Lightning occurrences and intensity over the Indian region: Long-term trends and future projections

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Abstract

Lightning activities constitute the major destructive component of thunderstorms over India. Hence, understanding the long-term variabilities of lightning occurrence and intensity and their inter-relation with various causative factors is required. Long-term (1998-2014) Tropical Rainfall Measuring Mission (TRMM) satellite-based lightning observations depict the most ~~abundant~~ frequent lightning occurrences along the Himalayan foothills, the Indo-Gangetic plains and coastal regions, while the intensity of these lightning strikes are found to be strongest along the coastal regions and Bay of Bengal. In addition, both the lightning properties show a very strong intensification (~1-2.5% annually) across all Indian regions during 1998-2014 with the maximum trends along the coasts. Accordingly, a detailed statistical dominance analysis is performed which reveals total column water vapor (TCWV) to be the dominant factor behind the intensification in lightning events, while instability, measured by the convective available potential energy (CAPE), and aerosols optical depth (AOD) jointly control the lightning frequency trends. An increase in surface temperatures has led to enhanced instability hence stronger moisture transport to the upper troposphere lower stratosphere regions especially in the along the coasts. This transported moisture helps deplete the ozone concentration leading to reduced temperatures and elevated equilibrium levels which finally results in stronger and more ~~abundant~~ frequent lightning events as also evidenced from the trend analysis. Consequently, the relationship between lightning and its causative factors have been expressed in form of multi-linear regression equations which are then employed on multiple global circulation models (GCM) to understand the long-term impact of urbanization on lightning over a period of 1950-2100. The analysis reveals a uniform increase in lightning occurrences, and intensity from both urbanization scenarios; however, an accelerated growth is observed in the RCP8.5 projections after the year 2050 as also observed from the surface warming trends. As a result, lightning frequency and intensity values across the Indian region are expected to increase alarmingly by ~10-25% and 15-50%, respectively, by the end of this century with highest risks along the coasts and hence it requires immediate attention from policy makers.

Keywords: Lightning; occurrences; intensity; CAPE; TCWV; AOD; GCM.

1. Introduction

Intense thunderstorm events form a very common climatic feature over the Indian subcontinent. These phenomena are generally accompanied by widespread lightning, wind gusts and heavy rainfall which induce various socioeconomic hazards. However, among all these by products, lightning occurrences have been found to cause the greatest damage to life with a death toll of more than 2500 every year since the last two decades (Livemint, 2000). In addition, the recent years have witnessed some most severe lightning calamities as per available records claiming more than 100 lives on 25 June 2020 (Washington Post, 2020).

Over the tropics, the non-inductive (collision based) charging interaction between ice crystals and graupel particles is found to be the major factor behind the evolution of lightning events during typical thunderstorms (Takahashi, 1978; Mansell and Ziegler, 2013). According, in this mechanism, the magnitude of charge generated per collision depends on the relative velocity of the colliding particles, the hydrometeor concentration of graupel and ice and their corresponding size distributions (Shi et al., 2015) and these in-turn are controlled by the atmospheric moisture content (total column water vapour), thermodynamic instability (convective available potential energy) and the possibility of cloud nucleation from aerosols. Additionally, Kumar and Kamra (2012) suggested that orographic lifting also has good influence on lightning but only in limited high-altitude regions of Indian Subcontinent.

Lightning flashes are found to be significantly correlated with convective rain, total column water vapour (TCWV), or surface relative humidity over both land and sea regions, according to previous studies (Price and Federmesser, 2006; Siingh et al., 2011; Shi et al, 2018). This is because, higher humidity levels lead to stronger hydrometeor concentration and updraft velocities, both of which contribute to intense lightning. Next, high values of instability represented by convective available potential energy (CAPE) are essential for lifting the available moisture with strong updrafts above the freezing level where they form ice and graupel particles which collide to initiate charge separation and lightning and this has already been demonstrated both theoretically and statistically in various previous research attempts (Galanki et al. 2015, Saha et al., 2017; Dewan et al. 2018).

Finally, coming to the impact of aerosols (AOD), a study by Shi et al., (2020) reported that the lightning flash rates are strongly correlated when AOD<1 due to the cloud/ice condensation nuclei formation characteristics from sulphates (Jin et al., 2018), desert dust (Boose et al., 2019) or even sea salt aerosols (de Leeuw et al., 2011). On the other hand, when AOD>1 then normally, larger concentrations of cloud condensation nuclei result in more supercooled droplets leading to stronger lightning (Williams and Stanfill, 2002). However, excessively high aerosol concentrations may also result in reduced cloud droplet size (Twomey et al., 1984) which reduces the efficiency of non-inductive charging process. In addition, an excess of absorptive aerosols (such as black carbon) warms the atmosphere and cools the surface (Kar et al., 2009; Talukdar et al., 2019) which further reduces the CAPE and lightning. Hence the reported relationships between lightning and aerosols is still unclear so, further studies are required to unravel it (van den Heever and Cotton, 2007).

Now from climatic point of view, a series of studies in recent years have shown that thunderstorm severity, lightning and its various controlling factors have been increasing prominently in the recent decades and this has been attributed to greenhouse emission induced surface warming effects both over India as well as across the globe. A study by Shindell et al. (2006) depicted that a minimum 10% increase in lightning activity can be expected due to every 1°C increase by global warming. Kandalgaonkar et al. (2005) suggested that a rise of 1°C in surface temperature over India has led to a 20–40% enhancement in average lightning flash density. According

to Riemann-Campe et al. (2009) and Prein et al. (2017) a recent increase of temperature has led to a rise in moisture ingress, consequently the frequency and severity of intense convective activities have shown a steep rise globally.

Over India, Murugavel et al. (2012) and Chakraborty et al. (2019) showed a systematic increase in CAPE which was attributed to thermodynamic instability conditions and large-scale dynamics coupled with a decrease in upper tropospheric temperatures during that period. Also, satellite measurements have shown a prominent increase in aerosol concentrations over Asia due to the intense growth in urbanization and industrialization (Massie et al., 2004). Consequently, a new set of research attempts have tried to express lightning and thunderstorm severities in form of their causative factors which are employed on global climate models (GCMs) to provide future projections of extreme events (Diffenbaugh et al., 2013). Romps et al (2014) expressed the lightning flash rate in terms of the product between CAPE and precipitation rate which when implemented on 8 climate models revealed an increase in lightning by 12±5% per degree Celsius of warming over the USA. Later, a range of other proxies were also used over GCMs for lightning projections, but all of them also provided a similar increase in lightning both globally as well as over the USA (Bannerjee et al., 2014; Romps, 2019). However, as already hinted by Michalon et al., (1999), many years ago, most of the modelling attempts are expected to fail in providing a holistic understanding about the changing lightning climatology; and interestingly this is also found true at present as evidenced from major disagreements in magnitude of the projected trends among all the above-mentioned studies.

With reference to the previous sections, it has been understood that first, a very few studies on lightning has been done on the tropics and especially over the Indian region (Pereira et al., 2010) and none of the remaining attempts have tried to depict the future projections of lightning. Second, all the above-mentioned studies have utilized very poor resolution lightning datasets and hence did not provide a holistic mechanism behind the climatological variations in lightning evolution. Finally, none of these attempts have tried to see the variation of lightning radiance or intensity which is expected to be much more connected with the underlying physical processes compared to the frequency values. Thus, in the present study, high resolution lightning datasets of frequency and intensity are used over the Indian region and an attempt is made to identify the most dominant factors affecting the spatial-temporal variabilities of the lightning properties in a complete manner. Finally, the results of this dominance analysis are expressed in the form of a multi-variate regression analysis and subsequently applied on multi-model GCM datasets to generate reliable future projections of lightning occurrences and intensity over Indian for next few decades subject to various urbanization scenarios.

The main organization of the paper is explained as follows. A detailed illustration of the various datasets used in this study are elaborated in the datasets section. Next comes the results section which is again divided into four subsections. The first two subsections discuss the spatial distribution of lightning and its 17-year trends and they also try to identify the dominant factors responsible for the multi-decadal changes in lightning. In the next part, a probable physical mechanism is proposed to relate how the recently accelerated global warming trends can modulate the climatic intensification and abundance of lightning. However, the final subsection tries to implement the above-mentioned hypothesis on multiple long-term global climate model datasets to provide reliable future projections of lightning intensity and occurrence subject to various degrees of urbanization. In the final section of the manuscript, all the results have been summarized to produce a simplified picture which tries to quantify the long-term impacts of global warming on lightning extremes over the Indian region for future policy makers.

