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# The impact of the Western Ghats on lightning activity on the western coast of India

A.K. Kamra <sup>a,\*</sup>, A.A. Nair <sup>b,1</sup><sup>a</sup> Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pune 411 008, India<sup>b</sup> Indian Institute of Science Education and Research, Dr. Homi Bhabha Road, Pune 411 008, India

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## ABSTRACT

The effect of the Western Ghats on the lightning activity across the west coast of India around the coastal metropolitan city of Mumbai during the 1998–2012 period is investigated using data from the Lightning Imaging Sensor (LS) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. A land–sea contrast of an order of magnitude in the lightning activity is observed even in a small area across the western coast of India. The shape of a zone of high lightning activity formed almost parallel to the Western Ghats during the onset and withdrawal phases of monsoon, strongly suggests the effect of the Western Ghats in its formation. Seasonal variation of the lightning activity in this area and also in each of its four equal sectors (two each over the Arabian Sea and over land) is bi-annual with one peak each in the onset (May/June) and withdrawal months (September/October) of monsoon and a sharp dip to very low values during the monsoon months (July/August) of maximum seasonal rainfall. The lightning activity in each sector is found to increase over the 1998–2012 period. However, the increase in lightning activity over the sector containing Mumbai is found to be greater during the pre- and post-monsoon periods and smaller during the monsoon period as compared to an identical sector immediately south of it.

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## 1. Introduction

Mountain ranges are known to affect the spatio-temporal distribution of precipitation and the spatial variability of the diurnal cycle of convective activity. During the Indian southwest monsoon season (June–September), convection occurs frequently at the west coast, where low-level flow enriched in moisture and marine aerosols, during its passage over the Arabian Sea, flows over the subcontinent. After crossing the coastline, the flow is further enriched by the continental aerosols and anthropogenic aerosols released by big cities such as Mumbai and Pune. The Western Ghats running almost

parallel to the west coast of India modulates the southwest monsoon airflow, which approaches the mountain-range just perpendicular to it. Interactions of convective activity, precipitation, aerosols, and terrain (landmass and altitudinal gradients) are crucial to the occurrence of lightning in the clouds formed over such regions. The purpose of this study is to investigate the spatio-temporal distributions of lightning in an area across the west coast of India with the help of satellite data.

Several studies made in the last decade report the influence of large cities on the lightning activity over and/or downwind of these urban areas (Orville et al., 2001; Steiger et al., 2002; Naccarato et al., 2003; Pinto et al., 2004; Farias et al., 2009; Kar et al., 2009; Lal and Pawar, 2011; Niyogi et al., 2011). Such influence can result from the heat island concept or the aerosol concept in which the enhanced number of cloud condensation nuclei causes more numerous but smaller water droplets, which transport more water to the mixed-phase level in clouds,

\* Corresponding author at: Indian Institute of Tropical Meteorology, Pune 411008, India. Tel.: +91 20 2590 4281.

E-mail addresses: [kamra@tropmet.res.in](mailto:kamra@tropmet.res.in) (A.K. Kamra), [nairarshad@students.iiserpune.ac.in](mailto:nairarshad@students.iiserpune.ac.in) (A.A. Nair).

<sup>1</sup> Tel.: +91 9762308328.

where they can participate in the electrification process (Williams et al., 2002). The enhanced aerosol particle concentration over urban areas has also been proposed to explain the enhanced cloud-to-ground lightning flashes over and downwind of urban and industrial areas (Orville et al., 2001; Steiger et al., 2002; Steiger and Orville, 2003; Yuan et al., 2011, 2012) and the enhancement in the positive cloud-to-ground flashes associated with forest fires (Lyons et al., 1998; Murray et al., 2000; Lang and Rutledge, 2006) and over oil refineries (Changnon, 1981).

Factors other than these have also been identified to influence the lightning activity in thunderclouds. For example, recent investigations reveal the dependence of lightning activity on regime variations of continental, monsoon, and oceanic deep convection over the tropics. These studies (Xu et al., 2010; Liu et al., 2012; Xu and Zipser, 2012) report relationships between lightning flash rates and radar reflectivity structures in thunderstorms over the tropics and subtropics.

Recently, Bhalwankar and Kamra (2013) have proposed that the enhanced distortion and break-up of the polluted drops and their characteristics to trigger and propagate discharge in lower electric field can significantly contribute to the enhancement of lightning activity in the clouds formed over big cities. Emissions from cities are also likely to introduce a larger number of freezing nuclei and thus lead to the formation of more ice crystals in clouds formed over such urban areas, which is generally considered vital to the electrification processes in clouds (Dye et al., 1988; Blyth et al., 2001).

