Atmospheric Dynamics related to Precipitation Microphysics near Land-Sea Boundaries: A Comparative Analysis of Monsoon Season in Eastern and Western Regions of India

Gargi Rakshit* (1), Mrutyunjay Mohapatra (1), K.C. Sai Krishnan (1), and Animesh Maitra (2)

(1) India Meteorological Department, Ministry of Earth Sciences, Government of India, New Delhi 110003, India

(2) Institute of Radio Physics and Electronics, University of Calcutta, Kolkata 700009, India

Abstract

This study explores the complex interaction among atmospheric parameters, encompassing instability, airflow patterns, and aerosol environments, impacting cloud microphysics and, consequently, the range of raindrop sizes during the monsoon season (June-September) in the land-sea regions of eastern and western India—namely, Kolkata (22.57°N, 88.37°E) and Desalpar (23.20°N, 69.44°E). In Kolkata, characterized by enhanced atmospheric instabilities, larger raindrops prevail than in Desalpar. The airflow patterns and local anthropogenic activities govern the prevalence of aerosol types and cloud features in these two locations. Notably, there is a significant contrast in aerosol compositions; Kolkata exhibits a higher concentration of sulfate aerosols, while Desalpar is characterized by dust and sea salt aerosols. This investigation highlights that, during the monsoon season, areas with a larger cloud-effective radius tend to experience a prevalence of smaller raindrop sizes. The pronounced variability in the raindrop size spectrum underscores the importance of establishing location-specific radar reflectivity (*Z*) - rain rate (*R*) relationships for reliable radar estimation of rain rates.

1. Introduction

The economic consequences of southwest monsoon precipitation on the Indian subcontinent are far-reaching, significantly affecting the livelihoods of millions. To enhance precision in estimating precipitation and address uncertainties, a comprehensive understanding of rain microphysics, cloud features, atmospheric parameters, and aerosol environments is imperative [1]. The sheer expanse and dynamic nature of the Indian subcontinent give rise to regional disparities in rain climate, resulting in a diverse pattern of precipitation microstructures along the land-sea boundary regions in both eastern and western India [2, 3, 4]. This heterogeneity is influenced by a complex interplay of atmospheric instability, diverse airflow patterns, aerosol environments, and moisture incursions [4]. While existing literature predominantly focuses on the seasonal variability of rainfall in specific areas, there is a significant gap in conducting a comprehensive investigation into the diverse atmospheric processes that govern the distribution of monsoon raindrop sizes in the land-sea boundary regions of eastern and western India [2, 3]. This study explores the fluctuations in raindrop size distribution (DSD) during the monsoon season in Kolkata and Desalpar, which represent the eastern and western regions of India near the land-sea boundary. The investigation specifically assesses the influence of atmospheric instability, quantified as convective available potential energy (CAPE) derived from ERA-5 re-analysis outputs, on the variations observed in the raindrop size spectrum. The characteristics of rainfall which is determined by DSD, are intricately linked to the microphysical attributes of clouds [5]. Additionally, the types of aerosols present play a pivotal role in influencing the distribution of cloud particles [5]. It is reported that the specific aerosol loading characteristics over a particular region are jointly determined by airmass inflow patterns and local anthropogenic activities [3]. Taking these factors into account, this paper examines the contribution of airflow patterns—derived from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model outputs—to aerosol features, utilizing MEERA-2 data. Cloud characteristics which are impacted by the prevailing aerosol environment at these two study locations, are extracted from space-borne measurements of MODIS. Subsequently, the study probes into the influence of varying raindrop sizes on *Z-R* relations, which are pivotal for accurately quantifying precipitation in weather radar and space-borne measurements [6].

In summary, this paper unveils the underlying physical phenomena shaping rain DSD in two geographically distinct locations in India. The findings from this research are essential for applications in radar and radio remote sensing, offering valuable insights into the intricate dynamics of precipitation within these regions.

2. Site meteorology, Data and Methodology

This study focuses on the atmospheric dynamics that impact the variation in rain DSD during the monsoon season (June-September) in two distinct locations: Kolkata

(22.57°N, 88.37°E), a metropolitan capital situated approximately 100 km from the Bay of Bengal coast in eastern India, and Desalpar (23.20°N, 69.44°E), a rural area located about 50 km from the Arabian Sea coast in the western region of India.

