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Lightning and convective rain study in different parts of India

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ABSTRACT

The effect of solar variability parameters (solar flux ($F_{10.7}$ cm), cosmic ray flux, sunspot numbers) and meteorological parameters on convective rainfall and lightning flashes in four different Indian regions of equal area is studied. Regions are selected having different topological, vegetation, proximity with ocean and habitat features. Solar variability shows statistically insignificant effect on lightning flash and convective rainfall. The seasonal variation of lightning flashes and convective rainfall in each region could be explained considering the variation of CAPE and surface temperature in that region. The dependence of lightning flashes and convective rainfall on meteorological parameters varies from region to region, as is evident from correlation studies. Lightning flashes is well correlated ($R = 0.81$) with CAPE in region R_1 and barely correlated ($R = 0.23, 0.24$) in region R_3 and R_4 whereas rainfall is well correlated ($R > 0.68$) in all the regions. Lightning flashes are better correlated ($R > 0.57$) with temperature in R_1, R_2 and R_4 and moderately correlated in R_3 ($R = 0.44$). Rainfall in R_3 is very well correlated ($R = 0.91$) with surface temperature and there is insignificant correlation in R_1 ($R = 0.09$). There is very good positive correlation ($R > 0.59$) between cloud cover and convective rainfall in the entire region and well negative correlation ($-0.83 < R < -0.61$) between OLR and convective rainfall. OLR and cloud cover show little impact on lightning flashes. Lightning flashes and convective rainfall show average positive correlation ($0.48 < R < 0.53$). Aerosol concentration is the largest in region R_4 and showed an increasing trend between 2007 and 2011. Lightning flashes and convective rainfall are positively correlated ($0.10 < R < 0.58$) with aerosol concentration.

1. Introduction

The incident solar radiation through scattering, reflection and absorption affect the surface and atmospheric temperature, which affect convective process leading to thunderstorm activity/lightning flashes and rainfall. The solar radiation reaching the Earth's surface can be indicated by the $F_{10.7}$ flux, cosmic rays and sunspot numbers. The $F_{10.7}$ flux is well correlated with the sunspot numbers whereas sunspot number showed opposite variation with cosmic rays because solar magnetic fields scatter cosmic ray flux in the interplanetary space. The incident solar irradiance differentially heats land and sea surfaces and helps in the development of convective systems responsible for the large scale thunderstorm/lightning and precipitation activity (Williams et al., 1989, 2004, 2005). The regional activity differs in the two cases. The activity ranking from the most active to the least active based on thunderstorm activity is Africa, South America and South Asia, whereas that based on rainfall is Southeast Asia, South America and Africa (Price, 2006, 2009; Christian et al., 2003; Singh et al., 2004; Siingh et al., 2007, 2011, 2013, accepted for publication). Studies showed that weak to moderate updrafts are required for rainfall whereas stronger and deeper uplift is necessary for lightning (Williams et al., 2004; Mach et al., 2010, 2011).

Early studies showed correlation between thunderstorm frequencies and sunspot numbers and the correlation coefficient varied from station to station (Fritz, 1878; Brooks, 1934).

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Brooks (1934) found a low correlation at mid-latitude and enhanced correlation towards the pole and the equator. Even at the same location thunderstorm frequency is differently correlated with sunspot numbers. For example, Aniol (1952) analyzed data from South Germany between 1851 and 1950 and found no correlation, whereas for the period 1889–1913, a negative correlation (correlation coefficient ~ −0.55) and for the period 1923–1944, a positive correlation (correlation coefficient ~ 0.74) was reported. Girish and Eapen (2008) reported maximum lightning activity during the declining and minimum periods of sunspot activity and minimum during the maximum sunspot periods.

Cosmic ray flux incident on the Earth's atmosphere is partly scattered by the Earth's magnetic field and hence its intensity and energy spectra are dependent on latitude, longitude and azimuth angle (Nehar, 1967; Smart and Shea, 2005; Siingh and Singh, 2010; Kirkby, 2007). During the disturbed condition magnetic field is modified leading to changes in cosmic ray flux (Desorgher et al., 2009). Cosmic rays affect the formation and characteristic features of different types of clouds (Harrison, 2004; Tripathi et al., 2008) through the production of ionization in the lower atmosphere affecting the electric field and current flowing through the cloud layers. Cosmic ray induced cloud nucleation hypothesis is being tested in CLOUD (Cosmics Leaving OUtdoor Droplets) experiment at CERN, Switzerland (Kirkby, 2007) and initial measurements yield encouraging results (Duplissy et al., 2010). On the basis of synchronous measurement of cosmic ray flux and atmospheric electric field, Wang et al. (2012) reported simultaneous changes in cosmic ray flux percentage change and electric field amplitude in ~80% cases. The change in counting rate did not occur when thunderstorm is just over electric field mill. The changes occur when electric field mill is not exactly below thunderclouds but in the control of bottom positive charge layer. Clouds affect radiation transfer mechanism of the atmosphere leading to changes in local/global mean temperature which controls lightning flash rates and precipitations. As the considered regions vary in longitudes and latitudes, it is interesting to study the effect of cosmic ray flux on lightning flash and convective rain.

The solar radiation heats the Earth's surface and adjacent boundary layer leading to rise in surface air temperature and thermodynamic instability of boundary layer, which help the formation of thunderstorm. The energy that feeds this process is the convective available potential energy (CAPE) (Williams, 1992). The complex interaction among CAPE, vertical air motion, vertical distribution of ice particles and microphysics controls electrical activity in thunderstorms (Williams, 1995). Studies showed that CAPE and surface temperature are highly positively correlated with lightning flashes and convective rain (Qie et al., 2003; Williams et al., 2005; Price and Asfur, 2006; Sekiguchi et al., 2006; Penki and Kamra, 2012a,b, 2013; Siingh et al., 2013). Yuan and Qie (2008) analyzed LIS, PR, and TMI data and tried to express the lightning flash rate of precipitation system as function of maximum snow depth, maximum storm top height and minimum polarization corrected temperatures, respectively. The most stable relationship was between flash rate and maximum snow depth. The spatial distribution of deep convective systems (DCSs) and CAPE shows that the DCSs occur mainly over land and is closely related with CAPE (Wu et al., 2013). They also reported that DCSs over the Tibetan Plateau and Northeast India during monsoon season are more frequent than in the Central and South India. DCSs have significant diurnal variation closely related to that of solar heating and dominantly occur from afternoon through mid-night, with peaks from 1500 to 1700 LT.

Studies showed that the cloud-to-ground lightning flash activities of a thunderstorm could be used in local short term forecasting of heavy rain or in precipitation estimation (Williams et al., 1989; Petersen and Rutledge, 1998; Soula et al., 1998) and flash flood or hailstone (Zhou et al., 1999). Thus high precipitation corresponds to strong atmospheric activity in convective systems. Zhou et al. (2002) showed that the average precipitation and lightning flashes in the main precipitation period are positively correlated with the coefficient = 0.86. Total lightning flashes and convective rain during 1998–2010 over the South and Southeast Asia exhibited positive correlation with coefficient 0.68 and 0.81 respectively (Siingh et al., 2013).

