URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Microphysical impact of aerosols on cloud electrification efficiencies over the Indian region

R. Chakraborty*(1) and A. Chakraborty* (1,2)
(1) Centre for Atmospheric and Oceanic Sciences, IISC, India
(2) Divecha Centre for Climate Change, IISC, India

Abstract

In the present study, an attempted has been done to explain the non-linear inter-relationships between lightning and its various controlling factors. It has been demonstrated both physically and statistically how an enhanced aerosol loading leads to formation of smaller ice radii which drastically decreases the cloud electrification processes especially over the land regions where ice forming dust aerosols are much more abundant. Accordingly, this relationship has been utilized on global model simulations to reveal a further intensification of lightning radiance efficiencies in the marine environments and a relative dimming in land regions based on prevalent aerosol concentrations in future decades which may be alarming for policy makers.

1 Introduction

Convective occurrences are found to be a predominant climatic feature over the Indian sub-continent and these events are usually accompanied by vigorous lightning episodes which cause tremendous damage to life and property. Nevertheless, such extremes also tend to be highly erratic in its position and timing; hence a series of studies have been undertaken at recent times to understand, characterize and predict such features [1-5]. However, the number of detailed studies on lightning activities are yet very limited. Since the year 2000, a few studies have been reported involving the use of ground based and satellite measurements to understand the spatio-temporal distribution of lightning and to unearth the various potential factors responsible for it [6]. In addition, some of them have also tried to deduce a set of equations to estimate the charge structure profiles associated with these lightning events [7].

Now, very recently, some studies [8] have revealed that atmospheric instability and moisture abundance catalyzes the genesis of tall and thick clouds essential for lightning events. [9]. However, the importance of aerosols on lightning is still debatable as it can have inhibitory or invigorating effects on such phenomena [10]. For instance, a study [11] showed an increase in lightning as AOD increases up to a definite threshold after which their inter-relationship weakens drastically. Hence it can be inferred that large-scale correlations between lightning and its various components fail to give an in-depth idea about the physical mechanism behind such extremes.

Accordingly, an attempt has been progressed to investigate the long-term trends of annually averaged lightning radiances over the Indian region along with its various responsible atmospheric components. The statistics are depicted in Table 1 for land and sea regions separately due to the drastic differences in radiance values between the two. The annual trends in lightning radiances are found to be least significant compared to its various components like moisture (TCWV), instability (CAPE) and aerosols (AOD). Hence it follows that it may be the efficiency and not the total frequency or intensity of lightning which is being controlled by the underlying macro or microphysical processes. Interestingly, a new term signifying the efficiency of lightning processes has also been recently coined [12] which is obtained by normalizing the average radiance with respect to the product of instability and rainfall. Hence, this parameter has been considered as a reliable measure of the lightning processes. However, for the sake of spatial uniformity, the total moisture content (TCWV) has been used in place of precipitation amount for radiance efficiency calculation over the Indian region.

Table 1:15-year trends of lightning radiance and its controlling factors

Sl No.	Name	Maritime		Continental	
		%Trend	r	%Trend	r
1	TCWV	0.3	0.58	0.2	0.56
2	CAPE	0.27	0.53	0.15	0.52
3	AOD	2.3	0.85	2	0.81
4	Rad	1.2	0.41	1	0.37

So, in view of the above, the present study aims to depict the spatio-temporal distribution of lightning radiance efficiency over the country and then it seeks to identify all the potential factors responsible for it. Next, the physical mechanism behind the proposed inter-relationships is demonstrated and then a mathematical expression has been derived. Finally, these equations have been implemented on multi-model simulations to project the future lightning efficiencies over the Indian region due to various urbanization levels.

