

# Lightning activity and its association with rainfall and convective available potential energy over Maharashtra, India

M. I. R. Tinmaker · M. Y. Aslam · D. M. Chate

Received: 20 August 2013 / Accepted: 3 January 2015 / Published online: 13 January 2015  
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**Abstract** This work presents the association of flash rate density (FRD) with surface air temperature, rainfall and convective available potential energy (CAPE) using satellite-based flash count grid ( $0.5^\circ \times 0.5^\circ$ ) data from 1998 to 2007 over Maharashtra, India. We investigate monthly to seasonal variations in lightning activity with rainfall and CAPE. The first peaks for FRD and rainfall found in June and July, respectively, followed by next peaks in September. The difference in peaks for FRD and rainfall of 1 month (June–July) attributed to the onset phase of summer monsoon in June (relatively less wet period favorable for more convective and lightning activity), thereafter, heavy rainfall in July over Maharashtra. The annual variations show that the September peaks for both FRD and rainfall are higher than that in June for FRD and for rainfall in July. FRD is moderately correlated with rainfall ( $r = 0.51$  at significant level  $<0.0001$ ). There is good parallelism in the variation of FRD, and CAPE as the correlation coefficient in between them is 0.78 at significant level  $<0.0001$ .

**Keywords** Flash rate density · Surface air temperature · Rainfall amount · CAPE

## 1 Introduction

Lightning activity and its associated rainfall are important weather phenomena over Indian region, particularly during pre-monsoon (March–May) and Post-monsoon (October–November) periods. The importance of lightning activity lies in the fact that it is associated with thunderstorms that contribute substantially to annual total rainfall over Indian region (Manohar et al. 1999). Lightning flash count for thunderstorm distributions is useful to

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M. I. R. Tinmaker · M. Y. Aslam · D. M. Chate (✉)  
Indian Institute of Tropical Meteorology, Pune 411008, India  
e-mail: chate@tropmet.res.in

M. I. R. Tinmaker  
e-mail: iqbal@tropmet.res.in

estimate lightning intensity, which in turn provides information on dynamics and micro-physics of convective storms. Investigation on this aspect of lightning activity will be helpful in understanding implications related to the growth of thunderclouds and their electrification (Tinmaker et al. 2010a).

The electrical activity inside thunderstorms is mainly initiated, and maintained by the updraft and concentration of ice particles (Williams 2001). The magnitude and vertical distribution of convective available potential energy (CAPE) play an important role in determining the updraft vertical velocity and vertical distribution of hydrometeors, which participate in the charge generation processes inside thunderclouds (Williams 1995). Vertical motions inside thunderstorm are owing to buoyancy forces out of temperature gradient inside cloud, difference in water vapor concentration and condensate between ascending and descending air parcels and its environment. In general, an atmosphere with larger CAPE is likely to produce a stronger updraft and more vigorous and electrically active storms. The relation between maximum updraft and CAPE is  $W_{\max} = \sqrt{2\text{CAPE}}$  (Williams et al. 2005). The updraft in turn will influence vertical development of precipitation in mixed-phase cloud, where the impact of charge separation believed to be greatest (Williams and Renno 1993). Thus, the magnitude of CAPE should show good correlation with lightning activity (Rutledge et al. 1992; Williams and Stanfil 2002).