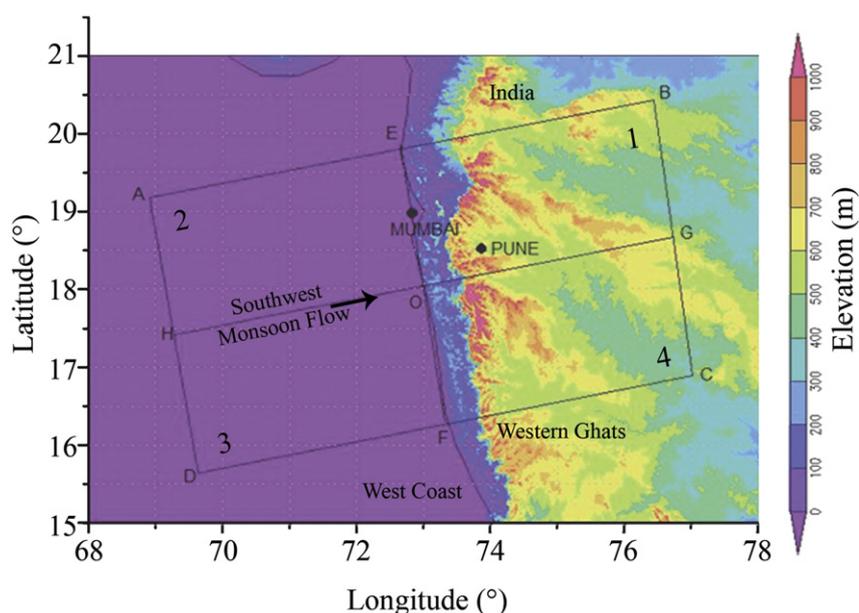
Here, we study the land–ocean contrast and the influence of the Western Ghats on the distribution of lightning activity across the west coast of India. The lightning data collected by the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall

Measuring Mission (TRMM) satellite for the 1998–2012 period is used for this study.

## 2. Area of investigation and its climatology

An area, ABCD with coordinates A ( $19^{\circ}11'N$   $68^{\circ}54'E$ ), B ( $20^{\circ}26'N$   $76^{\circ}26'E$ ), C ( $16^{\circ}54'N$   $77^{\circ}01'E$ ), and D ( $15^{\circ}40'N$   $69^{\circ}38'E$ ), oriented in the southwest–northeast direction on the west coast of India and including the city of Mumbai ( $18^{\circ}59'N$   $72^{\circ}50'E$ ), is selected for investigation. This area spanning  $800\text{ km} \times 400\text{ km}$ , illustrated on a topographical map in Fig. 1, is divided into four equal area sectors, 1, 2, 3, and 4 such that HG is in southwest–northeast direction and almost perpendicular to the western coastline, and EF is approximately along the western coastline of India. The city of Mumbai is located in Sector 1 on the mid-way of EO. Sectors 2 and 3 lie entirely over the Arabian Sea and Sectors 1 and 4 are almost entirely over the continent. The Western Ghats, a mountain range along the western side of India, runs almost parallel to the western coastline at a distance of 30–50 km and provides a barrier of approximately uniform height with peaks as high as  $\sim 1\text{ km}$  in this area.

The metropolitan city of Mumbai, with a population of  $\sim 12.7$  million (Census of India at <http://www.censusindia.gov.in>, 2011),  $\sim 1.8$  million automobiles (Motor Transport Statistics of Maharashtra at <http://mahatranscom.in>, 2011), a major shipyard, an international airport, and some major industries to its north, is a major source of pollution in this area. Another moderately big city of Pune on the lee side of the Western Ghats, having a population of  $\sim 4.8$  million (Census of India at <http://www.censusindia.gov.in>, 2011), but a larger number ( $\sim 3.7$  million) of automobiles (Motor Transport Statistics of Maharashtra at <http://mahatranscom.in>, 2011) also lies in Sector 1.



**Fig. 1.** The topography of the area of investigation ABCD oriented in the southwest–northeast direction. EF is approximately along the west coast of India. The metropolitan city of Mumbai is on the midway of EO. Pune is another major city in the area of interest as indicated. Sectors 1 and 4 are over land and Sectors 2 and 3 are over the ocean.

The major climatic feature of the area is the southwest monsoon, which normally sets-in in the second week of June and withdraws at the end of September in this area. The prevailing winds dominantly change to the southwesterly in direction during the monsoon season (Fig. 2). The moisture-laden southwesterlies in this season, after their long journey over the Indian Ocean and the Arabian Sea, shed most of their moisture west of the Western Ghats. As a result, the area located immediately west of the Western Ghats gets a seasonal rainfall approximately three times more than that of the area immediately east of the Western Ghats (Raghavan, 1964). In the southwest monsoon season, when the southwesterlies strike the west coast almost perpendicularly, Sectors 2 and 3 introduce marine/anthropogenic aerosols into Sectors 1 and 4, respectively. However, these aerosols are not as effectively transported to the east of the Western Ghats during the pre-monsoon (March–April–May) and the post-monsoon (October–November) seasons, because (i) winds are weak and have no preferential direction (Fig. 2) during these seasons, (ii) the coastal areas west of the Western Ghats experience the sea and land breeze conditions with a vertical depth of about 1 km above mean sea level, and (iii) the westerly airflow and the transfer of aerosols in the lower boundary layers, where most of the aerosol content lies, is blocked by the Western Ghats. The whole area, inclusive of oceanic and continental areas, experiences peak thundercloud activity during the pre- and post-monsoon seasons (Manohar and Kesarkar, 2003).