2 Dataset

For the present study, lightning intensity datasets (expressed as micro Joule per meter square) over the Indian region are utilized from ~95800 passes of

Lightning Image Sensor (LIS) on board Tropical Rain Measurement Mission (TRMM) satellite with a fine spatial resolution of 0.25X0.25 degrees during 2000-2014. A detailed information about the accuracy and retrieval algorithms for this dataset can be obtained from previous literature [13]. Further, monthly averaged datasets of AOD at 550 nm along with ice and liquid cloud effective radii (CERI and CERL) are taken from MODIS datasets.

In addition, monthly averaged profiles of cloud ice and liquid water along with the total and dust aerosol extinction coefficients have been utilized form TRMM and CALIPSO satellite observations. Finally, the gridded datasets of moisture content (TCWV) and instability (CAPE) are obtained from ERA5 reanalysis archives on a monthly averaged basis. It may be noted that all the pertinent calculations shown in this study are depicted at a convenient spatial resolution of 1X1 degree to preserve uniformity throughout the Indian subcontinent.

For future projection analysis, gridded historical (1950-2005) and future scenario (2006-2100) datasets of meteorological parameters and aerosols are employed from a set of General Circulation Models from Coupled Model Intercomparison Project (CMIP 5). In addition, two extreme representative concentration pathways (of 2.6 W/m2 and 8.5 W/m2) are utilized to understand the ploy of anthropogenic influences on the unprecedented growth of lightning activities in this century.

3 Results and Discussions

3.1 Spatio-temporal variation of Radeff

The seasonal averages of radiance efficiency referred to as Radeff and its controlling factors are depicted in Table 2.

Table 2: Seasonal averages of radiance efficiency and its controlling factors during 2000-2014

Sl	Parameter		Wint	Prem	Mons	Post
1	TCWV (kg/m2)	Sea	23	36	56	37
		Land	10	22	50	18
2	CAPE (J/kg)	Sea	100	1100	650	300
		Land	50	300	600	100
3	AOD	Sea	0.25	0.38	0.46	0.30
		Land	0.33	0.41	0.57	0.36
4	Radeff	Sea	2.0	0.20	0.10	0.5
		Land	6.5	0.25	0.20	1.8

As seen from the table, the average values of moisture availability and instability are found to the maximum during the premonsoon and monsoon season as shown by (Prem and Mons) which is quite expected owing to the abundance of very frequent thunderstorm activities during this period. Next, the values of aerosol loading are also markedly higher during these two seasons. Now according to previous studies, it is expected for these two seasons to experience the maximum lightning radiance and frequency. However, the radiance efficiencies show completely low values during these seasons and the maximum is found in the winter season (shown as Wint). From a normal perspective it seems that the winter season gets less moisture and instability as input and hence should show higher efficiencies compared to the premonsoon and monsoon season. But this cannot be considered as a strong argument because lightning occurrences happen due to multiple ice graupel collisions in the cloud which cannot be triggered without enough moisture or instability. Secondly, the aerosol loading is also quite low in winter which makes ice nuclei formation also difficult, yet it produces strong efficiency while in monsoon season, the reverse happens. Hence it follows that the obtained understanding on the inter-relationships between lightning radiance efficiency and its controlling factors is not as linear as shown in the previous studies and hence needs further investigation hereafter.

3.2 Physical mechanisms behind the evolution of lightning radiance efficiency

To get a better understanding of how various factors individually impact cloud electrification, datasets of all the three controlling parameters are accumulated over the entire time span. The resultant monthly dataset of 180 values each are sectored into 6 intervals of equal frequency. Next the corresponding values of lightning radiance efficiencies are plotted for each of those clusters. The resultant variations between AOD and radiance efficiency with cloud ice radius is shown in Figure 1.