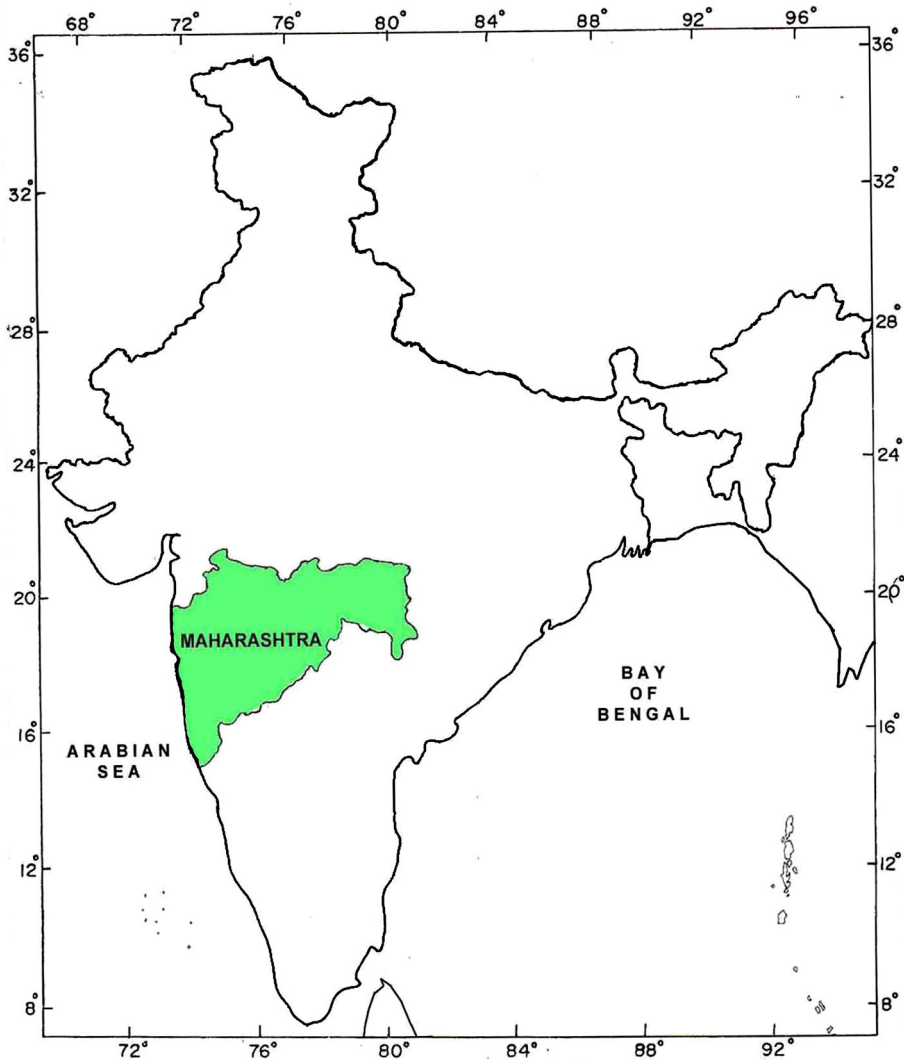
Considerable research work on various aspects of thunderstorm and lightning are available for various parts of the globe (Sohoni 1931; Rao and Raman 1961; Raman and Raghavan 1961; Williams 1961; Chaudhury 1961; Rao et al. 1971; Balogun 1981; Oladipo and Mornu 1985; Prasad and Pawar 1985; Sivaramkrishnan 1990; Price and Rind 1994; Moid 1995; Williams et al. 2004). Over Indian regions, few authors attempted to understand thunderstorm climatology, lightning–rainfall relationships, relationship between lightning activity and CAPE (Manohar et al. 1999; Kandalgaonkar et al. 2005a, b; Manohar and Kesarkar 2005). Kandalgaonkar et al. (2003) have shown that maximum lightning activity occurs in May with a superimposed diurnal maximum at 1330 IST (0800UTC). Manohar and Kesarkar (2005) examined the thunderstorm activity along east and west coast across the Indian peninsula that shows east coast experiences higher thunderstorm activity as compared to west coast. Furthermore, Kandalgaonkar et al. (2005a) have found that lightning activity has direct nonlinear correlation with latitude due to landmass distribution, orography and large-scale circulations. Tinmaker et al. (2010b) examined the spatiotemporal variation of lightning activity over the Peninsular India. They found that lightning activity is higher over south Peninsular India and eastern India. In addition, the relationship between lightning activity over Peninsular India and sea surface temperature showed good correlation.

Because of various research- and application-oriented needs of flash rate density (FRD), we investigate relationships of lightning activity with surface air temperature, rainfall and CAPE over Maharashtra, India. These results may be helpful in understanding the role of lightning activity in rainfall distributions over this region.

