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Integrated Multi-Sensor Observations of Tropical Rainfall and Atmospheric Processes

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Abstract

Tropical rainfall is a key driver of Earth's energy, water, and biogeochemical cycles, yet its variability and complex microphysics make it difficult to characterize. In this study, we integrate ground-based, remote-sensing, and satellite observations to investigate rainfall dynamics over Kolkata, a natural monsoon test-bed at the head of the Bay of Bengal. Using microwave radiometry, micro rain radar, disdrometers, and environmental sensors, we examine convective precursors, raindrop size distributions, radar bright-band features, atmospheric instability, and nowcasting algorithms. Results highlight that no single instrument can adequately capture rainfall evolution; however, integrated systems improve predictive skill and microphysical consistency. This framework advances understanding of tropical convective event formation, convective-stratiform partitioning, and rainfall impacts on satellite communication, while supporting more reliable forecasting in monsoon-dominated regions.

Keywords : *Tropical precipitation, Multi-sensor observation, Raindrop size distribution, Radiometric nowcasting*

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1. Introduction

Tropical rainfall is central to Earth's climate through its regulation of the global energy and water cycle. Precipitation in these latitudes is dominated by deep convection, mesoscale convective systems, monsoon circulation, tropical cyclones, and synoptic disturbances originating from ocean-continent interactions. Despite its significance, the characterization and prediction of tropical rainfall remain among the most complex challenges in atmospheric science. This difficulty arises from the rapid temporal evolution of convective cells, the heterogeneity of microphysical processes, the interplay between thermodynamic instability and dynamic forcing, and the influence of aerosols on cloud formation and precipitation efficiency. Tropical rainfall constitutes a major driver of global climate variability but remains challenging to characterize due to the rapid evolution of its convective systems

In addition, accurate rainfall prediction is of high socio-economic relevance for regions dependent on the monsoon for agriculture, hydroelectric resources, and drinking water supply, as well as for populations exposed to flash floods, urban flooding, and land falling tropical cyclones. Beyond socio-economic concerns, tropical rainfall imposes technological challenges relating to the design of satellite communication systems at microwave and millimetre-wave frequencies.

Kolkata (22.65⁰N, 88.45⁰E) serves as an ideal geographic test-bed for these studies due to its position near the head of the Bay of Bengal. It sits at a critical interface where hot, dry continental airflows from the Chotanagpur Plateau interact with warm, moist maritime flows from the sea. This convergence zone consistently boosts Convective Available Potential Energy (CAPE), fuelling intense atmospheric instability. The region is famous for "Nor'westers" - violent thunderstorms that occur during the pre-monsoon season. Additionally, as a major metropolis, Kolkata introduces a significant anthropogenic aerosol load, providing a unique opportunity to study the interactions between urban aerosols, cloud formation, and precipitation.

2. Analysis and Results

2.1 Tropical Atmospheric Setting and Rainfall Regimes

The tropical atmosphere is governed by large-scale phenomena such as the Hadley circulation, monsoon dynamics, tropical easterly waves, and intra-seasonal oscillations, as well as mesoscale processes including sea breezes, land breezes, and convective complexes. Kolkata (22.65°N , 88.45°E) serves as an ideal geographic test-bed for these studies due to its position near the head of the Bay of Bengal (Figure.1). It sits at a critical interface where hot, dry continental airflows from the Chotanagpur Plateau interact with warm, moist maritime flows from the sea. This convergence zone consistently boosts Convective Available Potential Energy (CAPE), fueling intense atmospheric instability. The region is famous for "Nor'westers" - violent thunderstorms that occur during the pre-monsoon season. The monsoon season is dominated by widespread stratiform and embedded convective precipitation, often associated with monsoon depressions and low-pressure systems. The post-monsoon period supports tropical cyclone development, making the region one of the most active basins for cyclogenesis.

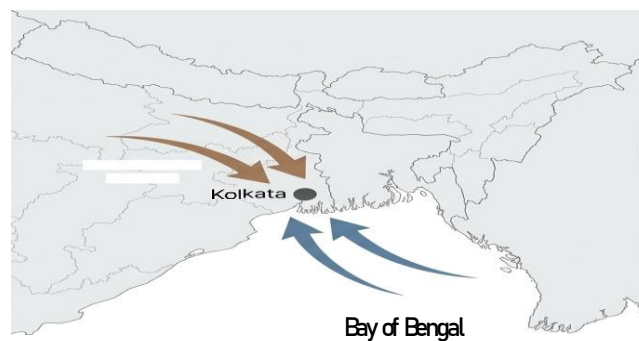


Figure 1 : Location of Kolkata at the critical land - sea boundary near the Bay of Bengal , creating a convergence zone for distinct air masses.