Aerosols present in the atmosphere affect the solar radiation through scattering, reflection and absorption of incident radiation and hence affect the solar radiation budget and the surface temperature. The aerosols indirectly affect cloud droplets size (Twomey et al., 1984), cloud life time and cloud extent (Hansen et al., 1997; Ackerman et al., 2000), precipitation process (Albrecht, 1989) and electrical properties of cloud and hence lightning discharges (Westcott, 1995; Stallins and Rose, 2008; Kar et al., 2009; Siingh et al., 2008, 2011, 2013). Enhanced aerosol concentrations cause a narrow droplet spectrum that inhibits collision and coalescence processes leading to reduced particle sizes and suppression of warm-rain processes (Rosenfeld, 1999) and enhancement of the growth of large hail and cold rain processes (Rosenfeld and Woodley, 2000). The enhanced aerosols derived from pollution, desert dust and biomass burning invigorate convective clouds (Koren et al., 2005) and leads to rise in cloud top heights, large anvils and more rainfall (Liu et al., 2007). The aerosol effects on cloud properties may vary with convective available potential energy (CAPE) and wind shear (Lee et al., 2008; Fan et al., 2009); relative humidity (Fan et al., 2007) and cloud morphology (Lee et al., 2010).

Aerosols may cause a decrease in the percentage of positive cloud-to-ground (+CG) lightning flashes and an increase in the total number of flashes (Orville et al., 2001; Steiger et al., 2002; Naccarato et al., 2003; Koren et al., 2005; Stallins and Rose, 2008; Kar et al., 2009; Wang et al., 2011; Tao et al., 2012). Aerosols act as cloud condensation nuclei (CCN) and also affect the charge separation mechanism (Jayaratne et al., 1983) in thunderstorms and may enhance −CG lightning activity (Steiger et al., 2002; Kar et al., 2009). High concentrations of pollutants in super cooled cloud droplets lead to negative charging of graupel at higher cloud temperatures, extending towards the cloud base and covering the positive charge center region (Pruppacher and Klett, 1997). This newly created stretched negative charge region makes tri-polar charge distribution in thunderstorms (MacGorman and Rust, 1998) and produces more −CG flashes. Enhanced −CG flashes decrease the relative frequency of +CG flashes. Williams et al. (1999) proposed that under continental and polluted boundary layer conditions, the available liquid water in the storm updraft shared by an innumerable number of small droplets, as a result mean droplet size is decreased and the coalescence process is thwarted. The available cloud water reaches the mixed phase region and participates in cloud buoyancy, precipitation formation, electric charge separation and increased lightning activity (Orville et al., 2001; Williams et al., 2002; Siingh et al., 2008). In a polluted environment ice forming and mixed-phase zone occur at higher levels (Rosenfeld and Lensky, 1998; Kar et al., 2009). The structure and location of charge distributions and occurrence of lightning flashes in thunderstorms under different conditions are simulated/studied (Williams et al., 1991, 1994; Altaratz et al., 2005; Mansell et al., 2010; Wang et al., 2011).

Yuan et al. (2011) reported anomalously high lightning activity in the presence of high aerosol loading from volcanic source. They found that ~60% increase in aerosol loading leads to a more than 150% increase in lightning flashes. Simulation studies related with urban regions show that the connection between aerosol and lightning activity is very complex (van den Heever and Cotton, 2007; van den Heever et al., 2006, 2011) and much more observational and simulation studies at regional and continental level are required.

Satellite measurements have shown a dramatic increase of the aerosol concentration over many countries in Asia due to urbanization/industrialization (Lelieveld et al., 2001; Massie et al., 2004), which might enhance deep convection and mixed phase processes leading to elevated electrification and enhanced lightning activity. Aerosols apart from the cloud invigoration may also restructure clouds (Koren et al., 2005). If the aerosols of large size (radii of order of micrometer) called giant CCN (GCCN) are present in the cloud, then they can initiate the warm-rain process (Johnson, 1982; Cheng et al., 2007). GCCN can lower the critical supersaturation and deprive small CN of the chance to activate into cloud drops (Cheng et al., 2007). The source of GCCN could be large sea salt particles generated by the breakup of air bubbles in the ocean or by wave tearing (de Leeuw et al., 2011) or mineral dust particles coated with hygroscopic materials during dust storms (Liu et al., 2011). Using model simulations Feingold et al. (1999) demonstrated GCCN to be less important in clean environment. They also noted that higher concentration of GCCN is required to produce drizzle in marine stratocumulus clouds at higher CCN concentrations.

In this paper, we have studied the dependence of lightning activity and rainfall on solar activity (solar flux, sunspot number, cosmic rays flux) in different parts of India. Area of investigation is chosen from the Southern India, Central India, North–West and North–East region of India which have different aerosol loadings due to different levels of industrialization, local land and orographic conditions. Region 1 is the peninsular part of India (8 °N–18 °N, 74 °E–79.5 °E); Region 2 is in the Central India (18.5 °N–23.5 °N, 74 °E–85 °E); Region 3 is the North–East India (22 °N–79 °N, 88 °E–96 °E); Region 4 is the North–West India (24 °N–31 °N, 70 °E–78 °E) which are shown in Fig. 1 and have almost equal area. The orography of different selected regions is different. Region 1 is surrounded by Arabian Sea and Bay of Bengal and covers larger latitudes and smaller longitudes, and experience early monsoon. Region 2 is the plain land area of the central part of India. During the summer monsoon period there is surface trough zone making low pressure belt over the north western region. The low pressure regime is characterized by the continental tropical convergence zone (CTCZ) extending west ward from the Bay of Bengal. The CTCZ gets established in this area in July at the onset phase of the summer monsoon and fluctuates over this zone throughout the peak monsoon months of July and August. Tropical synoptic and meso-scale system originating in the Bay of Bengal is embedded in the monsoon flow. These system progress in west or northwest direction and frequently passes this region and produces strong wind and heavy rain accompanied with lightning and thunder. Region 3 is the Eastern Himalayas, Northeast Hills (Patkai-Naga Hills and Lushai Hills) and the Brahmaputra and the Barak Valley Plains, just north of the mouth of the Bay of Bengal. This region has a predominantly humid sub-tropical climate with hot, humid summers, severe monsoons and mild winters and this is one of the most lightning prone regions in India. Every year the region receives quite a good number of thunderstorms during the pre-monsoon months. Region 4 is the major part of which is Great India Desert. The maximum lightning flashes in this region, occurs 2–3 h prior to that in the Central India (Penki, 2010). This difference in timings may be associated with the early heating of desert regions due to solar radiation and the consequently early development of convective activity. However, on seasonal scale there is lack of convective activity over the Thar Desert in the western slopes of Aravalli range. This is consistent with the role of Aravalli range for separating the western drier and more unstable air masses from the moist and relatively stable air masses from the Bay of Bengal. As these regions are orographically and economically quite different, it is interesting to compare the monsoon activity and urbanization effect on it in the selected regions.

We have analyzed data for the period 2003–2011. Section 2 briefly discusses the sources of data and analysis. Results and its discussions are given in Section 3. The dependence of lightning flashes and convective rainfall on the solar parameters such as cosmic rays, sunspot numbers and $F_{10.7}$ cm (solar flux) is briefly discussed in Section 3.1. Section 3.2 describes the variability of lightning and convective rainfall with meteorological parameters such as the surface temperature, CAPE (Convective Available Potential Energy), outgoing long wave radiation and convective cloud layer: total cloud cover. The correlations of lightning flashes and convective rainfall with meteorological parameters are studied. The effect of aerosols on lightning flashes and convective rain is studied in Section 3.3. Finally conclusions are summarized in Section 4.

