

# A study of lightning activity over land and oceanic regions of India

ASHA NATH<sup>1</sup>, G K MANOHAR<sup>2</sup>, K K DANI<sup>1</sup> and P C S DEVARA<sup>1</sup>

<sup>1</sup>Indian Institute of Tropical Meteorology, Pune 411 008, India.

<sup>2</sup>Formerly, Indian Institute of Tropical Meteorology, Pune 411 008, India.

Monthly variations of lightning activity over typical land and oceanic regions of India were examined using satellite data (OTD) for a 5-year period (1995–1999). It is noted that the nature of variation between surface air maximum temperature ( $T_{\max}$ ), thunderstorm days ( $Th_n$ ), and lightning flash count over ER and WR showed remarkable correspondence and sensitivity with each other on monthly time scale. As we move out of winter season and enter the monsoon season, via pre-monsoon season, the WR undergoes cooling relative to the ER in the range 0.1–1.2°C. As a result, WR experiences reduction of thunder days and lowering in flash count. This decrease in  $T_{\max}$ ,  $Th_n$ , and flash count over WR may also be associated with relatively small values of  $T_{\theta_w}$  and CAPE in comparison with similar values over ER during the monsoon season. Our observation of associated reduction in  $Th_n$  and lightning count per 1°C cooling in surface air maximum temperature suggests reduction of  $\sim 3.5$  thunderstorms per station and 73 flashes. Comparison of lightning flashes between pairs of coastal, oceanic, arid-zone, hilly, and island stations reveals distinct relationship between climate regime and intensity of lightning activity. We may conclude the results of this study by saying that the overhead lightning activity is a clear reflection of the status of the underlying ground-earth properties. A close and continuous monitoring of lightning activity may be considered as a need of present day scientific studies.

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## 1. Introduction

We live in the earth's environment which is constantly electrified. The knowledge of this important property of the atmosphere was truly sought only from the observation of a flash of lightning from a thundercloud. Otherwise, in the absence of a flash, in fair weather condition, it is nearly impossible to know that the earth's atmosphere is filled with electric currents. Lightning has played decisive role in the fixation of atmospheric  $NO_x$  and development of precipitation per lightning flash at the ground, and hence it is understood as a resourceful and essential natural phenomenon of great importance. These attributes of lightning are evident from many early and recent studies (Smyth 1907; Workman and

Reynolds 1949; Jones 1958; Malan 1958; Schonland 1964; Newcott 1993; Borucki and Chameides 1984; Pradeepkumar *et al* 1995; Petersen and Rutledge 1996) devoted to lightning research. With the progress in time, global lightning observations from satellite and also from the deployment of Schumann Resonance technique, have poured in large number for studies (Williams 1992; Nickolaenko and Rabinowicz 1995; Satori and Zieger 1996; Williams *et al* 2000; Boccipio *et al* 2000b; Williams and Stanfill 2002). From the results of above studies, it is apparent that the approach towards lightning studies in the early years was more academic, while the approach during the recent decade has been relevant to practical applications of the subject. Many of these studies suggest that their emphasis is more on the application aspects of

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lightning knowledge to climate related issues. For example:

- Lightning activity increases dramatically with the depth and vigour of convection over land and is dominant in the tropics (Orville and Hendersen 1986; Williams 1985);
- Approximately, two of every three flashes occur in the tropical belt:  $\pm 23^\circ$ ;
- Lightning observations from space revealed that tropical land areas exhibit substantially more lightning than do the central oceans. The land-ocean contrast in lightning activity is also one such front line topic.

From the above discussion, it may be inferred that lightning over land, over oceanic areas, over latitude belts, and over vivid climate regimes behaves differently. Over the Indian region, land and sea waters are juxtaposed to produce weather during major time (March–October) of the annual period. Also, India is gifted with the availability of varied climate zones such as semi-arid, coastal, island, hilly, inland and oceanic. Studies on lightning activity over different parts of India are infrequent (Aiya 1968; Boeck *et al* 1999; Manohar and Kandalgaonkar 1995; Manohar *et al* 1999; Kandalgaonkar *et al* 2003; 2005a, 2005b; 2006a, 2006b). Therefore, there is sufficient scope for the study of lightning activity over such locations. This work forms a case study of lightning activity over typical land–land and land–oceanic regions of India.

