

Research Paper

On the association between lightning and precipitation microphysics

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ABSTRACT

Lightning is one of the most important extreme weather conditions and is associated with heavy convective rain and thunderstorms. However, the present understanding of such systems as well their effect on precipitation characteristics are insufficient for proper modelling. In this paper, the rain microphysics is studied at Kolkata using an optical disdrometer in relation to the lightning activities. Lightning information is obtained from ground based World Wide Lightning Location Network and Lightning Imaging Sensor onboard International Space Station. The associated cloud features are studied with Doppler weather radar and MODIS satellite measurements. Results indicate significant change in rain microphysics between events with lightning and without lightning. The cloud microphysics indicates that the cloud top temperature is lower and cloud effective droplet size is smaller in case of lightning in comparison to non-lightning situation. On the other hand, large drops are abundant while small drops are less in numbers in rain with lightning than rain without lightning. The a value in Z-R relation is found to be significantly higher for rain with lightning than other type. The rain attenuation is also found to have significant variation under these two conditions. The implication of such varied rain microphysics on GPM Ku and Ka band radar are also reported.

1. Introduction

The lightning in recent past has become a serious concern for the atmospheric researchers. Lightning is one of such extreme weather events whose frequency and intensity are projected to increase under climate change scenario (Romps et al., 2014). The lightning and thunderstorms are usually associated with flash flood and heavy rain. These not only pose serious challenges to aviation sector, but also leads to loss of life and property. Hence, the proper understanding of lightning and associated rainfall as well accurate quantitative precipitation estimation (QPE) from remote sensing observations are of practical importance for disaster management as well urban drainage system planning purpose.

The knowledge of the microphysical structure of convection forming cloud is essential in order to predict a severe weather event. Study of lightning activity provides a pathway for studying convection (Roberto et al., 2016). Several researcher have tried to correlate lightning with the cloud microphysical parameters (Makela, 2004; Molinie and Jacobson, 2004). The variability of such correlation, however, has case dependency. This also have significant dependence on the environmental condition and initial perturbation responsible for cloud stimulation (Betz et al., 2013). Cloud top temperature reportedly has a negative correlation with the lightning whereas, the columnar ice

content in a cloud is found to correspond positively with the lightning flash rate (Solomon et al., 2003) The vertical distribution of ice particles also has a significant correlation with number of lightning flashes (Buiat et al., 2017) The flash rate, however, shows varied relation during different phases of development in mesoscale system like hail storm (Emersic et al., 2011).

On the other hand, lightning and microphysical parameters of rain are also reported to be well correlated. Strong inter-dependence has been observed between rain drop size distribution (DSD) characteristics and number of lightning flashes (Saylor et al., 2005). However, rapid change of rain DSD both in space and time is evidenced in convective thunderstorm. The updraft of such severe events are usually associated with large rain drops or groupel. Whereas, the spatial distribution of rain seems to have a negative correlation with cloud to ground lightning (Sun, 2019). Precipitation production in a convective system is also found to be well correlated with the polarity of lightning activity (Soula and Chauzy, 2001). Positive cloud-ground flash events correspond to higher rainwater volume than a negative one. The diurnal and seasonal cycle of convection and lightning has a noteworthy correspondence with higher rain rates in a rain intensity distribution. Strong correlation is reported between cloud-to-ground lightning density and the shape parameter. Several studies (Gungle and Krider, 2006; Zhou et al., 2002)

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have reported significant correlation between rainfall amount and number of lightning strikes.

The consequence of significantly varied rain microphysical parameters between lightning and non-lightning conditions can be very important for radar remote sensing of rainfall. As radar reflectivity is usually converted to rain intensity through a modelled equation, any variation of the model parameters will lead to decrease in accuracy of QPE. The rain attenuation in high frequencies will also be significantly different in that situation. It can offset the advantages of having two-frequency band radar in Global Precipitation Measurement (GPM) satellite if the DSD shape varies widely between lightning and non-lightning conditions. Several authors have worked on the behavioral difference of the relation between radar reflectivity, rain attenuation and intensity for stratiform and convective rain (Battan, 1973; Das and Maitra, 2017; Kozu et al., 2009; Thurai et al., 2016). However, there are not much studies on rain microphysical behaviour under lightning conditions.

The land region of ITCZ in eastern region plays an important role in maintaining a high temperature difference with the sea which helps in formation of convective systems. This, in turns, makes this region prone to frequent lightning flashes (Tinmaker and Chate, 2013). It is important to identify and track the growth of a major convective system in its early stages which often lead to severe thunderstorms. Satellites provide the measure of instability in convective system in shorter intervals of time. The lightning, however, can give real time information on the development of convection in the system. The area of convective system is directly proportional with the lightning activity. The maximum average lightning density is observed in initial life cycle of convective system whereas, average lightning life cycle is related with maturation of the convective system (Mattos and Machado, 2011).

Studies on relation between lightning and rain/cloud microphysics are, limited over Tropics, particularly at ITCZ region. In this paper, for the first time, rain microphysical behaviour with lightning has been reported from a ITCZ region, Kolkata (22.57° N, 88.36° E), India. The rain has been measured using an optical disdrometer. Lightning observations are made by Lightning Imaging Sensor (LIS) onboard International Space Station (ISS) and ground lightning network WWLLN. Associated cloud features are taken from MODIS (Moderate Resolution Imaging Spectro radiometer) on board TERRA satellite. INSAT -3DR imagery is used to understand the large-scale cloud system developed during the events. Further, the India Meteorological Department (IMD) Doppler radar is used to study the precipitation structure with a close-range observation.