2. Data selection

The lightning data (number of flashes) derived from Lightning Imaging Sensors (LISs) aboard Tropical Rainfall Measuring Mission (TRMM) satellite have been used with a nearly uniform flash detection efficiency of 93 $\pm$ 4% at night and 73 $\pm$ 11% in day time (Boccippio et al., 2002) within the field of view (FOV) of the sensor, and detects both intra-cloud and cloud-to-ground discharges during the day and night conditions. The LIS detects and locates lightning with the spatial resolution of 4–7 km and the temporal resolution of 2 ms over a large region of the Earth's surface along the orbital track of the satellite. The chosen area in the present study lies in the field of view of sensors which monitor storm system for 80 s, a period long enough to obtain a measure of the lightning flash in these storms. The monthly data available in the grid resolution of $0.5^\circ \times 0.5^\circ$ for the period 2003–2011 are downloaded from the website (http://ghrc.msfc.nasa.gov) for the region of interest.

In order to study the possible influence of solar activity on lightning and rainfall in the selected regions, the relevant data for sunspot number, cosmic ray flux and solar flux ($F_{10.7}$ cm) are considered for the period 2003–2011. Monthly mean

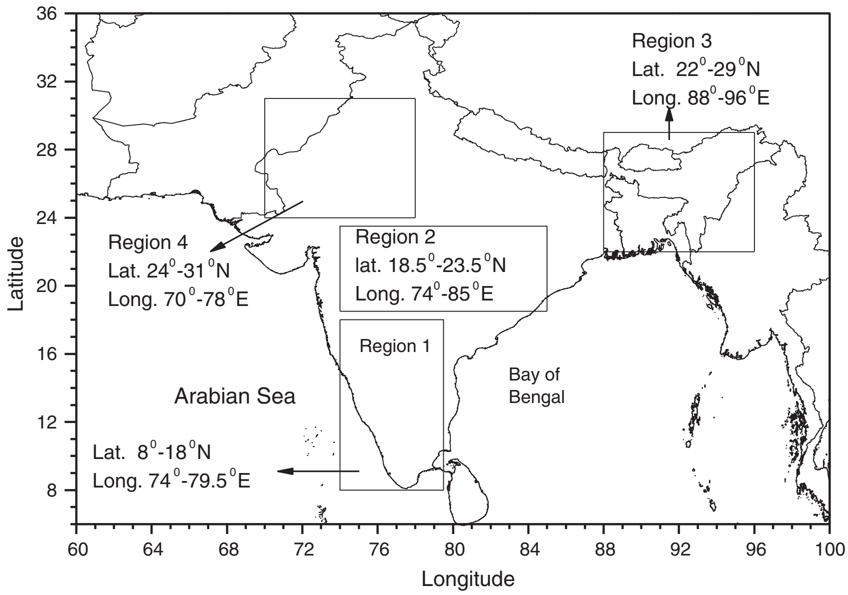

Fig. 1. Map of India showing four regions for the present study: Peninsular India (8 °N–18 °N, 74 °E–79.5 °E—Region 1); Central India (18.5 °N–23.5 °N, 74 °E–85 °E—Region 2); North East India (22 °N–79 °N, 88 °E–96 °E—Region 3); North West India (24 °N–31 °N, 70 °E–78 °E—Region 4).

sunspot number, cosmic ray flux, solar flux ($F_{10.7}$, cm) data taken from the websites: http://solarscience.msfc.nasa.gov/greenwch.shtml; http://cro.izmiran.rssi.ru/bjng/main.html; http://www-app3.gfz-potsdam.de; http://celestrak.com/SpaceData/SpaceWx-format.asp, respectively are analyzed. For the cosmic ray flux data we have used data from the nearest location for neutron monitoring station at Beijing (39.08 °N, 116.26 °E, altitude 48 m), China, operated by the Institute of Physics, Beijing. We could not locate any other station closer than this, which was operational during the reported period. Simulation results showed that in the chosen latitude and longitude range cosmic ray flux slightly increases with longitude (Smart and Shea, 2005; Siingh and Singh, 2010), although the increase is very small and the trend in variation remains almost the same. Hence, we considered these parameters to be same for all the four regions.

The convective rain data are derived from the TRMM PR 3A25 data product with a spatial resolution of 0.5° × 0.5° at 2 km height and it gives monthly mean rain rate (mm/h). It provides vertical profiles of the rain and snow from the surface up to a height of about 20 km. The radar is able to detect fairly light rain rates down to about 0.7 mm/h. During intense rains, when attenuation effects become significant new method of data processing has been developed (Simpson, 1988; Simpson et al., 1988). The precipitation radar is able to separate out rain echoes for vertical sample sizes of about 250 m, when looking straight down. The data are downloaded from the website www.daac.gsfc.nasa.gov.

The meteorological parameters such as surface temperature, CAPE, OLR (Outgoing Long wave Radiation), convective cloud layer: total cloud cover with 2.5° grid resolution from Climate Forecast System Reanalysis (CFSR) data developed by NOAA's National Center for Environmental Prediction (NCEP) (http://nomadl.ncep.noaa.gov/ncep-data/index.html) have been used. Aerosol optical depth (AOD) at 550 nm has been taken from the website (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=aerosol_monthly).

3. Result and discussion

3.1. Lightning flashes, convective rainfall and solar parameters

The variations of yearly mean convective rainfall and yearly mean number of lightning flashes during 2003–2011 are shown in Fig. 2a and b respectively. The variation of sunspot number, $F_{10.7}$ cm (solar flux) and cosmic rays are shown in Fig. 2c. Solar flux ($F_{10.7}$ cm) and sunspot numbers decrease up to mid 2006 go to a broad minimum up to mid 2009 and thereafter show an increasing trend. In this period cosmic ray flux shows an increasing trend. Fig. 2b shows a clear increasing trend of yearly mean lightning flashes for region R_3. Yearly flashes are largest in region R_3, then in region R_2. In regions R_1 and R_4, yearly lightning flashes have almost similar values. Yearly flash distribution shows an oscillating behavior (regions R_2, R_3 and R_4), although after 2009 this trend vanishes. Yearly mean convective rain is the largest in region R_3 followed by region R_1 during the period 2003–2009. The minimum convective rain is in region R_4. Regions R_1 and R_4 show an increasing trend except during the year 2009 where a dip is observed. Mean convective rain and lightning flashes are minimum in region R_4, which encloses Rajasthan and Gujarat states where cloud development and precipitation are lowest. Region R_1 has larger precipitation during 2010 and 2011 although lightning flashes is at the nearly lowest. The smaller lightning flashes suggest that the convection is weak. Both lightning and precipitation data show oscillating behavior, which is more clearly visible in the data of regions R_2 (Central India), R_3 (North–East) and R_4 (North–West India).