### 3. Data-set

Here, we use the lightning data obtained from the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite, launched into the low-Earth orbit with an altitude of 350 km, and subsequently raised to 402.5 km, and an inclination of  $35^\circ$  by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) on November 27, 1997. The LIS detects and locates cloud-to-ground, intra-cloud, and inter-cloud lightning in the tropical regions by identifying lightning from the associated changes in cloud brightness, even with sunlit clouds in the background. It has a field of view exceeding  $580 \times 580 \text{ km}^2$  at the cloud top, a storm-scale resolution of 5–10 km, a temporal resolution of 2 ms (Christian et al., 2000), and a flash detection efficiency of  $93 \pm 4\%$  at night and  $73 \pm 11\%$  during daytime (Boccippio et al., 2002). However, its detection efficiency may be slightly an underestimate in cases of intense convective systems where the flashes that occur in rapid succession illuminating the same cloud region may be grouped together when observed by the LIS and be considered as the same flash.

The LIS product, LIS Space Time Domain Search, provides individual flash information indicating flash time (UTC), latitude and longitude, radiance, duration, groups, events, and the orbit-ID. The LIS data was obtained from <http://thunder.msfc.nasa.gov/>, hosted by the Global Hydrology and Climate

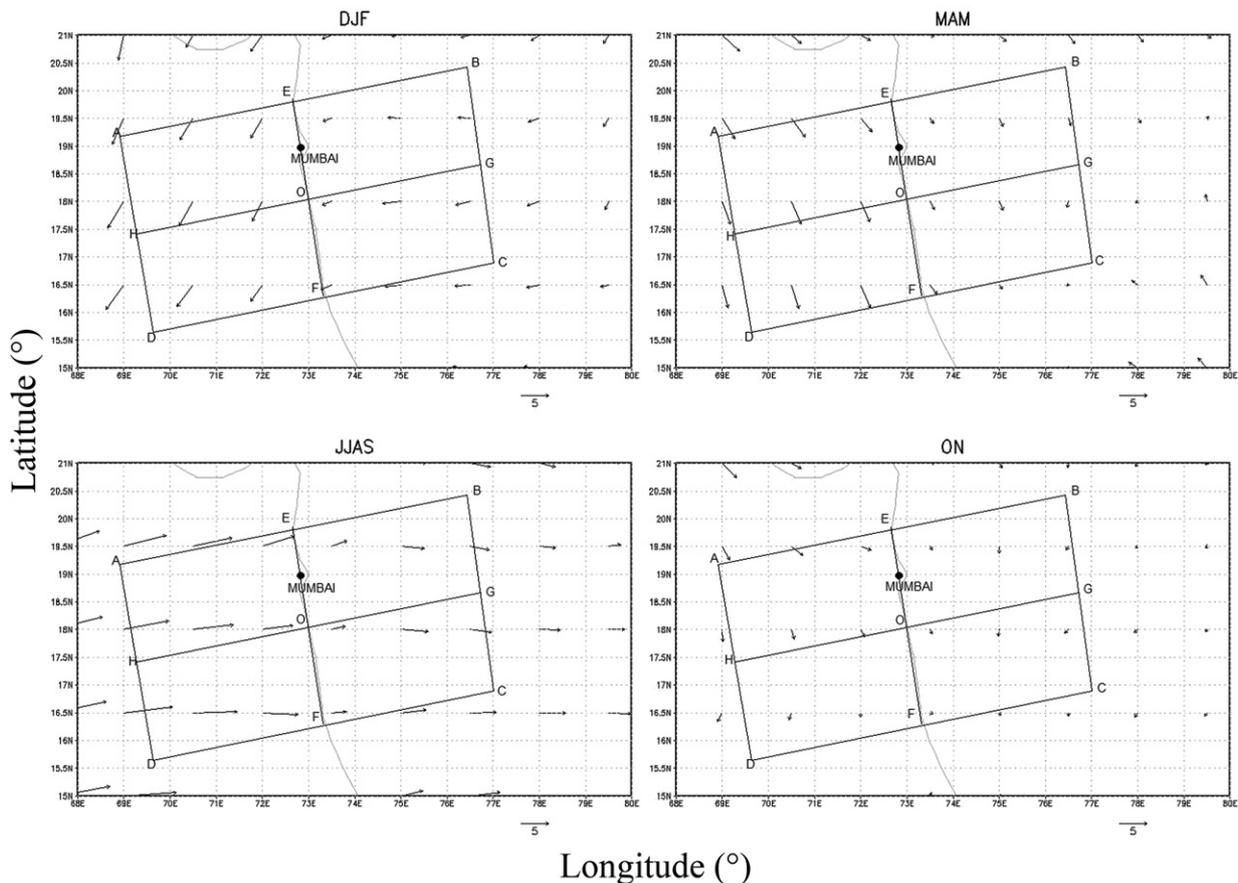


Fig. 2. Seasonal winds in winter (DJF), pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (ON) seasons in the area of investigation.

