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On the association of lightning activity and projected change in climate over the Indian sub-continent

Upal Saha [a,1], Devendraa Siingh [b,*,1], A.K. Kamra [b], Elissavet Galanaki [c], Animesh Maitra [d], R.P. Singh [a], A.K. Singh [a], Swastika Chakraborty [e], Rajesh Singh [f]

[a] *Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India*
[b] *Indian Institute of Tropical Meteorology, Pune 411008, India*
[c] *Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Lofos Koufou, 15236-Penteli, Athens, Greece*
[d] *Institute of Radio Physics and Electronics, University of Calcutta, Kolkata 700009, India*
[e] *Electronics and Communication Engineering Department, Sikkim Manipal Institute of Technology, Majitar, Rangpo, East Sikkim 737132, India*
[f] *Dr. K. S. Krishnan Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad 221505, India*

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ABSTRACT

The association of lightning activity with the long-term as well as seasonal spatio-temporal distribution of convective available potential energy (CAPE), surface convective precipitation, vegetation cover and anthropogenic aerosol loading over the Indian sub-continent has been studied for the period 2000–2014. The north-east to north-west arc including the foothills of the Himalayas is the primary seats of lightning occurrences. The correlations of lightning activity with each of aerosol loading, vegetation cover, convective instability and convective precipitation helps us in understanding the definite entity that is responsible for changing the lightning activity in different parts of this tropical region. Lightning flash rate (LFR) has significant positive correlations (r ~0.5–0.7) with AOD, CAPE and surface convective precipitation but significant negative correlation (r ~ − 0.4) with Normalized Difference Vegetation Index (NDVI). Using global circulation models from the Climate Model Intercomparison Project Phase 5 (CMIP5), time-series of observed and projected upper tropospheric water vapor, surface convective precipitation and aerosol optical depth (AOD) from the historical simulations (1996–2005) and RCP8.5 emission scenario (2036–2045) are analyzed over the Indian region that are vulnerable to climate change in terms of occurrence of convective events and associated hazardous lightning phenomena. This study indicates that upper tropospheric water vapor (300 hPa) has a significant linkage with the lightning occurrences associated with convective activities and strong updraft. During the mid- 21st century, AOD, surface convective precipitation and specific humidity are projected to increase by 1.42%, 2.01% and 1.40%, respectively which may result in regional changes in lightning activity over the Indian sub-continent.

1. Introduction

Lightning is a frequent natural phenomenon, associated with many different atmospheric and surface processes including severe weather conditions that cause substantial damages to agriculture, electric power networks, property and life. Hence, the spatial pattern of lightning occurrence is of considerable interest in the field of atmospheric science, disaster planning and management and the power utility/energy sector. Intense convective environment helps in cloud electrification and subsequent charge separation that leads to the generation of more lightning flashes over the moist tropics (Williams, 2005; Siingh et al., 2008, 2015a). Thus, the information concerning the lightning distribution in diverse geographical regions is of prime interest and can augment investigations on the interaction between the radiative properties of the surface and the atmosphere (Kilinc and Beringer, 2007). Lightning flashes are produced mainly from cumulonimbus cloud involving the four mechanisms - buoyant warm air rising due to intense surface heating, strong heating contrast between surfaces, frontal lifting, or by the uplift of air parcels due to orographic lifting (Sturman and Tapper, 1996). All of these processes may trigger convection and, hence, lightning activity. Therefore, it is considered as a form of natural hazards requiring risk analysis, in terms of changing regional climatic pattern, from both spatial and temporal perspectives (Elsom, 1996, 2001; Berz et al., 2001). Unprecedented changes in climates can

* Corresponding author at: Indian Institute of Tropical Meteorology, Pashan, Pune 411008, India.
E-mail addresses: devendraasiingh@tropmet.res.in, devendraasiingh@gmail.com (D. Siingh).
[1] Authors have equal contributions

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also bring benefits and threats to societies and the range of these will have a disproportional spread with respect to the manifestations both from anthropogenic effects and that due to weather extremes. Extensive meteorological and environmental conditions and their interactions with topography and landforms lead to the formation of clouds with great diversity in their microphysical and dynamical characteristics (Penki and Kamra, 2013a). There are indications of enhanced lightning activity related with the slope angle of the terrain. Specifically, Galanaki et al. (2015) showed that terrain slope enhances the lightning occurrence during winter and autumn in the Mediterranean Sea. Additionally, Ziv et al. (2009) showed that the combination of slope angle and coastline favors convection and the associated lightning activity in the area of Israel. The effects of topography also depend on the orographic jets, which occur under favorable conditions, such as, sufficient slope, steepness and mountain altitude (Egger and Hoinka, 1992). Therefore, thunderclouds developing in different seasons exhibit a large variety of lightning occurrences in different regions around the globe. A number of recent studies have been in focus investigating the relationship between lightning occurrences and physiographic characteristics (Zajac and Rutledge, 2001; Christian et al., 2003; Soriano et al., 2001a, 2005; Mazarakis et al., 2008; Kotroni and Lagouvardos, 2008; Bourscheidt et al., 2009; Goswami et al., 2010; Santos et al., 2013; Ramesh Kumar and Kamra, 2012a, 2012b; Cecil et al., 2015; Galanaki et al., 2015). Dissing and Verbyla (2003) found that the relationship between lightning and elevation in the interior of Alaska was generally positive up to a maximum elevation of 1100–1200 m. This corresponds with the study previously done by Schulz and Diendorfer (1999) in Austria, where lightning flash densities increases up to altitudes ranging from 500 to 2000 m. Orville and Silver (1997) suggested possible topographical effects on lightning activity over the contiguous United States, especially in the regions of the Appalachians and Arizona Rocky Mountains. Furthermore, there are studies on the relationship between lightning occurrences associated with convective activities and vegetation cover (Williams et al., 2002, Williams and Stanfill, 2002; Qie et al., 2003a, 2003b; Toumi and Qie, 2004). The Normalized Difference Vegetation Index (NDVI) represents vegetation cover and health of vegetation and plays significant role in the global climate studies including convective growth and lightning activity (Sellers et al., 1986; Mabuchi et al., 2005; Shilong et al., 2004; Kumar et al., 2016). The dense of the vegetation cover affects the amount of soil moisture. Indeed, the deeper roots in the forested areas can hold more water which affects the latent heat flux (Bonan, 2008) and the associated convection as well as lightning activity. Dissing and Verbyla (2003) found that the differential heating between adjacent surfaces with different vegetation cover may trigger mesoscale circulations that are likely to produce convection. O'Neal (1996) indicated that deciduous forests on the hills have significantly greater convective cloud cover than those in flat areas, while farmlands located in flat areas have more convective cloud cover than those in hilly areas over the Midwest USA. Kilinc and Beringer (2007) reported a noticeable difference in the distribution of the cloud to ground lightning flash density on the various types of vegetation in the northern territory of Australia. Kotroni and Lagouvardos (2008) obtained that the forested and wooded areas increases the production of lightning yield in contrast with shrubland areas.