## 2. Data and method of analysis

The Optical Transient Detector system (OTD) is a highly compact combination of optical and electronic elements. The OTD can gather lightning data under daytime conditions as well as at night. The OTD is a satellite-borne instrument and has been in operation in the low earth orbit since April 1995. The OTD revolves round the earth orbit at an altitude of  $\sim 710$  km with an inclination of 70 degrees with respect to the equator. With that orbit and a field of view of 100 degrees, it surveys nearly all areas of the globe where lightning normally occurs.

The typical observation time of OTD instrument over any given location is 2–3 minutes. This observation time is adequate to determine an instantaneous thunderstorm flash rate. OTD sees latitudes up to  $\pm 70^\circ$  and beyond. The OTD takes  $\sim 55$  days to come to its original position. OTD observations enable objective measurements of thunderstorms and provide flash count information in the tropics and extra-tropics. OTD has a

spatial resolution of 10 km and time resolution of 2 ms. More technical details and observation information can be found in Christian *et al* (1996) and Williams *et al* (2000). Boccippio *et al* (2000a) used lightning data from the U.S. National Lightning Detection Network (NLDN) to perform preliminary validation of the satellite-based OTD. Sensor precision, accuracy, detection efficiency, and biases of the deployed instrument were considered in their study. The sensor is estimated to have, on average, about 20–40 km spatial and better than 100-ms temporal accuracy. The detection efficiency for cloud-to-ground lightning is about 46–69%. A data retrieval algorithm for validating OTD was developed by Koshak *et al* (2000), which was found to be sufficiently accurate.

Global or regional lightning activity is a highly variable parameter on many time-scales. This variability is usually attributable to changes in flash rate per thunderstorm, and also to the number of thunderstorms themselves. It is reported (Williams *et al* 2000) that among the above factors, the contribution of number of thunderstorms is 2–3 times greater than that of the changes in lightning flash rate of an individual storm. In a recent study concerning thunderstorms over Indian region, Manohar and Kesarkar (2003) have pointed out a strong gradient in thunderstorm activity between the eastern and western regions of India. It is also mentioned that the strong gradient in thunderstorm activity is more or less a regular feature, which is attributable to differences in properties of many geophysical parameters (i.e., Bowen ratio, soil properties, vegetation, altitude above mean sea level, etc.) over the ER and WR. Further, it is known that the thunderstorms are the best known principal source of lightning activity. This important point and above results have strongly motivated us to take up the study of land–land and land–ocean contrast in lightning activity over India.

The geographic regions of India chosen for the present study include:

- Eastern region (ER) and western region (WR) of India,
- East coast of India and a strip of six oceanic locations, 110 km away from the east coast and located in the Bay of Bengal,
- West coast of India and a strip of six oceanic locations, 110 km away from the west coast and located in the Arabian Sea,
- Island stations, Port Blair and Minicoy,
- Two land stations: Jaisalmer (JSM) and Ahmedabad (AHM) situated in the semi-arid zone of NW India, and two land stations: Guwahati (GHT) and Agartala (AGT) situated in the hilly region of NE India.

