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Lightning and convective rain over Indian peninsula and Indo-China peninsula

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Abstract

The impact of surface temperature, CAPE, convective cloud cover, outgoing long wave radiation and aerosol concentrations on lightning flashes and convective rainfall in the Indian peninsular and Indo-China peninsular regions are compared. Results showed that the observed relationships between lightning, precipitation and considered parameters are very complicated. An attempt is made to tie these observed results with physical considerations. For better understanding of involved processes, regional scale simulations to replicate the observed features are required.

Keywords: Lightning; Convective rain; CAPE; Meteorological parameter; Aerosol optical depth

1. Introduction

Solar radiation heats the Earth's surface and air in the adjoining atmospheric boundary layer leading to formation of thunderstorm/convective clouds through the buoyancy forces. The surface temperature and its vertical gradient control development and intensity of convection, which affects lightning discharges and precipitation. In general, lightning discharges require deeper and stronger convection rate, whereas precipitation may occur even at weak and moderate convection. The regional distributions are ranked, from the most-to-the least, for thunderstorm activity as Africa, South America and Southeast Asia and that for rainfall activity as Southeast Asia, South America and Africa (Price, 2000, 2009; Christian et al., 2003; Singh et al., 2004; Siingh et al., 2007, 2008, 2011, 2012, 2013; Cecil et al., 2014).

Intense convection over tropical and sub-tropical regions impact global energy exchange and water substance reallocation (Chen et al., 2006). About 75% of water vapor supplied to the global tropical stratosphere in summer is from the South Asia monsoon region and Tibetan Plateau

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region (Zhou et al., 2002; Gettelman et al., 2004; Qie et al., 2003; Yuan and Qie, 2008; Qie, 2012). The land–sea distribution and thermal condition over Tibetan plateau terrain have profound impact on atmospheric circulation over South Asia and Southeast Asia. Romatschke et al. (2010) showed that deep convective system in South Asia move from the east coast of the Indian peninsula in the pre-monsoon season to western foothills of the Himalayan range in monsoon season. Heavy precipitation over India, China and Japan are reported which are influenced directly or indirectly by the Himalaya/Tibetan Plateau (Yihui and Chen, 2005; Fu et al., 2008; Qian et al., 2009; Takahashi et al., 2010; Qi and Wang, 2012; Siingh et al., 2013, 2014; Halder et al., 2014).

In it was believed that a mesoscale mountain imposes local and regional effects through the orographic lifting and windward rainfall and lee-ward rain shadow (Grossman and Durran, 1984; Jou, 1994; Colle and Mass, 1996; Ralph et al., 2003; Chen and Lin, 2005; Qie, 2012). However, the dynamical terrain effect could be seen up to 8000 km downstream in the central-western Pacific through the air–sea interaction under a stable trade-wind regime (Xie et al., 2001). The same group also reported that the terrain-forced convection from narrow mountains contributed significantly to the Asian Summer monsoon system through the Rossby wave response to the anomalous convective heating (Xie et al., 2006). The mesoscale convective system excited over Tibetan Plateau propagated eastward 3000 km downstream and leads to enhanced precipitation in the Yangtze River basin (Shi et al., 2008). Qi and Wang (2012) based on ensemble simulation showed that the Annam-Cordillera mountain (~900 m high) blocks/lifts the warm and moist air from the Bay of Bengal and forces upward motion and causes precipitation as far as 3000 km away over south and east China and western northwest Pacific.

Lightning and precipitation also depend on the aerosol concentration, surface temperature (land and ocean), convective available potential energy (CAPE), cloud cover area, outgoing longwave radiation (OLR), etc. (Massie et al., 2004; Cheng et al., 2007; Tinmaker et al., 2010; Yuan et al., 2011; Liu et al., 2011; Wang et al., 2011; Siingh et al., 2013, 2014; Kulkarni and Siingh, 2014). Aerosols present in the atmosphere scatter, reflect and absorb incident solar radiation and thus affect the solar radiation budget, surface temperature and outgoing long wave radiation. Indirectly aerosols also affect cloud droplet size (Twomey et al., 1984), cloud life time and cloud extent (Ackerman et al., 2000), precipitation process (Albrecht, 1989) and electrical properties of clouds (Westcott, 1995; Stallins and Rose, 2008; Kar et al., 2009; Siingh et al., 2008, 2011). CAPE and surface temperature are positively correlated with lightning flashes and convective rain (Penki and Kamra, 2012a,b, 2013; Siingh et al., 2013, 2014). The sea surface temperature (SST) is strongly related to atmospheric instability, significantly increases moisture advection and hence increases rain fall and lightning activity.

Reeve and Toumi (1999) suggested poor correlation between SST and lightning activity over sea, whereas Petersen et al. (1996) and Rivas Soriano et al. (2001) reported good positive correlation between lightning flashes and SST for the Arabian sea (correlation coefficient ~0.85) and Bay of Bengal (correlation coefficient ~0.92). Tinmaker et al. (2010) showed that SST of the Arabian sea and Bay of Bengal play a crucial role in the development of thunderstorm and lightning activity over the adjoining peninsular region of India. In order to understand this complex behavior, we decompose the relationships between SST and lightning into their components: (1) SST to rainfall amount, (2) lightning flashes and SST for a given rain fall amount.

Interaction of the mesoscale with the short-lived convection is a subject of great contemporary interest and mainly determines the precipitation and electrical properties of the resulting cloud systems in the area. Tropical regions are most suitable to study such interactions. In our area of investigations, the mesoscale convective activity embedded in the Asian monsoon system strongly interacts with continental, orographical and the sea/land breeze – induced convective activity (Romatschke et al., 2010; Medina et al., 2010). In this paper, we analyze lightning flashes and convective rain rate, SST, meteorological parameters, AOD and related parameters over the Indian peninsular (region R_1) and Indo-China peninsular (region R_2) regions and compare the results. The region R_1 lies between 8–18°N and 73–83°E; whereas the R_2 lies between 8–18°N; 98–108°E (Fig. 1). The selected regions belong to the same latitude range but different longitudes having different meteorological characteristics in different seasons. In R_1 region the Indian Summer Monsoon (ISM) operates, whereas R_2 region is an interface of the Indian Summer Monsoon and the Western North Pacific Summer Monsoon (WNPSM) (Wang and Lin, 2002). In both the ISM and WNPSM, the low level winds change from winter easterlies to summer westerlies.

2. Data analysis

The Indian peninsular region is bounded by the Arabian Sea on the west and the Bay of Bengal on the east, with an average elevation of 616 m. The mountain range of Western Ghats running along the western coast of India have mountain peak exceeding 2000 m in height with a gradual slope to sea level on the eastern side. Meteorological features in this region include development of an off-shore trough along the west coast of the southwest India during the monsoon season, a warm pool of air off-shore southern tip of India in the pre-monsoon month, and the north–east monsoon activity over south–east peninsular India during the post monsoon. These features influence and often cause development of thunderstorm with intense lightning activity. The Indo-China peninsula has an average elevation of 116 m and is bounded by the Bay of Bengal on its west and the South China Sea on the east. Moisture laden southwest

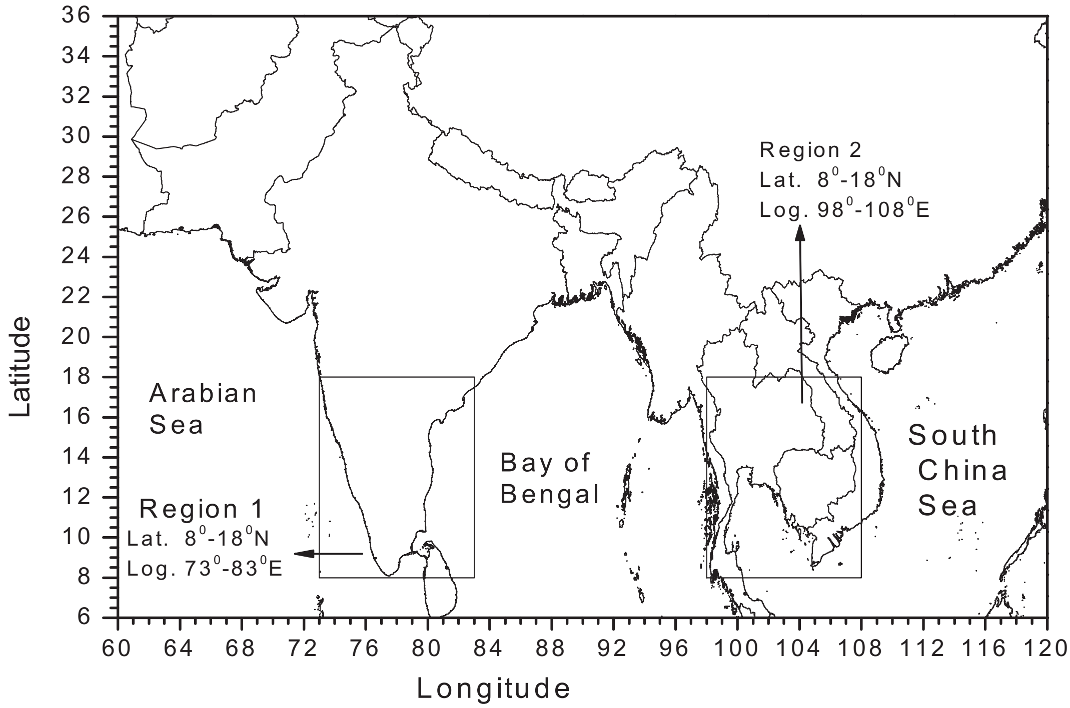

Fig. 1. Map of South/Southeast Asia showing two regions: Region R_1 (8–18°N, 73–83°E) and Region R_2 (8–18°N, 98–108°E).

monsoon winds from the Bay of Bengal and geographic location of the region are the main reason for high precipitation in this region. During summer monsoon months, the northward migration of ITCZ is another cause of high precipitation.