2. Datasets used

Lightning observations for the present study are obtained from Lightning Imaging Sensors (LISs) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite which orbits the earth at 350 km elevation between 35° N and 35ºS at a rate of 16 orbits/day (Christian et al., 2003). These LISs can detect both intra-cloud and cloud-to-ground discharges irrespective of day or night conditions with a flash detection efficiency of 73±11 % and 93 ± 4%, respectively (Boccippio et al., 2002). The lightning observations are done by monitoring illumination pulses along the 777.4 nm atomic oxygen multiplet with a very fine spatial (5.5 km) and temporal (2 ms) resolution. Every time an illumination pulse registers intensity greater than the predefined background noise level, it is considered as a separate lightning event after which all such events occurring within an integration time of 330 ms are collectively considered as a single lightning flash. The view times of these flashes are also recorded separately for obtaining the monthly flash rate climatological datasets. Here it may be noted that most of the past researches have used pre-processed monthly averaged lightning flash rates after 2.5º and 99-day smoothing of the actual data which may have compromised the actual distribution of lightning properties in those cases. Hence, in this study, the actual lightning observations from ~95800 satellite passes have been utilized during the total availability period of 1998-2014. These lightning flash (/km2) datasets are compiled monthly and then averaged annually while the lightning radiance values (J/m2/steradian/s^{-1}) are averaged directly on a yearly basis so that the magnitudes of both these parameters remain along the same scale of 0-1 for simplicity in analysis. However, for ease of region-wise analysis, the yearly time series of both these parameters has been analysed on a fixed grid resolution of 1 degree.

While utilizing the lightning radiance measurements from satellite observations, it may be best suited to explain the importance of this data towards weather and climate as this attribute has never been extensively discussed in past research attempts unlike lightning frequency or flash rate. It is well known that lightning activities originate due to charge separation in mixed phase clouds, but they require a sufficient amount of electrostatic charge to shatter the insolation capacity of the atmosphere and descend to the earth surface thereby causing widespread damage to life and property. However, a majority of these lightning occurrences are not strong enough and hence they remain as intercloud lightning without any real impact on the climate or socio-economy. On the other hand, according to some novel studies like Uman (1986) only 10-20% of the total lightning activities remain strong enough to reach the ground thus inflicting widespread socio-economic impacts. Consequently, the climatological variation of lightning intensity or radiance also needs to be monitored very closely by present policy makers in order to prevent the chances of any impending catastrophises in future.

Next, the gridded datasets of the causative meteorological factors namely CAPE and TCWV are utilized from the Climate Forecast System Reanalysis (CFSR) developed by NOAA's National Centre for Environmental Prediction (NCEP) (http://nomadl.ncep.noaa.gov/ncep-data/index.html) datasets (Kalnay et al., 1996) as provided by the ESRL PSD during the period 1948-2014. These datasets are provided at a coarse spatial resolution of 2.0° × 2.0° for CAPE and 2.5° × 2.5° for TCWV, hence it had to be interpolated to 1° resolution and averaged yearly for subsequent analysis. Secondly, the datasets of aerosol content (AOD) over the maximum availability period of 2000-2014 are obtained from Level-3 (L3) MODIS TERRA Atmosphere Monthly Global Product MOD08_M3 at 1X1 grid resolution (Platnick et al., 2015) over the Indian sub-continent. Further details can be obtained herewith (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=aerosol_monthly). Gridded altitude datasets at 0.25º resolution are taken from GMTED2010 global digital elevation model under TEMIS project

157 (Danielsen and Gesch, 2011). Finally, the future projections of lightning properties for various urbanization
158 scenarios are derived using gridded datasets of the temperature, humidity and ozone profiles with aerosol optical
159 depth at 550 nm from 11 general circulation models (GCMs) in the Coupled Model Inter-comparison Project
160 (CMIP5) archive (website: http://cmip-pcmdi.llnl.gov/cmip5/) during 1950-2100. Further details of these datasets
161 have been provided in Taylor et al. (2012) and also in subsequent sections of this study.

3. Results and Discussion

3.1. Spatial distribution of lightning properties

165 The climatological average of lightning frequency shown in Figure 1(a) depicts much higher values over the land
166 regions compared to Arabian Sea (AS) and Bay of Bengal (BoB). This is due to occurrence of stronger sensible
167 heat fluxes over the land regions resulting in stronger updrafts, and hence more lightning (Kumar and Kamra
168 (2012). The highest magnitude is observed along the foothills of Himalayas (72-95°E) which implies the effect of
169 orographic convection on lightning events. In these regions, the high values of lightning flashes are found
170 associated with the occurrence of a mountain breeze front during the afternoon hours (Boeck et al., 1999). The
171 secondary spatial maximum of lightning is observed along the coastline which can be attributed to widespread
172 moisture advection from the adjoining seas (Kumar and Kamra, 2012).

173 The BoB experiences moderately high lightning frequencies due to high seas surface temperatures (SSTs)
174 (above a critical threshold of 28°C according to Gadgil et al. 1984) which lead to frequent cyclonic storms and
175 lows in this region. However, AS experience lower lightning frequencies due to lower SSTs in this region (Kumar
176 and Kamra, 2012). Next, low lightning frequencies are observed along the peninsula due to reduced moisture
177 supply as it is geographical bounded by mountainous terrain along the coasts from both sides. In addition,
178 moderately high lightning frequencies are observed along the Indo-Gangetic plains (IGP) which can be due to the
179 complex interactions among the moderate moisture supply from BoB, local instability and the CCN effects from
180 transported (Boose et al., 2019) and emitted aerosols. Finally, very low values of lightning occurrences are seen
181 over West Central India (WCI) which can be due to dearth of moisture supply despite the contribution from
182 transported dust aerosols here.

183 Contrary to the occurrence climatology, the lightning radiance values (Fig. 1b) are much lower over majority
184 of land regions which is solely because of higher values of moisture content over the coastal regions leading to
185 more graupel (ice and hail particles concentrations above the freezing layer) as shown in Murugavel et al., 2012.
186 Yet, the maximum values of radiance are observed exactly along the coastline regions which reduce gradually as
187 one move further into the seas. This indicates the importance of thermal land-sea contrast which results in strong
188 moisture advection from both land and sea breezes along the land-sea boundary (Pielke, 1974) resulting in more
189 hydrometeors hence largest radiance. However, the presence of giant CCN marine aerosols particularly in AS (de
190 Leeuw et al., 2011) may also act as a secondary factor. Nevertheless, AS still experiences lower lightning radiance
191 than BoB probably due to its local meteorological factors as described earlier. Next, the lightning radiance values
192 are found distinctly lesser over PI, WCI and HIM as they receive much less moisture than the rest of India. In
193 Addition, a secondary maximum of radiances is observed over the IGP due to moderate moisture supply and
194 aerosols which can act as potential ICN/CCN thereby increasing the number of colliding hydrometeors for more
195 lightning radiance.

196   So, based on these spatial distributions of lightning occurrence and intensity, a group of 7 regions are
197   proposed for further analysis as depicted in Fig1d. The two coastlines share high lightning occurrences as well as
198   intensity hence are referred as Coasts. Second comes PI as a landlocked region between the Coasts with moderate
199   values of both lightning properties. Region 3 and 4 are taken for both sea regions namely BoB and AS as their
200   response to lightning occurrences and radiances are quite different. Next, the Himalayan foothills are considered
201   to observe the effect of orographic convection on lightning properties independently. Then, IGP is selected since
202   it experiences quite high lightning occurrences and intensity due to complex aerosol, instability and moisture
203   interactions. Finally, WCI a remote inland region is considered as it experiences lower lightning properties due to
204   meagre moisture supply despite an important contribution from land heating and aerosols.
205   The climatologically averaged distributions of lightning frequency and intensity along with 4 most potential
206   factors influencing them (TCWV, CAPE, AOD and Altitude) for different regions are shown in Fig. S1. For
207   lightning frequency, the mean and percentiles are highest in HIM and lowest in PI and AS. However, the extreme
208   values for the Coasts and WCI are found to be higher than HIM because of frequent cyclonic and low-pressure
209   systems prevalent in these regions (Fig S1a). The Lowest lightning frequency is observed over AS. The radiance
210   and CAPE follow similar variability i.e., higher values are observed over BoB and Coasts due to more moisture
211   availability and thunderstorm occurrences while the other regions experience low to moderate values (Fig. S1b).
212   Yet a lot of extremes are observed in IGP and WCI which implies that the occurrence of surface heating lead to
213   higher cloud base heights and more ice-phase hydrometeors; hence more lightning in these regions as also
214   supported from previous studies (Price, 2009; Shindell et al., 2006).
215   The total moisture content (TCWV) is found to be highest along the Coasts and adjoining sea regions as
216   from lightning occurrences and intensity. Incidentally, the remote inland locations like PI and WCI receive much
217   reduced moisture supply which is the primary reason behind the lower lightning radiances in those regions. Next,
218   the IGP and WCI regions show highest values of AOD due to dust transport from Thar and Sahara deserts along
219   with large scale emission from various anthropogenic activities which have very complex impacts on convection.
220   Likewise, the Coasts also receive moderate aerosol supply from the adjoining seas as already described before
221   which further support lightning formation. The HIM region depicts the highest altitude variation among all the
222   regions, of which a significant fraction is present above 4 km height thereby supporting widespread orographic
223   lifting induced lightning activities. Next, PI and IGP exhibit an infinitesimally small altitude variation (<500 m)
224   which may not be sufficient to support any orographic convection. Whereas in WCI, the altitude ranges are
225   considerably higher which in turn provides a small but vital contribution towards lightning as also supported from
226   various past research attempts (Barros et al., 2004).