## 2 Data and source description

The lightning imaging sensor (LIS) is a satellite-borne instrument used to detect lightning flashes (Christian et al. 1999; Bond et al. 2002). It is a National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) on Tropical Rainfall Measuring Mission (TRMM) Satellite. The LIS has developed with a higher sensitivity and spatial

accuracy than Optical Transient Detector (OTD) (Boccippio et al. 2002). It detects lightning flash with storm-scale (spatial) resolution (4–7 km) over a large region (600 × 600 km) of the Earth’s surface. Since November 28, 1997, LIS is into low Earth orbit at an altitude of 350 km. The inclination of the orbit is 35°, which allows the LIS to observe the lightning activity in the tropical regions of the globe. It detects the lightning activity with the detection efficiency of 90 % with little regional bias (Boccippio et al. 2000). However, according to Boccippio et al. (2002), flash detection efficiency is predicted to be  $93 \pm 4 \%$  at night and  $73 \pm 11 \%$  during the day. LIS records both cloud-to-ground and intra-cloud lightning and shows them as a total flash count. The TRMM satellite boosted from an average altitude of about 350 and 400 km before and after August

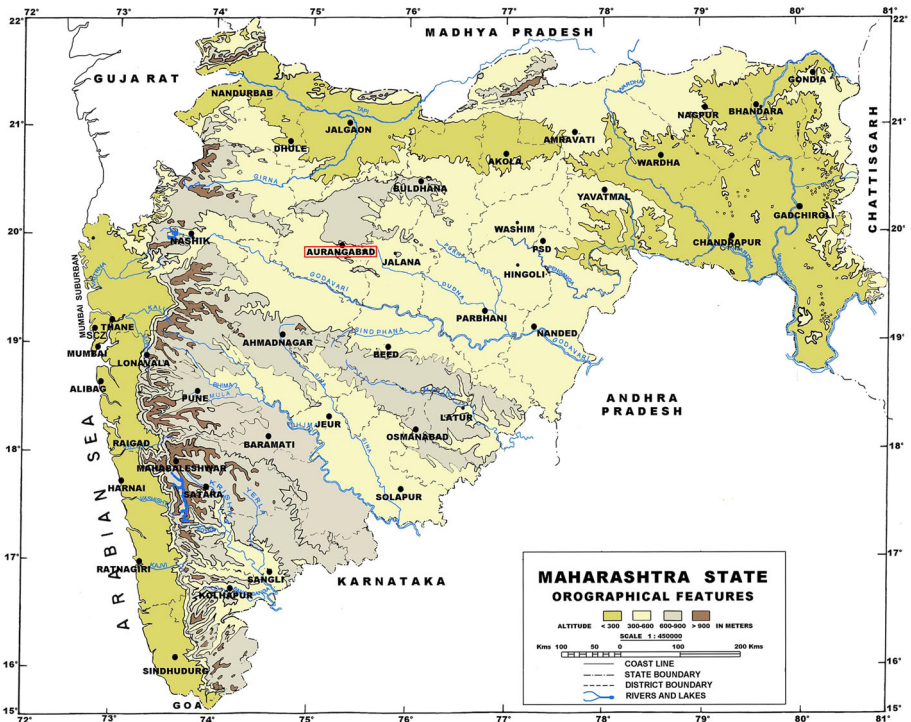


**Fig. 1** Map of India showing *inset* Maharashtra

2001, respectively. The higher altitude gives a correspondingly larger field of view for swath at each of the sensor's pixels and slightly longer sampling duration. Since a lightning flash typically illuminates a cloud top area significantly larger than field of view of a LIS pixel and detection threshold, setting remained unchanged after boost. One would not expect any change in detection efficiency with its altitudes. This increases total flash counts, but not flash rates (Cecil et al. 2014).

The present study uses LIS-retrieved FRD data for a period of 10 years (1998–2007) over the Maharashtra (16°–22°N and 72°–81°E). Figures 1 and 2 shows the map and orography of Maharashtra state. The LIS data are available on the NASA GHRC website ([http://thunder.msfc.nasa.gov/data/data\\_lis.html](http://thunder.msfc.nasa.gov/data/data_lis.html)). The monthly data are available over a grid (0.5° × 0.5°) for 10-year period (1998–2007). The flash rate density ( $f \text{ km}^{-2} \text{ year}^{-1}$ ) for the particular month at each grid point is obtained by dividing the flash count by the view time and the area of the grid, and by multiplying with total seconds of that year. From the calculated flash rate density for each month, the average flash rate density for each month for 10-year period (1998–2007) is obtained and compiled over monthly and seasonal scales. For this purpose, a year has been divided, into four seasons namely pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February) seasons (IMD 2005).