Lightning data (number of flashes) are derived from Lightning Imaging Sensors (LISs) aboard Tropical Rainfall Measuring Mission (TRMM) satellite, which detects and locates lightning flashes with the spatial resolution of 4–7 km over a large region in the grid resolution of 5° × 5° of Earth surface and temporal resolution of 2 ms with a nearly uniform (~90%) flash detecting efficiency. Both intra-cloud and cloud-to-ground lightning discharges during the day and night conditions are detected. The chosen area in the present study lies in the field of view of sensors that 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 for the period 1998–2010 are downloaded from the website (http://ghrc.msfc.nasa.gov).

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; it also gives monthly mean rain rate (mm/hour). The precipitation radar has a horizontal resolution at the ground of about 5 km. It provides vertical profiles of the rain and snow from the surface up to a height of about 20 km. This 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, SST, and convective cloud cover, convective rain precipitation rate 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 also been used. Aerosol optical depth (AOD) at 550 nm have been taken from the website (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=aerosol_monthly). The convective rain rate and convective precipitation rate represent almost the same physical quantity but are derived from two different sources.

3. Results and discussion

3.1. Lightning, convective rainfall and meteorological parameter

Owing to the close association between lightning and convective activity in a region, the relationship between lightning activity and several factors related to convections have been investigated by many investigators in different regions (Williams and Lhermitte, 1983; Williams and Renno, 1993; Zhou et al., 1999; Qie et al., 2003; Tinmaker et al., 2010; Tinmaker and Ali, 2012; Siingh et al., 2013, 2014). The main difference in convective activity over the peninsular and sea regions arises due to larger convection over land surface as compared to sea surface. Surface temperature, CAPE, OLR, aerosol loading, vapor content, humidity, etc affect the convective process and hence lightning and precipitation. In order to assess the impact of these variables, mean annual variation of number of lightning flashes, convective rain rate (TRMM data), surface temperature, convective total cloud cover, CAPE, AOD and convective precipitation rate (NCEP data) for the regions R_1 and R_2 during the period 1998–2010 are presented in Fig. 2(a) and (b). Mean number of lightning flashes in both the regions R_1 and R_2 show an increasing trends with correlation coefficient (R) 0.89 and 0.83 and significant levels (P) < 0.0001 and 3.4×10^{-4}, respectively. Mean convective rain rate in region R_1, shows an

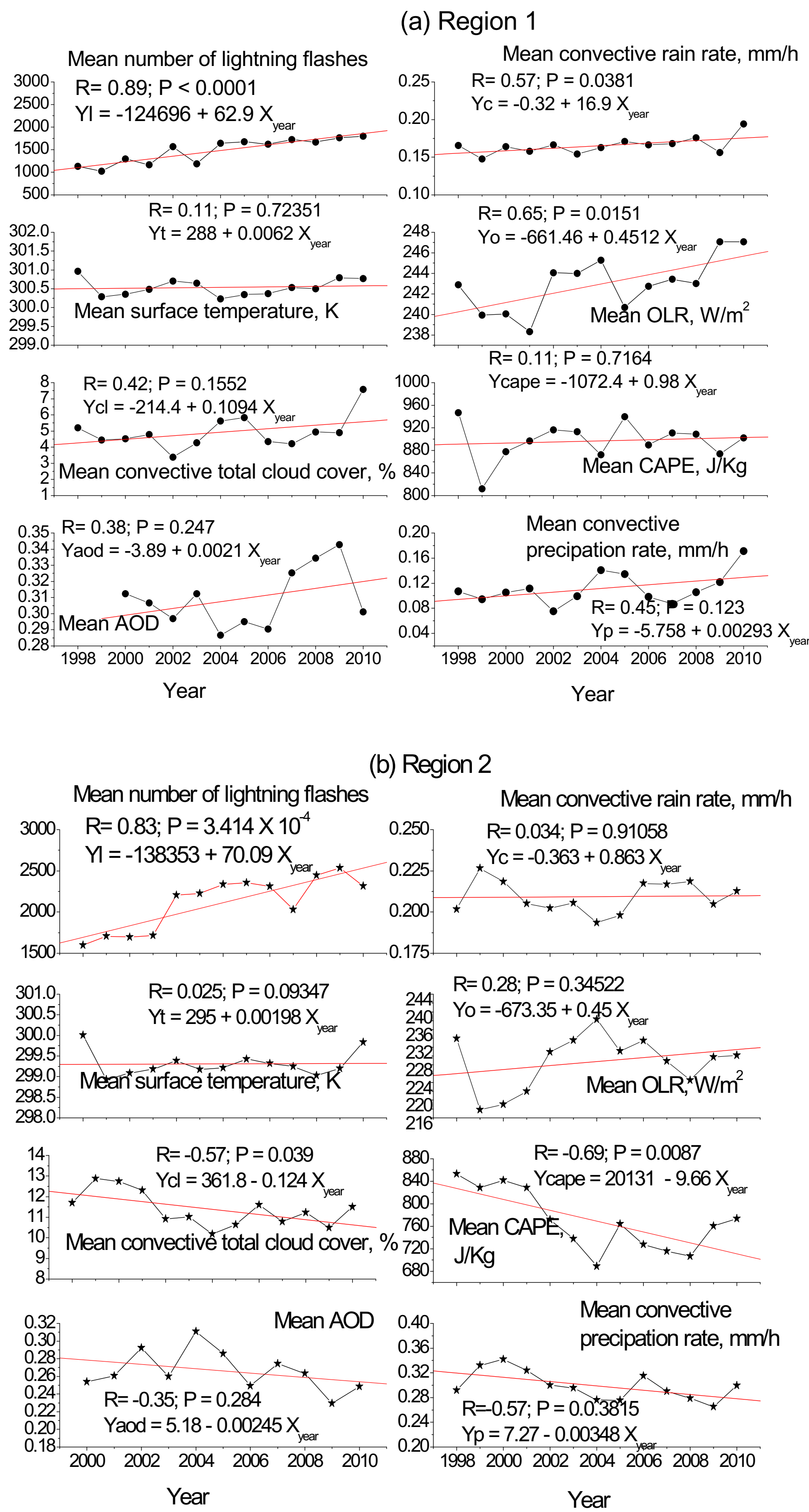

Fig. 2. Variation of yearly mean number of lightning flashes, convective rain rate, surface temperature, outgoing long wave radiation, convective total cloud cover, CAPE, aerosol optical depth, convective rain precipitation rate for region R_1 (a) and R_2 region (b).

increasing trend with $R = 0.57$ and $P = 0.0381$, however no such enhancements could be found in R_2 region. CAPE in region R_1 remains almost constant (with very slow increase $R = 0.11$, $P = 0.7164$) whereas in the region R_2, it shows a clear decreasing trend with $R = -0.69$, $P = 0.0087$. CAPE depends on the temperature, stability condition of boundary layer and moisture stratification present in the atmosphere. Decrease in any one or more parameters may cause decrease in CAPE. During the study period surface temperature in R_1 and R_2 increased slightly ($R = 0.11$, $P = 0.7235$; $R = 0.025$, $P = 0.09347$). Cloud cover and AOD vary from year to year but an increasing trend in region R_1 ($R = 0.42$, $P = 0.1552$ for cloud cover and $P = 0.38$, $P = 0.244$ for AOD) and decreasing trend in region R_2 ($R = -0.57$, $P = 0.039$ for cloud cover and $R = -0.35$, $P = 0.284$ for AOD) are observed. It is interesting to note that the surface temperature, AOD and CAPE in R_1 are higher than in R_2 region, but the percentage of cloud cover in R_2 region is almost double than that in R_1 region. The presence of larger percent of cloud cover and land surface in R_2 region result into approximately one and half times more lightning flashes and convective rain in R_2 region as compared to R_1 region. Lightning flash rates are higher on land surface as compared to ocean surface (Penki and Kamra, 2012b).

The mean annual AOD varies from year to year, which is lager in R_2 region as compared to R_1 region. The mean annual distribution of the surface temperature, percentage of cloud cover, CAPE and mean OLR are identical in the region R_1 but in the region R_2, the OLR and CAPE show relatively unusual large variation. OLR non-linearly depends on the nature and concentration of aerosols present in the atmosphere (Huang et al., 2009; Altaratz et al., 2014), which affects atmospheric temperature and hence CAPE. Atmospheric circulation affects surface temperature, aerosol concentration and nature, OLR and CAPE.