3.2. Temporal variation of lightning properties

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

229   The 17-year time series variations of mean annual lightning frequency and radiance are depicted for seven regions
230   and entire India in Fig. S2 along with their respective standard error values. Robust-fit regression analysis is
231   employed to study whether there are any statistically significant trends in the lightning frequency and radiance.
232   At the same time, a detailed description regarding the yearly % trends of lightning properties and their controlling
233   factors (TCWV, CAPE and AOD) are depicted along with their corresponding correlation coefficients in Fig. 2.
234   The trends of lightning frequency are found to be the highest over the Coasts, BoB and AS (with a total increase

235 of ~30%) with reasonably high correlation coefficient values which again can be attributed to an increase of both
236 moisture content and instability in these regions. However, the other regions depict much weaker values of both
237 these quantities. Here it is interesting to note that IGP depicts much weaker lightning trend which may be due to
238 the complex aerosol interactions as explained before. But in total, India has faced ~25% increase in lightning
239 frequency (with very high correlation values) in these 17 years which is alarming and hence will be discussed in
240 detail later in the study.

241 The mean annual lightning radiances show gradually increasing trends (with a total increase of ~20%) in
242 almost all regions. However, the magnitudes of % trends as well as the correlation coefficients are much lesser
243 compared to lightning frequency which implies that average radiance may not be a suitable parameter to
244 investigate the future variations in lightning. It is known that, TRMM observes both cloud-cloud and cloud-ground
245 types of lightning strikes together and out of the total, only the strongest 10% of the total strikes are intense enough
246 to reach the ground in the tropics (Uman, 1986) and cause immense damage to life and property (Holle et al.,
247 2019). Now, since it is more important to understand the trends of these extreme cases only, hence the regional
248 trends of 90th percentile of lightning radiances is examined (Fig.2a). The trends depict a very prominent all-India
249 trend of ~30% with higher correlation values compared to mean lightning radiance (Fig.2b). Additionally, the
250 coastal and sea regions depict much higher trends (>40%) than the rest of India which is extremely alarming for
251 policy makers at present. However, HIM has not shown any change in lightning radiance which may due to the
252 marginal increase in TCWV and CAPE there.

253 Further, it is investigated whether the proposed 90th percentile of radiance also agrees well with the
254 distribution of mean radiances over every Indian region; hence the corresponding values of both the quantities for
255 a total span of 68 seasons in 17 years are shown in Fig. S3. The figure depicts that the south Indian regions namely:
256 BoB, Coasts, PI and AS (with stronger maritime influence) exhibit prominent correlation values between the two
257 groups and the average ratio between the two is ~1.2; with a minimal amount of spreading which indicates that
258 there are no external factors affecting the average radiance distribution. But the northern inland zones depict a
259 prominent scattering between the groups (especially in IGP) and the ratio between them is also much higher (~1.4)
260 which indicates that some external factors such as aerosols may also exert an additional impact in intensifying the
261 radiance values well above the average radiance distributions. But overall, a good agreement is seen between the
262 lightning radiance groups thereby supporting the suitability of using p90 radiances only in the subsequent sections.

263 Next, the trends of TCWV (Fig. 2a) depict uniform trends (0.3% yearly or 5% in total) across all regions
264 with ~~descent~~decent correlation values everywhere except HIM which are caused by prominent GHG induced
265 global warming in the recent decades as shown in previous studies. CAPE which represents the atmospheric
266 instability is the main reason for lightning evolution, hence this parameter also depicts strong interzonal variability
267 like lightning. The Coastal regions and seas experience much stronger increase of ~9% in 17 years implying more
268 thunderstorm activity in the present due to prominent global warming induced land sea thermal contrast. However,
269 the rest of the country exhibits a much weaker increase (~5%) and further, the trends in IGP and WCI are even
270 lower due to the complex aerosol effect. Finally, AOD is found to increase most significantly throughout India
271 compared to the other parameters, however the south Indian maritime regions experience a much lower rise of
272 ~25% compared to deep inland regions (WCI and IGP) with ~40% increase indicating that aerosols may have
273 more dominant role in modulating the trends of lightning properties only in the continental North Indian regions.

274 **3.2.2. Investigation of the dominant factors affecting the lightning trends over India**

The previous sections depict a series of spatially varying complex interactions among TCWV, CAPE and AOD which resulted in an increasing trend in both lightning properties over the Indian region. Now, to identify the most dominant factors affecting the trends of lightning, a clustering analysis is done for each Indian region. Hence the datasets of lightning are taken for 15 years span (as AOD data is absent before 2000) and then they are sorted into three clusters based on magnitude. The mean and deviation of these clusters are depicted in Fig. S4 and Fig. S5 with respect to corresponding values of TCWV, CAPE and AOD. Factors having dominant influence are identified as those where the parameter mean increases sharply with the clusters with minimal mutual overlapping.

The analysis revealed that CAPE and AOD depict good clustering for occurrences while TCWV shows the best results for radiances over Coast and BoB. AS also behaves similarly, but in case of occurrences, AOD ~~fairs~~fares slightly better than the others implying a dominant contribution from CCN forming marine aerosol transport in this region. PI experiences lesser moisture ingress (due to its inland location) hence it relies more on dry convections which makes CAPE the major governing element for both the lightning properties. No single factor is observed to be dominant factor for lightning frequency in HIM as it mainly relies on orographic convection processes as already explained in preceding sections. But for radiance, TCWV still remains a dominant factor (Fig. S5). Next in case of IGP, CAPE exhibits fair linear clustering in occurrence while TCWV remains dependable for intensity. WCI behaves similar to PI but, here a secondary influence of AOD is also observed indicating the possible impact of transported dust (acting as ICN) which catalyses the formation of ice phase hydrometeors leading to more frequent and stronger lightning events.

Next, the clustering analysis is performed over the entire Indian region and is shown in Fig. 3. Based on clustering and correlation analysis for lightning frequencies, CAPE emerges as the dominant factor followed by AOD. This can be supported theoretically as the generation of lightning events only requires the availability of ice phase hydrometeors above the freezing level which is achieved mainly by the lifting mechanism due to CAPE followed by the aerosol CN effect. On the other hand, in case of p90 radiance, based on clustering and correlation coefficients TCWV emerges as the single dominant feature behind the strong rise in lighting radiances all over India. This result can also be explained theoretically as the inductive/non-inductive charging density responsible for lightning radiance is far more dependent on the local hydrometeor concentrations (arising from moisture abundance) compared to their relative vertical velocities (controlled by CAPE). Now interestingly, AOD has consistently maintained a complex secondary impact on both the lightning properties depending its tendency to either favour lightning (by creating more ICN/CCN formation due to dust or sulphate aerosols) or negatively by inducing cloud burn-off effect(due to black carbon aerosols) as already discussed in preceding sections. So, a detailed study needs to be done to untangle the AOD effect in aerosol sensitive zones like IGP and WCI.

Now, the temporal dominance analysis is repeated quantitatively using a multi-linear regression analysis. In this step, two equations are hypothesized where lightning frequency and radiance are expressed separately as a multi-linear addition of all three controlling factors. The proposed equations can be expressed as:

Lightning frequency = a1*TCWV + b1*CAPE + c1*AOD   (1)

& Lightning intensity = a2*TCWV + b2*CAPE + c2*AOD   (2)

Here, a, b and c represent the corresponding Multiple linear regression (MLR) coefficients for the three factors and the numbers 1 and 2 stands for lightning frequency and radiance, respectively. The corresponding variation of these MLR coefficients is shown in Fig. 4. CAPE acts as most dominating factors in all the regions expect over AS where AOD influence is very high. AOD is the second most controlling parameter in lighting

315 frequency (except over BOB and HIM). For radiances, the TCWV is the dominant factor in most regions (except
316 over PI and WCI). The reasons for this were discussed in previous section. Again, similar to AS, AOD plays the
317 most significant role in modulating both the lightning properties over IGP due to the role of complex aerosol-
318 cloud interactions.

319   Finally, over the Indian region, TCWV arises as the dominant parameter controlling the climatic trends of
320 radiances; however, for occurrence it is not so simple. Though CAPE manages to be the principal factor, yet the
321 relative contributions of AOD followed by TCWV cannot be neglected. Next, the applicability of the proposed
322 MLR equations for long-term studies are validated by showing the ratio between regressed and observed lightning
323 properties (Fig4 i & j). In case of occurrences, the ratio between the two is not perfect and a small overestimation
324 of ~5% is observed hence this bias has been corrected before using it in the coming sections. Whereas, the
325 regressed values of radiance match perfectly with observations. Henceforth, these MLR equations have been
326 utilized for deriving the reliable long-term projections of lightning properties in subsequent sections.