The DSD spectrum is estimated using measurements from Joss–Waldvogel disdrometers (JWD, Distromet RD-80) deployed at the two study locations. The disdrometer data for Kolkata are obtained from the Institute of Radio Physics and Electronics, University of Calcutta. Data for Desalpar disdrometer measurement are sourced from the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) data archive, accessible at: https://www.mosdac.gov.in/. JWD is capable of measuring raindrop sizes ranging from 0.3 to 5.5 mm across 20 different bins with an accuracy of approximately 5% [4, 6, 7]. In this study, DSD and rain rate data for the monsoon period spanning three years (2014-2016) are utilized.

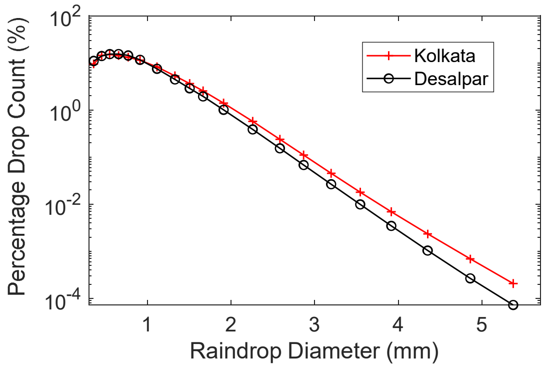

Figure 1. Percentage Drop count from disdrometer measurements over Kolkata (red) and Desalpar (black) during the monsoon season.

In the present study, Level 2 daily data for Cloud (MOD06) from MODIS (Moderate Resolution Imaging Spectroradiometer) available with a spatial resolution of 1 km are used. The cloud parameters are averaged over a spatial coverage of 1°x1°, centering the two study locations: Kolkata and Desalpar. The grid size is considered to obtain sufficient data points. For the present paper, cloud parameters, namely cloud effective radius (*CER*), *μm*, and cloud liquid water path (*LWP*), g/m^2, are obtained from 2014 to 2016. Data on aerosol optical thickness (AOT) for sulfate, sea salt, dust, and organic carbon extinction are derived from the monthly data product of MEERA-2: MERRA2_400.tavgM_2d_aer_Nx. This dataset provides information at a spatial resolution of 0.5°x0.625° encompassing the two study locations examined in the current investigation. Additionally, the assessment of convective available potential energy (CAPE) magnitude in this study is based on daily hourly ERA-5 data, which are available over a grid of 0.25°x0.25°, centered around the two study locations.

To discern the airmass inflow pattern distinctive to Kolkata and Desalpar in the monsoon season (June-September), the HYSPLIT model is employed. Back-trajectories spanning five days at 2000 m Above Ground Level (AGL) are obtained under isentropic conditions. The selection of airmass trajectory clusters is determined by minimizing the difference between trajectories within the same cluster and maximizing the dissimilarity between trajectories in different groups as reported earlier [3, 8].

3. Results and Discussions

3.1 DSD Spectrum Variability Associated with Atmospheric Instability over the Study Locations

To examine the distribution of raindrops of varying sizes over Kolkata and Desalpar, the rain DSD is presented as a percentage of raindrop counts based on ground-based disdrometer measurements (Figure 1). Notably, rain events in Kolkata (depicted in red) show a higher percentage of larger raindrops compared to Desalpar (in black) (Figure 1). Consequently, the prevalence of larger raindrops (>2 mm) is observed during the monsoon period in Kolkata compared to Desalpar. Given that atmospheric instability influences raindrop sizes, the scenario of CAPE (J/kg), obtained from the ERA-5 reanalysis output, is investigated.

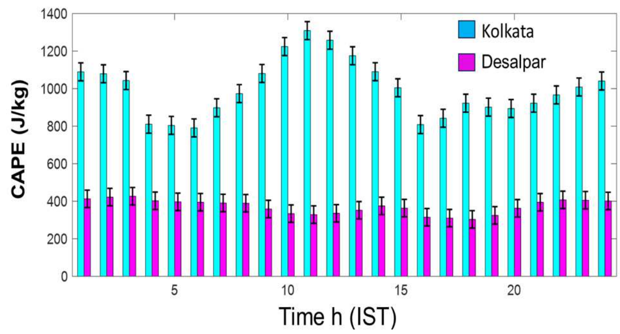

Figure 2. Diurnal variation of mean CAPE values depicted in barplot (with standard deviations) during the monsoon season over Kolkata and Desalpar during the monsoon season.