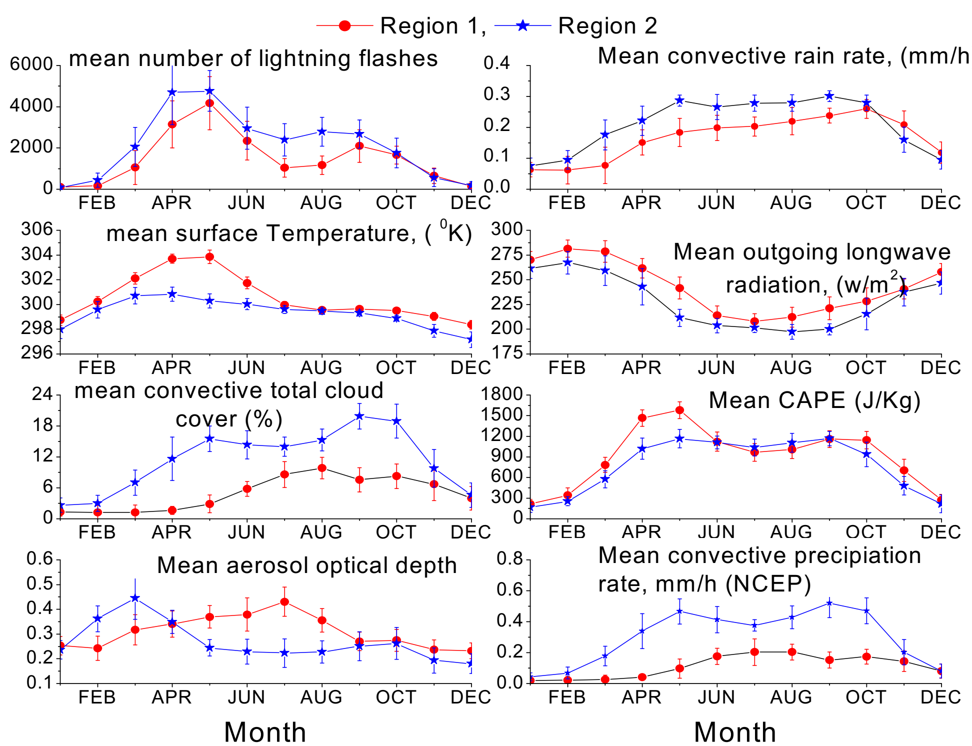

Fig. 3. Mean monthly variation of number of lightning flashes, convective rain rate, surface temperature, outgoing longwave radiation, convective total cloud cover, CAPE, aerosol optical depth, convective precipitation rate for R_1 and R_2 region. Vertical error bars show the standard deviations.

Table 1
Peak months for different parameters in the Indian and Indo-China peninsular regions.

Parameter	Primary peak		Secondary peak	
	R_1	R_2	R_1	R_2
Surface temperature	April, May	March, April	October	September
AOD	July	March	October	October
Cloud cover	August	May	October	September, October
CAPE	April, May	April[a]	October	September
Lightning Flash	May	April, May	September	August, September
Convective rain	–	May	October	September

[a] In R_2 region CAPE showed a very broad peak from April to September.

Since R_2 region is the buffer zone of ISM and WNPSM circulation, both circulation may have impact on AOD, OLR and CAPE of R_2 region. The Tibetan plateau and large scale mountain range in the vicinity could also play some role in convective process (Xie et al., 2006; Shi et al., 2008; Qie, 2012; Qi and Wang, 2012).

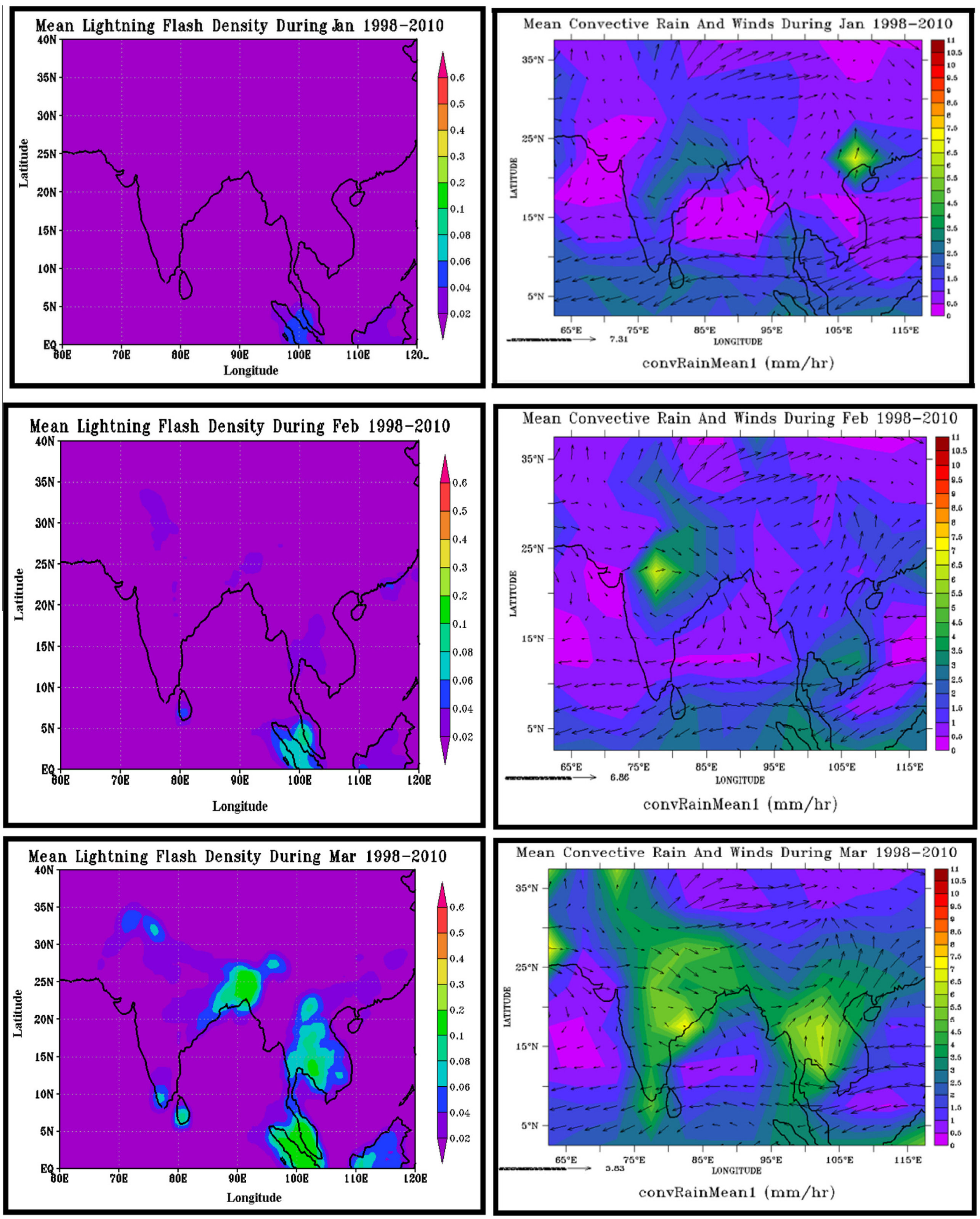

Fig. 4. Spatial plots of monthly mean of lightning flash density (Flashes km^{-2} day^{-1}), convective rain rate (mm/h) and wind vectors (850 hPa) for the period 1998–2010.