327 **3.3 Physical mechanisms driving the increasing trends in lightning properties**

328 In this section, the physical processes responsible for the increase in lightning occurrences and intensity over the
329 Indian region will be discussed. Recent studies showed a prominent increase in aerosols and GHG emissions over
330 the Coasts, IGP and WCI as seen from the very strong increase in AOD in the recent years. This phenomenon
331 resulted in widespread surface and atmospheric warming (Basha et al. 2017) and consequently a stronger surface
332 evaporation and moisture production. In addition, many recent research attempts have reported a net increase in
333 the Hadley cell and Brewer–Dobson circulation strength (Liu et al., 2012; Fu et al., 2015), which also assists in
334 additional moisture supply. Consequently, the increased moisture in the atmosphere further accelerated the
335 warming effect and TCWV growth in forms of a positive feedback (IPCC, 2007) primarily in the Coastal and
336 neighbouring sea regions like BoB and AS. However, the increased moisture supply in IGP or PI is mainly due to
337 the enhanced land-sea thermal contrast effect (due to GHG and aerosol emissions) which intensifies the moisture
338 converges in these regions.

339   To explain how thermodynamic instability or CAPE has been increasing recently, a previous study by
340 Chakraborty et al. (2019) is referred where long-term multi-station radiosonde observations depicted strong
341 increasing trends in CAPE and TCWV all over Indian region with the maximum values along the coasts and
342 surrounding inland regions. However out of the total column, the percentage trends in both instability and
343 moisture integrals (CAPE or TCWV) are found to be particularly higher above 300 hPa pressure levels which can
344 be associated with a gradually ascending level of neutral buoyancy (LNB/EL) during this period. Now as the EL
345 comes very close to the 100 hPa level during intense convective events, hence an observed cooling at its immediate
346 surroundings (135-95 hPa) is thought to be the main factor responsible for the EL ascent and CAPE increase in
347 these regions. The main reason for considering this hypothesis is based on a study by Dhaka et al. (2010) where
348 a very prominent anticorrelation was observed between the yearly average values of CAPE and their
349 corresponding upper-tropospheric temperatures at 100 hPa.

350   It has been well documented in past studies that ozone molecules act as the primary heat source component
351 at 100 hPa level (corresponding to the UTLS region) by absorbing the ultraviolet radiations (Mohankumar, 2008).
352 Now, the multi-station radiosonde observations from Chakraborty et al. (2019) depicted a clear rise in specific
353 humidity and a depletion in ozone mixing ratios at the same height range. These results were analogous with the
354 findings from Forster et al. (2007) according to which the recent decades have experienced an upper tropospheric

355 cooling due to a decrease in ozone concentration. Thus, a cooling trend at this height level can be explained by

356 the theory that excess moisture pumped to this height by intense convections get disassociated photolytically by

357 reactive oxygen atoms to produce two OH radicals which further decompose ozone to oxygen molecule and a

358 reactive oxygen atom in the UTLS region (Guha et al. 2017) thereby continuing the process. Consequently, this

359 feedback process would lead to a further ascent in EL and increase in CAPE; however, the magnitudes of the

360 resultant CAPE intensification will be highest over the coasts and surrounding seas due to a stronger moisture

361 advection in those regions.

362 Hence according to this hypothesis, the Coastal regions and seas experience more growth in TCWV and

363 CAPE which lead to formation of more ice phase hydrometeors thereby promoting an accelerated rise in lightning

364 radiance. On the other hand, larger CAPE favours more updraft velocities in the ascending particles which further

365 increase the probability of hydrometeor collisions leading to an increased lightning frequency. However, an

366 additional effect can also be cast by AOD by facilitating more CN formation (from dust, sulphate or sea salt

367 aerosols) which will strengthen the above-mentioned physical mechanism thereby leading to a stronger increase

368 in both lightning properties over the aerosol sensitive inland regions such as IGP, WCI and PI.

369 **3.4 Generation of reliable future projections of lightning frequency and intensity**

370 **3.4.1 Selection of GCMs for future projection analysis**

371 In this section, the MLR coefficients from previous sections are employed to provide reliable projections of future

372 lightning activities over the Indian region. Accordingly, the datasets of CAPE, AOD and TCWV are utilized over

373 a period of 150 years including first 55 years (1950-2005) from historical datasets and the rest (2006-2100) from

374 two extreme future scenarios namely: RCP2.6 and 8.5. A set of 8 global climate models (GCM) of CMIP5

375 (depicted in Table S1) are selected for analysis as all of them commonly provide the monthly mean estimates of

376 TCWV and AOD with daily profiles of temperature, humidity and ozone. The monthly average values of CAPE

377 are then calculated from daily T and RH profiles using the parcel approximation technique as described in past

378 research attempts (Chakraborty el al., 2018; Narendra Reddy et al., 2018). It may be noted that, the surface-based

379 CAPE (SB-CAPE) calculation technique has been used to obtain the current CAPE values in this study since they

380 measure the total buoyancy experienced by the parcel raised directly from the surface to any height of the

381 atmosphere irrespective of the prevailing atmospheric conditions, seasonality or the region where it is being

382 derived. Now, the datasets from each of these models are interpolated to a uniform 1X1 degree resolution after

383 which their performances are tested by comparing the simulated CAPE, TCWV and AOD values with respect to

384 NCEP NCAR reanalysis datasets. The results of this test are represented in terms of a Taylor diagram in Fig. 5.

385 The Taylor diagram results for TCWV, CAPE and AOD unanimously reveal that models ACCESS1.3

386 CSIRO MK3.6, MIROC5 and NOESM 1ME (represented as A, B, F and H in Fig.5.) depict good correlations

387 over the Indian region along with lower std and rms values. In addition, the model derived monthly inputs are also

388 validated against NCEP data for all seven regions in Fig. S6. The correlation coefficients for all regions commonly

389 show that models ACCESS1.3 CSIRO MK3.6, MIROC5 and NOESM 1ME again show much better agreement

390 with NCEP data. Hence these four models are considered further for lightning projection analysis. Next, the all-

391 India averaged regressed lightning occurrences and intensity values obtained from the models during 2000-2014

392 are plotted against their corresponding observations to check the reliability of MLR analysis on the modelled data.

393 The results depict a fair agreement between the two sets (r=0.76 in occurrences and 0.7 in radiance) in both the

394 cases. However, a very prominent underestimation bias has been observed (~24% in occurrences and ~18% in
395 radiances) which is probably because the modelled datasets are of much coarser resolution than the actual
396 observations, hence they will always depict much lesser average or variability compared to the former. However,
397 the inter comparisons between the modelled and observed lightning properties over all the regions commonly
398 depict quite high values of correlation with an overall underestimation bias of 17-25% thereby supporting the
399 reliability of MLR analysis. However, the underestimation biases obtained from inter-comparison tests must be
400 added with the regressed climatic projections for both zonal and all-India cases to get the actual lightning trends
401 in forthcoming sections.

3.4.2 Examination of the 150-year trends in various factors controlling lightning

403 The 150-year trends of various controlling factors associated with the climatic trends of lightning occurrences and
404 intensity are shown in form of normalized % change per decade for all seven Indian regions in Fig. S7. The surface
405 temperature trends are first considered as this parameter is closely associated with urbanization and GHG
406 emissions and it also acts as the primary driver behind the CAPE and TCWV trends. A moderate rise in RCP2.6
407 is observed (~0.5% per decade) which represents an all-India warming by ~1.6°C in total while the RCP8.5
408 scenario exhibits an extremely severe warming of ~5°C in the Coasts, WCI, BoB and IGP which is also expected
409 to cause a parallel increase in TCWV and CAPE in future. Next, at par with surface warming, TCWV exhibits a
410 moderate increase from RCP2.6 scenario but in case of RCP8.5, an alarming growth of ~40% is observed across
411 India (with the largest increase in the Coasts, BoB and AS) which will definitely lead to a parallel huge change in
412 extreme lightning radiances over the total span of 150 years.

413 In case of AOD, contrary to the extremely large increase of ~30-40% between 2000 and 2014 from MODIS,
414 a much smaller rise of only 20% is seen during a much larger span of 150 years. Now to understand the source of
415 this discrepancy, the 150-year time series of AOD is observed which reveals that the initially increasing trend of
416 aerosols reverses to a strong negative trend after 2020 which results in an overall weak positive trend. The sudden
417 decline in AOD can be explained by the fact that RCP2.6 scenarios are characterized by stringent control on GHG
418 emissions and aerosols after 2020. However, RCP8.5 scenarios exhibit a higher overall increasing trend
419 amounting to 60%. Now this improvement in AOD trend from the latter case is because after 2020 the AOD
420 values saturates and then it shows a weak negative trend implying minor aerosol emission restrictions in future;
421 hence, the net cancellation of trends does not happen here. Also, the net increase in AOD is moderate in the Coasts
422 but much higher in aerosol sensitive regions like IGP and WCI implying even a doubling of AOD in these regions
423 which again may cast some vital influence on the lightning frequency trends of these regions in future.