Map of India

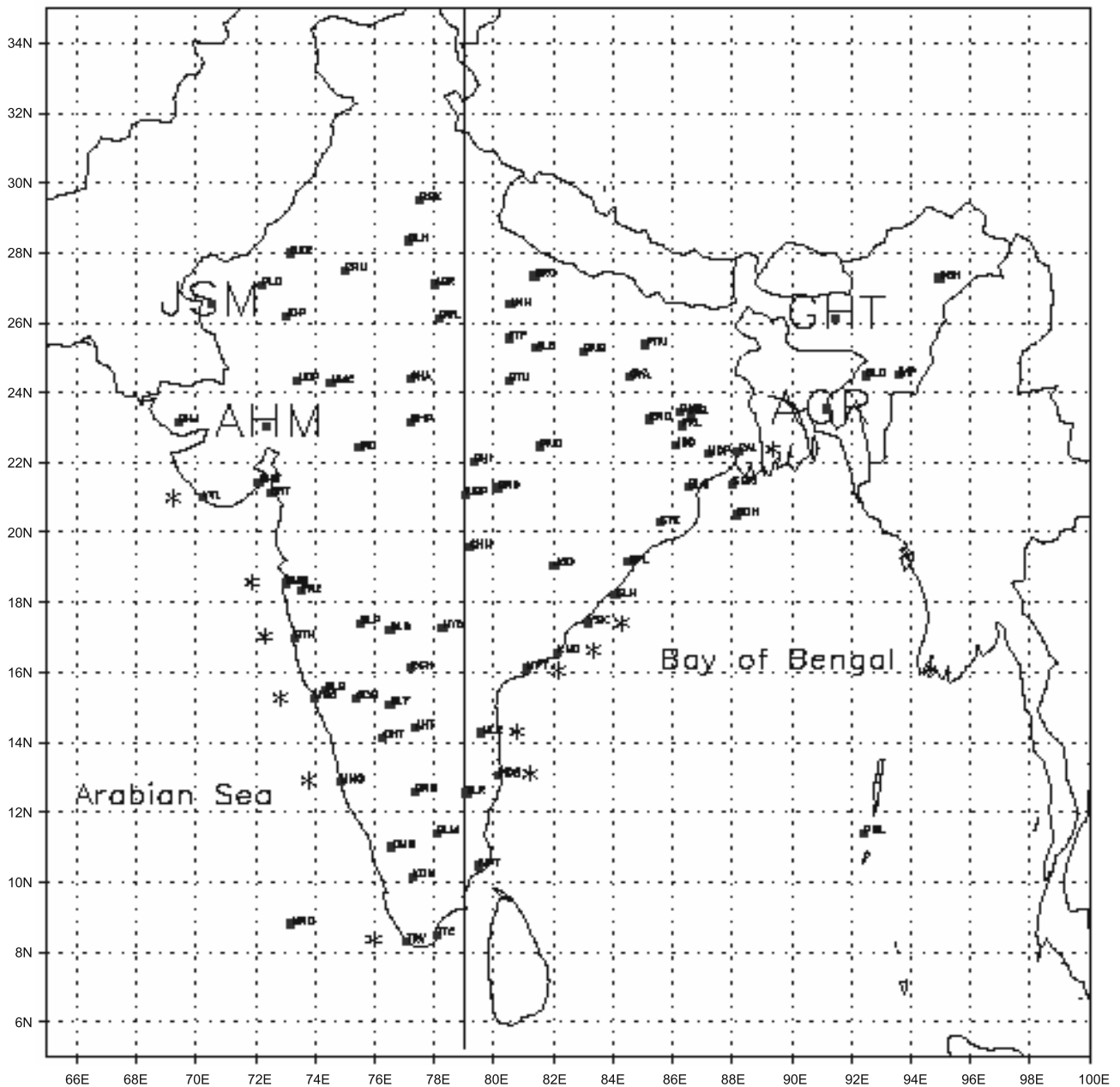


Figure 1. Map of India and the network of 66 land stations, six coastal stations each on ER and WR, two island stations {(Portblair (PBL) and Minicoy (MNC))}, and six oceanic locations each off the two coasts of India. The off coast locations are 110 km away from the coasts and are shown by asterisk mark.

This study mainly concentrates on:

- comparison between monthly (January–December) mean values of lightning counts over the two largest land regions: ER and WR,
- study of surface temperature and thermodynamic structure over ER and WR,
- occurrence of thunderstorms and development of lightning in relation to temperature change of surface air,
- comparative study of lightning flash count between pairs of above-mentioned typical land/oceanic regions of India, and
- a correspondence between lightning flash count and climate regimes over India.

Figure 1 shows the map of India and the location of 66 land stations, six stations each on east and west coasts, two island stations {Portblair (PBL) and Minicoy (MNC)}, and six oceanic locations each off the two coasts of India. Off-the coast locations are 110 km away from the coasts and are shown with asterisk mark. Table 1 presents some details of land and island stations considered in the present study. The daily lightning data recorded by the OTD for 5-year period (1995–1999)