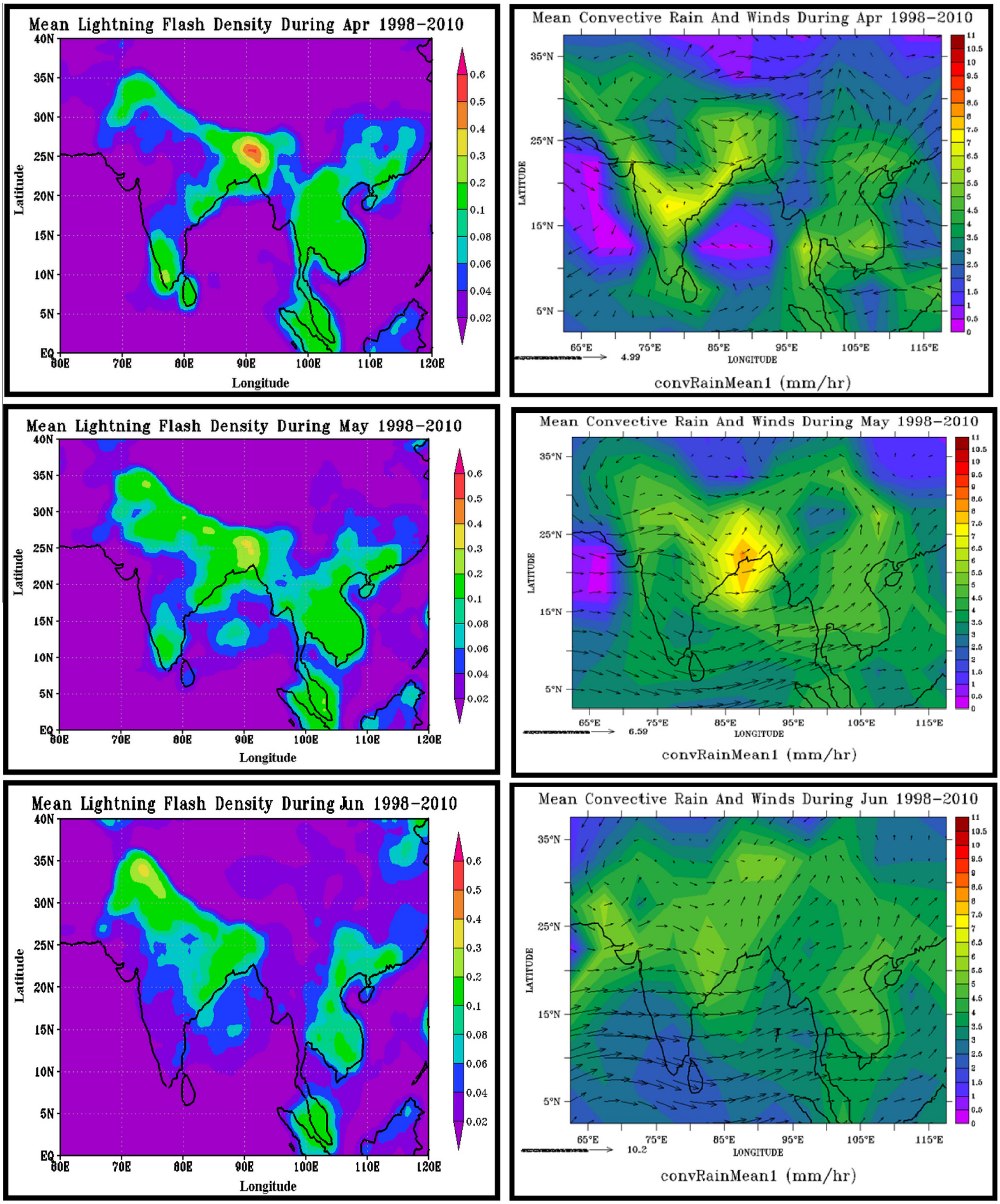

Fig 4. *(continued)*

In order to understand the large variation of some of these parameters in Fig. 2, we show the seasonal variations of all parameters in Fig. 3. Surface temperature, aerosols present in the atmosphere and surface properties control CAPE and cloud cover and finally affect lightning and precipitation. In both the regions, AOD and surface temperature show two peaks, although peak months differ in two regions (see Table 1). In both the regions, the seasonal variations of CAPE follow surface temperature. However, CAPE has equal value in both regions from June to

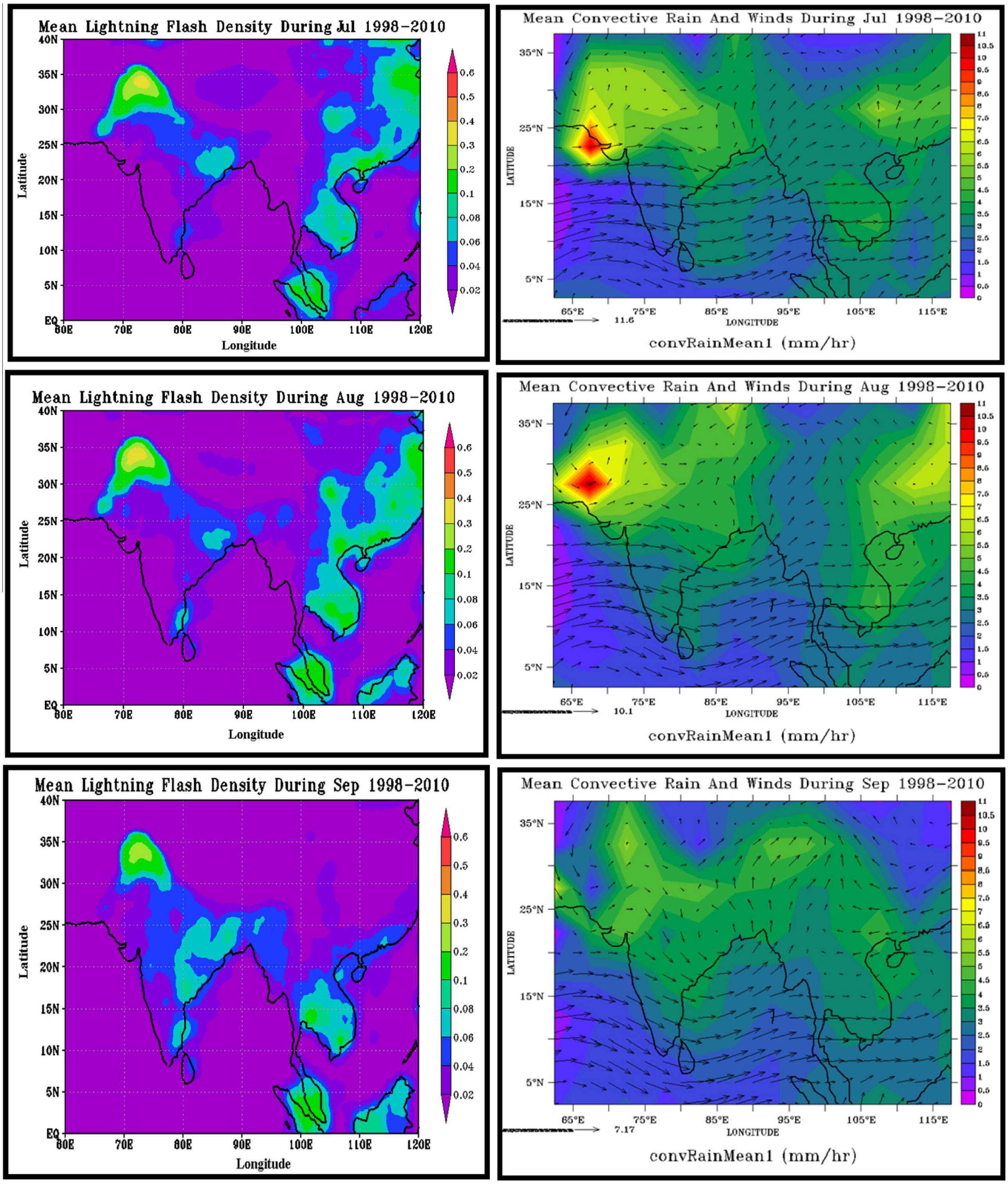

Fig 4. *(continued)*

September whereas surface temperature becomes equal from July to September. CAPE shows a maximum in April, May months along with a secondary maximum in October for the region R_1, whereas it showed a very broad peak of almost equal amplitude for R_2 region from April to September. The seasonal variation of surface temperature/CAPE explains observed lightning flashes in both regions. In region R_2, the primary and secondary maxima in lightning flashes appeared one month earlier than in region R_1. The main flash rate peak in R_1 region occurring in May is also confirmed from the results reported by Cecil et al. (2014). The convective rain in region R_2 has double peaks

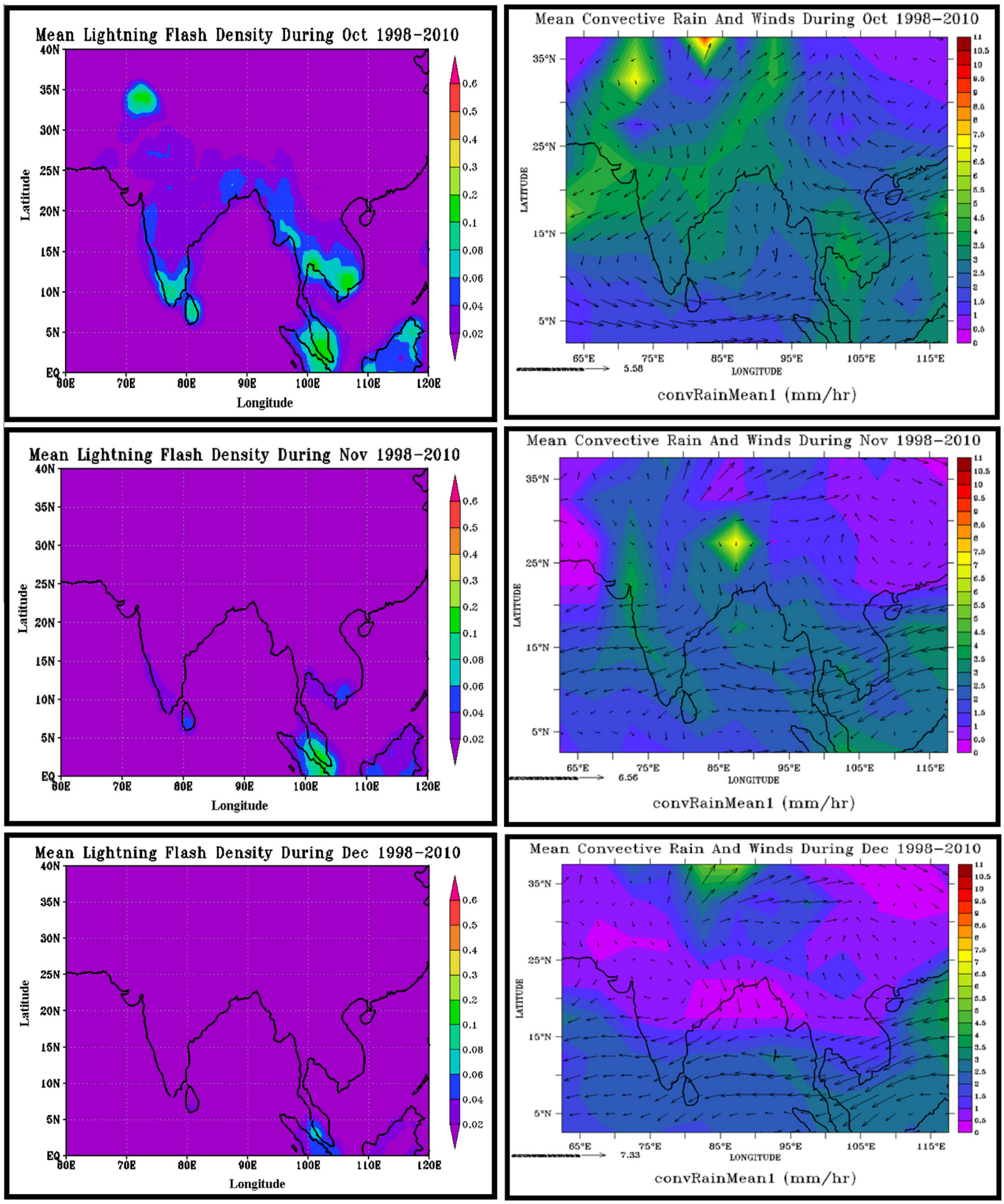

Fig 4. *(continued)*

in May and September–October. Matsumoto (1997) and Lau and Yang (1997) showed similar results for the Indo-China peninsula. Convective rain in region R_1 has only one peak in October. But convective precipitation rate show a tendency of double peak with the first one between July–August and the second in October.