424 Next in accordance with the TCWV and temperature trends, CAPE and MLCAPE depict a 15% and 8%
425 increase in total from RCP2.6 scenarios. Also, the CAPE trends are much higher than in MLCAPE which indicate
426 the validity of the upper tropospheric intensification theory as explained earlier. Again, the trends in CAPE and
427 MLCAPE are the highest being over Coasts and surrounding regions due to maximized moisture availability as
428 also shown in the previous studies. However, the RCP8.5 scenario shows an alarmingly high total trends of ~50%
429 and 20% in CAPE and MLCAPE respectively due to intensified global warming and moisture availability with
430 the highest rise of ~60% over the Coasts and seas which implies the possibility of accelerated growth in lightning
431 occurrence in these zones. However, inland regions (IGP and WCI) still show moderately high CAPE trends (due
432 to strong surface heating and aerosol trends) which may also lead to stronger lightning frequencies there.

433   Next, the trends in EL pressure level show an expected depletion (implying an ascent in EL) from RCP2.6

434   scenario with values between 0.5-1 % hPa per decade. However, in RCP8.5, the trends are further enhanced with

435   a range of 1-2% per decade with the largest changes occurring in the Coasts and BoB followed by IGP and WCI

436   due to a stronger increase in CAPE and TCWV. Similarly, the T100 cooling trends experience exactly similar

437   behaviour as EL with ~1-degree cooling in Coastal regions from RCP2.6 scenario while in case of RCP8.5, a

438   drastic cooling of up to ~2°C is observed in total which can highly invigorate the convective strengths leading to

439   much stronger lightning events in future. Next, in RCP2.6 case, SHUM at 100 hPa undergoes ~0.3% increase per

440   decade associated with a 1% decrease in ozone. Here it may be noted that the ozone depletion trends are much

441   higher than in SHUM only because the photolytic disassociation of a single water vapour molecule with reactive

442   oxygen atom produces two OH radicals which help in decomposition of two ozone molecules. However, using

443   RCP8.5 scenario, these phenomena gets further amplified where -0.6% per decade increase in SHUM and (-2%)

444   depletion in ozone is observed with highest magnitudes observed in the Coasts. Hence the results suggest that

445   under higher surface warming (RCP8.5 scenarios), CAPE and TCWV will increase by exactly same hypothesis

446   as shown in Section 3.3 which ultimately results in a very strong increase in lightning properties over India

447   Now, coexistent with the zonal decadal trends the all-India time series of all parameters are shown in Fig. 6.

448   The surface temperatures depict an increase by 2 and 4 degrees, while the TCWV and CAPE also rise by 10%,

449   50% and 20%, 40% respectively for the two pathways. However, it may be noted that the main difference in

450   TCWV trends between RCP2.6 or 8.5 scenarios mainly arises from its drastic increase in the latter case after 2050

451   which is again attributed to the accelerated global warming conditions experienced using RCP8.5 scenarios during

452   those decades. Next, the AOD follows a dampened increasing trend in both scenarios with the increase in latter

453   being slightly more prominent than the former. Now these dampened AOD trends are expected to reduce the net

454   growth in lightning occurrences (owing to AOD's prominent contribution in the lightning frequency MLR

455   coefficients), but such effects will not be discernible in the radiance trends as it depends primarily on TCWV only.

456   Now because of the CAPE and TCWV trends, EL has shown a prominent ascent coupled with strong UTLS

457   cooling and increased moistening and ozone depletion trends in both urbanization scenarios. However, the trends

458   in RCP8.5 scenario are consistently much stronger than the RCP2.6 case due to much stronger GHG induced

459   UTLS dynamics and CAPE intensification feedback effect. In addition, the main difference between the trends

460   from both scenarios is mostly prominent towards the end of 21st century as explained previously.

3.4.3 Expected overall trends in lightning frequency and intensity

462   The 150-year trends in lightning properties for all seven Indian zones are observed in Fig. S7. The lightning

463   occurrences depict an overall increasing trend of ~15-25% for the total 150-year span which after adjustment for

464   underestimation bias (20-27% as in Fig. S6) provides the actual trends to be 19-31%. However, this increase of

465   lightning occurrences is rather low compared to the 17-year trends from observations. Hence, the lightning

466   frequency time series for each zone is investigated separately which reveal that the lightning frequencies have

467   increased up to 2020 after which it gets saturated; nevertheless after 2050, it again started to increase up to 2100

468   thereby leading to much lower trend values (Fig. 6). However, this type of variation can be explained by the

469   secondary influence of AOD on lightning occurrences which also shows a dampened increase thereby

470   compensating the impact of increasing CAPE in totality. In addition, out of all regions, the strongest increase in

471   lightning frequency is mainly observed in the Coasts, BoB, PI, IGP and WCI which is primarily due to influence

472   of CAPE and moisture supply in the first two and due to dry surface heating and aerosol effect in the rest. However,

473   in RCP8.5 scenarios, a much larger trend values amounting to 29-41% are observed (after bias correction) which

474   is mainly attributed to the stronger increase in CAPE and TCWV and a weaker decline in AOD in this case.

475   However, the spatial distribution of the trends remains fairly like the RCP2.6 case.

476   The 150-year zonal trends in lightning radiance from RCP2.6 scenarios depict a prominent overall increasing

477   trend of 35-54% after zone-specific bias corrections. Here the radiance trends are found to be much higher than

478   in occurrences since the lightning radiance trends depend primarily on TCWV which also shows a prominent

479   increase across the 150-year span. However, the net radiances are still a bit lower than the expected trends from

480   observations due to the small declining trend contribution from aerosols. However, the RCP8.5 scenario depicts

481   a very alarming increase amounting to (56-97% after bias correction) which can be attributed to the stronger

482   increase in both TCWV and CAPE throughout 150 years coupled with a weaker decline in AOD. In addition, the

483   lightning radiance trends are found to be the strongest in the Coasts and BoB, due to the accelerated rise in TCWV

484   and CAPE while a slightly weaker trend is observed over IGP and WCI due to the compensating influence of

485   AOD in addition to the TCWV and CAPE trends.

486   Now, at par with the zone-wise decadal lightning trends, the all- India averaged time series of lightning

487   occurrences and intensity are depicted in Fig. 7. The lightning occurrences from RCP2.6 scenarios depict a weak

488   increasing trend amounting to 26% (after bias correction of 24%) over the 150-year time span. As already

489   explained, the weak trend observed is due to the cancellation between increasing trends of CAPE and TCWV

490   against a declining trend in AOD. But in case of RCP8.5, a considerable increase in lightning frequency amounting

491   to 35% is observed which is mainly due to a strong rise in CAPE and TCWV along with a weaker decline in AOD.

492   In case of extreme radiances, RCP2.6 scenario shows a moderate rise of ~45% throughout India (after a bias

493   correction of 18%). However, RCP8.5 scenario depict a much higher increase by ~73% which is due to the much

494   stronger rise in TCWV followed by CAPE with minimal contribution from AOD. In addition, an exponential rise

495   in both TCWV and CAPE are observed after 2060 because of excessive GHG emission induced global warming

496   thereby leading to the highest increase in lightning radiance over India after 2060.

497   Now finally, an attempt is made to estimate the net % increase in lightning properties starting from the

498   present (2010-2020) in order to describe the probable difference in lightning trends if two extreme GHG emission

499   policies are adopted. Under these circumstances, the lightning frequencies depict a weak rise of ~13% assuming

500   RCP2.6 scenario but this trend would increase to ~19% in case of RCP8.5 while in the coasts, the trends may be

501   slightly higher reaching a maximum of ~22% for the latter. Yet, these trend values are quite smaller and hence

502   can be avoided quite easily in the future. However, in case of extreme radiance, the minimum possible increase

503   considering stringent policy making decisions from RCP2.6 scenario is ~22% throughout India. But in absence of

504   such restrictions (RCP8.5) the overall increase in extreme radiance will be ~37% with respect to present. In

505   addition, due to the impact of stronger TCWV and CAPE trends, the Coastal regions can face even up to a ~50%

506   rise in extreme lightning intensities by 2100 which poses an extreme socio-economic threat and hence requires

507   immediate mitigation strategies from policy makers at present.

508

509   **4. Summary and Conclusions**

510   Lightning activities are considered as an essential by-product of thunderstorms and they pose the greatest damage

511   to life annually since the last few decades. However, only a few studies have been reported over India or globally

512   which attempted to understand the evolution and distribution of lightning processes in overall and thereby provide

a reliable estimate about the future projections of lightning. Hence, the present study, attempts to utilize high resolution lightning observations to explain its socio-temporal variabilities over India and also to identify the most dominant factors responsible for the evolution of such extremes. In addition, the proposed inter-relationships between lightning and its causative factors namely: moisture, instability and aerosols are also implemented in multi-model GCM datasets to derive reliable future projections of lightning properties over the Indian regions for the 21st century. The main highlights obtained from the present study include:

1. The highest climatological average of lightning occurrences is observed along the Himalayan foothills, followed by coastal regions and Indo-Gangetic plains which are mainly attributed to the influence of orographic convection, moisture ingress (due to land-sea thermal contrast) and aerosol cloud interactions.