Table 1. *Some particulars of the stations used in this study.*

Sl. no.	Station	Abbreviation	Latitude (N), deg. and min	Longitudes (E), deg. and min	Height above msl(m)
1	Agartala	AGT	23 53	91 15	16
2	Agra	AGR	27 10	78 02	169
3	Ahmedabad	AHM	23 04	72 38	55
4	Allahabad	ALB	25 27	81 44	98
5	Anantpur	ANT	14 41	77 37	350
6	Asansol	ASL	23 41	86 59	96
7	Bahraich	BRC	27 34	81 36	124
8	Balasore	BLS	21 30	86 56	20
9	Banaras	BNS	25 18	83 01	76
10	Bangalore	BNG	12 58	77 35	921
11	Belgaum	BLG	15 51	74 32	753
12	Bellary	BLY	15 09	76 51	747
13	Bhavnagar	BHV	21 45	72 11	11
14	Bhopal	BHP	23 17	77 21	523
15	Bhuj	BHJ	23 15	69 40	80
16	Bikaner	BKR	28 00	73 18	224
17	Bombay	BMB	18 54	72 49	11
18	Calcutta	CAL	22 32	88 20	6
19	Chandrapur	CHN	19 58	79 18	193
20	Chitradurga	CHT	14 14	76 28	733
21	Churu	CRU	27 50	75 00	291
22	Coimbatore	CMB	11 00	76 58	409
23	Cuttack	CTK	20 28	85 56	27
24	Dhanbad	DNB	23 47	86 26	257
25	Dibrugarh	DBH	27 28	94 95	111
26	Fatehpur	FTP	25 56	80 50	114
27	Gadag	GDG	15 25	75 38	650
28	Guwahati	GHT	26 11	91 45	54
29	Gaya	GYA	24 45	84 57	116
30	Gondia	GND	21 28	80 12	313
31	Gopalpur	GPL	19 16	84 53	17
32	Gulbarga	GLB	17 21	76 51	458
33	Guna	GNA	24 39	77 19	478
34	Gwalior	GWL	26 14	78 15	207
35	Hyderabad	HYD	17 27	78 28	545
36	Imphal	IMP	24 51	93 58	781
37	Indore	IND	22 43	75 48	567
38	Jagdalpur	JGD	19 05	82 02	553
39	Jaisalmer	JSM	26 54	70 55	242
40	Jamshedpur	JSD	22 49	86 11	129
41	Jodhpur	JDP	26 18	73 01	217
42	Kakinada	KND	16 57	82 14	8
43	Kalingapatnam	CLN	18 20	84 08	6
44	Kodaikanal	KDK	10 14	77 28	2343
45	Lucknow	LKN	26 52	80 56	128
46	Machalipatnam	MPT	16 11	81 08	3
47	Madras	MDS	13 04	80 15	16
48	Mangalore	MNG	12 87	74 85	22
49	Marmagao	MRG	15 25	73 47	62
50	Midnapur	MDP	22 25	87 19	45
51	Minicoy	MNC	8 18	73	2
52	Nagapatnam	NPT	10 46	79 51	9
53	Nagpur	NGP	21 09	79 07	310
54	Neemuch	NMC	24 28	74 54	496

Table 1. (Continued).

Sl. no.	Station	Abbreviation	Latitude (N), deg. and min	Longitudes (E), deg. and min	Height above msl(m)
55	Nellore	NLR	14 27	79 59	20
56	New Delhi	DLH	28 35	77 12	216
57	Patna	PTN	25 37	85 10	60
58	Pendra	PND	22 46	81 54	625
59	Phalodi	PLD	27 08	72 22	234
60	Port Blair	PBL	11 40	92 43	79
61	Pune	PNE	18 32	73 51	559
62	Purulia	PRL	23 06	86 30	255
63	Raichur	RCH	16 12	77 21	400
64	Ranchi	RNC	23 23	85 20	652
65	Ratnagiri	RTN	16 98	73 33	67
66	Roorkee	RRK	29 51	77 53	274
67	Sagar Island	SGRI	21 39	88 03	3
68	Salem	SLM	11 39	78 10	278
69	Sandheads	SDH	20 51	88 15	10
70	Satna	STN	24 34	80 50	317
71	Seoni	SNI	22 03	79 33	619
72	Silchar	SLC	24 49	92 48	29
73	Solapur	SLP	17 40	75 54	479
74	Surat	SRT	21 12	72 50	12
75	Thiruvananthapuram	TRV	8 29	76 57	64
76	Tuticorin	TTC	8 48	78 09	4
77	Udaipur	UDP	24 35	73 42	582
78	Vellore	VLR	12 55	79 09	214
79	Veraval	VVL	20 54	70 22	8
80	Visakhapatnam	VSK	17 41	83 18	3

were obtained at spatial resolution of  $0.5^\circ \times 0.5^\circ$  ( $\sim 55 \times \sim 55$  km) for all these locations.

To examine contrast in lightning activity over ER and WR, following the work of Manohar and Kesarkar (2003), India is demarcated by the  $79^\circ\text{E}$  longitude line drawn from south to north (see figure 1). It is believed that the demarcation of India in ER and WR, both contain equal number of stations, is quite suitable and logically appropriate for undertaking this analysis. Results of monthly mean values of lightning flash count at the above-mentioned six geographic regions are described in the following section.

