Rain Drop Size Distribution analysis at a tropical location near land-sea boundary

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Abstract:

Rain events can be characterized by rain drop size distribution (DSD) that denotes the number of drops as a function of diameter per unit size interval and per unit volume of space. DSD describes the microstructure of precipitation during different phases of rain varying both spatially and temporally. DSD can be influenced by the nature and origin of rain. The present study investigates the role of continental and maritime airflow in influencing the precipitation features near the land-sea boundary. Rain DSD data used in the present analysis are collected from a ground based disdrometer located at Kolkata, India during the year of 2011-2017. The dataset is divided into two categories namely, maritime and continental rainfall, based on the airflow trajectories associated with rainfall, respectively, from Bay of Bengal and from land surface in the west of Kolkata, as derived from TRAISTAT software. Variations of the DSD parameters using Gamma model is presented showing the abundance of smaller drops during maritime rain events whereas dominance of larger raindrops in the case of the continental rain events. The Z-R relations are also found to be significantly different for these two types of rain. The present study reveals the microstructures of rain at a location where the influences of both land and sea climatic features prevail.

Keywords: Drop Size Distribution, Continental Rain, Maritime Rain, Land-Ocean Boundary, Back Trajectories

Highlights

- Significant differences have been noted for continental and maritime rain near the land sea boundary.
- Abundances of smaller drops in Maritime rain and of larger drops in Continental rain are observed.
- Maritime rainfall shows lower intensity rain than continental rainfall.
- Differences in DSDs between continental and maritime rain become less prominent for increasing rain rate.

1 Introduction

Past studies on rain microstructures are mostly concerned with DSD variations with respect to locations and rain types (Rao et al. 2001; Tokay and Short 1996; Atlas et al. 1999; Rao et al. 2009; Rosenfeld and Ulbrich, 2003). Precipitation process near land-sea boundary has more variability (Singh and Moley 1991; Chakravarty et al. 2013) compared to the land and coastal locations separately. The aerosol transports from both land and ocean have significant influence on rain climatology as reported in earlier studies (Rosenfeld and Lensky, 1998; Radhakrishna et al., 2009; Fuentes et al., 2008). Limited studies are reported on the rain DSD difference due to maritime and continental circulation from a coastal location (Das and Chatterjee, 2018). Rain classification based on land and sea airflow at the locations like the present one (Kolkata, India) has not been investigated adequately. Earlier studies (Maitra et al., 2019; Rakshit et al., 2016; Jana et al., 2018) from Kolkata suggests the location to be important for the study of DSD variations as it is situated near the land-ocean boundary and thereby experiencing a variety of atmospheric processes influencing DSD. The main objective of
this study is to understand the role of continental and maritime air motion that influences the precipitation microstructure near the land-ocean boundary.

Kolkata is located in the eastern part of India which is about 70 km away from the coast of Bay of Bengal. Kolkata experiences a Tropical climate with the Indian summer monsoon. Rain brought by the Bay of Bengal branch of the monsoon gives maximum rainfall which occurs during June-August, the average annual rainfall being 1,582 mm.

![Fig. 1 (a) Geographic location of the experimental site, (b) Monthly average rainfall during the year 2011-2017 at Kolkata](image)

Fig. 1a is the geographical indication of the experimental site, Kolkata, India. Fig.1b depicts the average monthly variation of rainfall during the period of seven years with rainfall occurring mainly in the months of June, July and August. The highest amount of rainfall of about 300 mm in the month July has been recorded.

### 2 Data and Methodology

Rain DSD analysis is done with the dataset collected from a ground-based Joss and Waldvogel (JWD) disdrometer located at the Institute of Radio Physics and Electronics of University of Calcutta (22.5°N, 88.4° E), which is a tropical location near the land-sea boundary during the years 2011-2017. The range of raindrops that the JWD disdrometer measures is 0.3–5.5 mm and it arranges them in 20 bins. Rain in Kolkata is influenced by the wind containing moisture picked up from Bay of Bengal or it can be generated over the Indian landmass (Das et al., 2018; Tenório et al., 2012). The dataset is divided into two subsets namely, maritime and continental rainfall. Rainfall systems coming from the continent moving eastward, represents the continental subset. The other is composed of rainfall systems that developed over Bay of Bengal and moving westward representing the maritime subset. The rain events are segmented into maritime rain and continental rain using the back-trajectory calculation software, namely TRAJSTAT (Draxler and Hess, 1998). The long-distance pathways of airflow responsible for each rain event are traced using the HYSPLIT model (Kassomenos et al., 2010). This analysis of continental and maritime rain has been done with the five days back trajectories at a height of 2000m above sea level over Kolkata. For the present analysis, those dates are chosen where the back trajectory either fully covers the land or the sea.
For comparing DSDs, the number concentration of drop (Rosenfield and Ulbrich, 2003) is modelled with gamma distribution function (Kozu et al., 2006) given as,