AOD shows a maximum in July (R_1 region) and March (R_2 region) and equal values in September–October. Rain removes aerosols from the atmosphere; hence aerosol concentration should decrease with the advance of monsoon rain which is observed in R_2 region and not in R_1 region. There is a lag of almost one–two months between AOD and lightning/precipitation. Results show complex relation between aerosols and lightning/precipitation activities. Many observational and simulation studies of aerosol effects on precipitation yielded diverse results (Menon, 2004; Takemura et al., 2005; Tao et al., 2007). This may be because aerosol effect sensitively depends on water vapor supply and atmospheric instability (Matsui et al., 2004; Tao et al., 2007) and on the characteristics (size distribution, concentrations, chemical composition, surface properties, etc) of different aerosol types such as smoke (Kaufman et al., 2005), urban pollution (Kaufman et al., 2005; Huang et al., 2007, 2009) and mineral dust (Mahowald and Kiehl, 2003).

Maximum cloud cover months (July–August for R_1, September–October for R_2) do not represent the period of maximum lightning and precipitation. OLR was a maximum during the dry months January and February and showed broad minima during June to September (wet months). Thus, OLR does not only depend on surface temperature but it also depends on moisture present in the atmosphere and on the surface properties. OLR increases from August onwards, although precipitation remained at almost high value. Thus, dependence of OLR on surface temperature, moisture and precipitation is quite complex.

Lightning flashes and convective rain are higher throughout the year in R_2 region as compared to R_1, because R_2 encloses larger fraction of land surface where convective processes are more intense (Williams, 2005; Penki and Kamra, 2012b). In addition, the monsoon activity over R_1 region is controlled by the ISM circulation, whereas over R_2 region both ISM and WNPSM circulations are active. The onset date of the summer monsoon in the Indian peninsular region is early June and monsoon rapidly advances northwest ward (Krishnamurti et al., 1981). Over the Indo-China Peninsula, the summer monsoon abruptly sets in late April or early May, with dramatic changes of large-scale circulation (Wang and Lin, 2002). After onset, low-level easterlies and upper-level westerlies rapidly switch to westerlies and easterlies, respectively.

The secondary maxima in lightning flashes and the end of broad maximum in convective rain rate coincide with the withdrawal phase of monsoon, which accompanied with some thunderstorm activities. The results follow the fact that the drier climate results in more lightning flashes

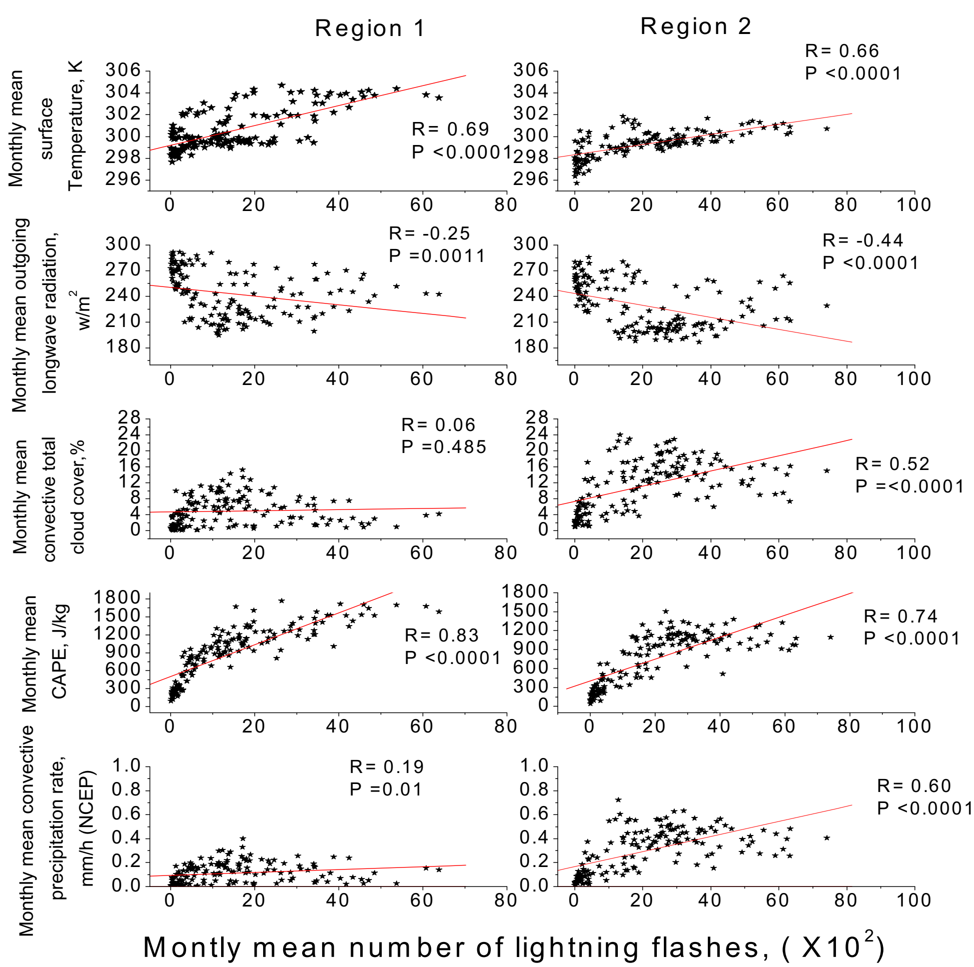

Fig. 5. Scattered plots of monthly mean number of lightning flashes with different meteorological parameters for the regions R_1 and R_2. Values of correlation coefficient (R) and significance level (P) of the parameters are also given in each panel.

(Price, 2009; Siingh et al., 2013, 2014). A drier surface allows for the development of a deeper convection (Williams, 2005), which enhances cloud height and suppression of rainfall (Price, 2009). Murugavel et al. (2012) have reported that the seasonal variations of CAPE show higher values over the Indian region where lightning is higher during the monsoon months compared to pre-monsoon or post monsoon seasons. They suggested that the thermodynamic conditions are favorable for higher CAPE together with large scale dynamics, which are necessary for

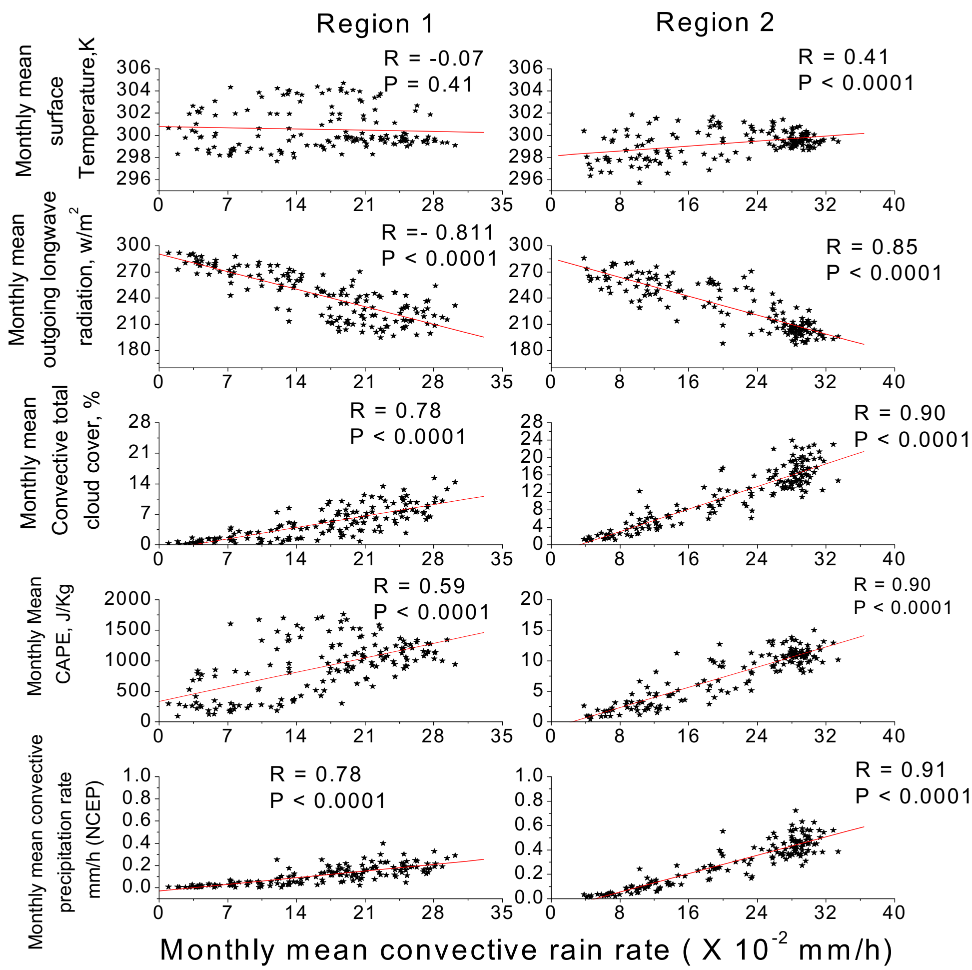

Fig. 6. Variation of monthly mean convective rain rate with meteorological parameters for the regions R_1 and R_2. Values of correlation coefficient (R) and significance level (P) of the parameters are also given in each panel.