2. Data and methodology

2.1. Instruments

The DSD measurement is carried by a laser based optical disdrometer (OTT Parsivel2) installed at Indian Statistical Institute, Kolkata. Kolkata is situated in the lower Ganges delta of eastern India on the bank of Hooghly River (Fig. 1). Kolkata is a tropical location in the ITCZ region. The city has a tropical wet and dry climate with an annual mean temperature of 24.8 °C. Kolkata gets most of its rain during June–Sept due to the south eastern monsoon wind. The average annual rain is about 1600 mm. Kolkata reportedly gets 70 thunderstorm days/year on an average.

The disdrometer used, is a particle size and velocity measuring device which is capable of measuring rain drops within a diameter range of 0.062 mm–24.5 mm and a velocity range of 0.05 m/s–20.8 m/s binned in 32 × 32 diameter and velocity classes. It generates a horizontal laser beam from the transmitter to receiver. Raindrops, depending upon their size, reduce the voltage at the receiver by blocking the beam. The magnitude of this voltage reduction gives the rain drop size whereas, the time span of this voltage reduction provides the particle speed. The two main limitations of Parsivel disdrometer are complementary to each other. Firstly, the sampling area is limited and secondly, there is a

possibility of getting multiple rain drops at a time in the sampling area. In practice, the chances of multiple drops at a time is reduced by achieving a smaller sampling area of ~54 cm². However, there still remains a small possibility of getting multiple drops simultaneously. This results in impractically large drop measurements. So, the drops with diameter >5 mm are discarded. The integration time of the measurements is fixed as 60s to reduce the statistical uncertainty. Parsivel disdrometer provides a limited accuracy in detecting drops smaller than 1 mm, however, the Parsivel 2 gives a significantly improved accuracy over the previous version of Parsivel 1 (Tokay et al., 2014).

The lightning information is primarily collected from a ground network WWLLN, and used along with the LIS observation. WWLLN is a global lightning network managed by University of Washington with 70 stations around the globe at VLF band. The network detects the lightning location along with the energy in every strike (Lay et al., 2004) by measuring the spheric in the VLF band due to a lightning flash from 3 or more stations. On the other hand, LIS onboard International Space Station measures the lightning at 777 nm with a help of CCD camera within the latitude range of ±48°. It has a resolution of 4 km at nadir and 8 km at limb in a 500 km swath. Unlike ground network, any point on the Earth is observed by LIS only for about 90 s in a single measurement.

MODIS level 2 cloud products have been used for the cloud properties. MODIS is a 36 band (in IR, near IR and visible range) imaging instrument on board Aqua and Terra satellites which regularly provided information about global neutral atmospheric dynamics. Cloud droplet size and cloud top temperature parameters estimated from visible and IR radiance are used in the present study. The cloud effective radius is available with 1 km resolution whereas the cloud top temperature is obtained with a resolution of 5 km.

Wind speed data is collected from the Automatic weather station situated at Kolkata airport within an aerial distance of 6 km. Qualitative indication of large scale cloud system is obtained from 10.6 μm brightness temperature from INSAT-3DR, one of the most recently launched meteorological satellite by ISRO which provides weather imaging in six frequency bands. The local cloud coverage and distribution of maximum reflectivity of the events are examined with a doppler weather radar operated by IMD Kolkata. The radar is located at an areal distance of ~20 km from the disdrometer location. This S-band weather radar is capable of scanning at azimuthal, elevational or volume scanning mode at a maximum speed of 6 rpm and a resolution of 0.25°. The present study has used the 'Max Z' product of this radar in volume scanning mode. It indicates the maximum reflectivity value in vertical, north-south and east-west direction and it is indicative of the cloud liquid water content.



Fig. 1. Study location (<https://www.google.com/maps/place/Kolkata>).

Table 1
Details of the events studied.

