Investigation of the Evolution of the Height Profiles of Rain Microphysical Parameters: A Seasonal Comparison at a Tropical Location

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Abstract

The present study reveals the role of atmospheric instabilities towards varied raindrop size distribution scenarios below and above the atmospheric boundary layer over a tropical location, Kolkata (22.57° N, 88.37° E), India near the land-sea boundary. The investigation has been undertaken from a set of experimental measurements which includes impact type disdrometer, Ka-band micro rain Doppler radar, multi-frequency radiometer, along with the outputs of ERA-5 re-analysis data. A detailed statistical and case study analysis revealed that significant drop break-up above the atmospheric boundary layer induces deviations in the usual power law relationship exhibited by rain rate (R) and mass-weighted mean drop diameter (D_m). The enhanced drop break-up phenomenon is seen to be more significant during the pre-monsoon season compared to the monsoon season.

1. Introduction

Unambiguous knowledge of raindrop size distributions (DSD) which evolve as a result of the interplay between drop break-up and coalescence processes, throughout the precipitating heights are found to be influenced by the prevailing atmospheric conditions [1-2]. Now, the estimation of rain microphysical parameters by radars relies on the relationship exhibited by the rain rate (R) and the mass-weighted mean diameter (D_m). In addition, devising the accurate quantitative precipitation algorithm requires consideration of the physical processes that influence the evolution of the three parameters of gamma model namely, intercept (N_0, $mm^{-1-\mu}\, m^{-3}$), shape (μ) and slope (Λ, mm^{-1}) along the rain profile [3]. The prevailing atmospheric instabilities below and above the atmospheric boundary layer (ABL) are surmised to act differently on rain microphysical parameters, some of these are yet to be adequately investigated in the tropics where such intense convective activities are common and hazardous [3-7]. Against the above backdrop, there is a dearth of investigation on the associated atmospheric phenomena for the variability of the vertical profile of rain DSD evolution, especially over the tropical region where two precipitation types namely convective and stratiform rain prevail as distinct features [8], [9]. The present study location is characterized by more frequent local convective rain during the pre-monsoon months (March-May) and widespread stratiform rain during monsoon (June-September) seasons [5, 9]. Hence the present paper endeavours towards investigating the physical phenomena along the precipitating height responsible for the vertical evolution of DSDs parameters over a tropical location Kolkata (22.57° N, 88.37° E) using both statistical analysis and case study investigations during 2013-2015.

2. Dataset and Instruments Used

Information on DSD and rain rate near the surface are obtained from an impact type Joss–Waldvogel disdrometer (JWD, Distromet RD-80) operated at the Institute of Radio Physics and Electronics, University of Calcutta, Kolkata. JWD provides raindrops ranging between 0.3 - 5.5 mm sizes at 20 different bins with about ± 5% accuracy [5, 8]. Secondly, a collocated frequency-modulated continuous wave (FMCW) micro rain radar (MRR) is operated to investigate the profiles of the rain parameters. This instrument utilizes the Doppler principle at Ka-band (24.1 GHz) and yields the vertical profiles of all rain parameters at 30s temporal resolution [9, 10]. Finally, a collocated ground-based microwave radiometer (RPG HATPRO) has been used to retrieve the atmospheric moisture and temperature profiles using standard retrieval techniques from 14 brightness temperature channels operated at the (22.234 – 31.4 GHz) and (51-58 GHz) frequency bands respectively [11-13]. These retrieved meteorological profiles have then been used to calculate the most important instability parameter characterizing the rain intensities namely the Convective Available Potential Energy (CAPE). In addition to this, the meteorological datasets such as the 2m surface temperatures and the lower tropospheric temperature gradient (derived from the difference between the 1000 and 700 hPa temperatures) datasets have been considered from the ERA-5 reanalysis archives at 0.25°×0.25° spatial resolution centering the location of Kolkata [14-15].

3. Results and Discussions

3.1. Variation of DSD parameters along the rain height for varied rain rates and seasons

To investigate the behavior of the rain microphysical parameters corresponding to varied raining conditions, surface rain rates measured by disdrometer are classified based on their percentiles of occurrence into six broad classes namely: *R1* (<0.65 mm/hr), *R2* (0.65-1.33 mm/hr), *R3* (1.33-3.22 mm/hr), *R4* (3.22-8.74 mm/hr), *R5* (8.74-28.76 mm/hr), and *R6* (>28.76 mm/hr)) respectively. Notably, these rain classes will be referred to investigate the variation of the rain microphysical properties in the subsequent sections.