Tropical rainfall can be broadly categorized into convective and stratiform types. Convective rainfall, typically associated with continental air masses, forms under strong vertical updrafts that enhance hydrometeor residence time and microphysical growth, resulting in broader drop size distributions with larger characteristic diameters and extended large-drop tails. In contrast, stratiform rainfall, commonly linked to maritime air masses, develops under weaker vertical drafts and lower melting layer heights, producing narrower distributions dominated by small drops, generally below 2 mm. Typical drop size distributions of convective and stratiform rain are shown in Figure 2. These contrasting DSD characteristics indicate that vertical draft intensity is a primary control on precipitation microphysics (Majumder et al., 2016), making raindrop size distributions an effective diagnostic of the underlying dynamical regime and essential for accurate radar and satellite rainfall estimation (Das et al., 2016; Das and Maitra 2018)

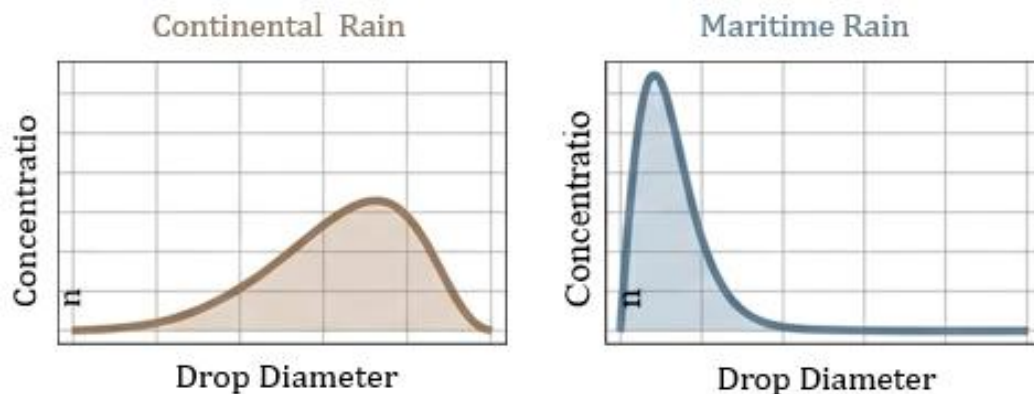


Figure 2: Typical drop size distributions during convective and stratiform rain.

This distinction also carries implications for latent heat release profiles, cloud microphysics, and remote sensing retrieval performance. Although convective rainfall occupies only approximately ten

percent of rainfall time, it can contribute more than half of the total rainfall accumulation in Kolkata. A defining radar signature of stratiform rainfall is the bright band, a localized enhancement in reflectivity that occurs at the melting layer where ice particles transition to liquid hydrometeors. In convective rain, strong vertical motions prevent the formation of the bright band (Figure. 3).

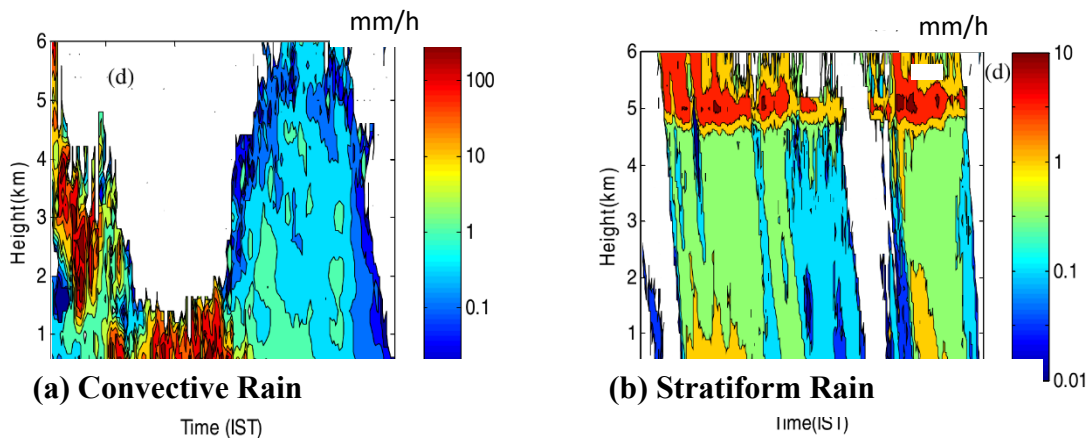


Figure 3 : Radar signatures show (a) no bright band in Convective rain and (b) presence of bright band during Stratiform rain.