### 3. Results and discussion

#### 3.1 Comparison of lightning flash count between eastern region (ER) and western region (WR) of India: A documentation of east-west contrast

Monthly mean variation of lightning flash count over ER and WR of India is shown in figure 2. Monthly and seasonal means of lightning flash count,  $T_h$  and  $T_{\max}$  over ER and WR are also

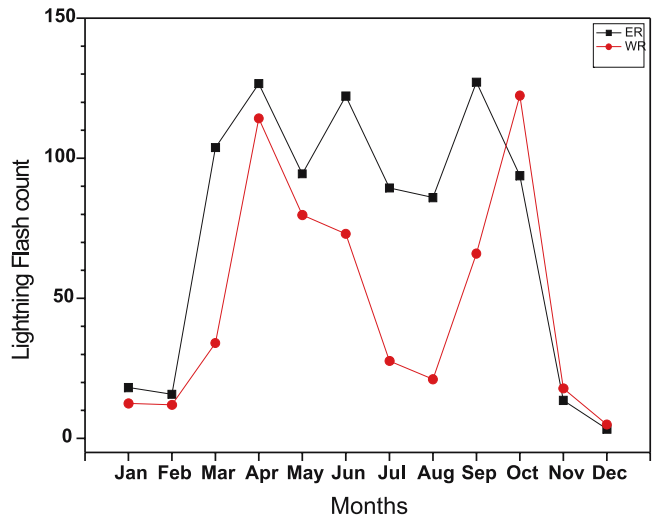


Figure 2. Monthly mean variation of lightning flash count over ER and WR of India: i.e., over the two largest land regions of India demarcated by  $79^\circ\text{E}$  longitude line.

furnished in table 2 for the convenience of quick reference. A careful examination of the plots in figure 2 reveals some distinct differences between their monthly values over ER and WR, and their seasonal pattern over the course of the annual

Table 2. Monthly and seasonal means of  $T_{max}$ ,  $Th_n$ , and lightning flash count over ER and WR.

	Eastern region			Western region		
	$T_{max}$	$Th_n$	Lightning	$T_{max}$	$Th_n$	Lightning
Monthly Means						
January	25.2	0.5	18.2	25.8	0.4	12.5
February	27.8	0.8	15.8	28.1	0.5	12.0
March	32.1	2.0	103.8	32.1	1.3	34.0
April	35.6	3.5	126.6	35.2	2.7	114.2
May	36.6	4.6	94.4	36.5	3.4	79.8
June	34.8	6.0	122.2	34.4	3.5	73.0
July	31.8	5.3	89.4	30.8	2.8	27.6
August	31.2	5.4	86.0	30.0	2.3	21.2
September	31.1	5.3	127.2	30.6	2.6	66.0
October	30.8	2.3	93.8	31.0	1.9	122.4
November	28.8	0.5	13.6	29.0	0.9	17.8
December	25.8	0.3	3.4	26.6	0.4	5.0
CC $T_{max}$ : $Th_n$	0.74			0.85		
CC $Th_n$ : Lightning	0.82			0.63		
CC $T_{max}$ : Lightning	0.84			0.73		
Seasonal Means						
JF	26.5	0.7	17.0	27.0	0.5	12.0
MAM	34.8	3.4	108.0	34.6	2.5	76.0
JJAS	32.2	5.5	106.0	31.5	2.8	47.0
OND	28.5	1.0	37.0	28.9	1.1	48.0
CC $T_{max}$ : $Th_n$	0.77			0.87		
CC $Th_n$ : Lightning	0.91			0.74		
CC $T_{max}$ : Lightning	0.96			0.92		

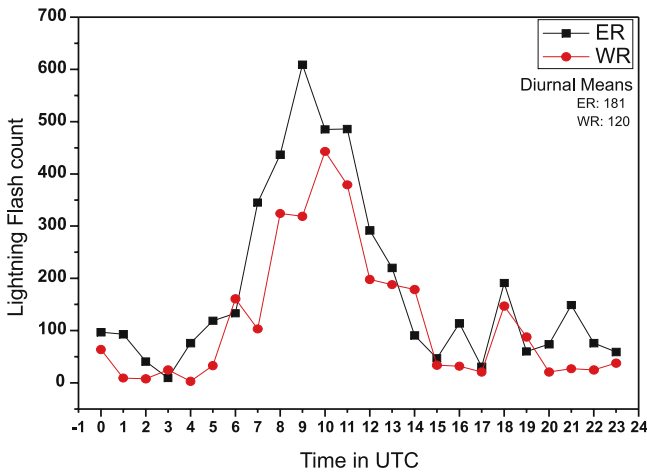


Figure 3. Diurnal variation of hourly mean flash count over ER and WR.