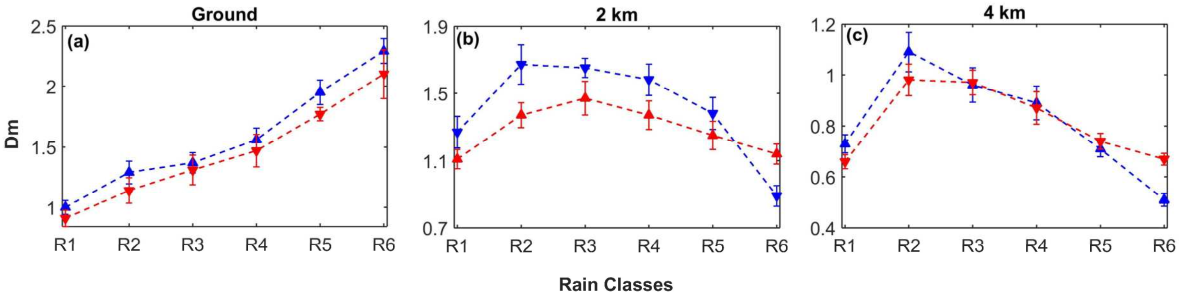

Figure 1. Variation of D_m for six rain rate classes during pre-monsoon and monsoon seasons at: (a) ground, (b) 2 km, and (c) 4 km heights.

The variation of D_m and three parameters of gamma distribution along the rain heights (ground, 2 km, and 4 km) corresponding to the six rain rate classes for the pre-monsoon (indicated in blue), and monsoon (indicated in red) are investigated as shown in Figure 1. This reveals that the D_m values increase with rain rate for all rain classes irrespective of the season at the surface (Figure 1(a)). Here, it may be noted that the D_m values are consistently higher during the pre-monsoon season than during the monsoon season as reported earlier [16]. This can be explained by the fact that the premonsoon season is more conducive for the genesis of localised convective activities which are mostly associated with stronger coalescence processes near the ground [15-17]. However, the situation changes drastically from 2 km height where, though the magnitude of D_m increases at lower rain rate classes from *R1* and *R2,* at high rain rate classes, D_m shows a decrement with rain rate resulting in a concave shape variation as shown in Figure 1(b). Finally, at 4 km, beyond *R3*, D_m values during pre-monsoon exhibit a value even lower than the monsoon season in contrast to that observed near the surface (Figure 1(c)). These findings show, the R-D_m relationship exhibits a reversal in the usual behaviour with the increase of rain rates above the boundary layer.

Next, the evolution of the three parameters of gamma model, namely, slope (Λ, mm^{-1}) shape (μ) and intercept (N_0, $mm^{-1-\mu}\,m^{-3}$), are investigated as shown in Figure 2. At the ground as D_m shows an increasing value with rain rates, Λ shows a decreasing value indicating the dominance of larger raindrops at high rain rates as in Figure 2 (a) [16]. However, above the ABL at 2 km, the decreasing slope of Λ with rain rate is not significant and finally reverses at around 4 km height for high rain rate classes (*R3, R4, R5,* and *R6*) (Figure 2 (b), (c)). Likewise, the shape parameter, μ, values also decrease with rain rate at the surface Figure 2 (d). However, at higher altitudes, and intense rain rate ranges (*R3, R4, R5*, and *R6*), an inversion in the usual relationship is observed which is more significant during the pre-monsoon season Figure 2 (e), (f). Finally, N_0, which is determined by the abundance of smaller raindrops, decreases with the rain rate due to the dominance of the coalescence processes at the surface [5] (Figure 2 (g)). However, with the increase in rain height, the magnitude of N_0 increases which may be due to the enhanced drop breakup at high rain rate regimes, particularly during the pre-monsoon season (Figure 2 (h), (i)). The variation of three parameters of gamma model with rain rate above ABL supports the enhanced drop breakup phenomena in an intense raining environment as also observed in the case of D_m.