The rainfall and temperature data for 10-year period (1998–2007) were obtained from India Meteorological Department and average over month. The daily CAPE data for Aurangabad station (in red box in Fig. 2) over Maharashtra are downloaded for the same



**Fig. 2** Orographic Map of Maharashtra (red box showing Aurangabad station for CAPE data)

period from the University of Wyoming website (<http://weather.uwyo.edu/upperair/sounding.html>) and average over month. Monthly mean air temperature (850 mb) and relative humidity data for the same period and region are extracted from Climatic Data Centre of the National Oceanic and Atmospheric Administration (NOAA).

### 3 Meteorological condition

A brief summary of the meteorological and weather conditions during different seasons over Maharashtra (IMD 2005) is as below:

#### 3.1 Pre-monsoon

The weather during pre-monsoon period is relatively hot and dry with daytime maximum temperature showing day-to-day variation in the range of 38° to 42 °C. Climatologically, the average maximum temperature during pre-monsoon is ~39 °C. Nighttime conditions are cool due to sea breeze, blowing from the Arabian Sea to the region over Maharashtra (IMD 1931). Occasionally, cumulonimbus clouds develop during the afternoon and evening hours. The dust loading is relatively moderate to high during this season.

#### 3.2 Monsoon

Onset of monsoon over the study region starts with thunderstorm and lightning activity. Southwesterly and westerly winds rich in marine air from the Indian Ocean and the Arabian Sea prevail over the region during monsoon with wet and humid weather condition. The region receives lightning mediated continuous or intermittent rain from cumulus and stratocumulus clouds under the influence of large-scale convergence due to synoptic systems. Occasionally, nimbostratus clouds provide heavy and moderate rain on the establishment of the monsoonal activity. With the revival of monsoonal activity after a break period, the developments of thunderstorms are common over the region.

#### 3.3 Post-monsoon

The remnant of the monsoon period's humidity and daytime heating paves way for the development of thunderstorm during October. However, chance for thunderstorms development decreases due to deficiency in moisture and intensity of radiation as the season progresses. Because of the cessation of rainfall activity after September, the average daily temperature increases. During October, days are hot (30° to 32 °C) and nights are cool (12° to 14 °C). The westerly flow weakens in the lower troposphere and easterly flow sets in accompanied by a rapid fall in temperature by the end of October.

#### 3.4 Winter

There is further decrease in surface air temperature with commencement of the winter. Climatologically, minimum and maximum temperatures of 12 and 30 °C, respectively, recorded over study region. Relative humidity (RH) >70 % was observed in the morning (0830IST or 0500UTC), and RH <35 % in the evening (1730IST or 1200UTC). General

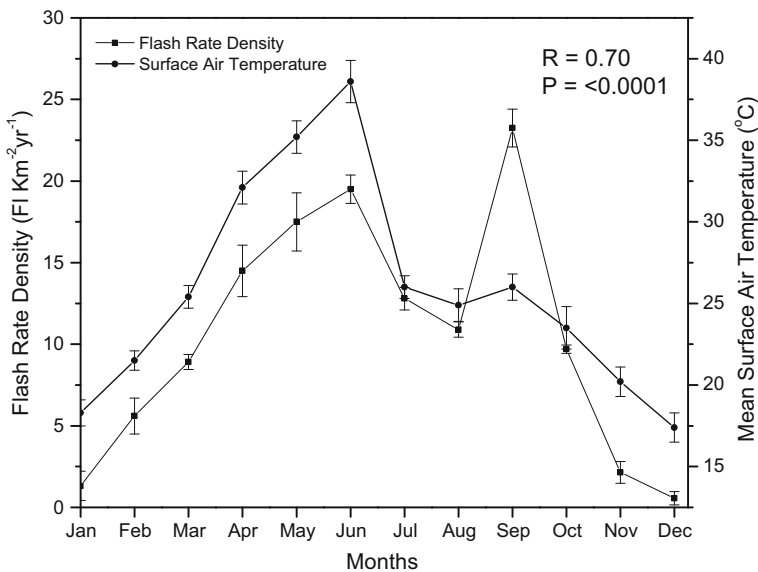
weather condition is fair that normally characterized by clear sky and low average relative humidity (about 45 %) with light surface winds.