The mean diurnal variation of CAPE is depicted through bar plots (with standard deviation) in Figure 2, distinguishing between Kolkata (cyan) and Desalpar (magenta). Kolkata experiences elevated CAPE values, signifying higher atmospheric instability, while Desalpar experiences comparatively lower instability. The seasonal mean CAPE values for Kolkata and Desalpar are 913.80 J/kg and 355.20 J/kg, respectively. Diurnal variations are observed in CAPE over Kolkata, but no such patterns are discerned over Desalpar. The intensified updraft associated with higher CAPE enhances the collision and coalescence process during rainfall, leading to an increased likelihood of larger raindrops, as evidenced by the current observations over Kolkata.

3.2 Influence of Airflow Pattern on Cloud Parameters and Aerosol Environment over the two Study Locations

As raindrop sizes are directly influenced by liquid droplets originating from clouds, an investigation into cloud features presented in terms of cloud effective radius is undertaken using space-borne data from MODIS. The boxplot of CER/LWP over Kolkata and Desalpar during the monsoon seasons from 2014 to 2016 is depicted in Figure 3. The normalization of CER with respect to LWP is performed to account for the hypothesis known as the Twomey effect (1977) [9].

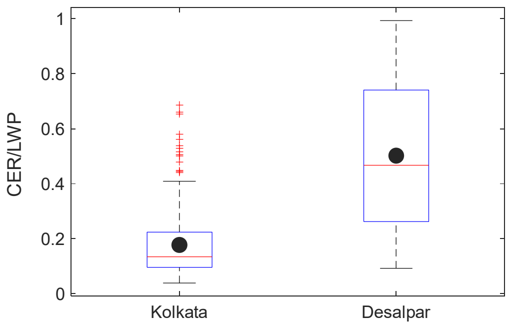

Figure 3. Box and whisker plot of the ratio of cloud effective radius to liquid water path (CER/LWP), (μm/(g/m^2)) over Kolkata and Desalpar estimated from MODIS during the monsoon period (June-September) of three years (2014-2016). The median is denoted by the red horizontal line in the box, mean is shown by a filled circle.

A larger CER/LWP ratio is observed over Desalpar (Figure 3), where comparatively lesser dominance of larger raindrops (Figure 1) and lower atmospheric instability prevails (Figure 2). Conversely, a comparatively smaller CER/LWP ratio is observed over Kolkata (Figure 3), aligning with a higher occurrence of larger raindrops and enhanced CAPE (Figure 2). The higher CER/LWP ratio is expected to be a result of larger cloud condensation nuclei (CCN) sizes. In this context, it may be noted that the seasonal airflow pattern from diverse sources within a particular region governs the aerosol environment at a site [8]. This prompts an investigation into the air mass inflow patterns that characterize the two study locations, Kolkata and Desalpar.

Figure 4 illustrates the clustering of five-day back trajectories over Kolkata and Desalpar throughout the monsoon season from 2014 to 2016, utilizing the HYPLSLIT Back Trajectory model. The diverse origins of air mass inflow are evident across the two distinct study locations. In the case of Kolkata, the influx comprises marine components from the Arabian Sea (56.9%) and the Bay of Bengal (16%) (Figure 4 (a)). Conversely, Desalpar experiences 31.4% of air mass inflow from the southwest Arabian Sea and a significant portion of 45.8% from the Middle East desert region (Figure 4 (b)). Therefore, it is anticipated that the diverse airflow patterns and the varied climatic and anthropogenic influences will be evident in the aerosol environment of the two locations. To explore this relationship, the aerosol optical thickness associated with different aerosol types is estimated from MEERA-2 data for the two study locations during the monsoon season (Figure 5).

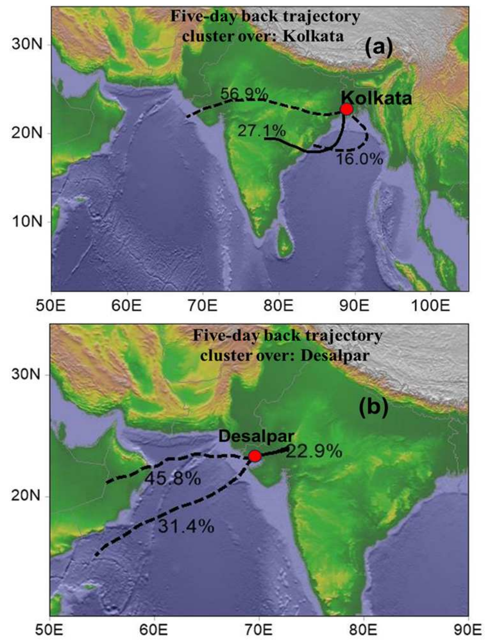

Figure 4. Five-day back trajectory cluster over: (a) Kolkata and (b) Desalpar during monsoon season (June-September) for three years 2014–2016.