Center (GHCC). During the 15-year period from January 1998 to December 2012, the total area ABCD exhibited a total of 19,758 flashes – 8483 in Sector 1, 1222 in Sector 2, 1244 in Sector 3, and 8809 in Sector 4.

Wind data (10 m U and V wind component) was obtained from [http://data-portal.ecmwf.int/data/d/interim\\_moda/](http://data-portal.ecmwf.int/data/d/interim_moda/) hosted by the European Centre for Medium-Range Weather Forecasts (ECMWF). Global 30 Arc-Second Elevation Data Set (GTOPO30), for the topography, was obtained from Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) through their website on [http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg\\_id=10003\\_1/](http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10003_1/).

## 4. Results

### 4.1. Spatial distribution of lightning

Fig. 3 shows spatial distribution of lightning activity in the area ABCD for the 1998–2012 period. Lightning activity is comparatively much lower over the oceanic area (Sectors 2 and 3) than over the land area (Sectors 1 and 4). Of particular importance is the development of a zone of high lightning activity, running almost parallel to the Western Ghats and located between the coastline and the Western Ghats. Monthly evolution of this zone of high lightning activity is most pronounced in the months of June and October, which are the months of arrival and withdrawal of monsoon, respectively (Fig. 4). To understand the time evolution of this zone of maximum lightning activity, we have plotted in Fig. 5 the monthly curves of average flash count in each of the 50 km wide column parallel to the coastline, versus the distance of the column from the coastline. An ocean to land enhancement of lightning activity can be seen to a variable degree, throughout the year. Moreover, the formation of the zone of maximum lightning activity is most pronounced during the onset (June)

and withdrawal (September/October) months of monsoon, when the accumulation of aerosols west of the Western Ghats is maximum as explained in Section 2. The shape and the location of this zone of peak lightning activity suggest a strong role of the Western Ghats in its formation. Noticeable is the eastward shift of the zone of maximum lightning activity in the northern part of Sector 1, where this zone follows the shift in the Western Ghats' position. The Western Ghats can influence the lightning activity by modifying the convective activity of the region due to orographic convection and by affecting the seasonal distribution of aerosols on either side of the mountain range.

Another important feature depicted in Fig. 5 is the increase in lightning activity at a distance of 250–400 km from the coastline in the pre-monsoon (March–May), monsoon onset (June), and post-monsoon (September–October) months. The lightning activity also shows a dip at a distance of 100–250 km from the coastline in the same months. While the increase in lightning activity of 250–400 km from the coastline may be associated with the continental convection during the summer months of March–June and with the instability in the withdrawal phase of the monsoon during September–October, the dip in the lightning activity may be related to the downward motion in the atmosphere on the lee side of the Western Ghats.

### 4.2. Monthly mean flash count

Fig. 6 shows that the variation of the monthly mean of the number of lightning flashes over the area ABCD during the 1998–2012 period is bi-annual. The monthly mean flash count (FC) starts increasing from its minimum value in winter to June and shows two peaks in the months of June (19% of the annual mean FC) and September (17% of the annual mean FC). The lightning activity is almost nil in the months of December