## 4 Results and discussions

### 4.1 Annual variation of flash rate density and surface air temperature over Maharashtra region

Figure 3 shows variations in monthly mean FRD and surface air temperature. It is clear from the Fig. 3 that the FRD increases consistently from the minimum value of  $1.32 \text{ fl km}^{-2} \text{ year}^{-1}$  in January to  $17.5 \text{ fl km}^{-2} \text{ year}^{-1}$  in May and  $19.5 \text{ fl km}^{-2} \text{ year}^{-1}$  in June. Thereafter, FRD decreases until August to its low of  $10.9 \text{ fl km}^{-2} \text{ year}^{-1}$ . Next peak in FRD of  $23.25 \text{ fl km}^{-2} \text{ year}^{-1}$  observed during September. Lightning activity diminishes in December with lowest FRD of  $0.56 \text{ fl km}^{-2} \text{ year}^{-1}$ . In FRD variations, peaks in June and in September may be due to the prevailing synoptic condition over landmass. During June and September, the winds in the lower troposphere over Maharashtra region were westerly, and that brings air masses loaded with moisture toward landmass from the Arabian Sea. The release of latent heat into the atmosphere through convection of air parcel loaded with more moisture content triggers the development of cumulus cloud. On many occasions, thunderclouds are due to intense development of conditional instability those subsequently produce lightning discharges (IMD 1931).

The annual variation of monthly mean surface air temperature shown in Fig. 3 with first peak in June and second one in September suggests that the onset period of summer monsoon is associated with intense solar heating over the Maharashtra region. The atmosphere becomes unstable mainly due to intense convection. When marine air from the Arabian Sea

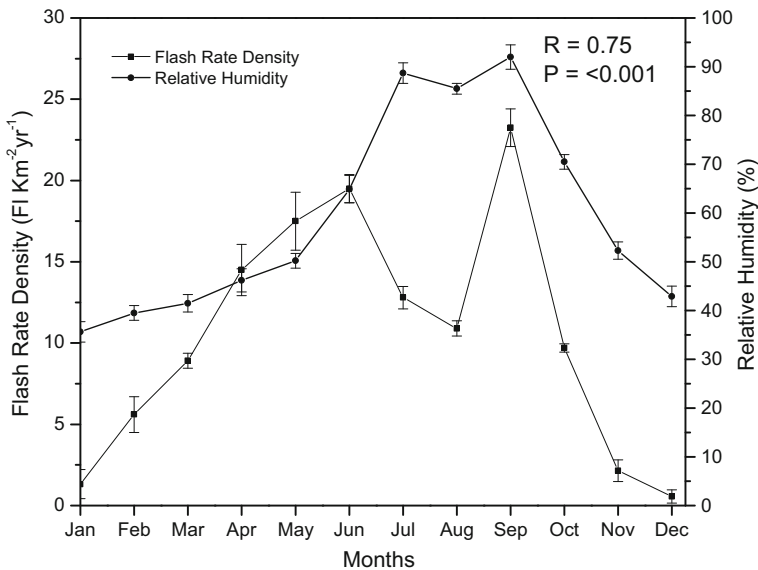


**Fig. 3** Annual variation of monthly mean flash rate density and surface air temperature over Maharashtra region during 10-year period (1998–2007)

passes across the landmass during June, the atmosphere becomes highly unstable due to availability of moisture above the lower troposphere. Because of development of intense conditional instability over the region, precipitation particles lifted above freezing level triggers ice nucleation processes. Consequently, thunderstorms developed during June have higher CAPE that results in peak FRD (Manohar et al. 1999; Williams and Stanfil 2002; Williams et al. 2005; Tinmaker et al. 2010a). The correlation coefficient between flash rate density and surface air temperature is found to be 0.70 (significant at <0.0001).