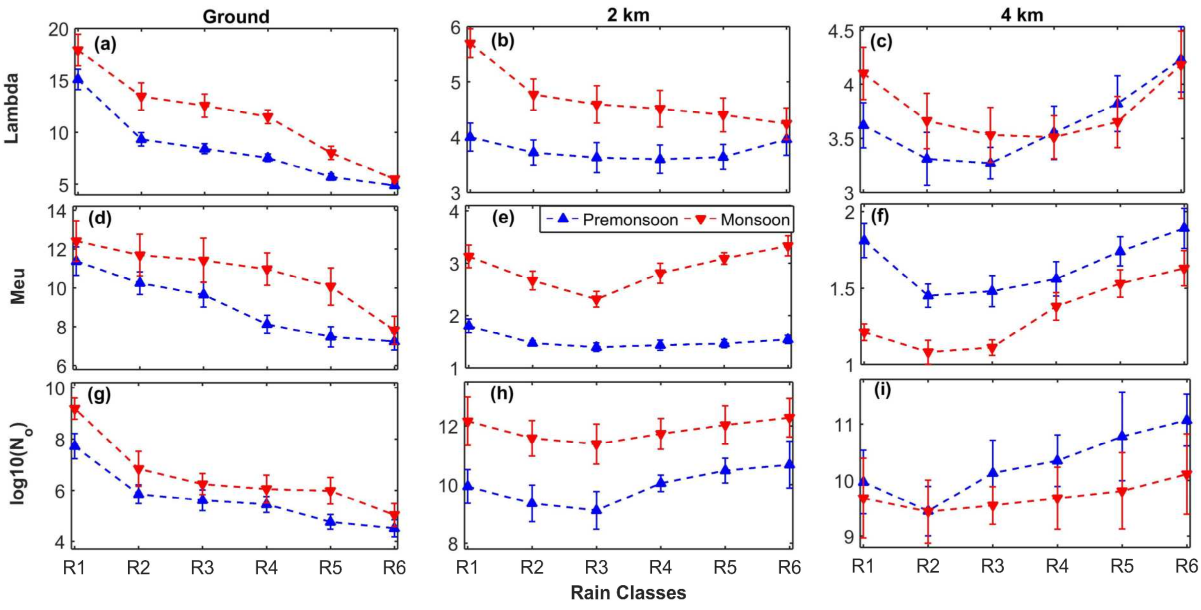

Figure 2. The variation of Λ ((a)-(c)), μ ((d)-(f)) and N_0 ((g)-(i)) for six rain rate classes during pre-monsoon and monsoon seasons at ground, 2 km, and 4 km heights.

3.2. Role of associated atmospheric dynamics behind diverse DSD features along rain height

The enhanced drop-break up above ABL over the present location which is mostly reported to be around 1.6 km [18] have led to further investigations regarding the scenario of atmospheric instability, and temperature difference above and below ABL since the impact of convective turbulence below the ABL, is expected to be completely dissimilar from that above it (>= 2 km) [19].

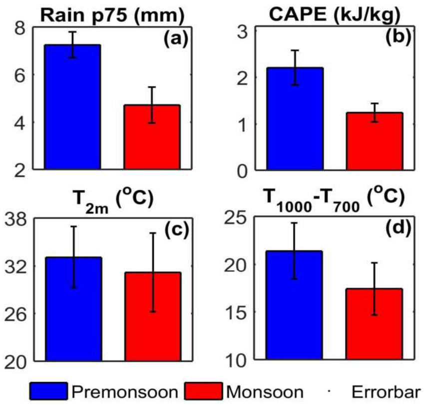

Figure 3. Bar plots of: (a) 75th percentile rain accumulation (mm), (b) CAPE (KJ/kg), (c) 2 m temperature (ºC), and (d) T_{1000} -T_{700} (ºC) during for premonsoon and monsoon season

In accordance the variability of the 75th percentile (P_{75}) of rain accumulation (which can be considered as an indirect measure of rain intensity of rain) is shown in Figure 3 (a) which depicts much higher values during the pre-monsoon season in contrast to the fact that the total monsoonal precipitation is ~5 times of the pre-monsoon amount. This can be partially attributed to previous studies reporting that convective cloud organizations which are more common during pre-monsoon play a primary role in simulating very heavy to extreme precipitation over land regions [20-21]. The next parameter CAPE, which is indicative of overall thermodynamic instability in the atmosphere [22-25]. CAPE values are found to be ~2.5 kJ/kg during pre-monsoon (Figure 3(b)). On the other hand, less CAPE values during monsoon corroborate with the calm nature of precipitation which is devoid of strong turbulence. Such conditions are expected to exhibit lesser drop break probability above ABL during monsoon compared to pre-monsoon as also observed from Figure 1 and 2.

Next, the other associated atmospheric properties playing a role for the genesis of convective rain events during the pre-monsoon period are investigated from ERA-5 re-analysis. Accordingly, 2 m air temperatures (T_{2m}) are depicted, as surface heat fluxes are an essential trigger for the intrusion of moisture into the troposphere for cyclogenesis and rainfall.