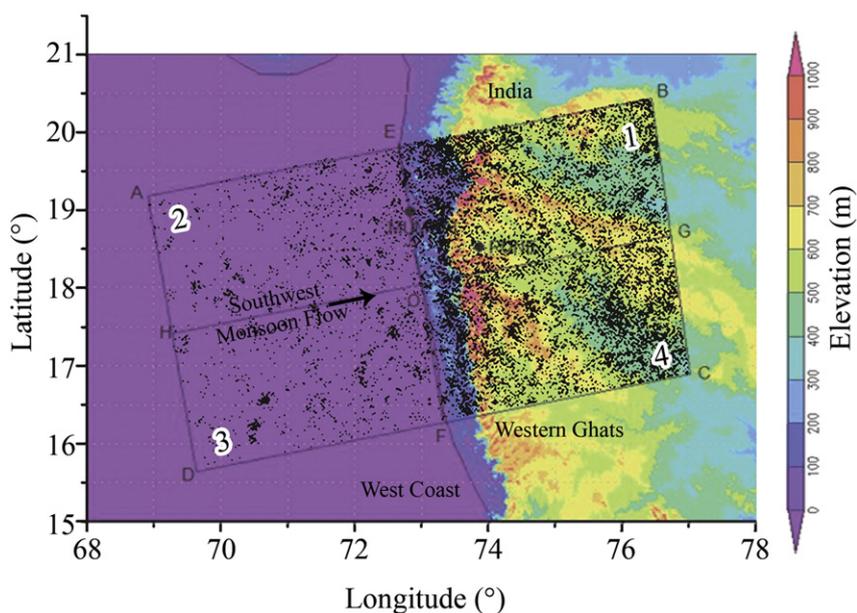
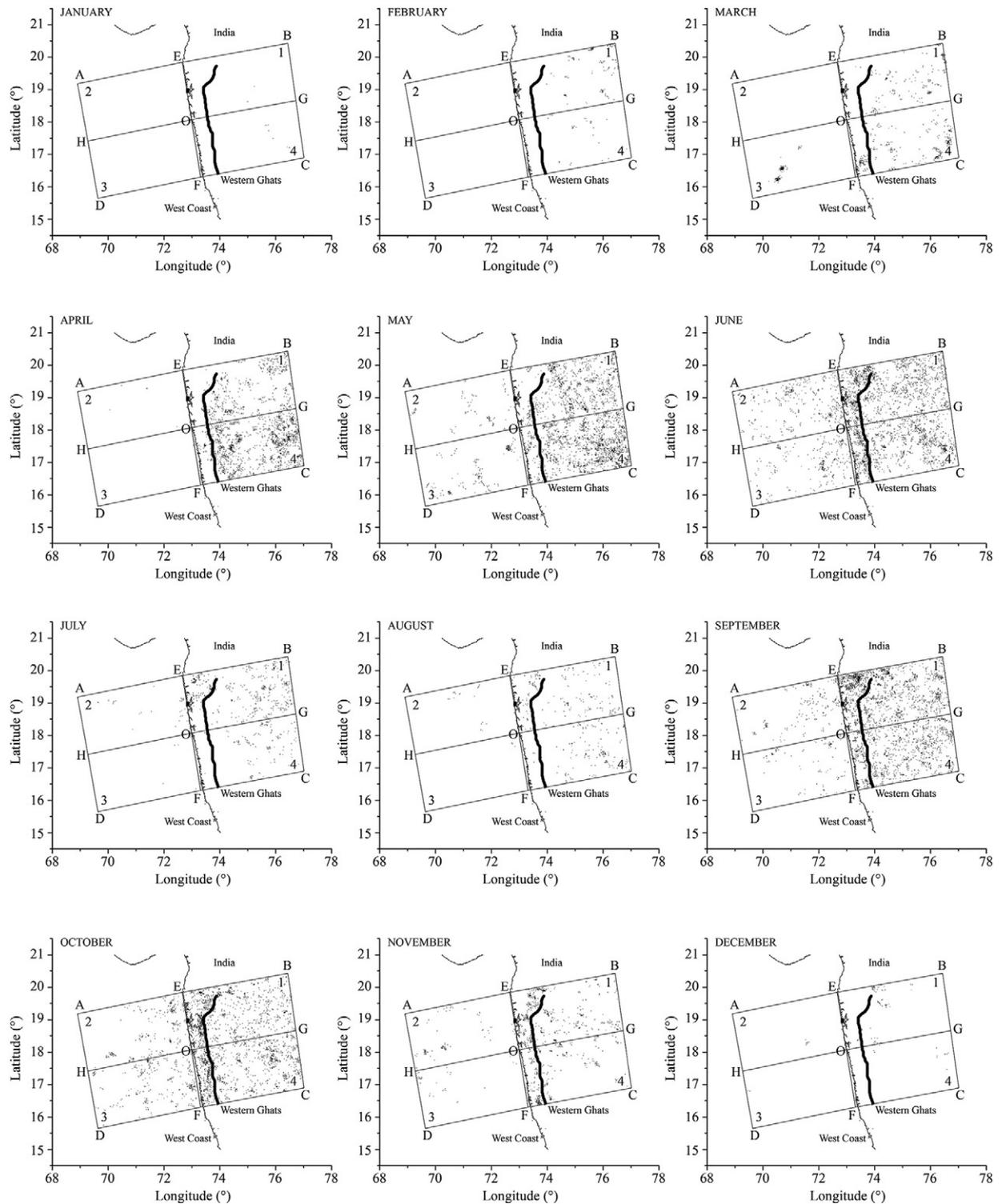


Fig. 3. Spatial distribution of lightning in the area ABCD during the 1998–2012 period. Each dot indicates the location of a lightning flash. Topography of the area is shown in the background.

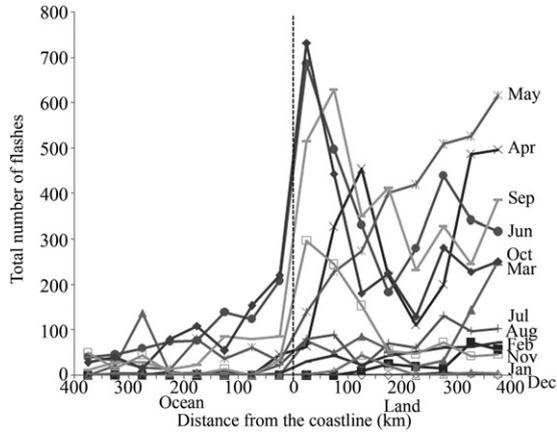


**Fig. 4.** Spatial month-wise distribution of lightning in the area ABCD during the 1998–2012 period. Each dot indicates the location of a lightning flash. Thick solid line shows the approximate position of Western Ghats in the height range 700–1000 m.

(0.53% of the annual mean FC) and January (0.06% of the annual mean FC). Further, the lightning activity rapidly decreases to very low values in the peak monsoon months of July (3.5% of the annual mean FC) and August (2.1% of the annual mean FC),

when the area receives the maximum rainfall of the monsoon season.