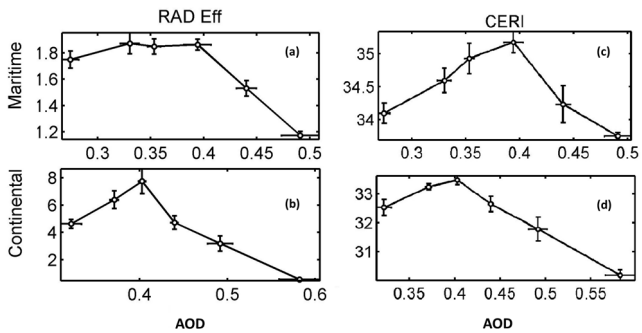

Figure 1: Cluster analysis results of radiance efficiency and cloud ice effective radius with respect to AOD

It may be noted that the corresponding plots for TCWV and CAPE have not been shown owing to the absence any definite pattern in those figures. However, as can be seen here, Radeff values are much higher in land regions than in seas. Next in sea regions, Radeff initially shows an invariable nature; however above AOD values of ~0.4 Radeff drops off quite rapidly. However, in land regions the variation is much more prominent. Here Radeff increases gradually till AOD reaches the same threshold; but above it, the efficiency falls off drastically to near zero values. Thus, the radiance efficiency seems to rise at lower aerosol concentrations but above a certain threshold value it falls down.

In previous studies, it has been documented that though aerosols help in heterogenous nucleation and cloud condensation nuclei (CCN) formation, yet as AOD increases drastically the available water vapor gets shared among multiple CCNs to produce smaller cloud drops. Now in lightning evolution physics, the net charge generation rate per collision between graupel and ice particles depends primarily on the ice particle radius, followed by its number concentration. Now as the radiance is proportional to ice diameter raised to the power of 6, hence a small dip in CERI can reduce the radiance intensity and hence its efficiency sharply. As CERI is also controlled by ice condensation nuclei concentrations (ICN) and AOD like in CCN case, hence, it is expected that a similar inter-relationship can also exist here, particularly because dust aerosols act as very good ICN particles. So, an increase in dust concentration aerosols in land regions and higher ICN, is expected to reduce CERI and hence Radeff values prominently as also supported from Figure 1(c, d). It may be noted that the drop in CERI over land is more than double of that in seas which also goes in line with the Radeff variation.

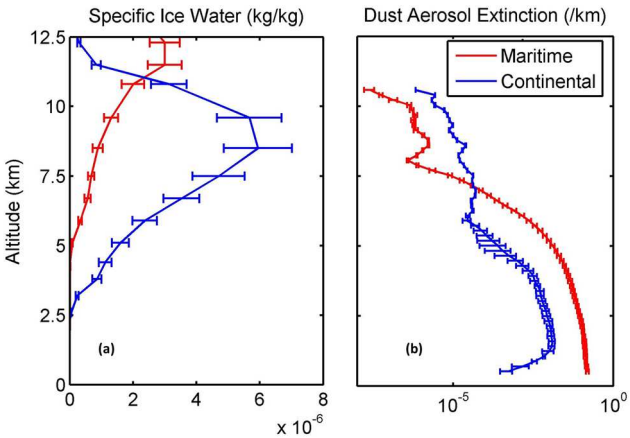

Figure 2: Profiles of ice cloud water and dust extinction over land and sea regions.

Next, to understand why the average values as well as the cluster variations of Radeff is stronger over land regions, the ice content and dust concentrations are analyzed using observation datasets. It is observed that between 5-11 km (which corresponds to -5 to -45 degrees centigrade where both graupel and ice can coexist), the ice content as well as dust concentration over land are much higher than the seas. This can be attributed to the presence of cooler and elevated Himalayan regions and also due to the north westerly transport of dust from the adjoining deserts.

3.3 Demonstration of the impact of increased dust aerosols on Radeff

In this section a real-life case study of the proposed hypothesis is presented over the desert regions of India where normally dust aerosols are the most abundant ICN particles. Monsoon averages of Radeff are shown during 2005-2011 in Figure 3 keeping year 2008 at the center since the same year experienced a vigorous dust storm on 16 June. Now, year 2008 shows the highest values of AOD (which is much higher than 0.4). Hence as expected, the values of CERI have also declined sharply by 2 um thereby leading to a marked reduction in the average radiance values there (not shown in Figure). However, interestingly in those years TCWV and CAPE did not decrease as prominently as AOD, hence Radeff shows a sharp dip thereby supporting the hypothesis.