2. Annual average values of lightning radiances are the strongest along the coastal regions and surrounding seas primarily due to the dominance of hydrometeor concentrations on the lightning charge density equations caused by enhanced moisture availability in those regions.

3. During the period 1998-2014, lightning frequencies exhibit a strong growth of ~1-2 % annually across all Indian regions with a strong inter-regional variability. However, the trend values are invariant and quite lower in the average radiance trends. Therefore, the trends in 90th percentile radiances are estimated which show prominent spatial variation with 2-2.5% increase annually along Coasts, BOB, PI and IGP. These zonal diversities in the lightning trends are also supported by the corresponding CAPE and AOD trends.

4. The clustering and multi-linear regression dominance tests depict that over India as a whole, atmospheric moisture (TCWV) is the principle factor controlling the lightning extreme radiance trends, while instability (CAPE) and aerosols (AOD) jointly play a strong role behind lightning frequency variation. However, in the latter, the proposed inter-relationships are found to deviate from region to region due to complex aerosol-cloud interactions towards thunderstorm genesis and lightning evolution.

5. Results from previous research attempts are employed to explain the underlying physical mechanism of these trends which inferred that an increase in surface temperatures has led to higher instability and moisture transport to the UTLS regions. This moistening resulted in ozone depletion and cooling which further uplifted the equilibrium levels leading to stronger CAPE and more ice-phase collisions above the freezing level; and eventually this complex feedback procedure ultimately leads to stronger and much more lightning events. A schematic of these processes has been depicted in Fig. 8.

6. The above-mentioned hypothesis is found to be most prominent in the coasts and surrounding seas due to its high moisture abundance. However, in addition to these factors, this mechanism will also be further invigorated/inhibited based on the prevailing RCP scenarios and also depending on the region-specific aerosol input on convective processes as discussed before.

7. These observed inter-relationships are expressed in form of multi-linear regression equations and then implemented on 4 suitable GCMs out of 8 available models during 1950-2100. The resulting multi-decadal projections reveal prominent trends in surface temperatures, moisture, instability and subsequent ozone and moisture concentrations in UTLS as proposed. However, a difference in urbanization rates led to much sharper trends in all parameters particularly after 2050 in the RCP8.5 case.

8. Consequently, the regressed lightning projections also depict an increase in both occurrences and intensity. However, the increasing trends are consistently higher in the RCP8.5 case. In addition, the increase in lightning frequency is found to be much slower than in case of intensities due to the dominant impact of

553   AOD trends which also show a comparative saturation or decrease after 2020. This can be attributed to a
554   probable increase in GHG emission restrictions by policy makers in near future.
555   9. Finally, the net intensification in lightning properties by 2100 with respect to present values depict that
556   number of occurrences would increase moderately by (10-17 % and 16-23%) for RCP2.6 and 8.5 scenarios.
557   However, extreme lightning radiances will increase much faster by 16-27% and 32-50% in RCP2.6 and 8.5,
558   throughout India.
559   10. In addition to the overall trends, certain regions like the coasts and surrounding seas are prone to be at the
560   higher lightning risk in future since they show much stronger increasing trends of ~50% (for radiance) in
561   absence of stringent GHG emission restrictions (as in RCP8.5) which is extremely alarming and hence should
562   be immediately addressed by policy makers.
563   It may be noted that this is the first ever study to use high resolution observations of lightning radiance as well as
564   frequency over the Indian region where a holistic inter-relation between lightning and its causative factors have
565   been proposed, tested and then implemented over a set of GCMs so as to provide a set of future projections for
566   both lightning properties till the end of this century. Now, the lightning projections laid out in this study can be
567   considered as reliable for forthcoming research attempts since both the equations and the models have been
568   repeatedly validated against observational datasets. Nevertheless, the projected lightning increase due to global
569   warming in this study is found to be much lesser than that obtained by simultaneous studies over the United States
570   (as evidenced from Romps (2019)), the reason for which can be possibly attributed either to stronger urbanizations
571   conditions in those regions or the choice of lightning proxies and GCM datasets used in that study.
572   However, from a closer point of view, the present study still has certain shortcomings. The primary limitation
573   is that it tries to provide an overall explanation for lightning trends over the Indian region. However, for specific
574   regions of the country such as WCI, HIM or IGP, secondary mechanisms from orographic influence or aerosol
575   effects (both radiative or microphysical) can also play a stronger role on the lightning trends and hence this
576   requires another dedicated study to address these issues. Secondly, the observed trends may vary strongly when
577   observed for separate seasons which have been averted here to provide a more focussed investigation on the
578   climatic trends of lightning. Finally, this study provides an overall mechanism of lightning; however, this
579   procedure may not be followed for all types of thunderstorm events, hence in future a suite of numerical models
580   and observations are required to explain how individual lightning events may be impacted by the complex aerosol,
581   instability and moisture interactions within the cloud over various meteorological conditions and Indian locations.
582
583   **Data availability**
584   High resolution lightning datasets for the present study have been obtained from LIS archives of NASA Global
585   Hydrology Resource Centre DAAC, U.S.A. (https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_trmm.html last
586   access: 16 December 2020). Gridded datasets of CAPE and TCWV are utilized from the CFSR reanalysis archives
587   developed by NCEP (http://nomadl.ncep.noaa.gov/ncep-data/index.html last access: 10 December 2020). The
588   datasets of AOD are utilized from Level-3 (L3) MODIS TERRA Atmosphere Monthly Global Product
589   MOD08_M3 (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=aerosol_monthly last access: 10
590   December 2020). Finally, the future projections of lightning properties are derived from 11 general circulation
591   models (GCMs) in the Coupled Model Inter-comparison Project (CMIP5) archive (website: http://cmip-
592   pcmdi.llnl.gov/cmip5/ last access: 1 December 2020).

593

Author contributions

RC performed complete analysis and wrote the first draft. MVR and SGB provided the initial concept and did the main editing while AC contributed to supervision, discussion, and editing.

597

Competing interests

The authors declare that they have no conflict of interest.

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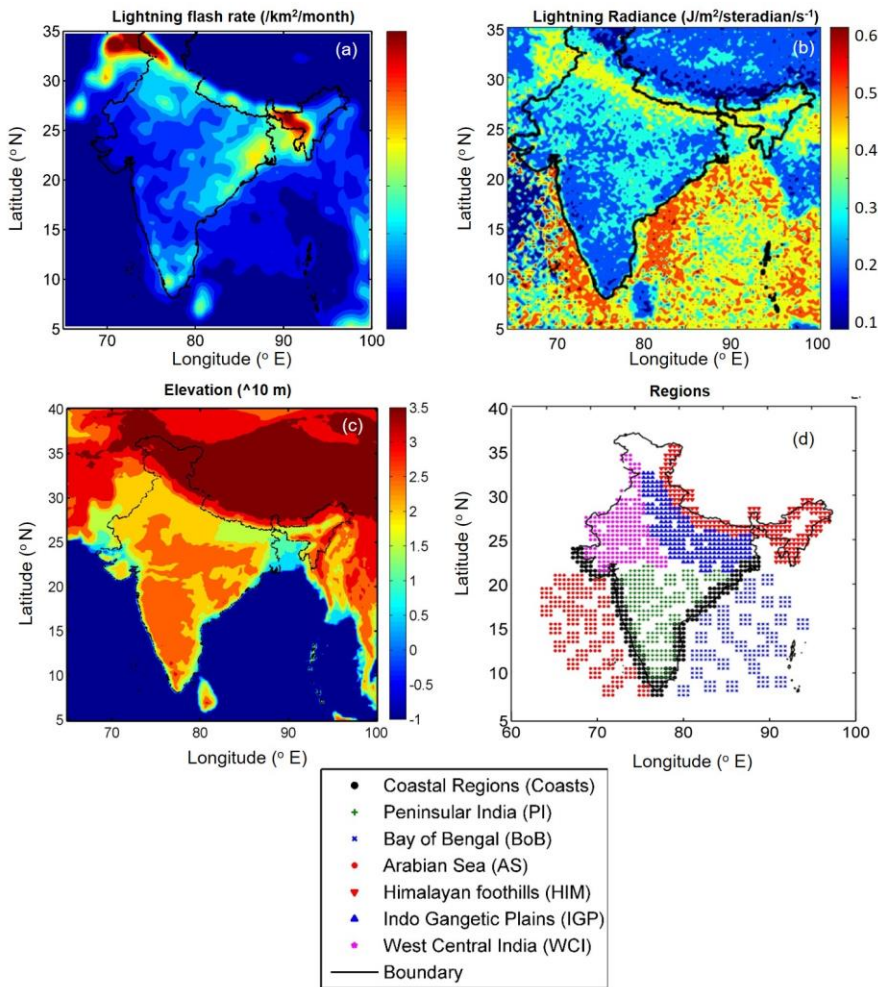
Figure 1: Climatological mean (a) lightning flash rate, (b) lightning radiance over India averaged during 1998-2014. (c) Altitude above mean sea level in log10 scale (Seas denoted by -1) (d) Representation of seven regions used in the study