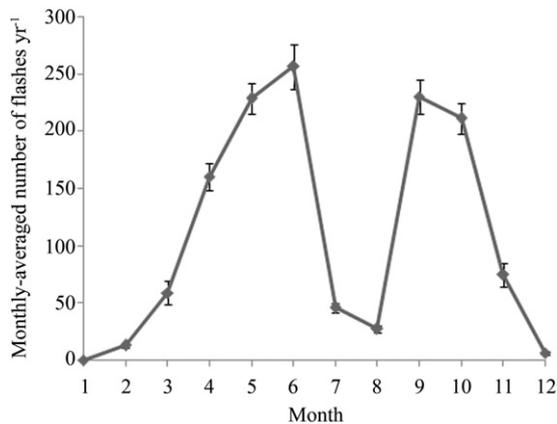
The curves of the monthly mean flash count drawn separately over each of Sector 1 to 4 also show bi-annual



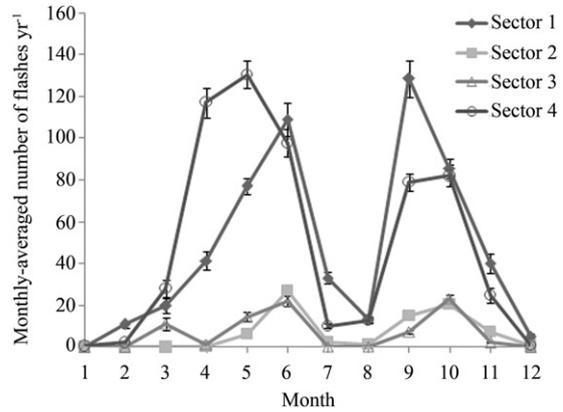
**Fig. 5.** Variation of the monthly number of flashes in each of the 50 km wide columns, parallel to the coastline, with distance of the column from the coastline, during the 1998–2012 period.

variation (Fig. 7). The following major differences in lightning activity over the different sectors are noticed:

- (1) Values of the monthly mean flash count over the oceanic sectors (2 and 3) are, on the average, approximately an order of magnitude smaller than those over the continental sectors (1 and 4).
- (2) The increase in the monthly mean flash count from the winter to pre-monsoon season is steeper in Sector 4, where it reaches higher peak value (~22% of the annual mean flash count) in May itself as compared to Sector 1, where the peak value (~19% of its annual mean flash count) reaches only in June. The corresponding values for Sector 2 and 3 are ~33% and ~27%, respectively, of their annual mean flash count in June; these values are, however, not statistically significant because of the small number of total flashes in these sectors.
- (3) The second peak in the monthly mean flash count (~23% of the annual mean flash count) appears in September over the continental Sector 1 but only in October over Sectors 2, 3, and 4 where they are ~25%, ~28%, and ~14%, respectively, of their annual mean values.



**Fig. 6.** Variation of the monthly averaged flash count in the area ABCD during the 1998–2012 period. Vertical bars show the standard errors.

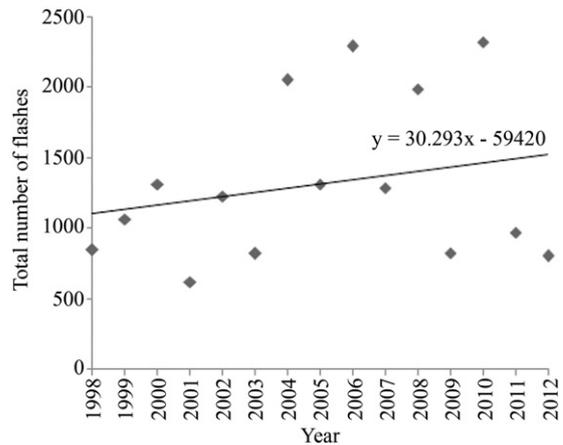


**Fig. 7.** Variations of the monthly averaged flash counts in Sectors 1, 2, 3, and 4 during the 1998–2012 period. Vertical bars show the standard errors.

- (4) Magnitudes of the first and second peaks are approximately equal over the oceanic Sectors 2 and 3. However, on continental sectors, while the magnitude of the first peak is greater in Sector 4 than in Sector 1, magnitude of the second peak is greater in Sector 1 than in Sector 4. Also, while the magnitude of first peak is greater than that of the second peak in Sector 4, the magnitude of the second peak is greater than that of the first peak in Sector 1.
- (5) Over the oceanic sectors, monthly mean flash count is very low or almost nil from December to April and in July and August.

4.3. Annual flash count

Figs. 8 and 9 show the annual variations of the number of flashes in the whole area ABCD and separately in Sectors 1, 2, 3, and 4, respectively, for the 1998–2012 period. Also shown in each panel of these figures are the regression lines for the respective data. Annual flash counts in the whole area, as well as in the individual sectors, increased during the 1998–2012 period, the increase being as much as ~38% in the whole area.



**Fig. 8.** Variation of the annual flash count in the area ABCD for the 1998–2012 period. Also shown is the regression line and equation.