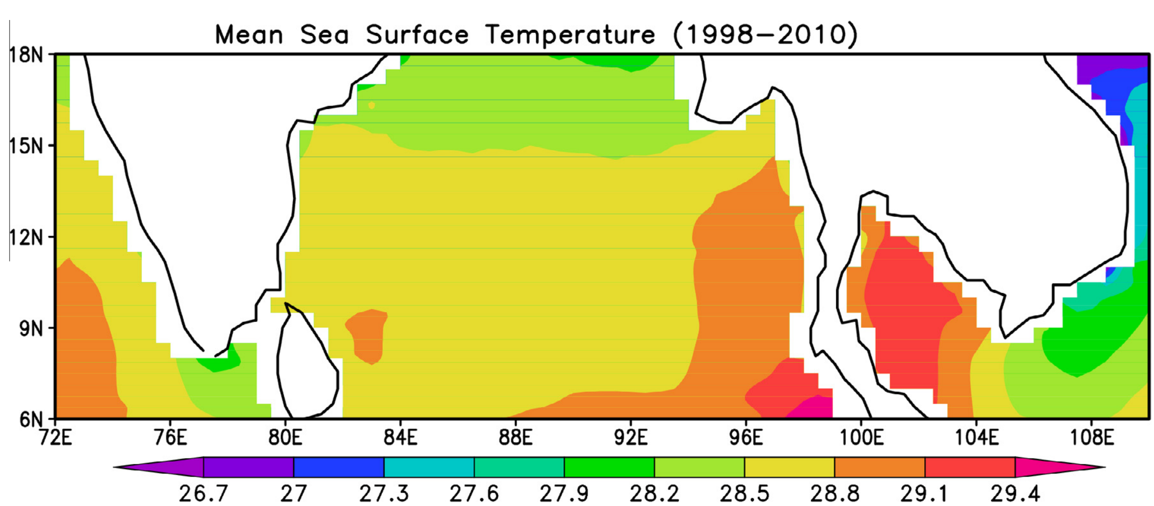

Fig. 7. Spatial plot of mean sea surface temperature for the period 1998–2010 covering both regions.

the organized monsoon convection. However, our results showed maximum CAPE in pre-monsoon for region R_1 and almost coincided with CAPE values of R_2 region during active monsoon season (June–September). Wu et al. (2013) showed that CAPE distribution is maximum over the Ocean, significantly different from the distribution of convective systems but consistent with the distribution of near-surface specific humidity. Earlier study also showed dependence of CAPE on near surface specific humidity (Riemann-Campe et al., 2009).

Fig. 4 showed seasonal variations of mean lightning flash density (Flashes km^{-2} day^{-1}) (left panel) and mean convective rain rate (mm/h) and mean wind vector at 850 hPa (right panel) for the period 1998–2010 over Asia (equator to 40°N, longitude 60°E to 120°E). The seasonal variability of lightning and convective rain in both the regions with the progress of monsoon could easily be seen. Monsoon sets in earlier in R_2 region in the month of April as a consequence of WNPSM system.

The increase in average lightning flashes and convective rain from winter to the summer months of April–May–June (Figs. 3 and 4) may be attributed to the increase in solar heating of the lower atmosphere and Earth–Ocean surface through the pre-monsoon season. This increasing trend slows down or even reverses after the onset of monsoon, due to the land surface cooling because of less radiation reaching the ground due to increased cloud coverage (Fig. 3) and cooling of land due to rainfall. However, monsoon current has convective mesoscale system embedded in it and can produce intense convective rain in some regions (Fig. 4). Because of large variability of this convective rain in space and time and non-uniformity of the rain fall induced cooling of the land surface, the trend in variability of average convective rain during monsoon season is not uniform in all regions. However, some broad feature in this variability can be compared.

It is well known that the ISM, WNPSM and East Asian summer monsoon regions are characterized with north east winds prevailing in winter and south west wind in summer. During the winter months (November, December, January and February), the wind pattern remains almost same but complex (Fig. 4). At low latitudes, (<12°N) wind is westerly except in the South China Sea, where the direction changes to south-westerly. In mid latitude region, wind is north easterly. In the transition region, vortex type wind system is seen. The sudden change in wind direction could be easily seen in the month of April. In R_2 region, this may be associated with WNPSM system. During May, June, July, August and September wind is easterly in both regions and ISM circulation becomes active over the whole region including R_1 and R_2 regions. There is transition in wind circulation during October and wind pattern becomes westerly during November onward. In both the peninsular regions, intense rain is seen in the month of March, which intensifies in April, merges into one in May and continued up to July. In August, the two systems separate out and again merge in September. The distribution of rainfall and lightning flash density (Fig 4) compare well with the distribution of deep convective system (DCS) in the region (Fig. 3 of Wu et al., 2013) during pre-monsoon and monsoon seasons. Occurrence, development and movement of convective systems are influenced by severe convection

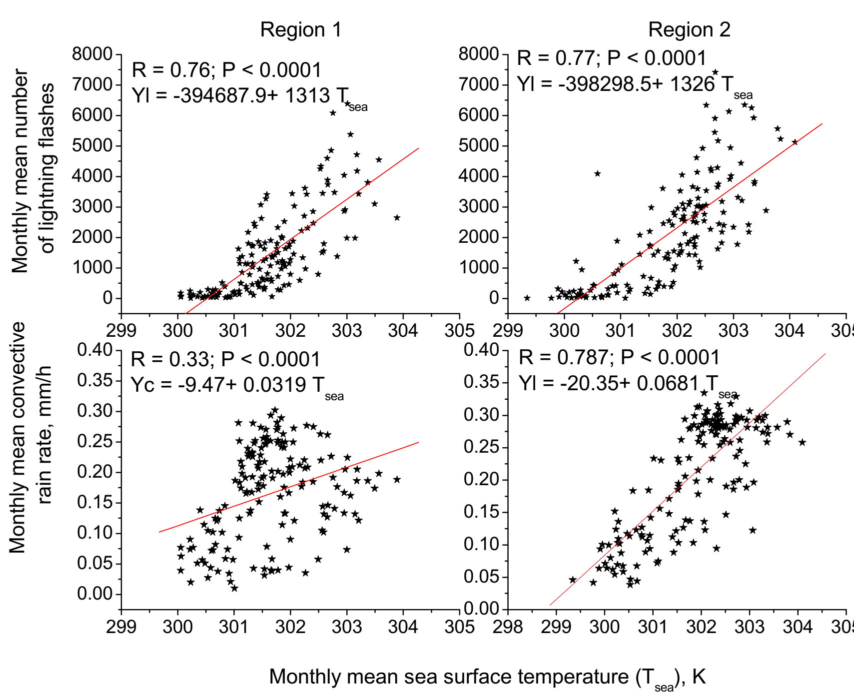

Fig. 8. Variation of monthly mean number of lightning flashes and monthly mean convective rain rate with sea surface temperature for the regions R_1 and R_2. Values of correlation coefficient (R) and significance level (P) of the parameters are also given in each panel.

which depends upon large-scale weather system and local thermodynamic conditions.

In both the regions, lightning flashes are positively well correlated with surface temperature and CAPE and negatively correlated with OLR (Fig. 5). Convective cloud cover and precipitation showed positive correlation in R_2 region and almost no significant correlation in region R_1. There are good positive correlation between convective rain and convective cloud cover, CAPE and precipitation and negative correlation with OLR (Fig. 6). Surface temperature does not show any role on convective rain in R_1 region, although positive role is observed in R_2 region. Present results are consistent with that of Dhaka et al. (2010) who showed that high CAPE is associated with high rainfall and that of Roy Bhowmik et al. (2008) who reported high value of CAPE during the pre-monsoon period.