period. We note that during the nine months of January–September, the ER curve lays well above the WR curve and during these nine months, there is a clear preponderance of higher ER values of flash count. During the three months of October–December, WR values are just marginally higher than those of the ER. The seasonal variation

over ER is a typical case of monomodal variation. It shows three nearly equal and equispaced maxima, interspersed with two minima. The seasonal variation of the WR is a more clear example of bimodal variation with the first peak in April and the second in October. The seasonal minimum over ER and WR is occurring in the month of August which is coinciding with the climatological singularity in the southwest monsoon rainfall of India (Ananthkrishnan and Pathan 1991). Now, we highlight the aspect of east–west contrast in lightning activity. As we start from the month of January and come upto the month of September, we pass through the three seasons, viz., winter, pre-monsoon and monsoon. It is interesting to note the seasonal trend of flash count during these three seasons. We note that the average excess flash count over ER during January and February months is 5; during March–May months the average excess over ER is 28 and during June–September months this average excess over ER is 59 flashes. It is important to note that these seasonal average excess values of lightning flash counts over ER are for each month of the season and for each station considered under study. This stepwise seasonal analysis of flash count reveals that as we

Table 3. Monthly mean maximum wet-bulb potential temperature ( $T_{\theta_w}$  °C) during the monsoon months of the years 1972 and 1975 over the ER and WR.

Months	1972				1975			
	WR (results based on data of 40 stations)		ER (results based on data of 38 stations)		WR (results based on data of 40 stations)		ER (results based on data of 38 stations)	
	$T_{\theta_w}$ °C	CAPE (J/kg)	$T_{\theta_w}$ °C	CAPE (J/kg)	$T_{\theta_w}$ °C	(J/kg)	$T_{\theta_w}$ °C	(J/kg)
June	24.9	1950	26.2	3300	24.6	1750	26.1	3200
July	24.8	1800	26.3	3500	24.8	1800	26.0	3150
August	24.2	1150	25.9	3000	24.9	1950	26.3	3500
September	23.5	500	25.5	2800	24.5	1600	25.9	300

move out of the winter season and enter the monsoon season via pre-monsoon season, the ER minus WR contrast widens more and more and becomes extreme around the monsoon season months. Only during the months October–December, the flash count of WR is higher than that over ER. This three months' average excess is 11 flashes while the annual average excess flash count over ER is 25 flashes. The annual mean flash count over ER is 361 and over WR it is 239. Figure 3 shows diurnal variation of hourly totals of flash count over ER and WR. This diurnal value is computed by considering the total five year (1995–1999) period diurnal data of the 40 stations each over ER and WR. It is seen that the ER and WR curves follow each other with striking similarity, but with the difference in flash count such that ER counts are consistently higher during major part of the diurnal period (20/24 h). Moreover, in both the regions, flash count shows a gradual increase from morning hours, attains maximum around 1000 h (UTC), thereafter it decreases and almost maintains a low-level during the night period. This feature clearly indicates the association between thunderstorm activity (manifestation of moist convection) and flash count over tropical landmass of India. The results of one recent and related study (Manohar and Kesarkar 2003) concerning thunderstorm activity and temperature structure over ER and WR of India showed that the annual total number of thunderstorms over ER are 4763 and over WR are 3194. This study also pointed out that the prominent difference in thunderstorm days over ER was associated during the four months of the monsoon (June–September) season. Further, it was shown that the excess occurrence of thunderstorms over ER was sensitively dependent on the subtle range of excess  $T_{\max}$  (0.15–1.2 °C) and higher values of CAPE (Convective Available Potential Energy) over ER (see tables 2 and 3). In an important study (Williams *et al* 2000) concerning thunderstorms and lightning activity, it was shown that on seasonal and diurnal time-scales, changes in the

number of storms dominate the variation in lightning activity by a factor of 2–3 than the change in the mean flash rate of a storm. It is felt that the above result of ER-WR contrast in lightning activity is a clear manifestation of the east–west contrast in thunderstorm activity over the Indian region.

### 3.2 Surface temperature and thermodynamic structure over ER and WR

In many previous studies (Williams 1992, 1994; Williams *et al* 1992; Jayaratne 1993; Manohar *et al* 1999, 2008; Kandalgaonkar *et al* 2003, 2005a, 2005b, 2006a, 2006b; Manohar and Kesarkar 2003, 2004, 2005) the use of surface air temperature (both dry- and wet-bulb) as a dependable parameter for studying connection between growth of thunderstorms and their electrical properties (lightning, point discharge current, etc.) has been discussed. Their results have shown high correlation on seasonal time-scales, particularly over tropics. Such an attempt has been made here by comparing the results of lightning flash count with number of thunderstorm days ( $Th_n$ ) and monthly mean maximum surface air temperatures ( $T_{\max}$ ) over ER and WR.