Besides the effect of topography and vegetation cover, the occurrence of lightning activity associated with convection are also due to a combination of other multiple factors, both thermodynamic and anthropogenic, with their relative importance varying from one region to another. The thermodynamic factors include the presence of instability, sufficient moisture and a lifting force (Doswell, 2001; Johns and Doswell, 1992; Williams et al., 2002; Midya et al., 2011; Saha et al., 2012, 2014; Chakraborty et al., 2015; Kumar et al., 2016) whereas many observations suggest that anthropogenic aerosols influence charge generation processes inside thunderclouds (Orville et al., 2001; Steiger et al., 2002; Williams et al., 2002; Steiger and Orville, 2003; Saha and Maitra, 2014). CAPE is widely used as a proxy for thunderstorm occurrence as it determines the available potential energy which can be converted into kinetic energy. In that way, CAPE affects the strength of the updraft which influences the charge separation process in the thundercloud (Williams and Renno, 1993). Thus, lightning occurrence and CAPE should show good correlation (Galanaki et al., 2015; Rutledge et al., 1992). Ramesh Kumar and Kamra (2012b) showed that 22% changes in lightning flash rate in the Himalayan foothills can be associated with variability in CAPE and more precisely the increase in CAPE due to orographic lifting in the Himalayan foothills in the north-eastern region may contribute to ~7.5% increase in lightning activity (Penki and Kamra, 2013a). Air in the tropical atmosphere holds more amount of water vapor than the polar atmospheres. This water vapor plays a vital role in the development of thunderstorms by release of latent heat during condensation and freezing processes (Midya et al., 2011; Saha et al., 2012), thereby initiating charge separation required for lightning occurrences (Brooks and Saunders, 1995). In general, the climate of Earth is believed to be much more sensitive to changes in water vapor in the upper troposphere, where the concentrations are naturally very low. The lightning activity is a means of monitoring the intensity of deep convections; hence it may be well correlated with the vertical transport of water vapor by thunderstorms in the upper troposphere (Price, 2009). Total lightning flashes and convective rainfall during 1998–2010 over the South and Southeast Asia exhibited positive correlation with correlation coefficients 0.68 and 0.81 respectively (Siingh et al., 2013, 2014, 2015b). Williams et al. (2002) have suggested that the observed contrast between lightning over continent and ocean may be due to differences in aerosol concentrations over land and ocean. Yuan et al. (2011) indicated that lightning activity are closely associated with aerosol loadings at both interannual and biweekly time scales. They estimated that a ~60% increase in aerosol loading leads to >150% increase in lightning flashes over the West Pacific Ocean east of the Philippines.

In an effort to better understand past and future climate change, general circulation models have become the forerunners of attempts to simulate future climate. With the release of new generation climate model simulations, known as Coupled Model Intercomparison Project phase5 (CMIP5), that represent the latest advancements in general circulation model (GCM) development and are an important component of the Intergovernmental Panel on Climate Change's (IPCC) assessment of climate science (Taylor et al., 2012). The projected change in future climate in terms of lightning activity as a result of thermodynamic and anthropogenic forcing is a topic of great societal concern due to the disastrous consequences associated with tropical convective storms. With the aim to contribute to the improvement of understanding of lightning occurrences over the Indian sub-continent, this work explores the possible relationship of the association of lightning activity with some surface meteorological parameters, such as CAPE and convective precipitation, with physiographic characteristics, such as topography and vegetation cover, and with anthropogenic aerosol loading. The present work investigates the long-term (2000–2014) as well as seasonal (summer, monsoon, retreating monsoon and winter) spatial changes of each of the parameters mentioned above that helps in the generation of lightning activity, either directly or indirectly. In particular, CMIP5 models are used to estimate future climate change in terms of upper tropospheric water vapor content; therefore, it is important to assess the simulation of lightning activity over the Indian sub-continent.

2. Data and methodology

The Indian sub-continent (7°N–38°N and 67°E–98°E) enjoys a subtropical climate in north and a tropical climate in south. This region is bounded by the Himalayan range in the north, Thar Desert in the west and the southern side is bounded by seas (Bay of Bengal in the South-East, Arabian Sea in the South-West and Indian Ocean at the South). The coastal regions of India are also bounded by hilly terrain (Eastern