As the monsoon settles, the thermal heating reduces over the region during July; the atmosphere becomes wet because of widespread cloudiness by continuous supply of moisture from the Arabian Sea. During monsoon, maritime clouds with moderate updrafts prevail over the study region causes minimum cloud electrification (Takahashi 1990; Manohar et al. 1999; Kandalgaoonkar et al. 2008). Under such circumstances, the warm rain process becomes effective in the development of clouds that reduces lightning flash count over study region. Atmospheric conditions during August were similar to that of July, and thus, the chances for development of severe thunderstorms are less during monsoon (Zipser 1994; Jenamani et al. 2006).

The reason for larger flash rate density in September than in June is withdrawal phase of the southwest monsoon and the onset of the northeast monsoon over the region. The monsoonal cloud and rainfall activity ceases due to withdrawal period in September. More incoming solar radiation in September than that during the monsoon period along with availability of sufficient moisture in the lower levels of troposphere to sustain thunderstorm development could results high flash rate density. Despite intense or moderate convection during the pre-monsoon (April–June) with the heating over Maharashtra, there is lack of enough moisture to trigger thunderstorm activity (Kandalgaoonkar et al. 2008). In addition, plot of annual variations of flash rate density and relative humidity as shown in Fig. 4 exhibits the highest peak in September. The correlation coefficient between flash rate density and relativity humidity is found to be 0.75 (significant at <0.001). It appears to be



**Fig. 4** Annual variation of monthly mean flash rate density and relative humidity over Maharashtra region during 10-year period (1998–2007)

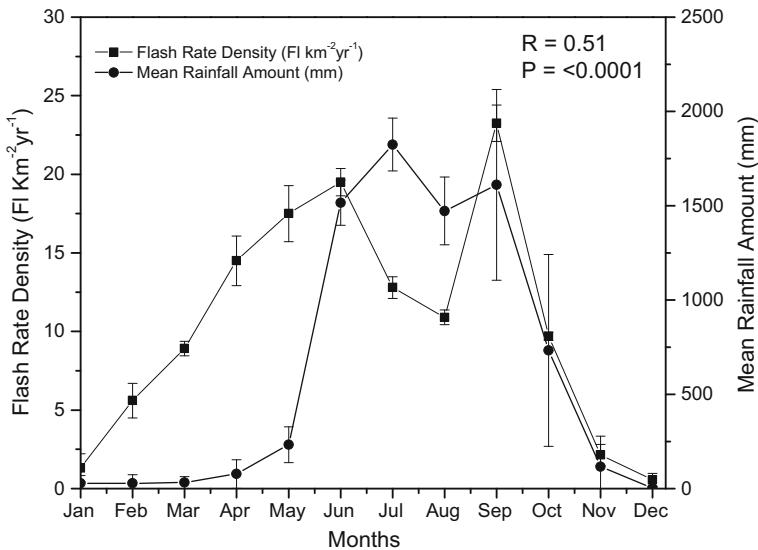


relative humidity is a better proxy for CAPE as well as for the development of thunderstorm and associated lightning activity in September (Williams and Renno 1993; Tinmaker et al. 2010a).

In Fig. 5, annual variations in monthly mean rainfall amount show systematic increase with the FRD. The minimum rainfall of 28 mm increases slowly up to 233 mm until May and reaches at its peak of 1,824 mm in July and a next peak of 1,611 mm in September, thereafter, lowest of 3.2 mm in December. The correlation coefficient between FRD and rainfall is 0.51, at significant level  $<0.0001$  (Fig. 6).