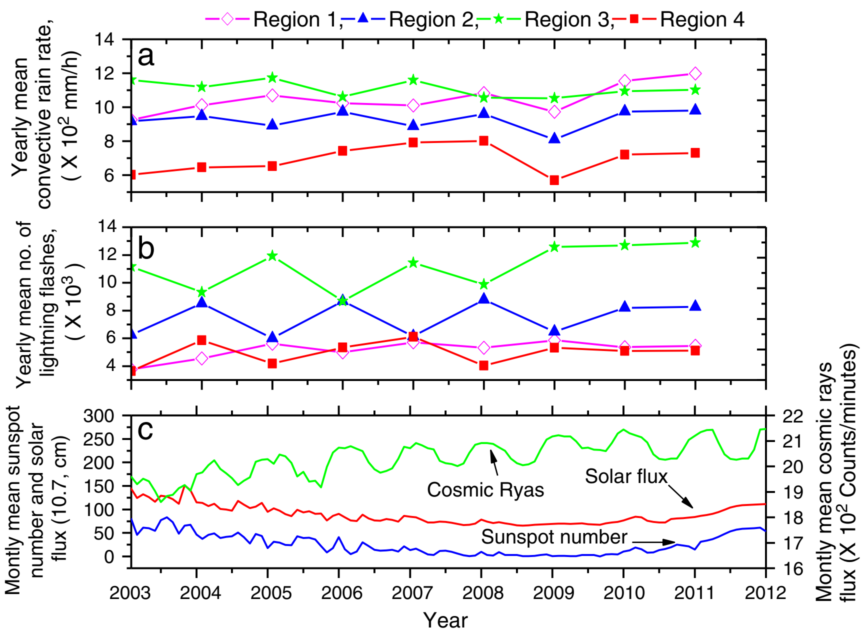

Fig. 2. Variation of yearly mean convective rain rate for regions R_1, R_2, R_3 and R_4 (a); yearly mean no. of lightning flashes for regions R_1, R_2, R_3 and R_4 (b) and sunspot number, cosmic ray flux, $F_{10.7}$ cm (solar radio flux) for the period 2003–2011 (c).

Correlation studies between sunspot numbers and mean number of lightning flashes for regions R_1, R_2, R_3 and R_4 showed statistically insignificant results in agreement with the results shown in Fig. 2. Similarly cosmic ray flux and solar flux ($F_{10.7}$ cm) also do not show any correlations with lightning flashes in all the regions. Derived correlation coefficients are very small (−0.11, −0.06, −0.11, and −0.04) for the solar parameters for all the regions, although anti-phase relation is observed, which is in agreement with the earlier results from low latitudes (Girish and Eapen, 2008; Siingh et al., 2013; Pinto et al., 2013). The correlation coefficient between convective rainfall and sunspot number in regions R_2 and R_3 is positive and negative in regions R_1 and R_4 but statistically insignificant. Siingh et al. (2013) considered a single region enclosed between latitude 8 °N and 34 °N and longitude between 60 °E and 95 °E and reported correlation coefficient between convective rain and cosmic rays to be −0.27 with statistically good significance level.

3.2. Lightning/convective rainfall variability with meteorological parameters

Surface temperature (Williams et al., 2005; Khain, 2009), relative humidity (Williams, 1992; IPCC, 2007), aerosol loading (Zhang et al., 2004; Wang et al., 2011) wind shear (Lee et al., 2008, 2010; Fan et al., 2009), ozone and other trace gas distribution (Pawar et al., 2012) and evaporative cooling (Tao et al., 2007) individually and jointly affect lightning and precipitation activity, which predominantly occur in deep convective systems. For the occurrence of deep convection, the requirements are the existence of unstable lapse rate, substantial moisture and low level lifting sufficient to release the instability. The temperature and moisture stratification control the convective available potential energy (CAPE) which affects lightning and precipitation distributions.

Fig. 3 shows the seasonal variation based on the monthly averaged data of lightning flashes, convective rainfall, CAPE, OLR, surface temperature and convective cloud layer: total cloud cover (%) of four regions (R_1, R_2, R_3 and R_4). The seasonal variations of lightning flashes show a maximum in the pre-monsoon months (April–May, partly June in some region) in all the four regions. However, the maximum of R_3 region is dominant one. There is a second maximum around the end of the summer monsoon (September, October). CAPE is the maximum for region R_1 with a primary maximum during pre-monsoon months and the secondary maximum around end months of the summer monsoon. For regions R_2, R_3 and R_4, the maximum CAPE occurs in the months of July–September. The seasonal distribution of CAPE and lighting flash in region R_1 are similar, whereas in the remaining regions CAPE does not show any maxima during the pre-monsoon months. However, temperature distribution shows a maximum during the pre-monsoon months which varies from region-to-region. In R_3 region temperature shows a broad peak (from April to September). The maximum lightning flash distribution during the month of April–May in region R_3 could be partly due to orographic and topological effects because both the temperature and CAPE during these months do not show any maxima.

Convective cloud cover and convective rainfall rate have almost similar behavior in all the regions (Fig. 3) with maxima in the active monsoon period (July and August). In region R_1 (Southern India) monsoon arrives earlier, so maximum is broadened and covers from June to October. Monsoon reaches in R_4 at the end and hence convective rain in magnitude and duration is lowest. In this region OLR is the highest and convective cloud cover is the smallest. The cloud cover is

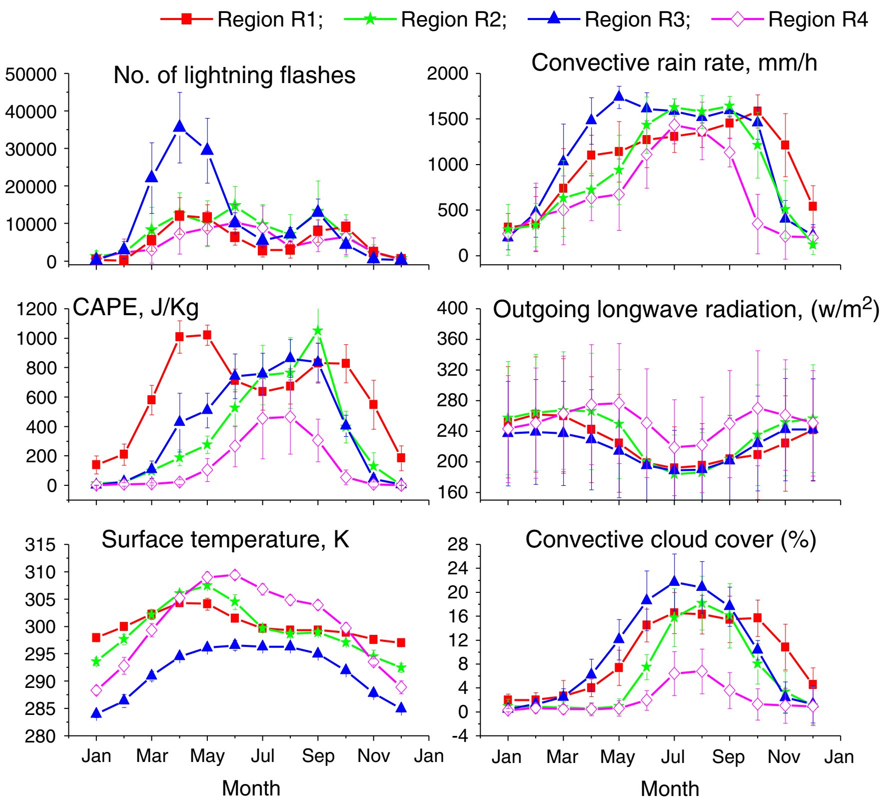

Fig. 3. Monthly variation of lightning flashes, convective rain rate, CAPE, outgoing long wave radiation, surface temperature, convective cloud layer: total cloud cover, for region R_1, R_2, R_3 and R_4. Vertical error bars show the standard deviations.

maximum in region R_3 and minimum in region R_4 (North–West India). The mean outgoing long wave radiation (OLR) shows broad minima during the monsoon period (July–August) for all the four regions R_1, R_2, R_3 and R_4.