Regions R_1 and R_2 partly include sea surface which are different in the two regions. The sea surface temperature (SST) in R_2 region is higher than in R_1 region (Fig. 7). Fig. 8 shows variation of lightning flashes and convective

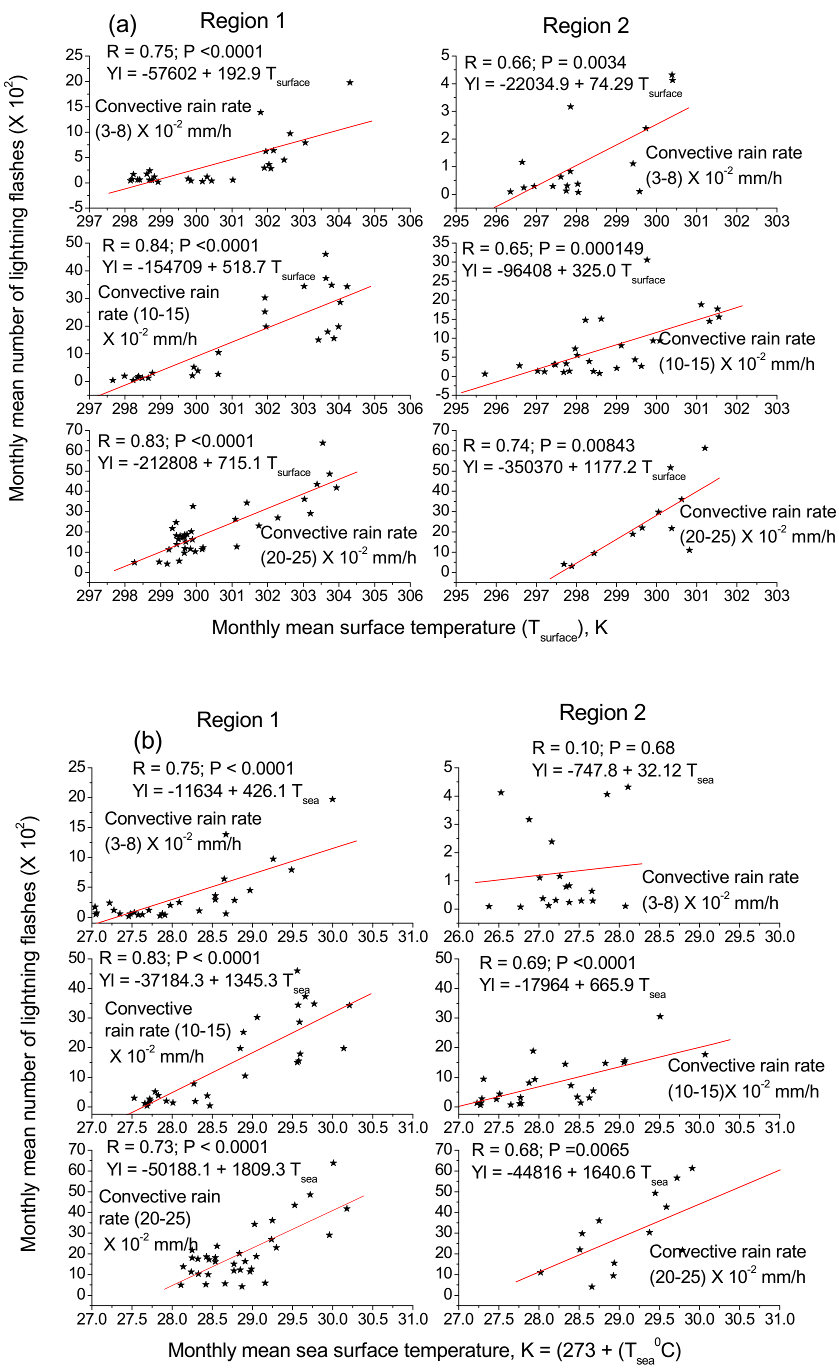

Fig. 9. Variation of lightning flashes with (a) surface temperature for different ranges of convective rain rate, (b) sea surface temperature for different ranges of convective rain rate. Correlation coefficient (R) and linear relation are given in each panel.

rain with SST. Lightning flashes had similar variation in both regions, whereas convective rain in R_2 region had better correlation than in R_1 region. This may be due to higher SST in R_2 region which may have enhanced convection process. Present results supported the hypothesis of Shareef (2009) who proposed that SST higher than 301 K enhanced the convective process. Higher SST is associated with lower air density and surface pressure, lead to pressure gradient over sea-surface causing the wind flow from a region of high pressure to low pressure. This ultimately results into convection over warmer sea-surface with enhanced thunderstorm activity.

Impact of land and ocean surface temperature over lightning and convective rain in two peninsular regions is complex. To find some insight dependence of lightning flashes with surface temperature for fixed convective rain were studied and results are shown in Fig. 9(a) (land surface) and Fig 9(b) (ocean surface). Lightning flashes showed better dependence on land and ocean surface temperatures in R_1 region than in R_2 region. In R_2 region for lower convective rain rate ($<8 \times 10^{-2}$ mm/h) lightning flashes were small and did not show any significant dependence on sea surface temperature. This may be because of weaker convection. In contrast R_1 region showed relatively higher lightning flashes (for lower rain rate) with good linear dependence. Further, both convective rain and lightning flashes were not observed in both peninsular regions when SST was lower than 300 K, which supports observations of Shareef (2009).

The orography and geographical relation of R_2 region also play significant role in the development of convective process and hence in the production of rain and lightning flashes. Tibetan Plateau and steeper orography contribute to more vigorous updrafts leading to high cloud tops and enhanced lightning flashes in thunderclouds (Williams, 2001; Penki and Kamra, 2013). Kriplani and Kulkarni (1998) reported that the southwest monsoon carrying enormous quantities of moisture from the Bay of Bengal and orography of the region R_2 are the main cause of high precipitation. Further, air from the Asian high reaches Indo-China through Eastern China and South China Sea and causes rain over the east coasts to the peninsular region. The convective heating of the atmosphere over the Bay of Bengal is also correlated to the strength of the low level jet stream (LLJ) through the peninsular India (region R_1) (Joseph and Sijikumar, 2004). During active intense monsoon (June to September), the core of the LLJ passes through the peninsular India between latitudes 12.5°N and 17.5°N and during weak monsoon LLJ by passes India and flows between 2.5°N and 7.5°N (Joseph and Simon, 2005). The moisture produced over Arabian Sea and South Indian Ocean is carried by the meridional wind through the LLJ. Wu et al. (2013) observed that the deep convective system over the land in the East Asian monsoon region are consistent with the distribution of CAPE, whereas in the South Asian monsoon region such systems are generally found in strong humidity gradient areas. In general strong temperature and humidity gradients produce intense thermal instability leading to the formation of deep convective systems.

The mesoscale mountain Annam Cordillera over the east Indo-China peninsula blocks the warm and moist air from the Bay of Bengal, lift them upwards and cause heavy precipitation on the windward side (Takahashi et al., 2010). Using a high-resolution regional atmospheric model including effect of mountain, Wang and Xue (2012) showed that the terrain-induced convection and the associated anomalous convective heating trigger a large-scale anomalous mid lower tropospheric anticyclonic circulation over the South China Sea, which modifies the large scale moisture transport associated with the summer monsoon and precipitation downstream. However, this effect is secondary compared to the direct orography blocking and lifting.

Feature of atmospheric structure over Indian peninsular region during monsoon months is low-level westerlies and upper-level easterlies. Takahashi et al. (2010) argued that similar structure might correspond over the Indo-China monsoon region. They have suggested that the observation of non-windward and early morning rainfall over the Indo-China peninsula may be due to offshore convective activity as was reported by Grossman and Durran (1984) for the west of the Western Ghats mountain of India.

Variation of lightning flashes with convective rain rate for both regions R_1 and R_2 are similar (Fig. 10) with correlation coefficient ~0.45 and 0.66 for R_1 and R_2 regions respectively. The higher correlation coefficient for region R_2 may be due to the role played by the SSTs and orography which enhance convection process. A positive

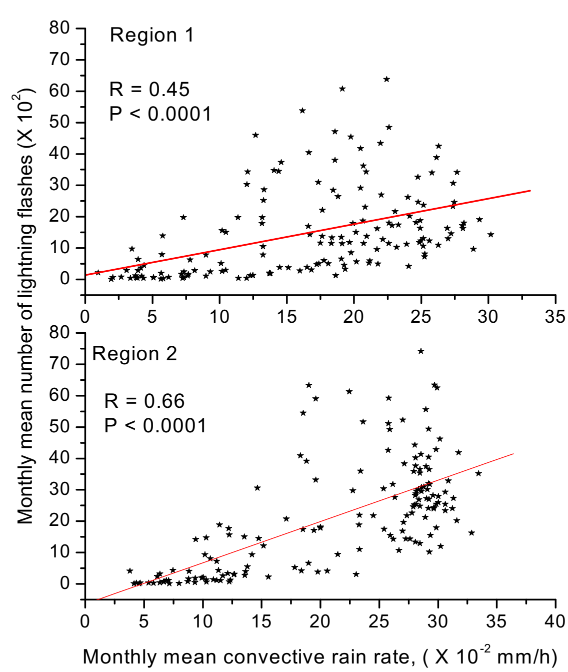

Fig. 10. Variation of monthly mean number of lightning flashes with monthly mean convective rain rate. Values of correlation coefficient (R) and significance level (P) of the parameter are also given in each panel.