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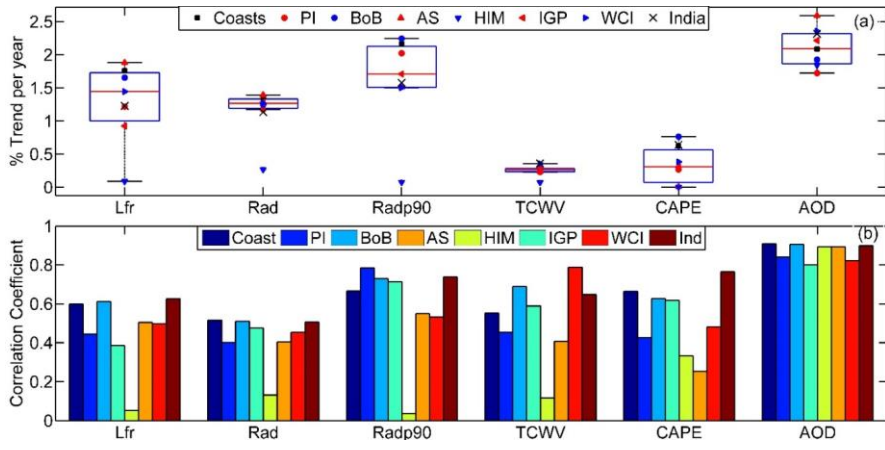
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750 **Figure 2**: (a) % yearly trends in lightning flash rate (Lfr), Average radiance (Rad) and 90th percentile of radiance (Radp90)
751 with TCWV, CAPE and AOD over seven regions and all India datasets. (b) Correlation coefficients corresponding to this trend
752 values.

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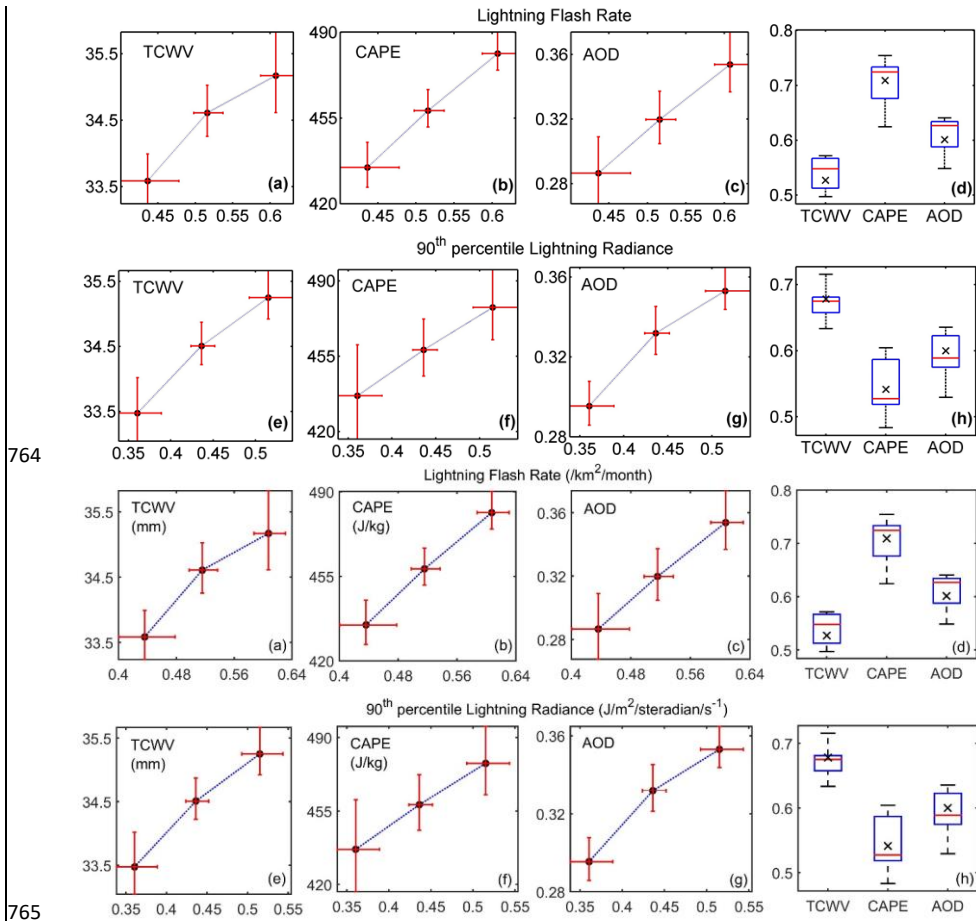
Figure 3. Temporal dominance cluster analysis results of lightning frequency and extreme radiances with respect to (a,e) TCWV, (b,f) CAPE and (c,g) AOD over entire Indian region, (d,h) distribution of correlation coefficient due to zonal clustering for both lightning parameters.

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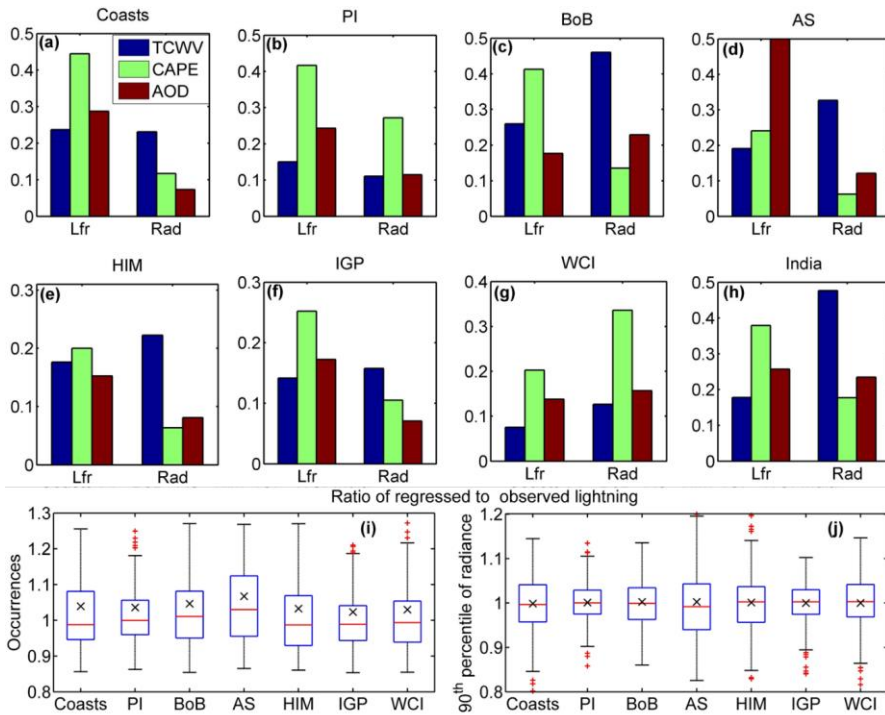
Figure 4: Temporal dominance analysis MLR coefficients of TCWV, CAPE and AOD for lightning frequency and radiance over (a) Coasts, (b) PI, (c) BoB, (d) AS, (e) HIM, (f) IGP, (g) WCI and (h) all India, (i,j) Zonal distribution of ratios between regressed and observed lightning frequency (Lfr) and 90th percentile of radiance (Radp90) over seven Indian regions.

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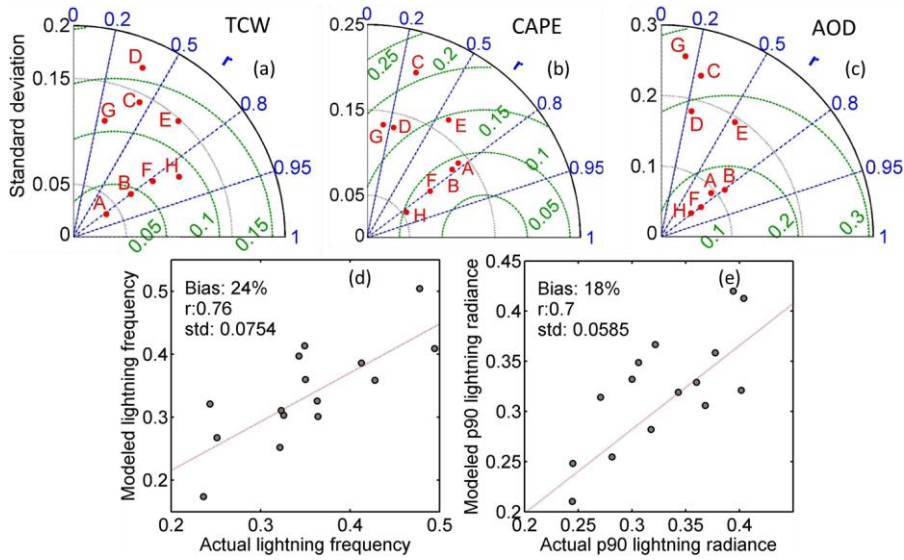
Figure 5: Taylor diagram representing the performance of 8 GCMs used in the study with respect to (a) TCWV, (b) CAPE and (c) AOD, (d,e) Covariation between regressed lightning properties from model mean with respect to observations for average flash rate (/km^2/month) and the 90th percentile of radiance (J/m^2/steradian/s^{-1}). Covariation between regressed lightning properties from model mean with respect to observations for occurrences and intensity.