	Date	Event type	UTC	Maximum rain intensity (mm/h)	Rain accumulation (mm)	Wind speed	Number of lightning strikes
1	April 7, 2018	Lightning	10:10–14:50	90.67	20.03	15.6	543
2	April 9, 2018	Lightning	16:47–18:12	9.095	3.59	7.4	51
3	April 11, 2018	Lightning	15:18–16:37	1.4	0.42	14.23	9
4	April 21, 2018	Lightning	13:00–13:37	87.75	11.80	5.6	49
5	April 22, 2018	Lightning	09:03–09:23	1.27	0.05	20.3	32
6	April 23, 2018	Lightning	13:59–14:19	6.53	0.72	8.2	22
7	April 26, 2018	Lightning	14:29–17:11	80.87	25.33	22.3	663
8	May 13, 2018	Lightning	07:44–10:37	73.56	57.34	11.6	307
9	May 18, 2018	Lightning	09:40–09:59	39.16	5.8	13.2	18
10	May 22, 2018	Lightning	10:50–13:00	76.17	34.11	12.1	171
11	June 1, 2018	Lightning	10:35–17:30	77.35	28.53	7.9	113
12	June 8, 2018	Lightning	12:08–13:17	124.2	16.26	7.2	91
13	June 9, 2018	Lightning	07:51–08:47	47.29	8.80	11.1	4
14	June 10, 2018	Lightning	07:14–07:50	58.2	7.29	7.25	61
15	June 11, 2018	Lightning	10:04–13:28	63.2	9.7	4.63	734
16	Aug 3, 2018	Lightning	10:08–13:45	59.77	21.11	8.16	151
17	Aug 6, 2018	Lightning	12:20–13:10	3.34	1.29	9.44	29
18	Aug 22, 2018	Lightning	11:50–13:43	81.97	30.53	8.3	161
19	Aug 25, 2018	Lightning	05:39–06:26	50.10	8.9	9.8	32
20	Aug 27, 2018	Lightning	00:30–01:46	16.83	3.34	14.7	8
21	Sep 13, 2018	Lightning	21:30–22:45	60.83	7.99	8.7	56
22	Sep 15, 2018	Lightning	07:50–08:57	23.20	2.40	9.3	211
23	Sep 26, 2018	Lightning	07:00–07:43	49.8	3.40	6.7	35
24	Nov 15, 2017	No lightning	01:30–17:30	23.88	24.28	3.1	0
25	Nov 16, 2017	No lightning	20:00–23:00	58.09	22.97	5.9	0
26	March 15–16, 2018	No lightning	21:30 (March 15)-00:50 (March 16)	6	0.60	11.1	0
27	April 7, 2018	No lightning	18:30–20:30	2.5	1.11	9.27	0
28	May 16, 2018	No lightning	04:45–05:25	46.71	4.83	15.8	0
29	June 17, 2018	No lightning	02:30–05:23	19.26	3.74	13.3	0
30	July 10, 2018	No lightning	06:10–07:00	13.10	3.79	20.1	0
31	July 14, 2018	No lightning	08:00–08:45	12.79	1.33	17.4	0
32	July 21, 2018	No lightning	01:30–15:10	40.55	17.53	22.5	0
33	Aug 1, 2018	Lightning	00:10–03:45	19.46	19.04	5.7	
34	Aug 2, 2018	No lightning	00:10–03:20	5.35	1.27	13.6	0
35	Aug 5, 2018	No lightning	12:21–13:25	6.7	1.18	5.3	0
36	Aug 7, 2018	No lightning	05:50–07:01	45.46	3.56	20.7	0
37	Aug 8, 2018	No lightning	05:30–6:05	31.29	3.06	15.7	0
38	Aug 13, 2018	No lightning	01:48–02:15	31.64	3.91	7.8	0
39	Aug 14, 2018	No lightning	04:30–05:41	25.72	1.39	15.3	0
40	Aug 15, 2018	No lightning	16:10–17:04	26.60	6.09	14.5	0
41	Aug 20, 2018	No lightning	07:30–06:22	20.7	1.89	12.1	0
42	Aug 28, 2018	No lightning	00:36–03:14	35.63	3.68	12.9	0
43	Aug 29, 2018	No lightning	10:36–11:39	39.50	8.54	13.1	0
44	Aug 31, 2018	No lightning	3:46–10:03	10.89	3.45	8.5	0
45	Sep 2, 2018	No lightning	04:00–07:26	67.02	23.50	14.7	0
46	Sep 20, 2018	No lightning	16:08–18:29	82.42	17.36	14.4	0
47	Oct 10, 2018	No lightning	08:45–15:25	4.55	1.88	12.8	0
48	Oct 29, 2018	No lightning	12:27–16:05	3.75	3.29	9.6	0

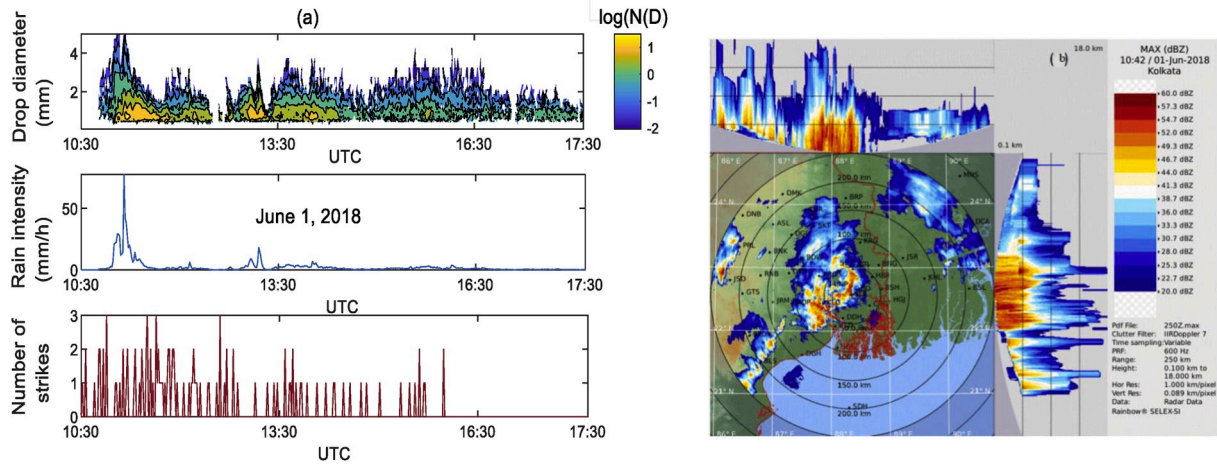


Fig. 2. (a) Rain DSD, rain rate and lightning flashes (b) Maximum reflectivity obtained from Doppler weather radar volume scan on June 1, 2018.