\[ N(D) = N_0 D^\mu e^{-\Lambda D} \]  

where, \( N(D) \) (m\(^{-3}\) cm\(^{-1}\)) is the number of drops per unit volume per unit size interval and the parameters \( \mu, \Lambda, \) and \( N_0 \) signify the shape, slope, and intercept of the distribution. The method of moments technique is used for computing the distribution parameters using the following relations (Kozu and Nakamura, 1991).

The \( N_0 \) (m\(^{-3}\)) parameter, is given by

\[ N_0 = \frac{\Lambda^{(m+4)} M_3}{\Gamma(m+4)} \]  

The slope parameter \( \Lambda \) (mm\(^{-1}\)), is given by

\[ \Lambda = \frac{\langle D^{4} \rangle M_4}{M_4} \]  

where \( \mu \) is the shape parameter without dimensions and is given by

\[ \mu = \frac{\langle D^2 \rangle - \langle D \rangle^2}{\Gamma(1-G)} \]  

where \( M_2, M_4, M_6 \), are the 3\(^{rd}\), 4\(^{th}\) and 6\(^{th}\) moments of the drop size distribution.

The rain integral parameters can be estimated using the formula as,

Rain Rate, \( R = \frac{\pi}{6} \cdot \frac{3.6}{1000} \cdot \frac{1}{At} \sum D_i \left( \frac{n_i D_i^2}{V(D_i)} \right) \) (mm hr\(^{-1}\))  

Radar Reflectivity, \( Z = \frac{1}{At} \sum \frac{n_i}{V(D_i)} \cdot D_i^6 \) (mm\(^{6}\) m\(^{-3}\))

Where, \( A \) represent total area of observation, \( t \) denotes time interval between the successive observations, \( n_i \) denotes total number of drops in \( i^{th} \) drop size class, \( D_i \) represent mean diameter of \( i^{th} \) drop size class and \( V(D_i) \) is the fall velocity of a rain drop having diameter \( D_i \).

### 3 Results and Discussions

Case studies have been made for two particular rain events depicting maritime and continental rain. The red line indicates the continental air flow as the wind direction fully covers the land mass before rain occurrence at Kolkata, while the blue line corresponds to the maritime airflow as the wind contains trajectory coming from Bay of Bengal indicating it picked up moisture from the sea surface. This analysis has been done to study the differences in rain DSD characteristics of maritime and continental rain as indicated by the wind trajectories.
Fig. 2 Back trajectories of wind regenerated by Trajstat for a single day of maritime (October 20, 2017) and continental rain (October 25, 2017)

Fig. 3 (a) Rain drop size distribution, and (b) rain rate variation during a maritime rain event on October 20, 2017
Rain drop size distribution has been studied for rain originating from sea and land separately for two such typical days in the month of October, 2017. It is seen that for similar rain rates which are around 40-60 mm/h, the rain drop size distributions do not show the same pattern. Based on the trajectory wind directions on October 20, it was identified as a maritime rainy day. In the figure the colour bar indicates the number of rain drops. The DSD variation pattern shows the abundance of drop sizes from 1 to 2 mm and the presence of drop sizes above 3 mm is marginal. This clearly indicates that this particular rain event has abundance of small rain drops than large rain drops. On another day, when the back trajectory to the present location covered the landmass, the rain event is identified as a continental type and the DSD variation is investigated for this event.

Fig. 4 (a) Rain drop size distribution, and (b) rain rate variation during a continental rain event on October 25, 2017

In this event, the significant presence of large raindrops above 3 mm size is noticed and raindrops as large as 5 mm also occurs. This indicates that the event has higher number of larger drops compared to the earlier maritime rain event. This analysis of two rain events of continental and maritime type prompts us to a further investigation with a large number of rain events for the period of seven years 2011-2017.
In the Fig. 5, those days on which the back trajectories covered the landmass during 2011-2017 have been considered for the analysis of continental rain. The wind directions of the different days are indicated with different colors in the figure.
Again, maritime rain has been considered on those days on which wind trajectories are from Bay of Bengal and Indian Ocean during the entire period of 2011-2017 as shown in Fig. 6. trajectories being indicated by different colours.