Desalpar experiences elevated levels of both sea salt and dust aerosols (Figure 5 (b), (c)). Dust particles, particularly those with a soluble coating, tend to be highly effective as giant CCN generators [3]. Larger-sized dust particles, functioning as large CCN, play a crucial role in initiating drizzle and precipitation [3]. Additionally, sea salt aerosols, being hygroscopic, can generate comparatively larger CCN [3]. In contrast, although the concentration of sulfate aerosols is high over Kolkata (Figure 5(a)), the dust extinction AOT is comparatively lower compared to Desalpar. The organic carbon extinction AOT is high over Kolkata, though its dominance is less compared to other aerosol types over both the study locations (Figure 5 (d)). The presence of sulfate aerosols alone tends to decrease CER by increasing CCN concentration, resulting in a low CER/LWP over Kolkata. Giant aerosols promote the rapid growth of raindrops, causing them to fall through the cloud updraft and consequently enhancing the liquid water content in the lower part of the cloud [3]. Additionally, smaller raindrops correspond to larger CER, as this enhances the collision-coalescence process between raindrops and cloud droplets, inhibiting the growth of raindrop sizes.

Variations in the DSD have a notable impact on the radar reflectivity (Z) and rain rate (R) values, which are estimated based on the 6th and 3.67th moments of the raindrop size distribution respectively [6]. Hence power-law Z-R relations ($Z=AR^b$) for the two study locations namely, Kolkata ($Z=344.6R^{1.301}$), and Desalpar ($Z= 167.4R^{1.536}$) showed distinct variability. The coefficient *A* aids as an indicator of the total number of drop sizes, while the exponent *b* represents the underlying microphysical processes [10]. Notably, both coefficient (*A*) and exponent (*b*) exhibit significant variations near land-sea boundaries in the eastern and western regions of India, even within the same season. Therefore, the present results highlight the need for refining *Z-R* relationships on a region-specific basis to ensure precise estimations of rain rates.

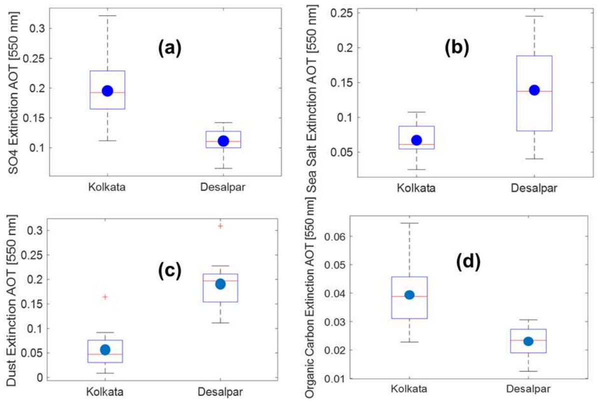

Figure 5. Box and whisker plot of aerosol extinction AOT for: (a) SO4, (b) Sea salt, (c) Dust extinction, and (d) Organic carbon over the two study locations obtained from MEERA-2 during the monsoon season (2014-2016).

4. Conclusions

This study presents a concerted multi-technique examination of the associated atmospheric parameters impacting the variability of precipitation microstructure over the eastern and western regions of India near land-sea boundary during the monsoon unraveling the following:

I. Raindrop size distribution differs between the land-sea boundary regions of eastern (Kolkata) and western (Desalpar) India during the monsoon. Kolkata, with higher CAPE values, exhibits larger raindrop sizes than Desalpar.

II. The inverse relationship between *CER* and raindrop size is evident, as *CER/LWP* is low over Kolkata, indicating a higher occurrence of larger raindrops, while Desalpar shows higher (lower) *CER/LWP* (raindrop size) values.

III. Various air mass inflow patterns, anthropogenic activities, and geographic locations impact aerosol properties, cloud features, and as a result raindrop size over Kolkata and Desalpar.

IV. Significant variations in *Z-R* power law relations between these two locations are crucial for accurate quantitative precipitation estimation in radar remote sensing applications and for calibration purposes.

This comprehensive investigation into the variability of rain microstructure during the monsoon across diverse regions of India advances our comprehension of atmospheric dynamics. The acquired insights facilitate predictions pertaining to water recharge, surface runoff, and vegetation stress, contributing valuable input for the development of regional climate models crucial for operational meteorology.

5. Acknowledgements

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