Plotted in figure 4 (a and b) are the monthly mean maximum surface air temperature ( $T_{\max}$ ), number of thunderstorm days ( $Th_n$ ), and lightning flash count over ER and WR respectively. Table 2 presents monthly and seasonal mean values of above three parameters over ER and WR for brevity. It may be noted that the correlation coefficients between these ( $T_{\max}$ – $Th_n$ ,  $Th_n$ –lightning– $T_{\max}$ –lightning) parameters over ER and WR based on 12 monthly values are respectively 0.74, 0.82, 0.84 and 0.85, 0.63, 0.73 which are significant at level of 0.01. The seasonal correlation coefficients are also highly significant. From figure 4 and table 2, it can be seen that for an increase in temperature from 25.8 °C (January) to 36.5 °C (May), the average lightning flash count increased

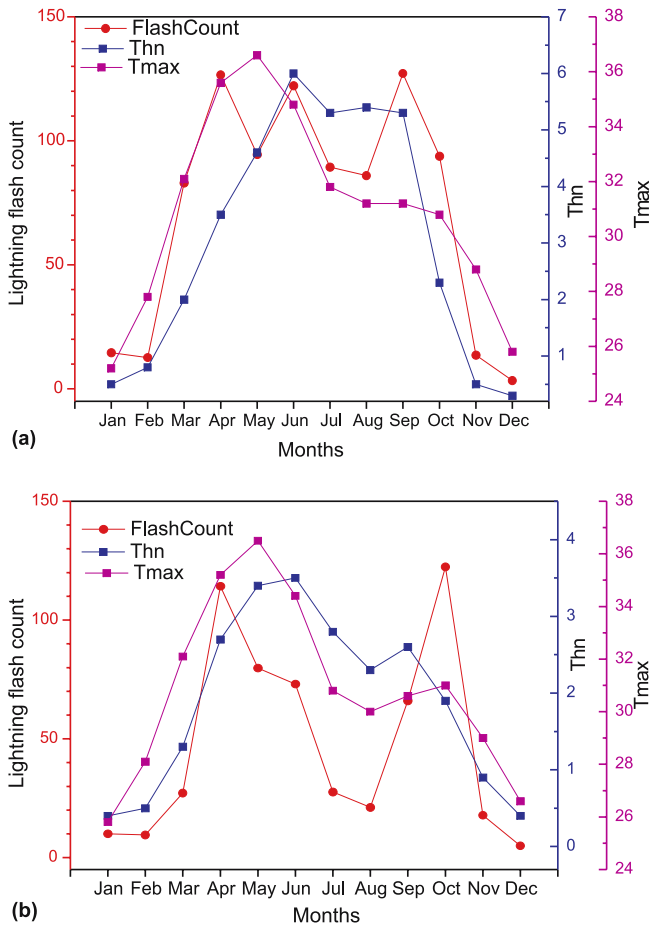


Figure 4. Monthly mean maximum surface air temperature ( $T_{max}$ ), number of (a) and (b) thunderstorm days ( $Th_n$ ), and lightning flash count over ER and WR.  $T_{max}$  and  $Th_n$  results are reproduced from Manohar and Kesarkar (2003).

from 12 to 80 and  $Th_n$  increased from 0.4 to 3.4 for WR. Similar increases in both lightning flash count and  $Th_n$  with increase in  $T_{max}$  have been noticed for ER also. We thus note the effect of surface maximum air temperature on the development of thunderstorms and hence on lightning activity. The general expectation is that the temperature structure during the monsoon season months over WR must indicate lower values than those over ER. We examined  $T_{\theta_w}$  (wet-bulb potential temperature) and CAPE over ER and WR to supplement this observation (table 3). We see that  $T_{\theta_w}$  as well as CAPE values over WR are systematically lower than those over ER. Reduction in lightning flash count is in agreement with the results of Rutledge *et al* (1992) concerning electrical output of thunderstorms during two episodes of Australian monsoon.