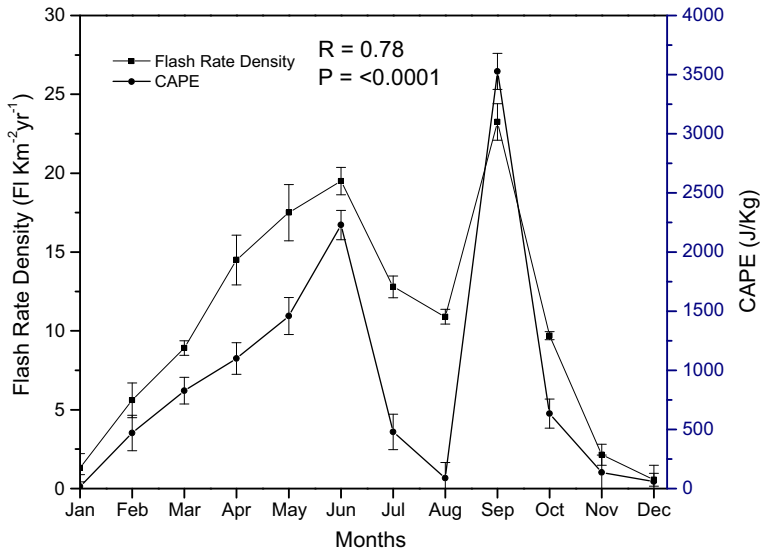
#### 4.2 Annual variation of flash rate density and CAPE over Maharashtra region

Figure 6 shows annual variation of monthly mean FRD and CAPE over the Maharashtra region during the study period. The CAPE and FRD show a trend similar to that of FRD with rainfall variation from January to December with a first peak in June and next one in September. The CAPE shown in Fig. 6 exhibits the highest peak in September. Additionally, correlation coefficient between FRD and CAPE is relatively high (0.78, significant at  $<0.0001$ ). It means transformation of very high CAPE into kinetic energy of updraft in the convective system is responsible for high FRD (Williams and Renno 1993, Murugavel et al. 2014). The high CAPE plays an important role in determining the updraft velocity and vertical distribution of hydrometeors that enhances the charge generation processes inside thunderclouds (Williams 1995). As shown in Fig. 7, the variation of flash rate density and air temperature (at 850 mb) is in phase with first peaks for both FRD and air temperature in June and next highest peak for FRD in September with lower air temperature. Despite low air temperature, due to ample amount of latent heat release from clouds, convective activity sustains with enough amount of moisture contents in September which will help to develop more thunderstorms and lightning in the month of September

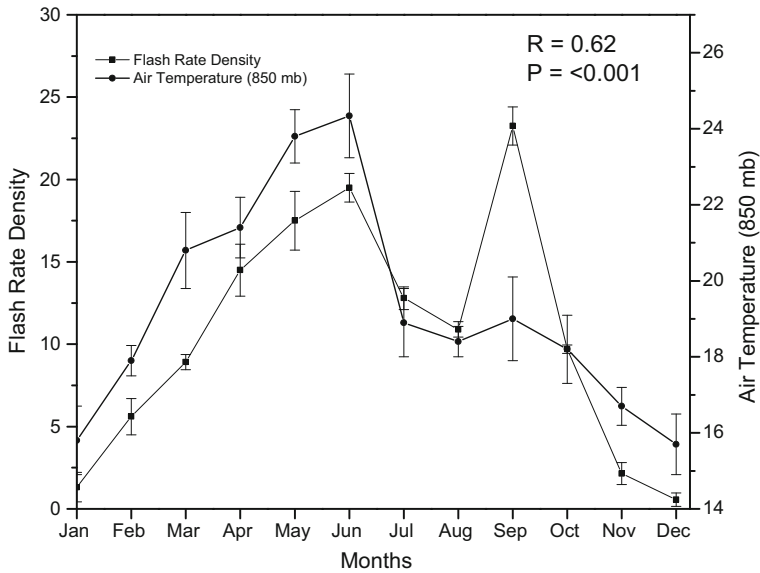


**Fig. 5** Annual variations of monthly mean flash rate density and rainfall amount over Maharashtra during 10-year period (1998–2007)





**Fig. 6** Annual variations of monthly mean flash rate density and CAPE over the Maharashtra during 10-year period (1998–2007)



**Fig. 7** Annual variation of monthly mean flash rate density and air temperature (850 mb) over Maharashtra region during 10-year period (1998–2007)