Raindrops in continental rainfall grow in the form of ice particles. In contrast, raindrops of maritime rainfall grow by the collision–coalescence mechanism (Suh et al. 2016). So, the mass-weighted drop diameter of continental rainfall observed on the ground is larger than that of maritime rainfall. Specific heat is a major climatological feature that creates differences between DSDs in maritime and continental regions. As these two regions have different thermal capacities, there might be a significant variations of DSDs in these two types of rain. Distinguishable DSD variations for maritime and continental rain are studied for different rain rates for the period 2011-2017.

Fig. 6 Back trajectory wind directions regenerated by Trajstat for maritime rain.
To investigate the DSD differences between maritime and continental rainfall, six rain rate classes namely (0 < RR < 2, 2 < RR < 4, 4 < RR < 8, 8 < RR < 16, 16 < RR < 32 and RR > 32 mm/h) are considered by following the rain rate classification criterion of Tokay and Short (1996). For each rain rate class, DSD variations are depicted in Fig. 7. In the first rain rate class (Fig. 7a), 0 < RR < 2 mm/h, small-size drops (D < 1 mm) have higher a concentration in maritime than in continental rain and a reverse pattern is observed for the midsize to large drops (D \geq 1 mm). Raindrops of diameter smaller than 1 mm have a lower concentration, and raindrops larger
than 1.2 mm have a higher concentration in continental as compared to maritime rainfall in the second rain rate class \(2 < RR < 4 \text{ mm/h} \) (Fig. 7b). In third rain rate class \(4 < RR < 8 \text{ mm/h} \), raindrops of diameter less than 1.4 mm are more in maritime than continental rainfall, and raindrops with diameter above 1.4 mm diameter are more in continental than maritime. Raindrops above 1.6 mm diameter have a higher concentration in continental than maritime in the fourth rain rate class \(8 < RR < 16 \text{ mm/h} \). In the remaining two rain rate classes \(16 < RR < 32 \text{ mm/h} \), \( RR > 32 \text{ mm/h} \), continental rainfall has a higher concentration than maritime for the raindrops above 2-mm diameter. For both cases, with the increase in rain rate, the breadth of DSD shape increases, the tail of DSD shifts toward the larger diameter, and the concentration of small drops decreases (Fig. 7). It may also be noted that the difference of DSD in continental and maritime rain reduces with increase of rain rate.

3.1 Mass Weighted Mean Diameter

![Distribution curve of Mass Weighted Mean Diameter (\( D_m \))]()

Mass weighted drop diameter, \( D_m \) (Suh et al. 2016) is obtained as the ratio of fourth to third moment of DSD (Seela et al. 2018).

\[
D_m = \frac{M_4}{M_2}
\]

(8)

The distribution curve of \( D_m \) is distinctly different for maritime and continental rain. Peak PDF values for maritime rain is around 1.3 indicating dominance of smaller diameter raindrops while for continental rain the peak PDF value is nearly 2. The broader peak of occurrence probability for continental rain also shows that this type of precipitation is subject to wider atmospheric variation compared to maritime rain.
3.2 Z-R Relation for Continental and Maritime Data Subsets.

![Graph showing Z-R relations for Continental and Maritime Data Subsets.](image)

**Fig. 9** Radar rainfall estimation plots for both Continental and Maritime rain

The Z-R relations can indicate microphysical process involved with raindrops. A difference in the DSD between Continental and Maritime rainfall event implies that the parameter $A$ and $b$ of the radar rainfall estimation relation $Z = A R^b$ will also vary due to geographic location, atmospheric condition, and type of instrument (Campos and Zawadzki, 2000; Rosenfeld and Ulbrich, 2003; Das and Maitra, 2018).

The coefficient $A$ indicates the size of the drops (larger $A$ for larger drops) and the power $b$ indicates the influence of drop size and number concentration. A larger $b$ (greater than 1) signifies size or mixed controlled case, namely collision and coalescence, whereas $b \sim 1$ signifies number-controlled case (collision, coalescence and breakup) that produces equilibrium DSD (Atlas et al., 1999; Rosenfeld and Ulbrich, 2003; Steiner et al., 2004).