2.2. Data and methodology of analysis

Rain DSDs of 48 events measured during the period of November, 2017 to October, 2018 are selected for this study. Amongst these days, 23 events had lightning. The events are described in Table 1 along with type, average wind speed, duration, maximum rain rate and rain accumulation information. Number of lightning flashes, as detected by WWLLN network, are also mentioned in Table 1.

Cloud properties such as cloud top temperature and effective droplet radius as well rain microphysical parameters such as drop size distribution (DSD), radar reflectivity and rain attenuation are then analyzed under these two types of rain conditions, i.e. with or without lightning. The cloud properties are studied for $5^\circ \times 5^\circ$ area surrounding the study location. As the satellite is not geostationary, only a few pass over the study regions are obtained for each selected events. To get a statistically stable observation, a $5^\circ \times 5^\circ$ grid is taken surrounding Kolkata and all pixels are studied. Hence, a one to one correspondence between rain microphysical parameters with cloud properties are not possible, however, it provide characteristic features of the overall cloud system under different conditions.

To quantify the effect on rain microphysics, lognormal model has been used to model the DSD (Das et al., 2010; Vidyarthi et al., 2011) and given by (Timothy et al., 2002)

$$N(D) = \left(\frac{N_T}{\sigma D \sqrt{2\pi}} \right) \exp \left[-\frac{0.5(\ln D - \mu)^2}{2\sigma^2} \right] \quad (1)$$

Where $N(D)$ is the number density of rain drops (in $\text{m}^{-3}\text{mm}^{-1}$), N_T is the total number of rain drops, D is the rain drop diameter (in mm), μ and σ are the mean and standard deviation of $\ln(D)$. The lognormal parameters of the model are estimated using method of moments (Kozu and Nakamura, 1991) and further modelled in terms of rain rate as:

$$N_T = a R^b \quad (2)$$

$$\mu = c + d \ln(R) \quad (3)$$

$$\sigma^2 = e + f \ln(R) \quad (4)$$

Since, rain DSD has a strong dependence on the rain rate, the events are further subdivided in four rain rate classes i.e. I) low (1mm/h-5mm/h), II) medium (5mm/h-10 mm/h), III) high (10mm/h-40 mm/h), and IV) very high (40mm/h-200 mm/h). The empirical co-efficient a , b , c , d , e , f are obtained by linear regression method. The rain integral parameters are obtained from the DSD (Ippolito, 1986). Rain attenuation is estimated using Mie scattering theory assuming spherical shape and 303K medium temperatures.

3. Results and discussion

3.1. Case studies

To understand the characteristic differences of cloud and rain patterns between the lightning and non-lightning events, two events with

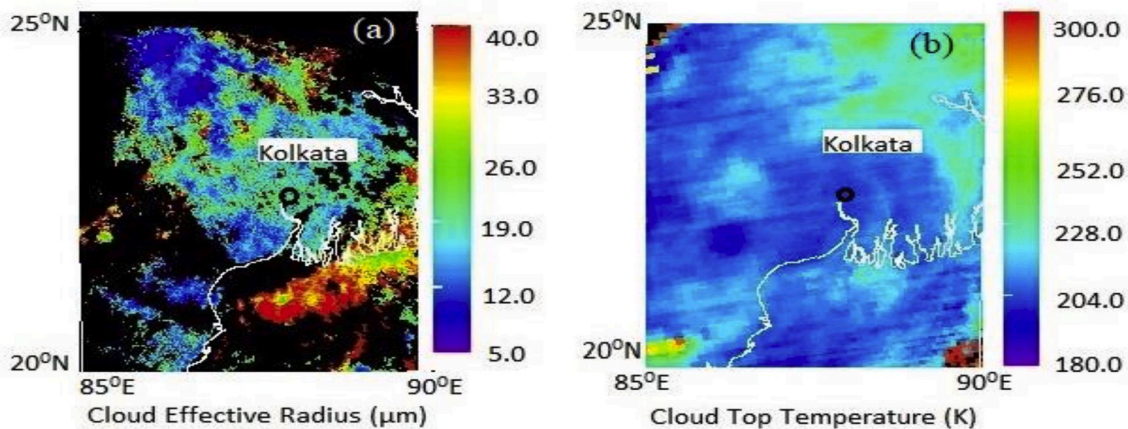


Fig. 3. (a) Cloud effective radius and (b) Cloud top temperature on June 1, 2018.