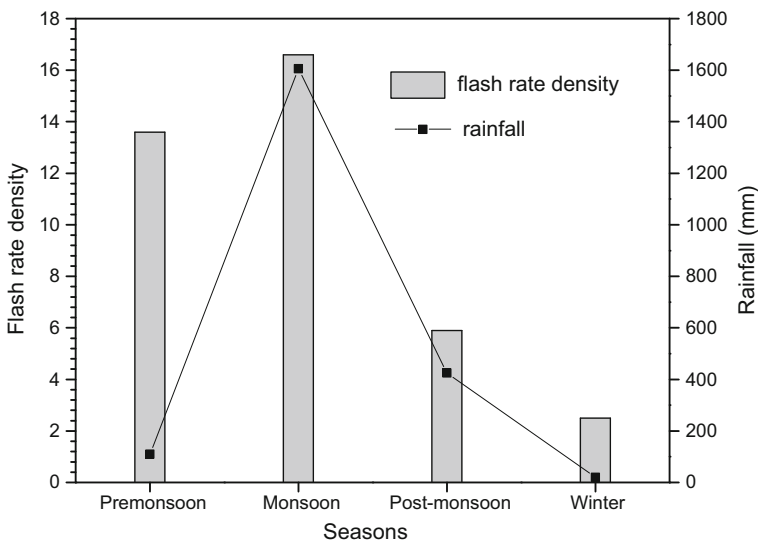
(Tinmaker et al. 2010a). A good correlation coefficient of 0.62 (significant at <0.001) between flash rate density and air temperature (850 mb) support the aforementioned variability of FRD with CAPE (Fig. 7).

### 4.3 Seasonal variation of flash rate density and rainfall amount over Maharashtra

The FRD and rainfall amounts averaged over seasons for the study period are shown in Fig. 8. The FRD is higher than that rainfall amount in pre-monsoon, post-monsoon and winter seasons, but, both FRD and rainfall amount are of similar magnitudes in monsoon. For pre-monsoon, correlation coefficient between FRD and rainfall is 0.57, whereas it is 0.32 for monsoon. Onset, the revival of monsoonal rainfall and withdrawal phases are mainly associated with the merging of thunder activity (Manohar et al. 1999; Williams and Satori 2004; Tinmaker et al. 2010a). Hence, the rainfall amount confined to certain FRD depends on the availability of moisture and hygroscopic particles those act as cloud condensation nuclei (Koteswaram and Srinivasan 1958). After the cessation of rainfall activity at the end of September onward, average daily temperature increases. During October, days are hot ( $30^{\circ}$ – $32^{\circ}$  °C) and nights are cooler ( $12^{\circ}$ – $14^{\circ}$  °C). The remnant of monsoon period's humidity and daytime heating paves way for development of thunderstorm during October. Westerly flow weakens at the lower troposphere, and the easterly flow sets in followed by a rapid fall in the ambient temperature. In winter, the frequency of development of thunderstorms decreases due to the lack of moisture in air masses over the study region. Weather condition is fair and normally characterized by clear sky with low relative humidity (Tinmaker et al. 2010a).

## 5 Conclusions

The present paper is an analysis of FRD in terms of its association with surface air temperature, rainfall and CAPE over Maharashtra during 10-year period (1998–2007). The analysis has shown the following principal results.



**Fig. 8** Seasonal variation of flash rate density and rainfall over Maharashtra during 10-year period (1998–2007)

1. The monthly variation in FRD and rainfall exhibits their maxima in June and July, respectively, and their next peak observed in September. Difference of about a month in observed peaks in between FRD and rainfall is because of the prime period of the onset phase of monsoon with convective activity in June and stabilized rainfall in July.
2. The annual variations show the second peaks are higher for both FRD and rainfall in September than those for them in pre-monsoon (May–June) period.
3. During monsoon, the FRD and rainfall are observed to be lower and higher, respectively. The maritime clouds with moderate updrafts prevail over the study region causes minimum cloud electrification during monsoon season.
4. CAPE could be a good indicator for thunderstorm activity as correlation coefficient in between FRD and CAPE is 0.78 at significant level  $<0.0001$ .
5. On a seasonal scale, FRD is higher than rainfall during the pre-monsoon, post-monsoon and winter seasons, but both are similar in magnitudes during monsoon.

**Acknowledgments** The authors are thankful to the Director, IITM, Pune, for his kind support and valuable guidance to this work.

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