The dependence of monthly mean lightning flashes on various meteorological parameters is seen through scatter plots shown in Fig. 4. Correlation coefficient and significance level is also given. CAPE is well correlated (R = 0.81) in region R_1 and moderately correlated (R = 0.23, 0.24) in regions R_3 and R_4. The monthly mean surface temperature is well correlated (correlation coefficient lying between 0.44 and 0.63) with lightning flashes having high significance level for the entire Indian regions (R_1, R_2, R_3 and R_4). The dependence of lightning flashes on outgoing long wave radiation shows some negative correlation in regions R_1 and R_2 whereas regions R_3 and R_4 do not show any convincing relation. Total cloud cover shows some positive correlation but with small significance level.

Fig. 5 depicts dependence of monthly mean convective rainfall rate on CAPE, temperature, OLR and total cloud cover. In all the four regions convective rain increases with CAPE and cloud cover having good correlation coefficient with good significance level. Rainfall also shows good correlation with temperature in regions R_2, R_3 and R_4 and no significant correlation in R_1. Convective rain is negatively correlated with outgoing long wave radiation. Fig. 6 shows the scattered plots of monthly mean convective rain with monthly mean lightning flashes for the all selected regions. The variation of all the regions is similar with good positive correlations (R lying between 0.48 and 0.52) having good significance levels in all the regions. The obtained correlation coefficient along with significance level for lightning flashes and convective rain rates with meteorological parameters are presented in Table 1.

In region R_1, the CAPE seasonal variation clearly explains the lightning flash variation. In region R_2, CAPE value starts increasing from February onwards, reaches to a maximum in the month of September and then decreases; whereas the surface temperature rise becomes a maximum in May and then starts decreasing. Thus the combined seasonal distributions of CAPE and temperature could explain the lightning flash distribution. In this region larger convective rain is during June to September. Thus CAPE variation could explain the convective rain variation. In region R_3, CAPE is quite large during April to September and surface temperature is large from April to September. Accordingly lightning flash is higher during March to June and convective rain is higher during April to October. In this region, in addition to CAPE and surface temperature, geophysical location and its orography also play a role. In region R_4, surface temperature is higher from March to October, but CAPE is higher from June to September. Lightning flash distribution shows relatively higher values during April to July and convective rain is higher from June to September. Thus higher surface temperature may cause larger convection and consequently higher lightning flashes and CAPE variation could explain precipitation variation. The present results are in agreement to those reported earlier (Williams, 1992, 2005; Price and Asfur, 2006; Siingh et al., 2013). Studies

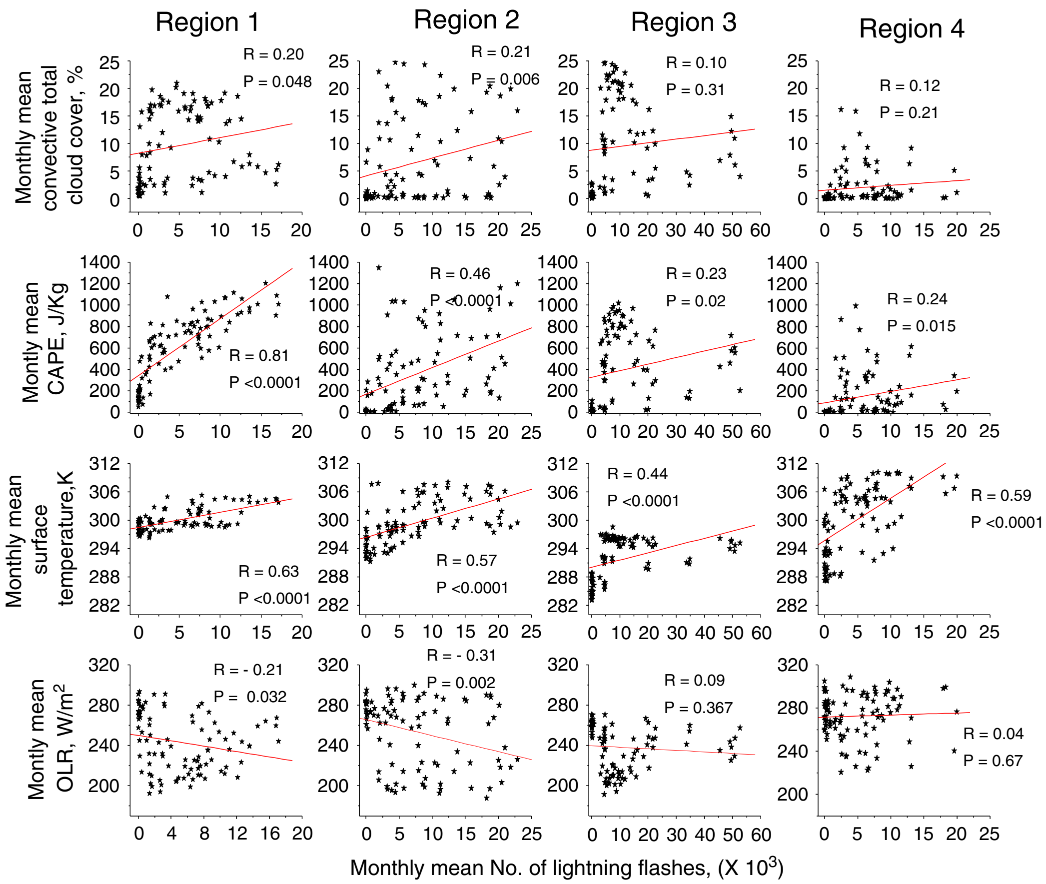

Fig. 4. Scattered plots of monthly mean no. of lightning flashes with different metrological parameter for regions R_1, R_2, R_3 and R_4. Values of correlation coefficients and significance level of the parameter are also given in each panel.

showed that an average increase of 1 K could lead to an increase of 40 ± 14% lightning flash rates (Reeve and Toumi, 1999; Kandalgaonkar et al., 2005; Pinto and Pinto, 2008). Simulation results show that an enhancement of 1 K global temperature may lead to ~10% enhancement in lightning activity (Shindell et al., 2006). The high lightning flash in region R_3 during pre-monsoon is attributed to convective instability leading to development of Nor'westers (Tinmaker and Ali, 2012). Also orography of the region and the availability to plenty of moisture may help in the thunderstorm developments. We observed second peak in September, as is also reported by Tinmaker and Ali (2012). The first peak may be associated with intense insolation and extensive moisture content in the lower troposphere level in addition with synoptic conditions of the region. The moisture content and orography of the region are attributed to the second peak. In region R_1 during the months of April–May differential heating of land region and adjoining oceanic region along with low-level moisture provided from sea may lead to thunderstorm development and lightning activity. Our results are in close agreement with that of Tinmaker et al. (2010). The second relatively small peak during October could be associated with occasionally occurring cyclones over the southern Bay of Bengal and the southern Arabian Sea.

Temperature and CAPE do not have identical seasonal variations in all of the four regions. Temperature has a maxima between April and June in regions R_1, R_2 and R_4, whereas R_3 has almost constant maximum temperature between May to August, CAPE has a maximum during April–May in R_1, August–September in R_2 and R_3 and July–August in R_4 region respectively. Considering all the four regions as a single zone, Siingh et al. (2013) showed that the seasonal and annual variations of temperature and CAPE are almost identical and hence CAPE or temperature could explain the trend of total lightning flash variation and the results were in accordance with the fact that drier climate results in more lightning (Price, 2009). Our results are in partial agreement with that of Murugavel et al. (2012) who showed that the seasonal variation of CAPE over the Indian region was higher during the monsoon compared to pre-monsoon or post monsoon seasons. The difference may be due to the smaller size of the region considered and the role played by geography/orography of the region and its surroundings, which are averaged out in larger size of the area considered.