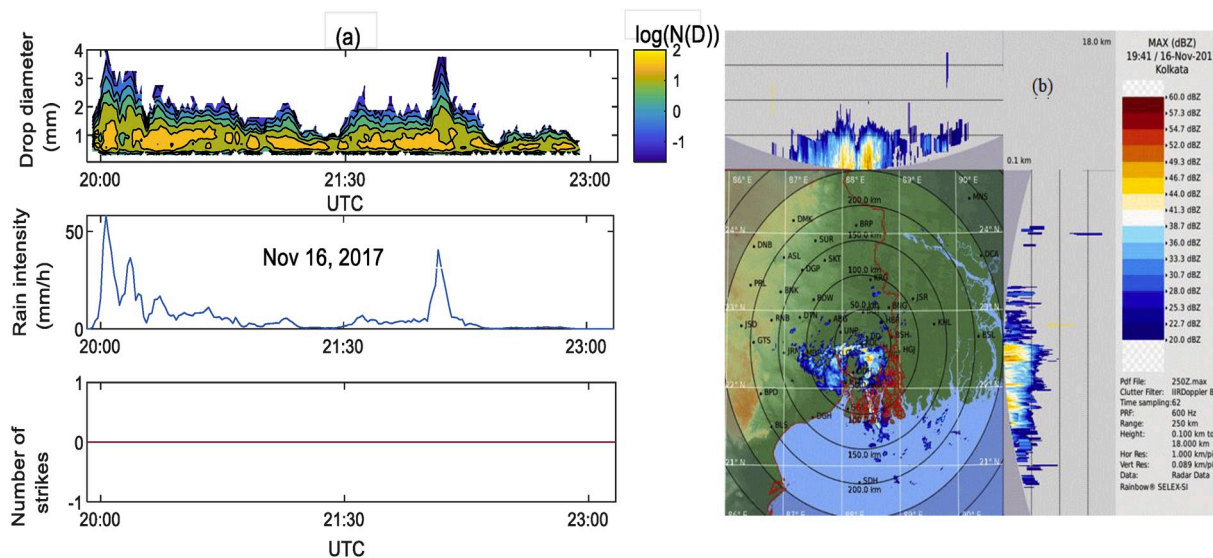


Fig. 4. (a) Rain DSD, rain rate and lightning flashes (b) Maximum reflectivity obtained from Doppler weather radar volume scan on Nov 16, 2017.

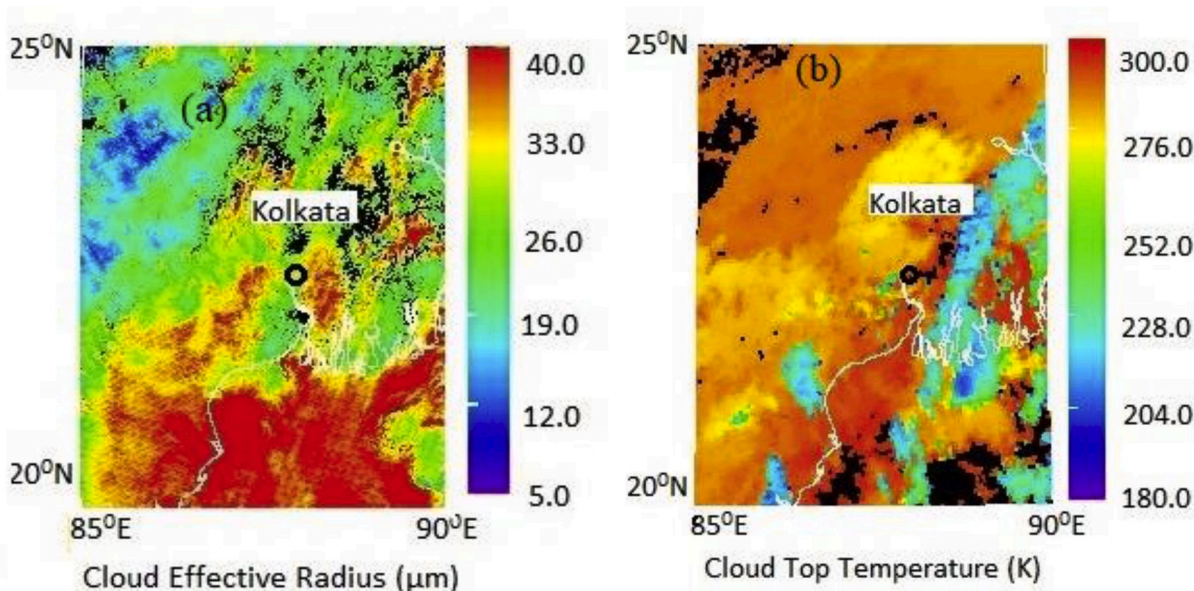


Fig. 5. (a) Cloud effective radius and (b) Cloud top temperature on Nov 16, 2017.

similar rain pattern are discussed next. These two events are having similar rain intensity and comparable horizontal wind velocities.

3.1.1. Lightning event on June 1, 2018

The rain event observed on June 1, 2018 lasted for 420 min with a maximum rain intensity of 77.35 mm/h. The rain rate, associated DSD and lightning activity have been shown in Fig. 2(a). 113 strikes were detected during this rain event. The average wind speed was 7.9 km/h. The spatial distribution of lightning strikes in a $1^\circ \times 1^\circ$ vicinity around the study location is shown by assimilation of LIS and WWLLN data during the event (supporting figure given in supplementary Fig. 1(a)). The INSAT satellite imaging shows a large areal expansion of the convective system developed indicated by the low brightness temperature at $10.6 \mu\text{m}$ (supporting figure given in supplementary Fig. (b)). This is reported to be a favorable condition for cloud-ground lightning (Gungle and Krider., 2006). Further, a close-range cloud image is observed by Doppler weather radar during the event. This shows the

presence of a thick cloud system over the study location (Fig. 2(b)). The cloud properties during the event are shown in Fig. 3(a and b). Both effective radius and cloud top temperature surrounding the study location had a dominance of low values. The radar reflectivity for this event is estimated by empirical relation $Z = aR^b$. The power law coefficients a and b are computed by linear regression method as 630.95 and 1.2, respectively (supporting figure given in supplementary Fig. 2).