2.2. Multi-Sensor Observational Framework and Instrumentation

Due to the multifaceted nature of tropical rainfall, no single sensor can provide complete observational coverage of the coupled processes governing cloud formation, precipitation evolution, and hydrometeor fallout. The Institute of Radio Physics and Electronics at the University of Calcutta employed a comprehensive suite of ground-based, remote sensing, and satellite-integrated instruments (Figure. 4) to observe the tropical atmosphere (Maitra et al., 2014, 2016). These instruments include the multi-frequency microwave radiometer, micro rain radar, Joss-Waldvogel disdrometer, laser precipitation monitor, optical rain gauges, GPS receivers, electric field mills, and sun photometers,

among others (Sarkar et al., 2015). Each instrument contributes information from a distinct physical perspective, and the integration of these data sources yields a holistic view of atmospheric processes that would be otherwise inaccessible.

Microwave radiometers such as the RPG-HATPRO operate as passive remote sensing instruments that measure atmospheric brightness temperatures at multiple frequencies. Channels in the 22–31 GHz band are sensitive to atmospheric water vapor, while channels in the 51–58 GHz oxygen absorption band provide temperature profiling capability. The radiometer offers continuous temperature and humidity profiles up to approximately 10 km altitude with high temporal resolution.

The micro rain radar (MRR) is an active vertically pointing Doppler radar operating at 24.1 GHz. It transmits electromagnetic pulses upward, measures backscattered power from hydrometeors, and retrieves Doppler spectra, from which drop size distributions, rain rate profiles, and vertical reflectivity profiles can be derived.

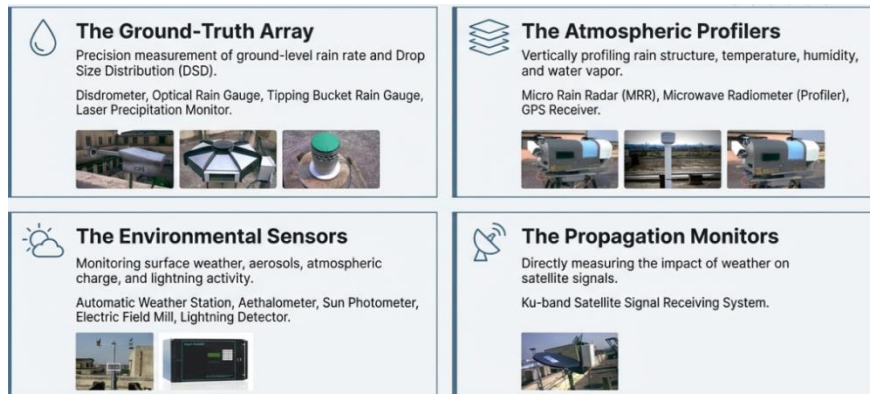


Figure. 4: Multi-sensor array at the Institute of Radio Physics and Electronics, University of Calcutta, used for comprehensive observations of the tropical atmosphere.



2.3 Atmospheric Thermodynamics and Instability Mechanisms

Understanding the thermodynamic environment preceding rainfall is essential for interpreting subsequent microphysical and dynamical evolution. Instability indices such as CAPE, Lifting Index, K-Index, and Total Totals Index quantify the buoyancy of air parcels and the likelihood of thunderstorm development. The microwave radiometer enables the retrieval of temperature and humidity profiles with sufficient temporal resolution to observe the growth of instability prior to rainfall. For instance, brightness temperature measurements at water-vapor-sensitive frequencies increase before precipitation onset due to enhanced cloud water path and pre-convective moistening. Brightness temperature variations at 22 and 31 GHz act as early indicators of rain and can precede rainfall by more than one hour (Chakraborty et al, 2014, 2016; Maitra and Chakraborty, 2018). This makes radiometric measurements valuable for convective nowcasting applications.

Atmospheric relative humidity profiles also reveal pre-convective signatures. During intense convective events in Kolkata, anomalous decreases in relative humidity have been observed in the 1-2km altitude range within the boundary layer. These anomalies may be explained by entrainment of dry air into convective updrafts, the release of latent heat, and the removal of moisture through hydrometeor fallout. Such anomalies were detected during strong convective scenarios and linked to thermodynamic processes as well as aerosol influences. These observations suggest that aerosol-thermodynamics feedbacks represent a non-negligible component of tropical rainfall variability.