We found good positive correlation (correlation coefficient > 0.78) between convective rainfall and CAPE in all the three regions (R_2, R_3 and R_4) with high significance level except in R_1 region where correlation coefficient is 0.68. In contrast some studies reported negative correlation between CAPE and rainfall (McBride and Frank, 1999; Sobel et al., 2004; Yano et al., 2005) and in some cases essentially no relationship

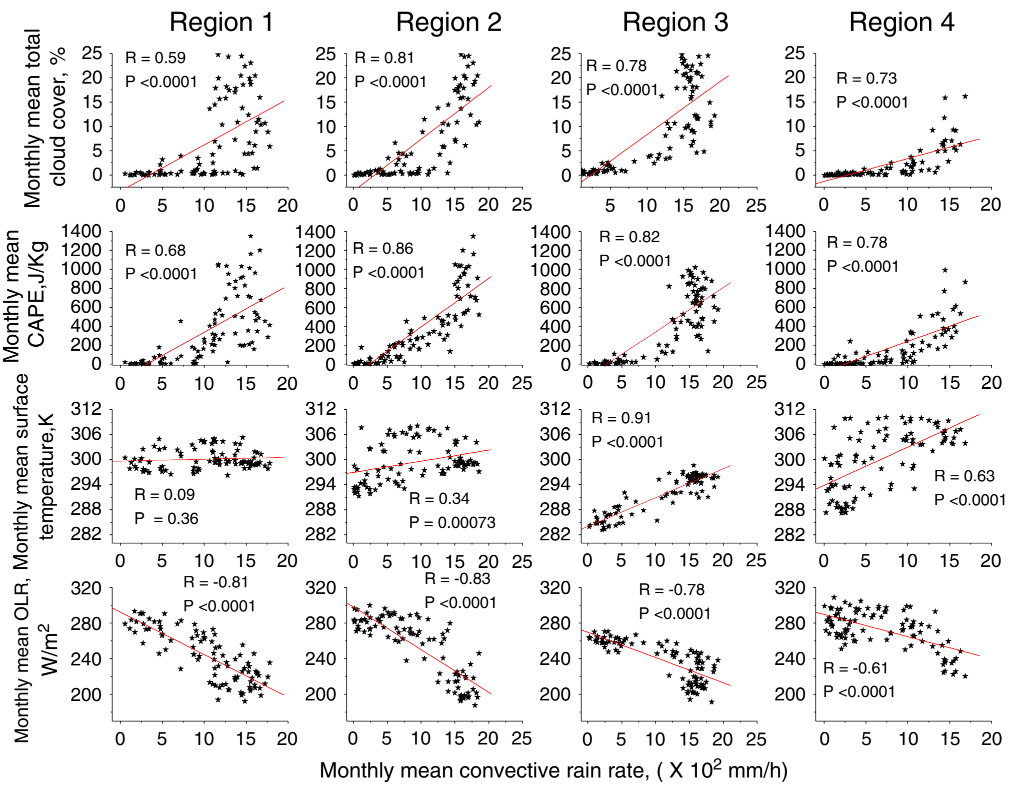

Fig. 5. Same as Fig. 4 but for the monthly mean convective rain rate.

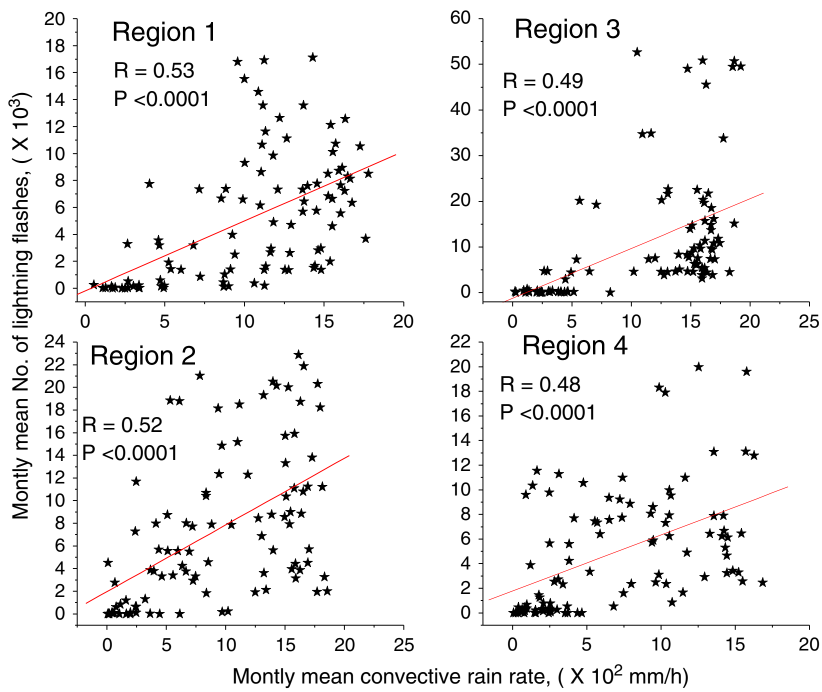

Fig. 6. Scatter plots for monthly mean no. of lightning flashes with monthly mean convective rainfall with for regions R_1, R_2, R_3 and R4 are shown along with correlation coefficient and significant level of the parameter.

Table 1
The correlation coefficient (R) and significant level (P) of both lightning flashes (LF) and convective rainfall (CR) with meteorological parameters.

Meteorological parameters	Region R_1		Region R_2		Region R_3		Region R_4	
	LF	CR	LF	CR	LF	CR	LF	CR
Total cloud cover %	R = 0.20 P = 0.048	R = 0.59 P < 0.0001	R = 0.21 P = 0.006	R = 0.81 P < 0.0001	R = 0.10 P = 0.31	R = 0.78 P < 0.0001	R = 0.12 P = 0.21	R = 0.73 P < 0.0001
CAPE	R = 0.81 P < 0.0001	R = 0.68 P < 0001	R = 0.46 P < 0.0001	R = 0.86 P < 0.0001	R = 0.23 P = 0.02	R = 0.82 P < 0.0001	R = 0.24 P = 0.015	R = 0.78 P < 0.0001
Temperature	R = 0.63 P < 0.0001	R = 0.09 P = 0.36	R = 0.57 P < 0.0001	R = 0.34 P = 0.0007	R = 0.44 P < 0.0001	R = 0.91 P < 0.0001	R = 0.59 P < 0.0001	R = 0.63 P < 0.0001
Outgoing long wave radiation	R = −0.21 P = 0.032	R = −0.81 P < 0.0001	R = −0.31 P = 0.002	R = −0.83 P < 0.0001	R = 0.09 P = 0.367	R = −0.78 P < 0.0001	R = 0.04 P = 0.0.67	R = −0.61 P < 0.0001

could be found (Peppler and Lamb, 1989; Zhang, 2002). Adams and Souza (2009) suggested that the relation between rainfall and CAPE depends on the region and most of the time it is not consistent. The orography and local meteorological conditions play a significant role in cloud development and hence in lightning and rainfall activity. More studies are required selecting regions having varying orography and meteorological conditions to sort out the role of orographic and metrological conditions.