3.1.2. Non-lightning event on Nov. 16, 2017

The rain event on Nov 16, 2017 had no lightning (Fig. 4(a)). The overall characteristic of this rain event is similar to the previous event. The span of the rain event was about 180 min with a maximum rain intensity of 58 mm/h. The average wind speed during the event was 5.9 km/h. No lightning strikes were detected during the event in the vicinity of the study location (supporting figure given in supplementary Fig. 3 (a)). The areal expansion of the convective system is smaller than the day with lightning (supporting figure given in supplementary Fig. 3(b)).

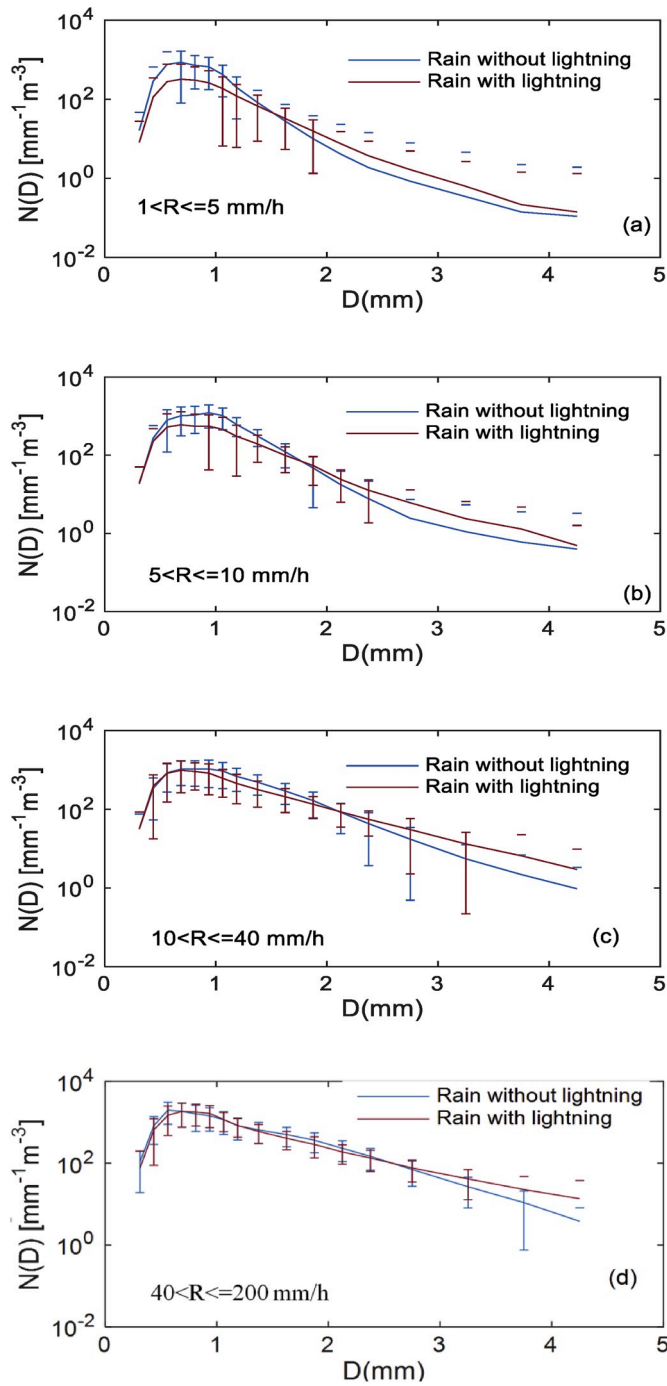


Fig. 6. Average number concentration for rain categories without and with lightning for rain rate (a) 1–5 mm/h, (b) 5–10 mm/h, (c) 10–40 mm/h, and (d) 40–200 mm/h.

The close-range ground radar image suggests presence of shallow cloud over the study location (Fig. 4(b)). The cloud properties during the event are shown in Fig. 5(a and b). Both the effective radius and cloud top temperature values surrounding the study location had a dominance of high values. The coefficient a and b of Z-R relation for this event was calculated as 125.89 and 1.5, respectively (supporting image is provided in supplementary Fig. 4).

3.2. Long term statistics

To get a statistically meaningful conclusion about the rain and cloud

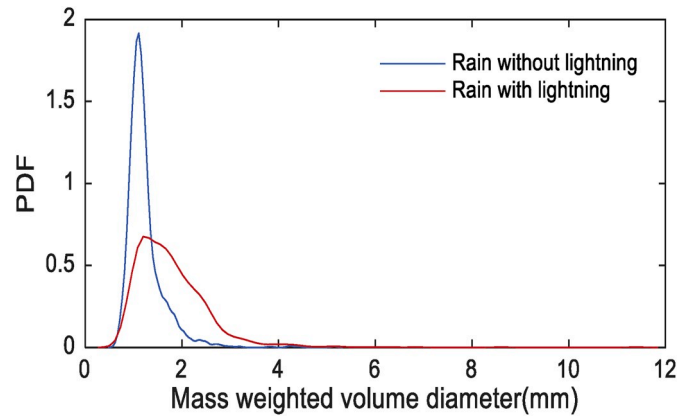


Fig. 7. Mass weighted volume diameter for two types of rain.