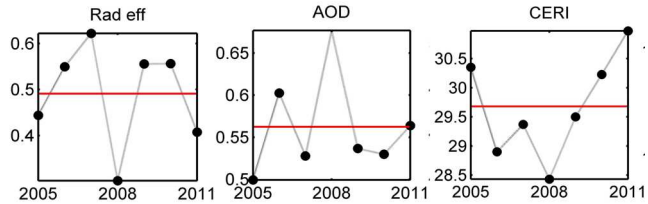

Figure 3: Monsoon season averaged Radeff, AOD and CERI over the Indian desert regions

Now, as the proposed hypothesis has already been demonstrated both physically and statistically, next an attempt is progressed to quantify the effects of all three parameters on Radeff using multi-linear regression (MLR) analysis. However as already seen before, the inter-relationships between Radeff and AOD reverses after an almost fixed thresholds, hence the quantification is done separately for both the cases.

Table 3: MLR coefficients for radiance efficiency

Sl		Regime	AOD	TCCWV	CAPE
1	Sea	<0.4	0.409	0.463	0.089
		>0.4	-0.702	-0.225	-0.049
2	Land	<0.4	0.357	0.375	0.146
		>0.4	-0.913	-0.315	-0.104

Hence, the 15-year datasets are accumulated and MLR coefficients are calculated separately for both the aerosol classes over land and sea regions and are shown in Table 3. It is evident that AOD always assumes the primary role of controlling Radeff followed by TCWV and CAPE and the polarity of its dependance reverses above AOD=0.4. However, interestingly the MLR coefficients for TCWV and CAPE also revert like AOD. This is mainly because when AOD is low, it helps lightning and there TCWV and CAPE further catalyzes it. But when AOD is high the effect of TCWV and CAPE is overpowered to ultimately reduce radiance; however, TCWV and CAPE values do not reduce, hence the Radeff values drop drastically. But now, as these equation coefficients have been framed hence, they will be implemented on multiple global climate model simulations to get future projections of Radeff for various urbanization levels.

3.4 Future projections of lightning efficiency using RCP scenarios

In view of the above, CMIP5 datasets of 150 years (1950-2100) are prepared by merging the historical and the

scenario data from a set of GCMs and then MLR derived Radeffs are shown for RCP2.6, 8.5 scenarios in Figure 4.

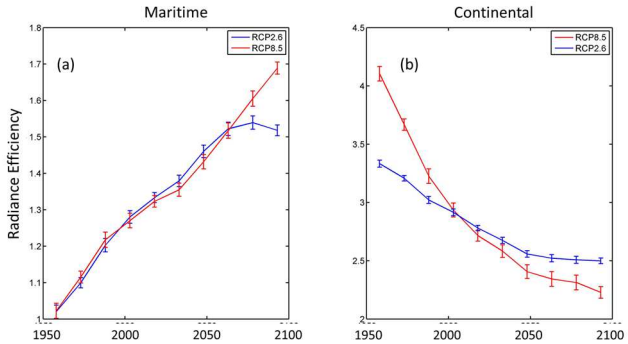

Figure 4: Radiance efficiencies over sea and land regions using RCP 8.5 (red) and RCP 2.6 (blue) scenarios

From the figure, a prominent increase in Radeff is observed in the seas while a drastic drop is seen in land regions. Also, in both cases the slopes of the multi-decadal variations are also much stronger in RCP8.5 due to a stronger increase in AOD from this scenario throughout the country. Here it maybe noted that in maritime regions, the annual AODs have increased but have never crossed the threshold 0.4 hence they cast a catalyzing effect on the lightning processes leading to an accelerated growth in Radeff in future which is really alarming for current policy makers. However, over land, AOD was always higher than 0.4 hence a further rise in its value has led to a staunch decrease in Radeff as also expected from the proposed hypothesis.