Siingh et al. (2013) reported good correlation (correlation coefficient ~ 0.68; significance level $P < 0.0001$) between lightning flashes and convective rain for the whole Indian region whereas in the present study we find correlation coefficient between lightning flash and convective rainfall to be 0.53, 0.52, 0.49, and 0.48 in regions R_1, R_2, R_3 and R_4 respectively with very good significance level. Thus, in Indian region, convective rain and lightning could be attributed to deep convective clouds in accordance with the proposition of Price and Federmesser (2006) and Gungle and Krider (2006). Based on the studies of individual thunderstorms, a positive correlation is attributed to the microphysics and dynamics of deep convective clouds. The correlation coefficients in all the four regions suggest that convective processes on the macroscopic level are similar although orographically/geographically there is some difference between the regions. For example, region R_1 is bounded by the Arabian Sea and Bay of Bengal whereas region R_4 encloses most of the desert area of Rajasthan and Gujarat. The orography of R_3 is much different than the rest of the regions. Liou and Kar (2010) reported different rain yields per flash for inland and coastal regions over Taiwan, which is also different for different seasons. These differences were attributed to cloud base height and CAPE.

3.3. Aerosol effect

Earlier studies showed the effect of urbanization in terms of changes in aerosol distribution, lightning and rainfall pattern (Landsberg, 1970; Huff and Changnon, 1972; Orville et al., 2001; Naccarato et al., 2003; Pinto et al., 2004; Burian and Shepherd, 2005; Farias et al., 2009; Kar et al., 2009; Turner and Annamalai, 2012). In order to study the effect of aerosols (urbanization) during 2003–2011 in the four selected regions (R_1, R_2, R_3 and R_4), we have plotted yearly averaged value of CAPE, temperature and aerosol optical depth (Fig. 7). CAPE showed increasing trend in regions R_1, R_3 and R_4 and a decreasing trend in region R_2. (Fig. 7). Temperature showed an increasing trend in all the four regions (Fig. 7). The annual surface temperature in R_1 and R_4 regions is almost equal but the CAPE is the largest in R_1 and the least in R_4 region. The mean aerosol optical depth is the largest in R_4 and the least in R_1 (Fig. 7). The largest aerosol concentration in R_4 may be due to the fact that the region includes desert land of the Rajasthan and Gujarat provinces. The loosely bounded soil surface easily moves up in the atmosphere even with moderate winds. Aerosol optical depth shows small increase in regions R_1, R_2 and R_3 and decreases in region R_4. Annual variations are represented by linear expressions in each panel for different regions. The variations of monthly mean convective rain and monthly mean lightning flashes with monthly mean aerosol optical depth is shown in Fig. 8. In each panel correlation coefficient and significant level is also given. Lightning flashes have positive correlation with correlation coefficient varying between 0.30 and 0.47. The correlation coefficient for convective rain varies between 0.10 (R_3) and 0.25 (R_1). Regions R_2 and R_4 have much improved correlations both for lightning flashes ($R = 0.37, 0.41$) and convective rain ($R = 0.52, 0.58$). In the considered locations, region R_3 shows least correlation ($R = 0.10$) between convective rain and aerosol optical depth and highest correlation ($R = 0.47$) between lightning flashes and AOD.

Fig. 8 clearly shows that the responses of aerosols to lightning and rainfalls are different in different regions. Increased aerosol concentration increases lightning flash (Williams et al., 2002), whereas the increase or decrease of rainfall as a function of aerosol concentration enhancement depends on concentration and size distribution of aerosols (Rosenfeld et al., 2008; Koren et al., 2008). They have shown that rainfall increases with AOD, becomes maxima at AOD of ~0.25 and decreases with greater AOD. In contrast, we find an increasing trend in rainfall and lightning flashes. Out of all regions, R_3 has peculiar effect of aerosols. Lightning flashes increases with AOD whereas rainfall increase is low and the significance level is also quite poor. In this part of India, generally wide spread outbreaks of “Nor-westers” causes severe thunderstorms (Koteshwaram and Srinivasan, 1958). Nor-westers are the result of large scale flows due to the superposition of favorable upper and lower tropospheric conditions. Generally Nor-wester is associated with a low pressure region (trough) in the upper troposphere along with a jet stream. In the lower troposphere a trough helps in converging winds. Rain in this region is also controlled by orographeric conditions of the region and its proximity with the ocean and “Tibetan Pathar”. Similarly region R_1 is enclosed from three sides by ocean and as a result large scale enhancement rate

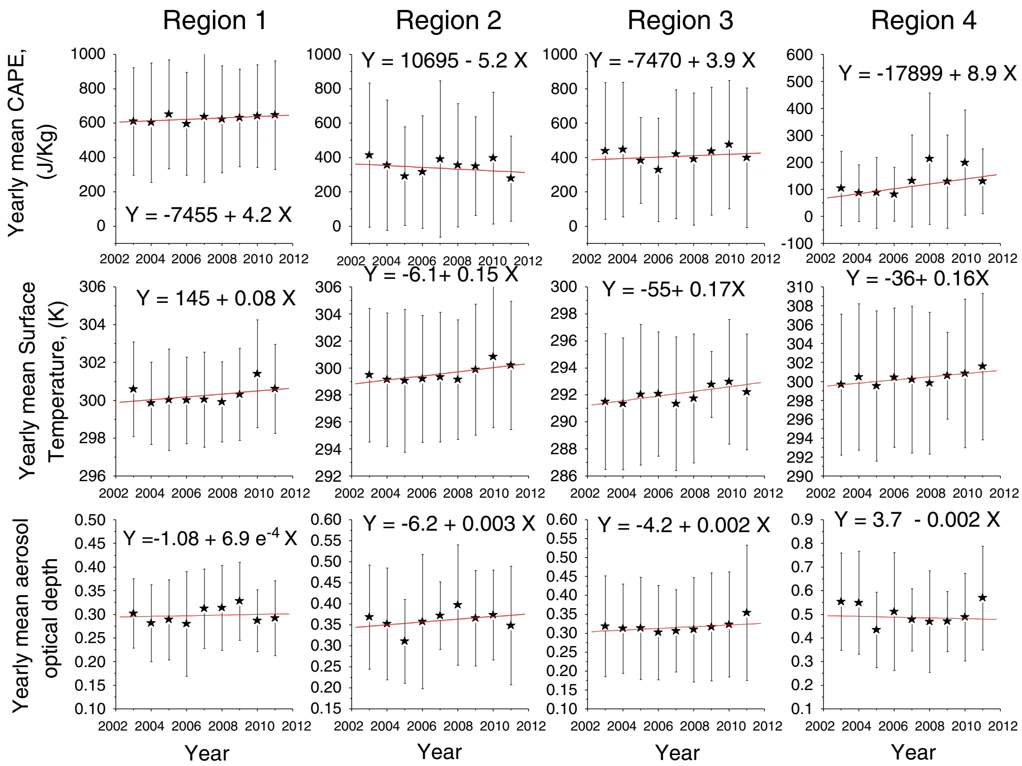

Fig. 7. Yearly variation of the mean CAPE (convective available potential energy), mean surface temperature, and aerosol optical depth for regions R_1, R_2, R_3 and R_4. Linear relationship for each region is given in each panel.

in rain by an increase in AOD is not observed. The effects of aerosols on cloud properties depend on CAPE and wind shear (Lee et al., 2008; Fan et al., 2009), cloud morphology (Lee et al., 2010), and relative humidity (Fan et al., 2007). Hygroscopic aerosols increase their size as relative humidity increases and may serve as CCN and hence affect precipitation and lightning activity. Based on measurements and simulations, Wang et al. (2011) showed that enhanced aerosol loading suppresses light and moderate (<25 mm per day) rainfall but enhances heavy rainfall. Aerosol loading leads to efficient mixed phase processes and enhances convection. Recently attempts have been made to sort out conditions under which clouds and precipitations are suppressed or enhanced by aerosol (Li et al., 2011a,b; Niu and Li, 2011; Tao et al., 2012).