Table 2
DSD parameters of the two rain categories.

Event Type	DSD parameters		
With lightning	$N_T = 445 R^{0.45}$	$\mu = 0.086 \ln R - 0.052$	$\sigma^2 = 0.025 \ln R + 0.081$
Without lightning	$N_T = 992.27 R^{0.38}$	$\mu = 0.098 \ln R - 0.025$	$\sigma^2 = 0.026 \ln R + 0.063$

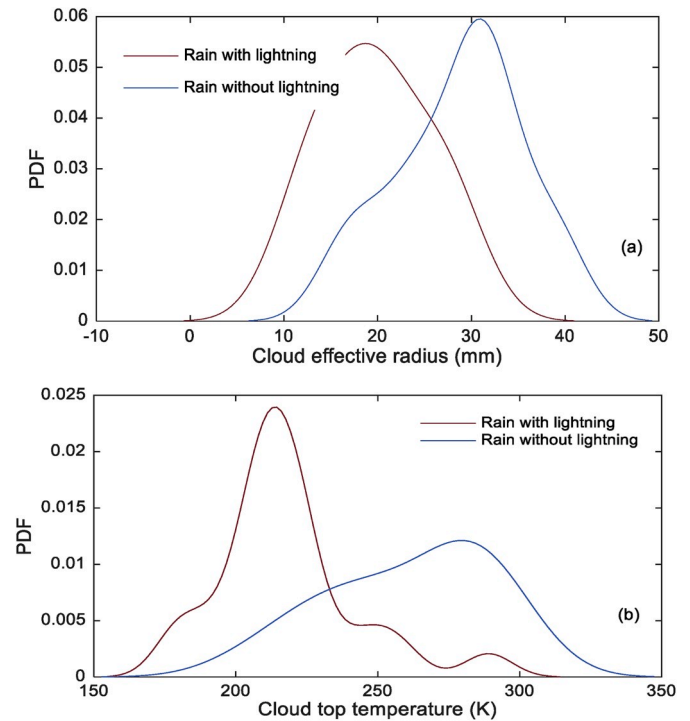


Fig. 8. Probability density function of cloud properties: (a) Cloud effective radius (b) Cloud top temperature.

features during lightning and non-lightning conditions, statistical descriptions of these characteristics are presented next. A total of 48 rain events have been considered for the statistical study of rain events with/without lightning and depicted in Table 1. As already pointed out that rain microphysics has strong dependence on rain rate, the events are divided into four rain rate classes and the analysis are performed separately on each class.

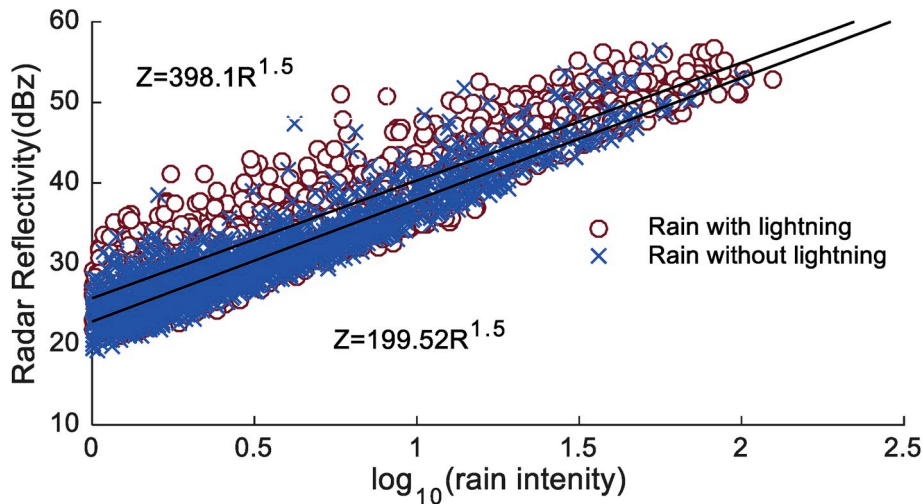


Fig. 9. Z-R relation obtained for two rain events with and without lightning.

3.2.1. Rain microphysics

The drop size distribution of these two types of events showed clearly distinct behaviour. Fig. 6 shows the number concentration of rain drops for these two types of rain. The number concentration is higher for small drops under non-lightning conditions than the lightning conditions in all four rain rate classes. It is to be noted that the instrument has a limitation in counting very small drops. The inverse scenario is observed after a critical drop diameter which shifted towards large drops with increase in rain rate. The critical diameter varies between 1 and 3 mm drop sizes depending on the rain rate. The result indicates a clear dominance of large drops in rain with lightning. Large rain drops usually indicate coalescence through collision process and the existence of large drops indicate high level of convective activity. The dominance of larger drops in lightning events is further supported by the distribution of mass weighted volume diameter for the two rain categories as indicated by Fig. 7.