Figure 3 (c) shows that T_{2m} in the pre-monsoon is higher by ~1 ºC than that in the monsoon seasons which plays a role for a stronger convective growth during the pre-monsoon season. Next in association with the near-surface heating, the temperature difference between the surface (T_{1000}) and the free troposphere (T_{700}) is investigated. A significant temperature gradient enables an efficient intrusion of surface moisture to the lifting condensation level resulting in cumulous cloud development which is always associated with strong turbulence and more favourable chances of drop breakup above the ABL. Here, as expected, a much higher temperature gradient is observed during the pre-monsoon compared to the monsoon season (Figure 3(d)).

3.3. Demonstration of the observed microphysical features using case studies

In the preceding sections, it has been hypothesized how turbulence develops due to atmospheric instabilities beyond the boundary layer during convective rain (more commonly in the premonsoon season) leading to the observed breakup in raindrops. In view of the above, it is now attempted to demonstrate this phenomenon using case studies on 28 April 2015 and 8 August 2015 representing rain events from the pre-monsoon and monsoon seasons respectively. Figure 4 depicts the DSD distribution profiles ((Figure 4(a)-(b))).

The DSD profiles are investigated which reveal that during rain events of the pre-monsoon season, between 2-5 km, the larger drops (>3 mm) depict a sharp decline in their concentrations (Figure 4(a)). Thus, these observations agree with the proposed hypothesis which states that free tropospheric turbulence above the ABL, impacts the rain DSD during intense rain resulting in enhanced raindrops breakup process. On the other hand, during the monsoon season where stratiform rain is more predominant [16], the drop densities are more or less uniform up to 4 km followed by a usual increment corresponding to bright band occurrence around 4.5 km altitude (Figure 4(b)). Thus, it supports the absence of instabilities as observed in convective cases leading to no breakup of larger drops during a monsoon rain event.

Finally, in addition to the rain properties, the thermodynamical features of these two case studies are also presented from the in-situ observations and reanalysis datasets. First, for the pre-monsoon event, high CAPE values are observed (~2.8 kJ/kg) implying the presence of extreme turbulence throughout the free troposphere while for the monsoon event, the values are low (~0.2 kJ/kg) indicating calm weather.

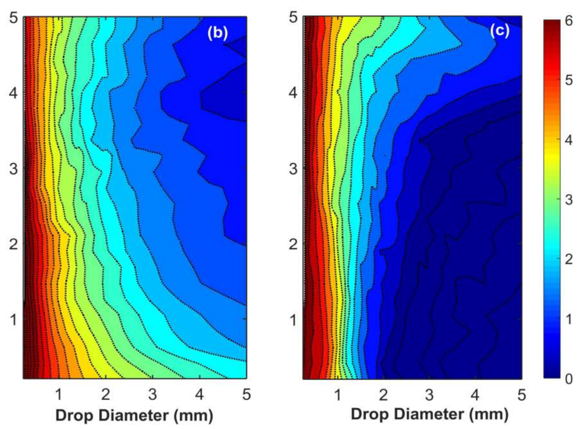

Figure 4. Profiles of (a, b) mean DSD for two rain rate cases on 28 April 2015 (premonsoon) and 08 August 2014 (monsoon)

These observations are further supported by large precipitation accumulation (P_{75}) values (~35.8 mm) for the rain event during the pre-monsoon season in contrast to the monsoon (~0.3 mm). Next, the pre-monsoon season case study depicts significantly higher surface temperatures

(~30.5 ºC) than the monsoon case study (~29.4 ºC) signifying its role behind convective genesis. Also, the lower tropospheric temperature gradient is investigated (T_{1000}-T_{700}) which revealed that the pre-monsoon event on 28 April 2015 experienced a sharper temperature gradient (~19.7 ºC) which is much higher than its monsoon on 8 August 2015 (~14.3 ºC) as expected.

4. Conclusions

The present study highlights the diversity in rain microphysical features prevailing along the rain heights corresponding to the tropical raining environment during the pre-monsoon and monsoon seasons. After extensive investigations, it has been revealed that the usual R-D_m power law relationship observed near the surface gets altered above the boundary layer heights. The deviation of this power law above the boundary layer occurs due to anomalous enhancement in drop break-up over the coalescence process which is more prominent during the pre-monsoon season. Further, it has been unveiled that the turbulent nature of the free troposphere above ABL expressed in terms of CAPE and lower tropospheric temperature gradients during pre-monsoon exhibit a strong impact on the falling rain drops resulting in their enhanced drop breakups.

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