Long-term trends in lightning frequency and intensity over the Indian region

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Abstract

We explain various aspects related to lightning occurrence frequency and intensity over the Indian region. Lightning frequency and magnitude are found to be larger in the east coast and adjoining regions. Atmospheric instability and aerosol concentrations appear to be the dominant factor affecting lightning occurrences while moisture content modulates the lightning intensity. A mechanism has been devised to explain how enhanced global warming can lead to taller and thicker clouds reaching up to the upper troposphere lower stratosphere region thereby leading to stronger and more lightning activities. Finally this hypothesis has been utilized to understand the futuristic scenarios of lightning over the Indian region using global model simulations.

1 Introduction

Convective activities are a prominent climatic feature over the Indian sub-continent, and they are accompanied by wind gusts and torrential rain [1] which cause tremendous damage to life and property. However, lightning is the most erratic and devastating factor not only because of the damage caused but also due to uncertainty of its position and timing during severe thunderstorm frequency. In the last few decades there has been a series of studies both in India and abroad to understand, characterize and predict thunderstorms [2-4], however the number of detailed studies on lightning activities are really very limited.

Since the last decade, a few studies have been reported to use ground based and satellite measurements for lightning research globally. While some of them focused on the spatio-temporal distribution of lightning, the others have listed the potential factors responsible for it [5]. It has been hinted that regions having mountainous features experience orographic lifting leading to intense rain and lightning [6]. On the other hand, specific types of aerosols from deserts/seas are found to be transported to the coasts where they help in cloud formation leading to severe lightning [7]. Recently, some of them have also tried to derive a mathematical model to show the typical charge structure associated with lightning activities [8].

Over the Indian region, some studies have tried to utilize and correlate lightning activities with several atmospheric parameters. Some studies have emphasized that the atmospheric instability component followed the moisture availability helps formation of thicker and taller clouds which are essential for lightning events. Hence the surface temperatures, thunderstorm strength (measured universally in the form of Convective Available Potential Energy or CAPE) and moisture (Precipitable Water Vapor or PWV) are found to be the dominant factors affecting lightning [9,10]. But on the other hand there also has been a mention about the importance of orographic distribution and aerosols which can additionally trigger lightning; however the exact roles of aerosol on lightning and thunderstorms is still unclear as it has both an inhibitory and invigorating effect on these phenomena [11].

Now despite these studies there is still a dearth of understanding on lightning genesis as large scale correlations cannot give an idea of the extreme events which create the most damage to infrastructure and life. Also most of the studies have failed to consider all the dominant components together and hence have only given a partial and incomplete understanding of lightning charge structures. Consequently, it is very difficult to find studies which tried to project the futuristic trends of lightning flash rate and intensities based on observations and modeling except a few in the US who have projected an increasing lightning due to global warming [12].

In this scenario, the present study aims to accumulate the available datasets of lightning and other atmospheric parameters over the Indian region to investigate the spatial distribution of lightning followed by its up to date trends over various regions. Next an exhaustive analysis seeks to identify the dominant factors leading to lightning and then using those factors it will first be understood whether and how the lightning activities have a risk of getting more severe in the coming decades. Finally model simulations of those parameters will be employed to show the project the future of lightning hazards in coming years due to various levels of urbanization influences.

2 Dataset

For the current study, observations of lightning frequency and intensity are taken over the Indian land region from ~95800 passes of Lightning Image Sensor (LIS) on board Tropical Rain Measurement Mission (TRMM) satellite during 1998-2014. Further information about this dataset can be obtained from previous literature [13]. This dataset is averaged over 0.25X0.25 degree boxes for the present study. Lightning flash rate data is utilized as flashes per square km which the intensity data is utilized as micro Joule per metre^2.

Multi-station radiosonde datasets from 37 locations across Indian region are utilized as from the Integrated Global Radiosonde Archive (IGRA-2) during 1980-2016. Further details regarding the dataset are available from previous literature [14-15]. At least 10000 profiles are taken from every radiosonde station and these datasets are utilized to calculate the instability indices and moisture content according to standard parcel theory as described in previous studies [2].

Gridded historical (1950-2005) and future scenario (2006-2100) datasets of various atmospheric parameters and aerosol concentrations are used from 11 General Circulation Models from Coupled Model Intercomparison Project (CMIP 5). To understand the impact of urbanization, two extremes of representative concentration pathways (of 2.6 W/m2 and 8.5 W/m2) corresponding to no and high urbanization conditions are used in this study.