A clear difference in coefficient ($A$) and exponent ($b$) values of Z-R relations can be noticed between continental and maritime rainfall from the above figure. The radar rainfall relation for continental rain is $Z = 446.4 R^{1.261}$ and that of maritime rain is $Z = 270.7 R^{1.167}$ which depicts that continental rain has higher $A$
value than maritime rain. This reveals that continental rain mainly is mostly composed of moderate to large drop size raindrops, while small drops are dominant in maritime rain.

### 3.3 Gamma Model Parameter Analysis

As already mentioned, the gamma DSD parameters, \((N_0, \mu, A)\) could be effectively used to study the natural variations in the characteristics of precipitation (Seela et al., 2018). Variations of the gamma parameters with rain rate has been studied, to inquire the difference between continental and maritime rain and are shown below.

### 3.4 Variation of \(N_0\) with Rain Rate

![Variation of \(N_0\) with Rain Rate](image)

**Fig. 10** Variation of \(N_0\) versus \(R\), for Continental and Maritime rain.
Estimation of total rain drop number with rain rate is done using the power law relation, \( N_0 = A R^b \), where \( A \) denotes the total number of drops and \( b \) denotes the microphysical process. From fig.10c it is seen that coefficient \( A \) is 0.4002 for continental rain and 0.7311 for maritime rain, indicating that more number of drops are present in maritime than in continental rain. The values of \( b \) also differ for both the rain types depicting the difference in microphysical process.

3.5 Variation Of \( \mu \) and \( \Lambda \) With Rain Rate

![Graphs showing variation of \( \Lambda \) and \( \mu \) with rain rate for continental and maritime rain.]

Table 1. \( \Lambda \) and \( \mu \) relation with rainfall for continental and maritime rain.

| Rain Type          | \( \Lambda \) relation | \( \mu \) relation |
|--------------------|------------------------|--------------------|
| Continental Rain   | \( \Lambda = 12.64 R^{0.4886} \) | \( \mu = 11.43 R^{0.3792} \) |
| Maritime Rain      | \( \Lambda = 18.77 R^{0.429} \) | \( \mu = 14.23 R^{0.3456} \) |

The \( \mu \) parameter describes the breadth and the shape of the DSD where less (greater) than 1 denotes concave upward (downward) shape and zero denotes an exponential shape (Ulbrich, 1983). The \( \Lambda \) parameter describes the truncation of the DSD tail along \( D \) i.e. a larger (smaller) \( \Lambda \) truncates the DSD towards smaller (larger) \( D \). Larger \( \mu \) and \( \Lambda \) values in maritime than continental indicates a narrower DSD shape, and this characteristic can be seen in Fig. 11.

4 Conclusion

In this study, maritime and continental rainfall showed some contrasting characteristics. The dataset of DSD spanning over 7 years and measurement with a disdrometer over Kolkata revealed less intense rainfall occurring in maritime rain compared to continental rain. Mean raindrop concentration of both the rain clearly shows a demarcation with dominance of smaller drops in maritime and midsize and larger drops in continental rainfall. The reflectivity-rain rate relation \( Z = 446.4 R^{1.26} \) for continental rain and \( Z = 270.7 R^{1.267} \) for maritime rain also supports the observation. Strong convective activity occurring due to heating of earth’s surface results
in the formation of continental clouds where water vapour gets transferred to higher altitude resulting in rapid
development of ice crystals above the melting layer. Vapor deposition, aggregation, rimming process makes the
ice crystals to grow into large snowflakes occurring in convective clouds of continental rain. These bigger ice
crystals melt to precipitate as bigger raindrops, which are able to fall and smaller drops, on the other hand, are
lifted up by strong updrafts. An increase in the collision-coalescence process aided by updraft by holding the
small drops aloft results in large values \( D_m \) at the ground. In contrast, since maritime rainfall is linked with small
updraft and downdraft and low melting layer heights, there is no adequate time for the drops to grow bigger in
size as in the continental rainfall, causing smaller size raindrops to dominate compared to continental rainfall.
The present location provides an opportunity to study the microphysics of rain of different origins which are
influenced by atmospheric conditions over land and sea. This has applications in radar-based measurements of
rainfall and in indicating changes in regional climate scenario.

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data collection and analysis were performed by [Pallabi Saha], [Souvik Majumder] and [Animesh Maitra]. The
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Compliance with ethical standards

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Code availability Not applicable.

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