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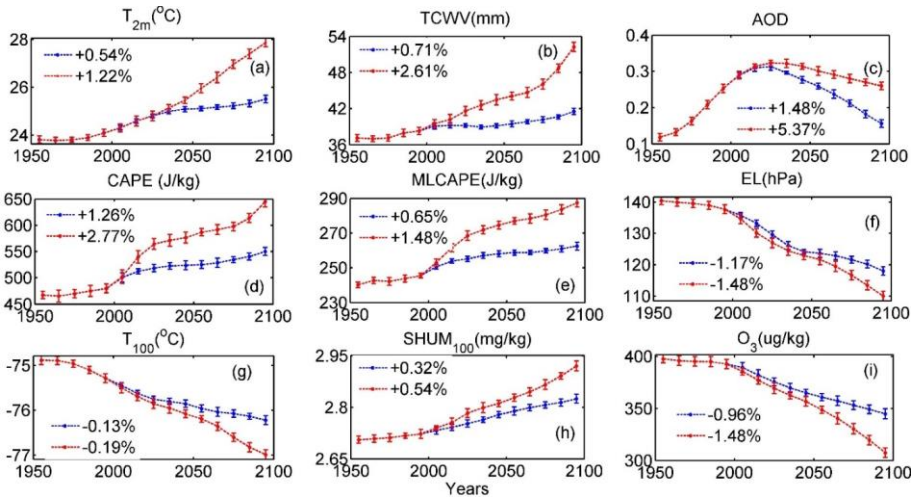
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791 **Figure 6**: 150-year multi-model all-India average projections of various parameters using RCP 2.6 (blue) and RCP 8.5 (red)
792 scenarios for (a) 2 metre temperature, (b) TCWV, (c) AOD, (d) CAPE, (e) MLCAPE, (f) EL, (g) Temperature 100 hPa, (h)
793 Specific humidity, (i) Ozone mixing ratio same level. Legends indicate 5-yearly linear significant trends of these parameters.

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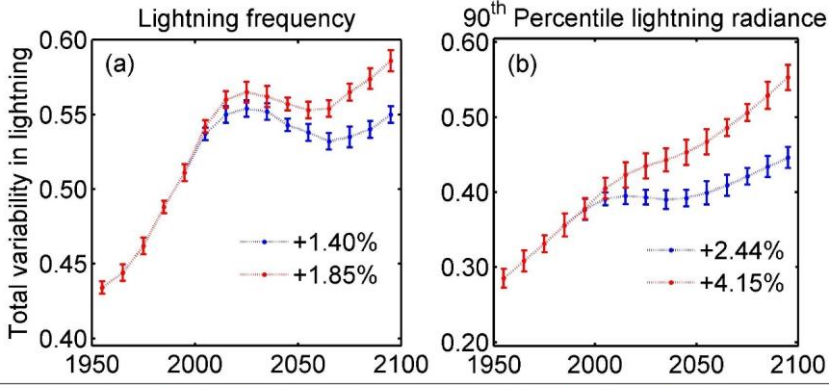
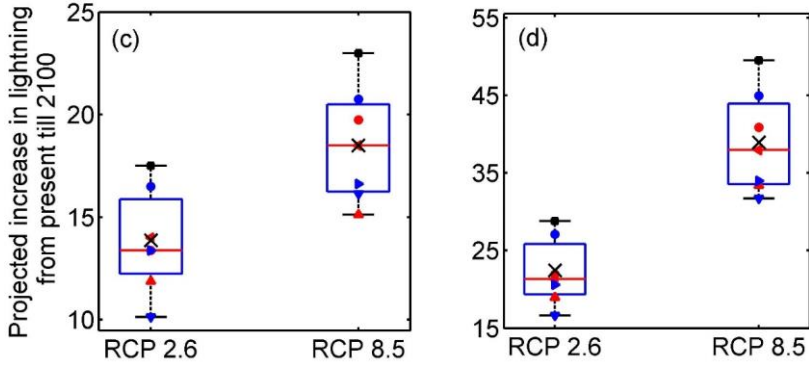
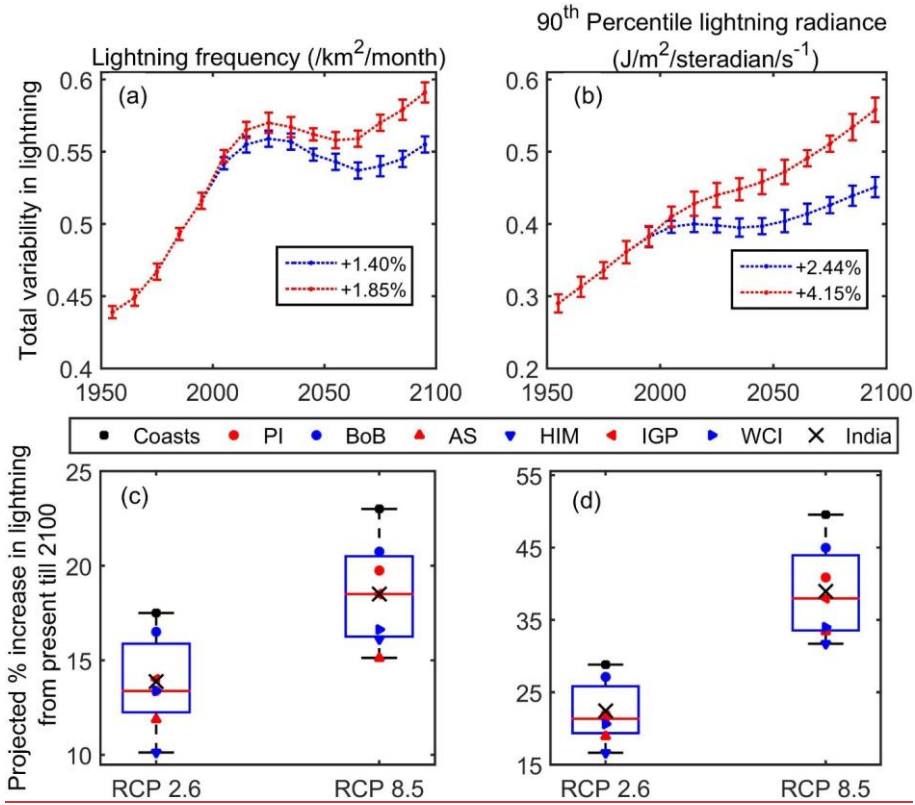
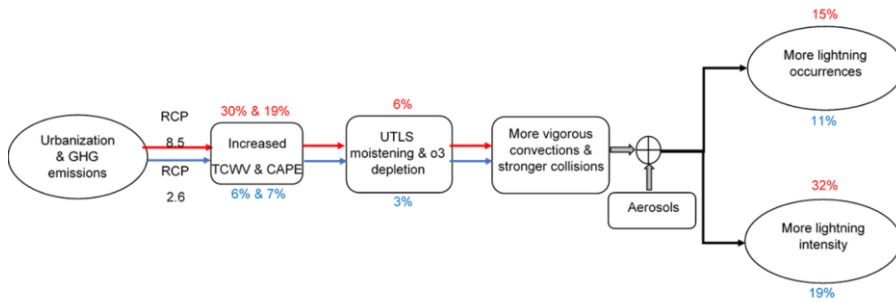


Figure 7: 150-year multi-model all-India average projections of (a) lightning occurrences and (b) 90th percentile radiance using RCP 2.6 and RCP 8.5 scenarios (c,d) Zonal distribution of trends in lightning occurrence and intensity between present decade (2011-2020) and 2091-2100. Legends in the top panel indicate the 5-yearly linear significant trends of these parameters.

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819 **Figure 8**: Proposed hypothesis to explain the long-term growth in lightning properties over Indian region between present
820 (2016-2020) and the distant future (2096-2100) assuming RCP 2.6 and 8.5 scenarios shown in blue and red
821 respectively. ~~Proposed hypothesis to explain the long-term growth in lightning properties assuming RCP 2.6 and 8.5 over~~
822 ~~Indian region~~