3 Results and Discussion

3.1 Spatio-temporal variation of lightning

The TRMM pass datasets of lightning flash rate and radiance are accumulated to compute the total annual flash rate and radiance climatology. Figure 1 depicts a bimodal distribution of lightning flashes with very high values (~ 50 flashes/km2/year) at the coastal regions, the Indo-Gangetic plains and the foothills of Himalayas. On the other hand, parts of the central and western Indian regions receive much lesser amount of lightning flashes. This may be attributed to the dearth of moisture availability in those regions. On the other hand, the north eastern Himalaya foothills and parts of Pakistan receive strong lightning. While the north eastern region has more chances of cloud development owing to its proximity to the Bay of Bengal, the abnormal lightning increase over Pakistan may be attributed to the desert dust aerosol dominance. The Indo-Gangetic plains are believed to have slightly higher flash rate due to combined effect of dust transport from the deserts as well as well as its comparative closeness to the Bay of Bengal. Another interesting result shows an east-west coast asymmetry in flash rate. It may possibly be due to the ease of moisture laden winds to enter the eastern coasts because of low and discontinuous mountain ranges in the eastern side compared to the high and continuous western Ghats which block the moisture growth in western peninsula. The lightning flash radiance distribution shows similar spatial variation except for the highest values along the Eastern coasts and surrounding peninsula. This is because, the amount of charges required for an intense lightning strike are mainly controlled by the cloud water content; and moisture from the surrounding seas.

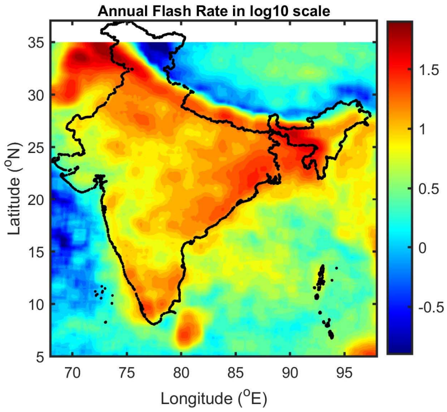

Figure 1. Average annual flash rate spatial distribution over Indian region during 1998-2014.

Next, the 17 year datasets of lightning flash and intensity are investigated over the Indian regions both seasonally and annually. Except for the winter season, almost the entire subcontinent experiences a statistically significant rise in flash rate by about ~1% per year. The percentage values are again found to be slightly higher of ~1.5% in the eastern coasts. The lightning radiance on the other hand has not shown such prominent strengthening in overall, but in that case it is more important to see the variation in number and magnitude of radiance extremes. Hence the frequency distribution of radiances is observed seasonally. Two separate time periods are chosen of 8 years each one before 2006 and the other after it. The distribution analysis in Figure 2 signifies a minor weakening in lightning radiances over winter which needs to be studied in future attempts.

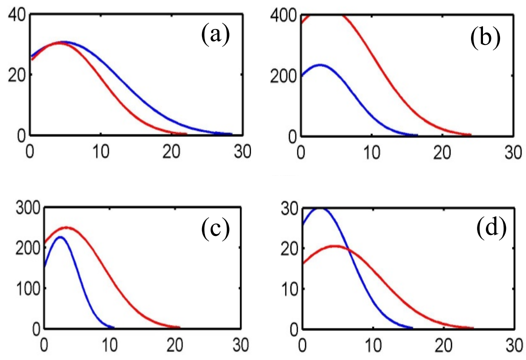

Figure 2. Distribution of lightning radiance values blue (1998-2005) and red (2007-2014) during (a) Winter, (b) Premonsoon (c) Monsoon and (d) Post monsoon

But it may be noted that both the number as well as the extreme magnitude of lightning radiances after 2006 are much stronger than that before it. This hints towards a possible strengthening of lightning intensity and frequency over the years. This hypothesis can be considered valid as few studies over India have already reported an increasing convection strength and moisture growth over the same time from radiosonde observations.

3.2 Physical mechanism behind lightning severity trends

In order to understand the dominant factors affecting lightning flash and radiance, the spatial distribution of lightning properties is correlated with certain essential atmospheric parameters in past attempts, namely: surface temperature, cloud base height, moisture availability, convective strength, altitude and aerosols. It may be noted that if the moisture component is taken separately, then the surface temperature bears a strong impact on the cloud base and indirectly to the total columnar instability values; consequently here the cloud base height, moisture availability, altitude and aerosols are shown for the east and west coasts (experiencing the strongest lightning properties and trend values). It may be noted that both the East and west coasts are shown to investigate the possible asymmetrical lightning properties between the two regions. For this analysis, the lightning flash rate in these grid points are sorted and grouped into three non-overlapping sets of magnitude 0.15, 0.3 and 0.6 flashes/km2 respectively and the mean and standard deviation of corresponding parameters are shown.