4. Summary and conclusion

The difference in surface topology of the region, vegetation, proximity to the ocean, atmospheric circulation pattern, industrialization and pollution, all may influence the lightning and rainfall activity. All these prompted us to examine the relation between lightning and rainfall activity in different parts of India. The available lightning and convective rainfall data for the period 2003–2011 are analyzed and their dependence on solar activity and meteorological parameters are studied. The results show that there is no significant correlation between lightning flashes and convective rain fall with solar flux, cosmic rays and sunspot numbers in all the four regions. Yearly distributions show the largest number of mean lightning flashes and mean convective rain from region R_3 and least rain fall from region R_4. Lightning flashes from region R_1 and R_4 are almost of the same magnitude and have the lowest value. The results are almost similar to that of Siingh et al. (2013) where all the four regions were considered as a single zone. This shows that the impact of solar activity parameters on lightning and convective rain remain almost similar throughout the Indian region.

The seasonal variation of lightning flashes shows maxima in different regions between April and June with a secondary maximum around the September whereas convective rain shows broad maximum between the months of May and October. Total cloud coverage and mean outgoing long wave radiation show opposite seasonal variation. Cloud coverage almost could explain the pattern of rainfall variation but not the lightning seasonal variation. In region R_1, temperature and CAPE exhibit similar seasonal variation with a maximum in the months of April and May, whereas in all the other regions, there is shift in the months of maximum temperature and maximum CAPE. The maximum shift of three months corresponds to region R_2 (Central India). The seasonal variations of CAPE show higher values during the monsoon period compared of pre-monsoon/post-monsoon, in agreement with the results of Murugavel et al. (2012). Either the temperature variation or the CAPE variation alone could not explain the seasonal variations of lightning flashes and convective rain. However, temperature in association with CAPE could explain

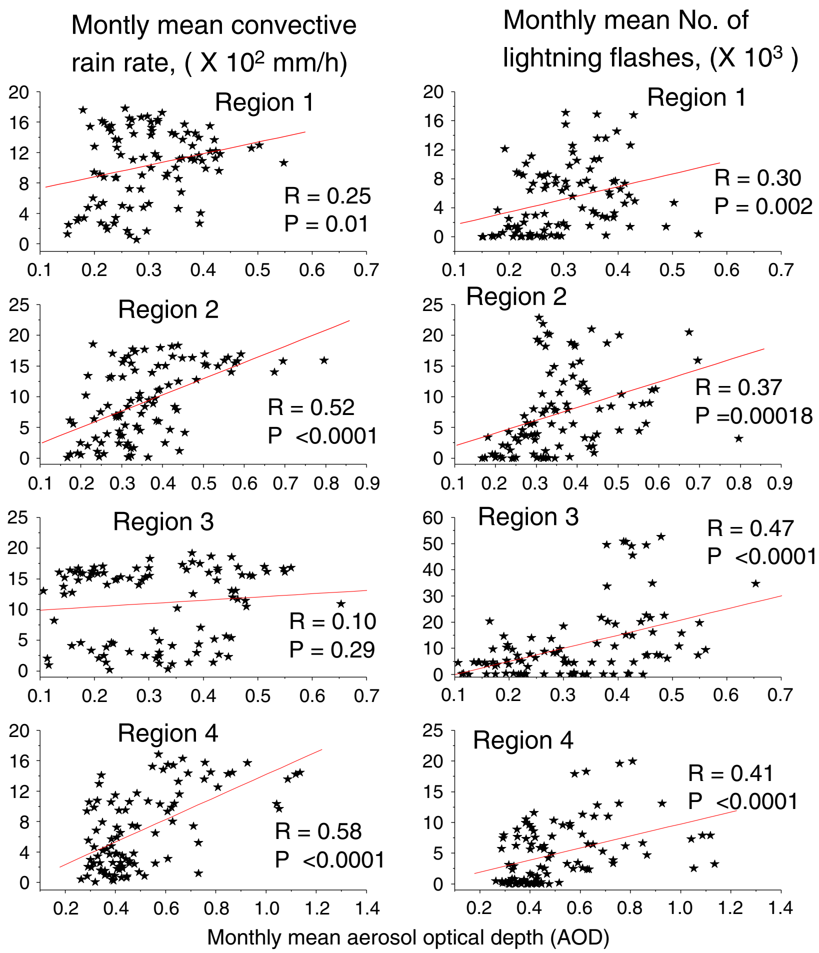

Fig. 8. Scattered plots of monthly mean convective rain and monthly mean no. of lightning flashes with aerosol optical depth for regions R_1, R_2, R_3 and R4 along with correlation coefficient and significant level of the parameter.

the seasonal variation of lightning flashes and convective rains, the dependence of CAPE and temperature on lightning and convective rain activity becomes more apparent in terms of correlation studies. In region R_1, CAPE is well correlated with lightning activity (correlation coefficient R ~ 0.81) and to a comparatively lesser extent with convective rain activity (R ~ 0.68). On the other hand CAPE is well correlated (R > 0.78) with rainfall in regions R_2, R_3 and R_4, but lightning activity is not so well correlated (R > 0.23) in these regions. Surface temperature is better correlated with lightning flashes (R = 0.63, 0.57, 0.44, and 0.59 in R_1, R_2, R_3 and R_4 respectively). Correlation between surface temperature and rainfall is statistically insignificant in region R_1 and low significant in R_2, whereas it is quite well correlated (R ~ 0.91) in R_3 but not so well correlated (R = 0.68) in R_4. The cloud cover and outgoing long wave radiation could not show any significant impact on lightning activity in regions R_3 and R_4. In R_1 and R_2, they have some impact. Cloud cover shows positive effect in all the regions, whereas OLR has negative effect in R_1 and R_2 and no impact in R_3 and R_4. The cloud cover and rainfall are well correlated in all the regions. OLR and rainfall are oppositely (negative correlation coefficient) well correlated in all the four regions. Lightning flashes and convective rainfall are positively correlated (~0.50) in all the four regions.

One of the implications of urbanization/industrialization is the enhanced aerosols in the atmosphere, which can enhance or reduce rainfall and lightning flashes. Aerosols in the presence of high humidity and instability can enhance convection and hence can increase precipitation and lightning activity (Bell et al., 2008). During the period of analysis statistically significant change in the aerosol concentration is not observed in any region. Regions R_2 and R_4 exhibit good correlation between AOD and convective rain (R ~ 0.52, 0.58) and lightning flashes (R ~ 0.37, 0.41) with good significance level. Regions R_1 and R_3 have quite different orography and show some correlation with smaller significance level; except in region R_3 lightning flashes have relatively better correlation with very good significance level. Although, in the present study the effect of aerosol on cloud properties seems to be different in different regions, but the same may be due to the meteorological parameters. In the present stage of knowledge, it is a daunting task to separate meteorological and aerosol effects. As interactions of meteorological variables, aerosols, cloud and precipitations are very complex, precise observational and numerical studies are required.

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