radar Z is corrected by $+10.0$ dBZ. Observed: 2.0 mm ($08:30$ – $08:45$) + 2.8 mm ($08:45$ – $09:00$) = 4.8 mm (Table 3).

Table 3 QPE demonstration, 16 April 2026. Calibration: $+10.0$ dBZ.

Z–R	08:30–45	08:45–00	Total	Error	RMSE
Observed	2.00	2.80	4.80	—	—
Overall (959, 1.62)	5.61	0.29	5.90	+23%	3.11
Mature (840, 1.66)	5.51	0.31	5.82	+21%	3.04
Climatological	6.30	0.32	6.62	+38%	3.51
M-P (200, 1.60)	15.49	0.80	16.29	+239%	9.65

All site-specific Z–R produce totals of 5.8–6.6 mm (factor 1.2–1.4× overestimate), while M-P overestimates by +239%. The RMSE differences are small at $n = 2$ and should not be interpreted as evidence of one relation outperforming another. The principal finding is the order-of-magnitude improvement over M-P.

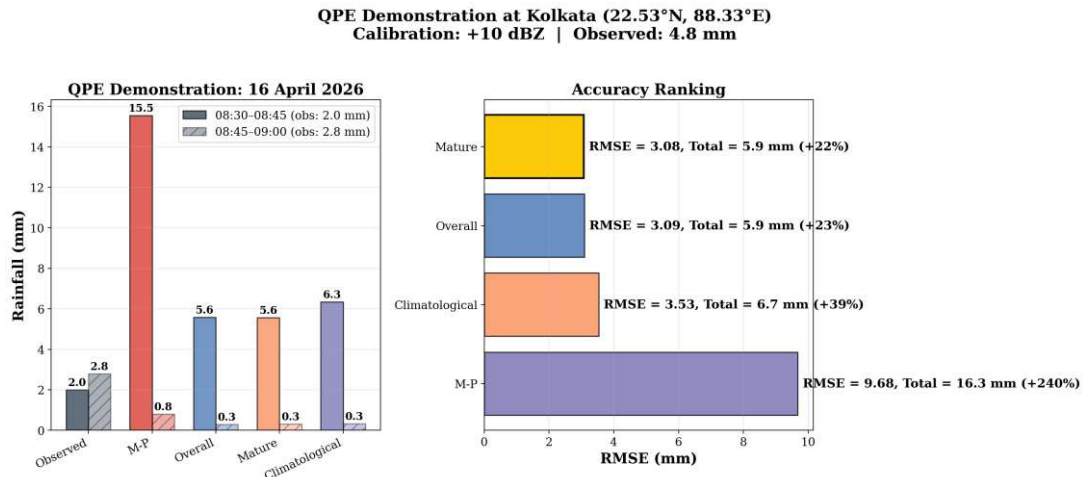


Fig. 8. QPE demonstration. (a) Per-window comparison. (b) RMSE ranking.

4. Discussion

4.1. Physical interpretation of DSD evolution

The systematic DSD evolution (D_m : 1.56 → 2.37 → 1.91 mm) requires careful interpretation. The ‘developing’ phase at the disdrometer samples the storm’s leading edge—stratiform precursor or gust-front outflow—before the convective core arrives. The small-drop, high-concentration DSD reflects light rain ahead of the main updraft, not the updraft microphysics itself. As the convective core passes (mature phase), collision–coalescence produces $D_m = 2.37$ mm. During dissipation, size-sorting drives the return to smaller mean sizes.

4.2. Implications of Z–R non-separability

The F-test ($p = 0.152$) shows that the Z–R parameterisation absorbs the DSD variation into a narrow exponent range (1.60–1.66). A single $Z = 959R^{1.62}$ suffices without real-time phase identification. This prefactor is consistent with other tropical continental sites: $a = 868$ at Gadanki (Narayana Rao et al. 2001), $a = 790$ at Pune (Chakravarty and Raj 2013). However, this Z–R applies to local convective storms and should not be used for tropical cyclone precipitation. Karmakar et al. (submitted) derived $Z = 218R^{1.38}$ for TC Remal using the same infrastructure, showing a factor-of-4 prefactor difference ($a = 218$ vs 959) reflecting

the distinct microphysics of TC rainbands versus continental convection. Together, the two studies establish that operational QPE over Kolkata requires a two-regime approach.

4.3. Radar calibration and error sources

The -10.0 dBZ bias has multiple contributors. At 12.1 km, the 3-dB beam spans -55 to $+157$ m AGL—the negative lower edge indicates potential ground clutter contamination. However, the Doppler clutter filter and the consistency of the bias across events suggest a primarily instrumental offset. The seasonal variation (-5.1 to -11.6 dBZ) may reflect differential wet-radome attenuation. This finding is diagnostic; operational application requires independent validation via sun-scan calibration (Holleman et al. 2010).

4.4. Limitations

The phase classification is based on rain-rate evolution at a single point and cannot distinguish intrinsic storm maturity from advection. The QPE demonstration rests on a single event (4.8 mm); this is illustrative, not definitive. The single-polarisation radar limits microphysical interpretation. Seasonal bright-band characterisation rests on limited events per season. The JW disdrometer's 5.3 mm upper limit may underrepresent convective DSD tails.

5. Conclusions

(1) DSD parameters evolve systematically: D_m increases from 1.56 mm (developing) to 2.37 mm (mature) and decreases to 1.91 mm (dissipating), tracing a loop in D_m – N_w space consistent with Bringi et al. (2003).

(2) An F-test demonstrates that phase-specific Z – R are not statistically separable [$F(4, 1204) = 1.68$, $p = 0.152$]. A single $Z = 959R^{1.62}$ ($R^2 = 0.882$) is recommended, consistent with the climatological $Z = 870R^{1.59}$.

(3) The site-specific Z – R reduces QPE error from $+239\%$ (M-P) to $+21$ – 38% .

(4) Radar–disdrometer comparison (36 pairs) reveals -10.0 dBZ calibration bias ($r = 0.643$) with seasonal variation.

(5) QVP bright-band heights vary from 3.2 km (winter) to 5.8 km (post-monsoon).

(6) Combined with TC Remal ($Z = 218R^{1.38}$), operational QPE over Kolkata requires a two-regime approach.

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