2.4 Precipitation Microphysics and Rain Drop Size Distributions

Raindrop size distributions offer insight into cloud microphysical processes and are fundamental to both remote sensing retrievals and hydrological modelling. In continental convective environments, strong updrafts support the growth of large ice particles aloft, which melt into larger raindrops upon



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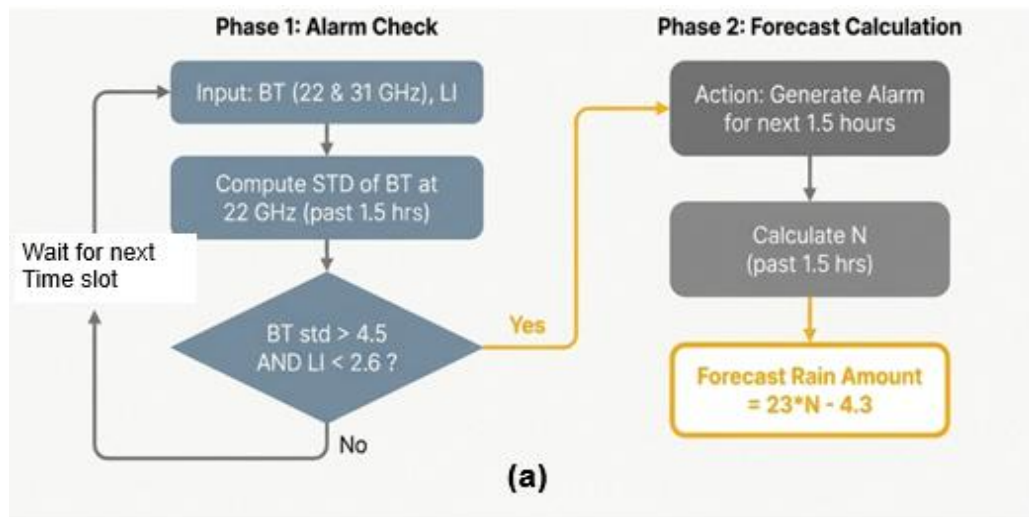
descent. Conversely, maritime stratiform rain is typically associated with weaker updrafts and lower melting layer altitudes, yielding a distribution dominated by smaller drops. This results in larger median volume diameters in continental convective rainfall and smaller diameters in maritime stratiform rainfall. These microphysical differences translate into disparate radar reflectivity signatures, since reflectivity is proportional to the sixth power of drop diameter.

Vertical profiling from the MRR reveals additional microphysical signatures associated with intense tropical convection. One notable feature is a localized decrease in radar reflectivity near altitudes of approximately 1–2 km during high rain-rate events (Rakshit et al., 2024). This reflectivity dip is attributed to the breakup of large drops as they descend through regions of strong vertical wind shear and turbulence within the atmospheric boundary layer (Maitra et al., 2019). The breakup process redistributes mass from larger to smaller drops, altering the DSD and reducing reflectivity despite sustained rainfall intensity (Fig.5). Such vertical microphysical variability cannot be captured by surface measurements alone and highlights the value of radar-based profiling in understanding precipitation processes

Modelling of DSDs is frequently performed using three-parameter gamma or lognormal distributions. While the gamma model is widely used, the lognormal model often provides superior fits in maritime stratiform precipitation where small drops are abundant but large drops are rare. Studies in Kolkata suggest that the lognormal distribution better represents lower number densities of small drops compared with the gamma distribution in tropical rainfall regimes (Maitra, 2000). Such microphysical modelling advances improve the accuracy of radar Z - R relationships and satellite retrieval algorithms, particularly in heterogeneous tropical environments.

To enhance predictive reliability, a two-step nowcasting algorithm has been developed (Maitra and Chakraborty, 2018). The first step triggers an alarm if the standard deviation of BT at 22 GHz exceeds 4.5 and the Lifting Index (LI) falls below 2.6. Once the alarm is active, the second step utilizes the Normalized BT variation (N) at 31 GHz to estimate the quantity of rain accumulation using the regression formula: $\text{Rain Amount} = 23 \times N - 4.3$.

This nowcasting methodology is shown schematically with a case study in Figure. 5. This composite model achieves a detection efficiency of approximately 80% with an actionable lead time of about 75 minutes.