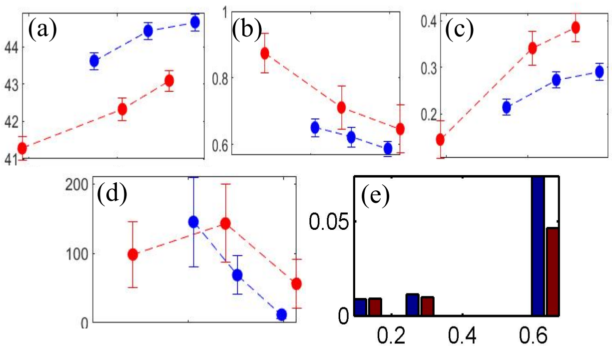

Figure 3. Distribution based dominance test of lightning flash rate on (a) PWV, (b) CBH, (c) Altitude, (d) AOD and (e) flash rate groups over the East (red) and West (blue) Coast with standard deviations

The dominance analysis results of PWV over lightning flash rate (Figure 3(a)) shows a strong increase respect to flash rate as moisture availability increases the cloud content and hence the chance of lightning. The cloud base heights show an inverse relation with flash rate because lower cloud base leads to taller clouds, hence more flashes. The Aerosol Optical Depth shows an increasing relation with flash rates as sea salts from the adjoining seas are hydrophilic aerosols which increase chances of cloud formation and lightning. The altitude/orography did not give any prominent agreement with lightning flashes. But in all cases the eastern coasts have a much stronger and sensitive dominance on lightning activities than western coasts where the density of flashes is also found to be much smaller than the former. When similar tests were done with respect to flash radiance only PWV was found to have a dominant influence on flash radiance because the charge amount which manifests the lightning energy is purely controlled by moisture content, hence PWV. It may further be noted that these dominance relations were utilized in form of a multi linear regression test and the resultant coefficients are found to estimate the lightning property climatology with very high accuracy levels (errors within 10 – 20% of the observed values).

Now, to investigate how moisture content and instability followed by aerosols controls the frequency and strength of lightning activities radiosonde measurements of meteorological parameters and aerosol index measurements were utilized. An in-depth study showed that in the last four decades due to predominant global warming and urbanization, the land sea contrast along the coasts have probably increased which has led to more moisture advection. Further by influence of more instability, this moisture is slowly lifted close to UTLS where excess water vapor participates in ozone reduction and cooling which elevates the neutral buoyancy layer. This further increases cloud vertical extent leading to more hydrometeor concentration hence more lightning. This hypothesis can be further supported when more CCN forming sea salt aerosols are advected close to the coasts in presence of increased land sea contrast due to more global warming. But this fact also points towards the possibility of stronger lightning in the coming decades due to accelerated global warming.

3.3 Future projections of lightning using RCP scenarios with historical data

On the basis of the obtained set of multi linear regression equations, the next steps is to give reliable projections of lightning flash and radiances over the Indian region using various urbanization scenarios. A set of 11 GCMs from CMIP5 were found to contain all the components required for analysis and a Taylor diagram test is done to see whether the datasets are consistent over Indian region. PWV from all 11 models had a reasonable correlation and low normalized standard deviation with respect to reanalysis datasets and hence were considered for further study. In the final frame work, a set of 150 years (1950-2100) of input is prepared by merging the historical and the scenario data. In a previous study, it was depicted that thunderstorm severity has a distinct periodicity of ~ 15 years; hence 10 periods of 15 years each are considered.

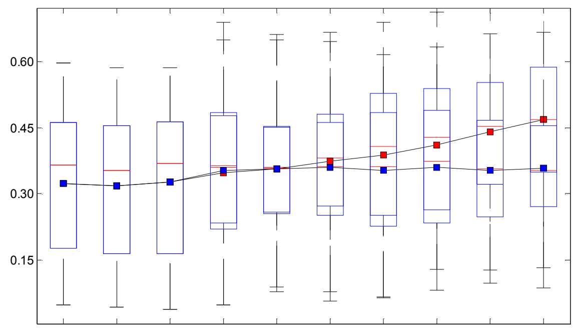

Figure 4. Lightning flash rate variation over Indian region during 1950-2100 (with 10 equi spaced intervals of 15 years) using RCP 8.5 (red) and RCP 2.6 (blue).

The multi model distributions of both RCP 2.6 and 8.5 depict a steady rise in lightning flashes (Figure 4) up to 2025 (present). However, in RCP 2.6 subject to a mild reduction in urbanization, a very weak decline in flash frequency is observed over the Indian region. But on the contrary, RCP 8.5 scenario experiences a rapid increase of ~50% of mean value by 2100 as a multi-model mean. Though this result is merely an average of 11 models with significant variance, yet it follows that in the coming years due to more land heating and instability, cloud column height will ascend leading to more lightning frequency with the highest being at coasts due to moisture abundance. The same experiment when conducted on the 95th percentile of flash radiance shows ~ 10 times increase from RCP 8.5 scenario which is attributed to more moisture especially at the coasts; which should be a problem of concern for future researches.

4 Conclusion

The present study has been tried to unravel the various aspects related to lightning frequency and intensity over the Indian region. Atmospheric instability and aerosol concentrations appear to be the dominant factor affecting lightning frequency while moisture content dictates the lightning intensity. A hypothesis is proposed to explain how enhanced global warming leads to stronger and more lightning activities and the results of this hypothesis imposed on the global model simulations depict a strong increase in lightning strength and number in the coming decades provided the greenhouse emission continues to rise at the present rate.

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