Over the continental sectors, the increase in flash count is larger and steeper over Sector 4 (~47%) than over Sector 1 (~8%). Corresponding increases in annual flash counts are ~258% and ~132% over Sector 2 and 3, respectively; these values are, however, not statistically significant because of the small number of flashes in these sectors.

Figs. 8 and 9, in addition to showing a long-term increasing trend in lightning activity, show its high and low values in alternate years. Although the reason for such a biennial variability in lightning activity is not known, its possible linkage with quasi-biennial oscillation (QBO), a quasi-periodic oscillation of 24–30 months of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere, needs to be examined. Possible influence of the QBO on lightning production and deep convection in the tropics is already indicated by Hernandez (2008) and Hernandez and Schumacher (2008). Effect of the QBO in modifying lightning activity is not within the scope of this paper. However, the QBO's role in affecting the factors which can influence the occurrence of lightning in a cloud, such as the tropopause temperature, and height (Collimore et al., 2003), the upward and downward motions in Hadley cell circulation, the frequency of the southwest monsoon cyclonic disturbances in the Indian continent (Bhalme, 1972), and aerosol optical depth in tropical regions (Beegum et al., 2009) need to be examined in detail.

**5. Relative variations of lightning activity over Sectors 1 and 4 in different seasons**

Over the oceanic Sectors 2 and 3, mean values of the monthly flash count and their peak values in the months of June and October are approximately equal to each other. We have used this fact to get a non-dimensional number to assess the difference in lightning activity over Sectors 1 and 4 in different seasons. The non-dimensional number, N, is defined as:

$$N = (N_1/N_2) / (N_4/N_3) \tag{1}$$

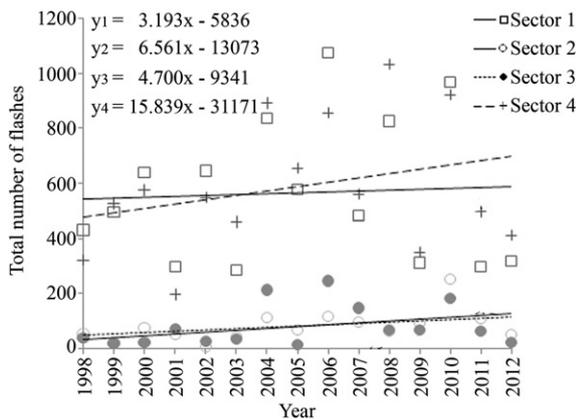


Fig. 9. Variations of the annual flash count in Sectors 1, 2, 3, and 4 during the 1998–2012 period. Also shown are the regression lines and equations for different sectors.

where  $N_1$ ,  $N_2$ ,  $N_3$ , and  $N_4$  are monthly mean values of flash count over Sectors 1, 2, 3, and 4, respectively, for the 1998–2012 period. Fig. 10 shows the monthly variation of N. Changes in N represent the changes in monthly flash count in Sector 1 with respect to those in Sector 4. Values of N for the months of November to March are not plotted in Fig. 10 since the values of  $N_2$  and/or  $N_3$  in those months are about zero. Values of  $N > 1$  in May and October mean that the lightning activity in the Sector 1 is more than in Sector 4 at the times of onset and withdrawal of the monsoon. On the other hand, values of  $N < 1$  during the July–September period mean that the lightning activity in Sector 1 is less than that in Sector 4 during the monsoon season.

**6. Discussions**

In this study, the LIS data is collected only for a few minutes each day during satellite passes over a region. However, since the statistical averages are calculated for a period of 15 years, the analyzed variations are likely to be reasonably representative of the area.

Higher values of the annual mean flash count over Sectors 1 and 4 as compared to those over Sectors 2 and 3 confirm the land–ocean contrast of an order of magnitude in lightning activity (Orville and Henderson, 1986; Christian et al., 2003; Ramesh Kumar and Kamra, 2012a). Such an enhancement, in this case, may be mainly associated with the difference in the continental and oceanic convections and with the orographic lifting of the air mass by the Western Ghats. Accumulation of aerosols or formation of mountain waves (Wallace and Hobbs, 2006; Ramesh Kumar and Kamra, 2012b) for the development of an arc of high lightning activity in the foothills of Himalayas, may contribute to the formation of the zone of high lightning activity west of the Western Ghats as well.

Monthly variations of flash count over the continental sectors show one peak, each in the months of May/June and September/October. While the May/June peak over continental sectors can be attributed to the increasing surface temperature from January to May/June, the September/October peak is most probably due to the instability of the atmosphere during the