4 Conclusion

The present study has attempted to explain the non-linear inter-relationships among lightning radiance and its various controlling factors. It has been depicted that increased aerosol concentrations can lead to smaller ice radii which highly inhibits cloud electrification processes especially over the land regions with a relative abundance of dust aerosols. This relationship when utilized on global model simulations reveal an intensification of lightning efficiencies in marine regions and a relative dimming over land in future which can be alarming for policy makers.

5 Acknowledgements

One of the authors (R. Chakraborty) acknowledges the financial support provided under INSPIRE Faculty Fellowship funded by DST for completing this work.

6 References

1. R. Chakraborty, G. Basha and M.V. Ratnam, “Diurnal and long-term variation of instability over a tropical region”. *Atmospheric Research*, **207**, 2018, pp 145-154,

2. G. Rakshit, R. Chakraborty and A. Maitra, “Effect of vertical wind on drop size distributions in boundary layer”, 2016 *International Symposium on Antennas and Propagation*, IEEE, 2016, pp 846-847,

3. R. Chakraborty, G. Basha M. Venkat Ratnam, “Long-term trends of instability and associated parameters over India obtained using radiosonde network”, Atmospheric Chemistry and Physics, **19**(6), 2019, pp 3687–3705.

4. BK Guha, R Chakraborty, U Saha, and A Maitra: “Tropopause height characteristics with ozone, stratospheric moistening during convection over India”. *Global and Planetary Change*; **158**., pp 1-12, 2017.

5. A. Maitra and R. Chakraborty: “Prediction of Rain Occurrence and Accumulation using Multifrequency Radiometric Observations”. *IEEE Transactions in Geoscience and Remote Sensing*, **56(5)**, 2789-2797, 2018.

6. Y.A. Liou and S.K. Kar, “Study of cloud-to-ground lightning and precipitation and their seasonal and geographical characteristics over Taiwan”, *Atmospheric Research*, **95**, 2014, pp 115–122.

7. Z. Shi, Y.B. Tana, H.Q. Tang, J. Sunc, Y. Yanga, L. Penga and X.F. Guo, “Aerosol effect on land-ocean contrast in thunderstorm and lightning frequency”, *Atmospheric Research*, **164–165**, 2015, pp 131–141,

8. D. Siingh, P.S. Buchunde, R.P. Singh, Asha Nath, Sarvan Kumar and R.N. Ghodpage, “Lightning and convective rain study in different parts of India”, *Atmospheric Research*, **137**, 2014 pp 35–48.

9. P. Murugavel, S. D. Pawar and V. Gopalakrishan, “Climatology of lightning Indian region and relationship with convective available potential energy”, *International Journal of Climatology*, **34**, 2014, pp 3179–3187

10. R. Chakraborty, BK Guha, S. Talukdar, MV Ratnam, and A Maitra: “Growth in mid-monsoon dry phases over India: influence of anthropogenic aerosols”. *Atmospheric Chemistry and Physics* 10/2019; 19(19):12325-12341.

11. Z. Shi, HC Wang, YB Tan, LY Li CS Li., “Influence of aerosols on lightning in central eastern China”, *Atmospheric Science Letters*, e957, pp: 1-10, 2020,

12. D.M. Romps, J.T. Seeley, D. Vollaro and John Molinari, “Projected increase in lightning strike in United States due to global warming”, *Science*, **346(6211)**, 2014, pp 851-854, doi: 10.1126/science.1259100

13. D.J. Cecil, D. E. Buechler and R.J. Blakeslee, “Gridded lightning climatology from TRMM-LIS and OTD”, *Atmospheric Research*, **135–136**, 2014, pp 404–414, https://dx.doi/10.1016/j.atmosres.2012.06.028