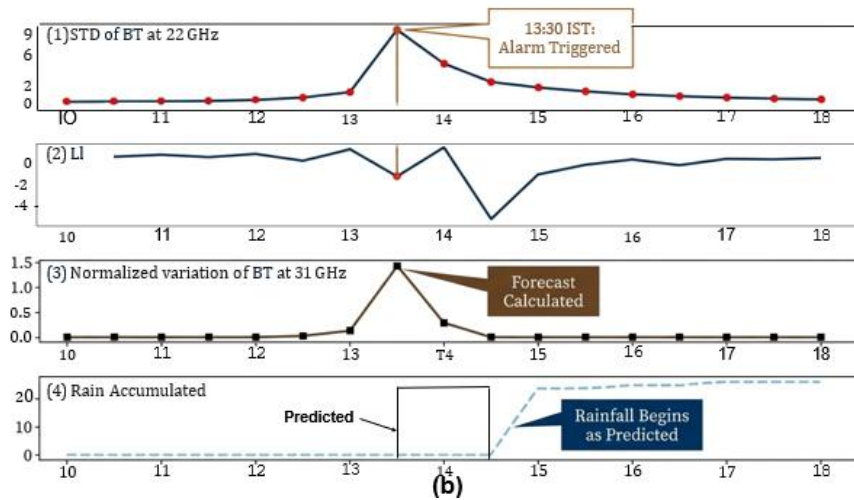


Figure. 6: (a) Two-step methodology for nowcasting rainfall amounts during events with a 1–2-hour lag, and (b) validation of the methodology through a case study of a rain event.

2.6 Radio Propagation and Satellite Communications Implications

Rainfall affects satellite communication systems through attenuation, depolarization, scattering, and scintillation. The severity of attenuation depends on rain rate, drop size distribution, and path geometry. Fig. 6 indicates gas attenuation, cloud attenuation, rain attenuation, depolarization, and tropospheric scintillation as relevant mechanisms affecting satellite links in tropical environments. Improved microphysical characterization enables more accurate prediction of propagation effects (Maitra, 2004) and supports adaptive fade mitigation techniques such as power control, coding

schemes, and diversity. Therefore, integrated multi-sensor rainfall studies offer tangible benefits to telecommunication system design.

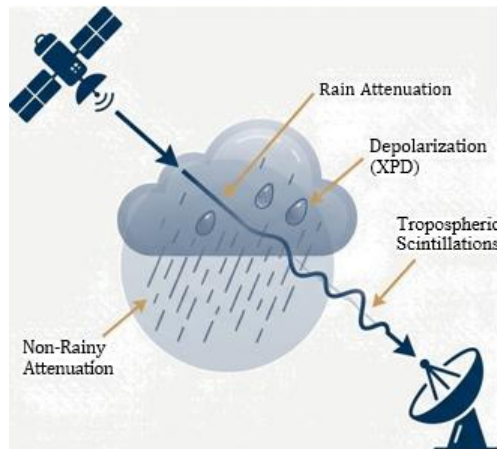


Figure. 7: Tropical rain's Impact on Satellite Communications: radio wave propagation impairments include rain attenuation, non-rainy attenuation, depolarization and scintillations.

3. Discussion and Conclusions

The present study demonstrates that an integrated multi-sensor observational framework is essential for advancing the understanding and prediction of tropical rainfall over the Kolkata region. Passive microwave radiometry, active radar profiling, surface disdrometer measurements, and satellite observations each provide complementary insights into the atmospheric system; however, physically consistent interpretation emerges only through joint analysis of these datasets. Radiometric observations reveal systematic increases in water-vapor and liquid-water sensitive brightness temperatures preceding rainfall onset, underscoring the importance of evolving thermodynamic



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preconditioning rather than instantaneous instability thresholds in convective initiation. Microphysical analyses highlight pronounced regime dependence: convective rainfall is characterized by broader drop size distributions and larger characteristic diameters, whereas stratiform rainfall exhibits narrower spectra and distinct melting-layer signatures. A notable feature during intense convective episodes is a localized reduction in radar reflectivity near 1–2 km altitude, attributed to enhanced breakup of large drops within the boundary layer, emphasizing the role of near-surface dynamics in modulating precipitation structure.

Radiometer-based nowcasting further demonstrates that physically interpretable precursor signals can yield actionable lead times of approximately one to one and a half hours for convective rainfall prediction.

Rainfall degrades satellite links through propagation effects such as, attenuation, depolarization, and scintillation. Enhanced microphysical characterization improves propagation predictions and supports adaptive mitigation strategies underscoring the value of multi-sensor rainfall studies for satellite communication link design.

These outcomes provide means for advancing precipitation science, supporting satellite communication system design, and informing hydrometeorological risk management in the tropics. The overarching conclusion is that a holistic understanding of tropical rainfall processes can only be achieved through the integration of ground-based sensors, satellite remote sensing, and large-scale atmospheric models.



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