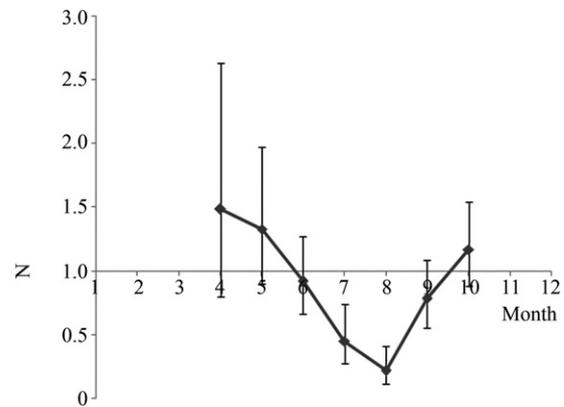


Fig. 10. Monthly variation of the mean values of the non-dimensional number N (defined in Eq. (1)). Values of  $N > 1$  or  $< 1$  show whether the flash count is greater or smaller over Sector 1 than over Sector 4 with respect to Sectors 2 and 3, respectively. Values of N from November to March are not plotted for the reasons explained in the text. Vertical bars show the standard errors.

withdrawal phase of the monsoon. The sharp decrease and low values of flash count in July/August may be associated with the cutting-off, by absorption and scattering, of short-wave solar radiation from reaching the Earth's surface by increasing cloudiness during monsoon season. Cooling of the Earth's surface by the rainfall during those peak monsoon months may also contribute to these low values.

Our results of total lightning showing high and low values in alternate years in Figs. 8 and 9 suggest a detailed investigation of the postulated linkage of QBO and lightning activity in the tropics. Such a linkage may develop through two hypothesized mechanisms, i.e. (i) modulation of the tropopause height which may determine the altitude up to which deep convection can penetrate and (ii) modulation of cross-tropopause shear which may affect the shearing of cloud tops (Hernandez, 2008; Hernandez and Schumacher, 2008). Possible association of the biennial variabilities in AOD and QBO is another factor needed to be investigated to understand the possible link of such a variability in lightning activity.

Small and almost equal values of annual flash count over the oceanic Sectors 2 and 3 are dramatically enhanced over the continental Sectors 1 and 4. However, these enhancements are not equal over Sectors 1 and 4; being larger and faster over the Sector 4 than the Sector 1. Moreover, the relative increases in flash count over Sectors 1 and 4 with respect to Sectors 2 and 3, respectively, are not equal in different seasons, being greater during the onset and withdrawal phases of the monsoon and smaller during the monsoon months of peak rainfall (Fig. 10). These observations may possibly be explained if aerosols are considered as modulator of lightning activity (Rosenfeld and Lensky, 1998; Rosenfeld and Woodley, 2001, 2003). Addition of aerosols can, both, increase or decrease the lightning activity as explained below. Southwesterlies in the southwest monsoon season introduce marine aerosols which are rich in hygroscopic cloud condensation nuclei (CCN) into Sectors 1 and 4. Addition of these marine aerosols adds to the enhancement of lightning activity over the continental sectors (Williams et al., 2002). However, in addition to the abundance of marine aerosols, the anthropogenic aerosols emitted by the city of Mumbai are also inducted into Sector 1. The combined concentration of aerosols due to both, marine and anthropogenic, sources in the southwest monsoon season may increase the availability of cloud condensation nuclei in Sector 1 to the extent that prevents the growth of cloud droplets from reaching the critical size required for the charge separation process to operate (Rosenfeld and Lensky, 1998; Rosenfeld, 2000; Khain et al., 2001; Rosenfeld and Woodley, 2001, 2003) and thus reduce the thundercloud electrification and lightning activity in Sector 1. Thus, the effect of aerosols may be to enhance the lightning activity in the onset and withdrawal phases of monsoon and reduce the lightning activity in the monsoon months of peak rainfall. These opposite effects of aerosols in different seasons may approximately nullify each other in Sector 1 when the change in annual values of lightning activity is examined over a longer period. Such a hypothesis can explain the observation of almost no change in the number of flashes in Sector 1 over the 1998–2012 period in Fig. 9. The result supporting the above conclusion is illustrated in Fig. 10, where the values of  $N$  remain less than 1 during the southwest monsoon months of June–September when the prevailing southwesterlies in the area systematically induct only marine

aerosols into Sector 4, but both marine and anthropogenic aerosols into Sector 1. On the other hand,  $N$  is greater than 1 in May and October, when the prevailing winds, being weak and having no preferential direction, do not induct enough of marine aerosols into Sectors 1 and 4. It must be cautioned, however, that aerosols are certainly not the sole driver for the variability in lightning over Sectors 1 and 4 and that other factors, such as those discussed in the introduction, may contribute or even dominate for causing such changes in lightning activity.

## 7. Conclusions

Our analysis of the LIS data for the 1998–2012 period shows a strong effect of the Western Ghats on lightning distribution, especially during the onset and withdrawal phases of the monsoon season, between the coastline and the Western Ghats. Further, the present analysis confirms a land–ocean contrast of about an order of magnitude in the lightning activity within a small area across the west coast of India near Mumbai. The monsoon season exerts a strong effect on lightning activity over land areas. Lightning activity undergoes a bi-annual variation in this area. While the flash count peaks near the onset and withdrawal phases of monsoon season, it dramatically falls to very low values during the monsoon months of maximum rainfall.

Annual mean value of flash count increases in this area by 38% during the 1998–2012 period. Over land, the sector having Mumbai undergoes only an 8% increase in the annual mean value of flash as compared to an increase of 47% in an area immediately south of Mumbai.

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