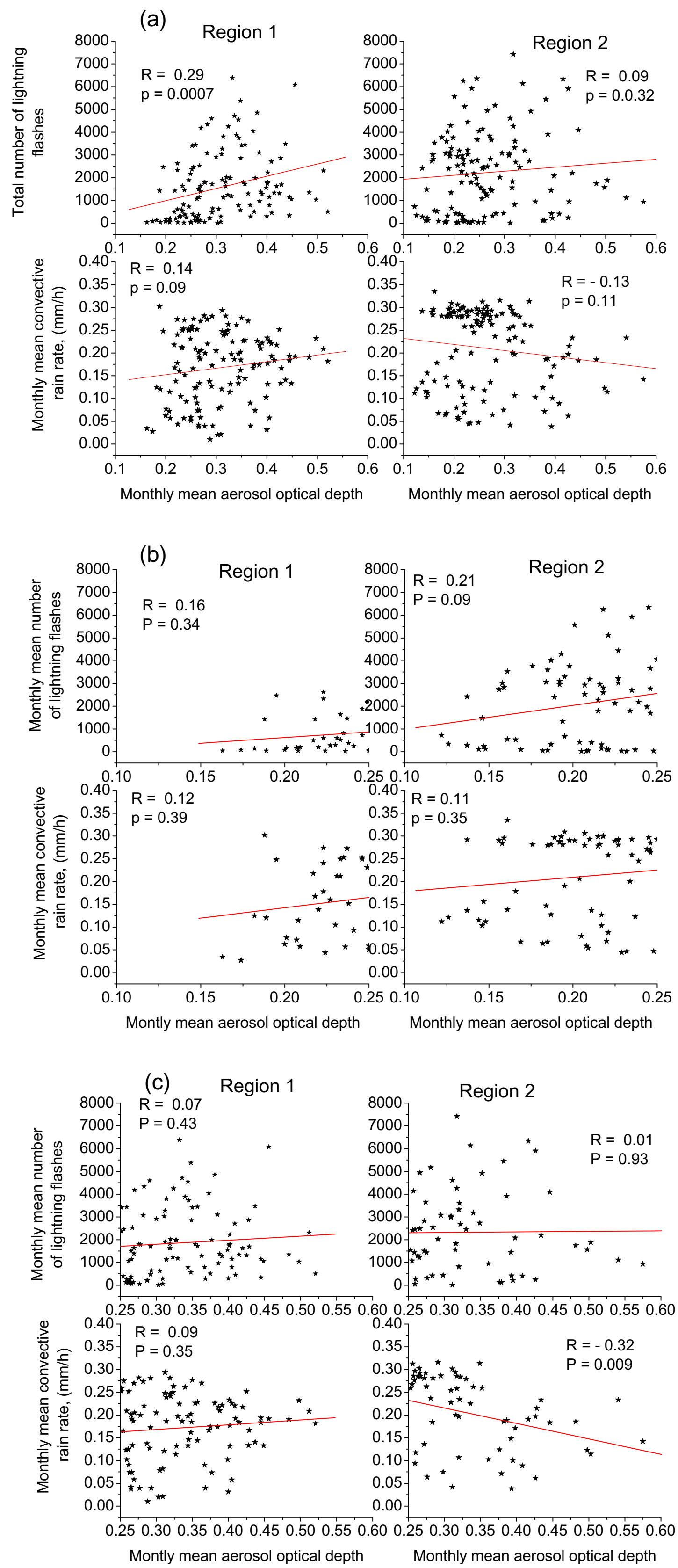

Fig. 11. Variation of lightning flashes and convective rain rate with AOD, (a) for AOD 0.1–0.60 observed range, (b) same as (a) for AOD $\leqslant 0.25$, (c) for AOD $\geqslant 0.25$. Values of correlation coefficient (R) and significance level (P) of the parameter are also given in each panel.

correlation between rainfall and lightning activity in individual thunderstorms (Price and Federmesser, 2006; Gungle and Krider, 2006) have been attributed to the microphysics and dynamics of deep convective clouds, which is also valid for R_2 region because it is in warm pool, has high sea surface temperature, and steep orography.

3.2. Aerosol effect on lightning and convective rainfall

The distribution of aerosol optical depth for the period 1998–2010 showed that AOD is more in the region R_1 than R_2 (Fig. 2). Presence of higher aerosol concentration in R_1 region showed some impact on lightning activity and convective rain having correlation coefficient (R) 0.29 and 0.14, respectively (Fig. 11(a)). For region R_2 convective rain showed a negative trend with $R = -0.13$ (Fig. 11(a)). The increase or decrease of rainfall as a function of aerosol concentration enhancement depends on concentration and size distribution of aerosols (Rosenfield et al., 2008; Koren et al., 2008). They have also shown that rainfall increases with AOD, becomes maximum at $AOD = 0.25$ and then decreases with higher AOD. In order to test this hypothesis, the scattered plots of lightning flashes and convective rain with AOD were separated in two parts, for $AOD < 0.25$ and $AOD > 0.25$. Results are shown in Fig. 11(b) and (c). We found an increasing trend for $AOD < 0.25$ with poor correlation coefficient (in the range 0.11 and 0.21) in both regions. For $AOD > 0.25$ no trend could be observed for lightning flash distribution. However, in R_2 region, convective rain showed a decreasing trend ($R = -0.32$). Thus, the hypothesis of Koren et al. (2008) is valid in R_2 region. In R_1 region, convective rain did not show any significant trend. There are reports suggesting both suppression of rain (Givati and Rosenfeld, 2004; Jirak and Cotton, 2006; Jiang et al., 2008; Li et al., 2011) and an enhancement of rain (Bell et al., 2008; Li et al., 2008, 2011; Koren et al., 2012) associated with high aerosol concentration.

The aerosol level in the atmosphere reduces solar radiation at the surface, absorbs heat, causes troposphere heating and hence enhances thermally driven circulation leading enhanced monsoon rainfall (Wang, 2004). Lau et al. (2006) showed that locally emitted black carbon combined with mineral dust during spring at the southern slope of Tibetan Plateau enhanced dry convection heating of the mid troposphere causing large scale meridional temperature gradient and monsoon rainfall during June and July. This simulation result was supported by the observations of Gautam et al. (2009). There are considerable debate on the hypothesis that black carbon enhances the monsoon activity (Nigam and Bollasina, 2010; Lau and Kim, 2011). Ackerman et al. (2000) suggested that enhancement of black carbons/soots may lead to cloud burning (evaporation). However, observations by Norris (2001) over Indian Ocean contradict this hypothesis, where it is shown that enhancements of black carbon increase cloudiness. Our results show very small enhancement of convective rain in region R_1 and decrease in region R_2. Thus it is apparent that the role of aerosol in convective process is quite complex. With increasing industrialization and population in both the regions, concentrations and types of aerosol species and their vertical distributions are expected to change. Further, impact of aerosols also depends in complex way on the local meteorological parameters and hence there is a need to make regional modeling studies in coordination with more precise observations in order to quantify the overall contribution of aerosols to monsoon variability and to understand the physical processes involved.

4. Summary

Two peninsular regions of almost equal area having same latitudes but different longitudes surrounded by the Arabian Sea and Bay of Bengal (R_1 region) and by the Bay of Bengal and South China Sea (R_2 region) having different orography are considered. It is observed that the annual mean surface temperature, CAPE, OLR and AOD are higher in the region R_1 as compared to R_2, but the annual mean convective cloud cover, lightning flashes and convective rain are higher in R_2 region. Attempt has been made to explain the results considering orography and changes in large scale circulation pattern involving ISM and WNPSM systems. In the region R_1, ISM system produces rain/lightning flashes, whereas R_2 region is covered by both systems. Seasonal variation of lightning flashes shows peak during pre-monsoon months (April, May) along with a secondary peak during withdrawal period of monsoon. Convective rain in R_1 region increases during monsoon period with a maximum in October, whereas it remained almost constant in R_2 region during May to October. Convective cloud cover is the highest during September–October in R_2 region, whereas in R_1 it is highest in August. As expected during the period of large cloud cover, OLR becomes minimum in both the regions.

Lightning flashes in both the regions are well positively correlated with surface temperature ($R \sim 0.69$, 0.66) and CAPE ($R \sim 0.83$, 0.74) and negatively correlated with OLR ($R \sim -0.25$, -0.44). Interestingly in R_1 region lightning flashes do not show any significant correlation with convective cloud cover, although in R_2 region a good positive relation ($R \sim 0.52$) is observed. Convective rain in both the regions R_1 and R_2 shows good positive correlation with CAPE ($R \sim 0.59$, 0.90) and total cloud cover ($R \sim 0.78$, 0.90) and negative correlation without going long wave radiation ($R \sim -0.81$, -0.85). Surface temperature does not show any significant impact in the Indian peninsular region, although in the Indo-China peninsular region an enhancement in convective rain is observed. The enhancement in the sea surface temperature clearly shows enhancement in the convective rain of both regions. Convective rain and lightning flashes are better correlated in R_2 region as compared to R_1 region.

The impact of aerosols in both the regions R_1 and R_2 is quite different. In the region R_1, lightning flashes and convective rain show increasing tendency (R ~ 0.29, 0.14) with aerosol concentration, whereas in R_2 region convective rain showed decreasing trend. The increasing and decreasing trend could be understood in terms of different processes active in the core and peripheral part of the cloud and competition between them. The inter-relation of aerosols on CAPE, surface temperature, cloud cover, OLR and their impact on cloud processes have to be investigated in detail.

The results presented in this paper clearly suggest the need of regional modeling studies along with more observations at regional basis in order to understand physical processes involved and to quantify interdependence of various parameters and their impact on convective process leading to lightning flashes and precipitation.

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