One can note that the peak of the distribution is shifted towards larger drops for lightning events. Detailed comparative analyses of rain DSD parameters computed by lognormal model under these two rain conditions are presented in Table 2.

3.2.2. Cloud properties

In Fig. 8 the distribution of cloud properties, namely cloud effective radius and cloud top temperature, under varied lightning conditions are shown. The cloud properties have been studied for all the rain events and average values are provided in supplementary Tables 1 and 2. Results clearly indicate the dominance of small cloud particle during lightning (Fig. 8(a)).

The result finds good agreement with the basic growth mechanism of ice particle which often results into breakage of ice into smaller particles which provides the basis of lightning due to its nature of positive charge acquisition. The distribution of cloud top temperature (Fig. 8(b)) for rain class with lightning has a peak towards low brightness temperature in comparison with the non-lightning class and in agreement with the previous observations (Makela, 2004; Molinie and Jacobson, 2004).

3.2.3. Z-R relation

A comparative analysis of Z-R relation is done for these two rain categories so that behavioral change of this relation can be studied. The power law coefficients for the rain class without lightning is found to be 199.52 and 1.5, respectively. In case of rain class with lightning, a and b values are found to be 398.1 and 1.5 (Fig. 9). This indicates a significant difference in estimated rainfall for same value of reflectivity and will be

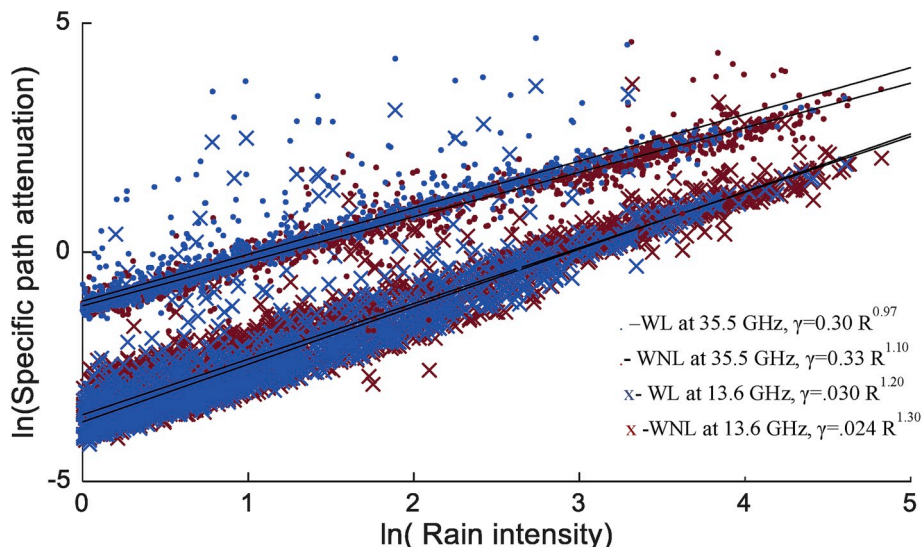


Fig. 10. Specific path attenuation for rain with lightning (WL) and without lightning (WNL) at 13.6 GHz and 35.5 GHz.

an important source of errors in QPE for weather radars.

3.2.4. Rain attenuation

High frequency is now commonly used in radar for precipitation studies and signal above 10 GHz are very susceptible to rain attenuation. Here, modelling of rain attenuation has been attempted with a special emphasis on GPM frequencies at 13.6 GHz and 35.5 GHz. The specific attenuation (γ) is related to the rain rate by the relation $\gamma = kR^\alpha$ and is modelled separately for the two above mentioned climatic conditions. The obtained result indicates a higher path attenuation in case of rain with lightning at the GPM Ku band frequency whereas, the inverse scenario is noticed for GPM Ka band (Fig. 10).

Specifically, K and α value at the Ka band frequency (35.5 GHz) are 0.300 and 0.970, respectively during rain with lightning whereas, these values are 0.330 and 1.100 during rain with no lightning. On the other hand, the k and α values are 0.030 and 1.200 respectively during lightning and 0.024 and 1.300 during non-lightning conditions at Ku band (13.6 GHz).

4. Conclusion

This study has attempted to achieve a characterization of the cloud and rain microphysics during lightning and non-lightning events. Small cloud droplet size associated with low cloud top temperature are found to be conducive for lightning activities. The higher instability in convective cloud results into more collision and breakage of ice particles into smaller particles which moves upwards acquiring positive charge. Thick clouds found to be more favorable for lightning because of a colder cloud top at a greater altitude. Significant differences have also been observed in the basic properties of the precipitating system as well. Both microphysical and integral parameters of rain seemed to have distinguishable behaviour for lightning events from non-lightning rain events. Important conclusion from this study is that both radar reflectivity and rain attenuation are significantly varied under these two types of climate conditions. The radar reflectivity is greater in case of rain events with lightning because of dominance of larger rain drop. Significantly high a value of Z-R relation is obtained for lightning events in comparison to non-lightning events. The results also indicate that the lightning information can be used to improve radar QPE. Rain attenuation during these two climatic conditions are observed to have opposite effects in two GPM frequencies. An estimate of the path attenuation for the two radar frequencies used by GPM under lightning and non-lightning conditions are also provided. The conclusions from this study can be helpful in characterizing and modelling tropical thunderstorm systems resulting in heavy rainfall and lightning.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jastp.2020.105350>.

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