Studies in the past by Williams *et al* (1992); Williams (1992, 1994) and Jayaratne (1993) have used the monthly mean maximum wet-bulb temperature to examine its association with deep convection in the tropics (Williams 1997). Also, in

an earlier study, Manohar *et al* (1999) have used the monthly mean maximum values of surface wet-bulb temperature to understand the association between wet-bulb temperature and thunderstorm days over the Indian region. In a recent study of spatio-temporal variability of lightning activity over the Indian region, Kandalgaonkar *et al* (2005b) have documented the role of surface maximum air temperature and showed a pronounced effect of temperature rise in exponential increase in lightning flash density. They have also suggested an approximate increase of 20 to 40% in lightning flash density for every rise of 1°C in surface air temperature. The present observation of reduced lightning activity and reduced number of thunderstorm days over WR, as compared to that over ER, corroborate the results of Manohar and Kesarkar (2003). We note (table 3) that the monthly mean maximum wet-bulb potential temperature values during June–September are higher in the range 1.2–2.0°C and CAPE values are as much higher as the CAPE values themselves over ER than those over WR. These results favour the development of frequent and deep convective storms that may produce more lightning over ER. In many studies mentioned at the beginning of this section, the use of wet-bulb ( $T_w$ ) as well as wet-bulb potential temperature ( $T_{\theta_w}$ ) has been made to study the connection of this parameter with convective development of thunderstorms and the output of lightning. Wet-bulb temperature and its relation with the thermodynamics of air and human comfort has also been studied in the context of the Indian region since long (Normand 1921; Jeevanand Reddy 1976, Doraiswamy 1945). Wet-bulb temperature is a parameter that takes care of moisture or humidity content of the surface atmosphere. The use of wet-bulb temperature is consistent because it takes care of temperature and moisture content (humidity) of the atmosphere both of which are important to the thermodynamics of moist convection. Sensitivity results of  $T_w$  indicated that as  $T_w$  increased from 25 to 27°C, lightning count increased by two-fold, while in other case, for a change of 1.9°C, the lightning activity increased by 20-fold. These results are representative of land locations situated in the tropics (Williams 1992). These results have produced valid evidence to show the dominance of ER over WR in terms of  $Th_n$  and lightning flash activity. This study corroborates the findings of Rao *et al* (1971) that there exists an east–west gradient in  $Th_n$  activity over Indian region. This validation of the results requires some more fundamental explanation in terms of other parameters. It is well known that the elevation of land surface above the mean sea level is an important surface property that decides the surface heating of the land region. The lower land regions are systematically



Table 4. Values of relative cooling in  $T_{\max}$ , reduction in  $Th_n$  and lightning flash count over WR with respect to ER during April–September.

Months	Cooling in $T_{\max}$ ER minus WR ( $^{\circ}\text{C}$ )	Reduction in $Th_n$ ER minus WR (days)	Reduction in lightning flash count ER minus WR flash count (Number)
April	0.4	0.8	12.4
May	0.1	1.2	14.6
June	0.4	2.5	49.2
July	1.0	2.5	61.8
August	1.2	3.1	64.8
September	0.5	2.7	61.2
Mean	0.6	2.1	44.0
CC $T_{\max}$ : $Th_n$	0.70		
CC $Th_n$ : Lightning	0.97		
CC $T_{\max}$ : Lightning	0.75		

hotter than the far elevated ones. Previous study (Manohar and Kesarkar 2003) has shown that the mean altitude of ER is  $\sim 313$  m (amsl) and that of the WR is  $\sim 580$  m (amsl). This difference in altitude by a factor of about two is an important surface property in maintaining a  $T_{\max}$  contrast over ER and WR.

### 3.3 Occurrence of thunderstorms and development of lightning in relation to surface temperature

The occurrence of thunderstorms and development of lightning in relation to temperature change of surface air, on monthly time-scales, has been a topic of long standing interest in many recent studies (Kandalgaonkar *et al* 2005b and references therein). These studies strongly suggest a close association between surface air temperature and development of thunderstorms. Since lightning originates mainly from thunderstorm clouds, it is also likely that similar relationship should also prevail between these parameters. We have examined one such relationship in this section using the monthly mean data of these parameters over ER and WR. Table 2 provides monthly mean values of  $T_{\max}$ ,  $Th_n$  and lightning flash count over ER and WR. We see that during January–February months,  $T_{\max}$  over WR is higher than over ER. During the period April–September, we see that  $T_{\max}$  over ER is higher than over WR. This observation suggests that WR undergoes more cooling relative to ER. This transformation is very systematic and meaningful because there is also simultaneous reduction in  $Th_n$  values over WR. The reduction in  $Th_n$  following the reduction in  $T_{\max}$  is explainable on the basis of the reduction in CAPE and reduction in buoyancy of a parcel of air (Price 1993). Table 4 provides the details of the values of relative cooling in  $T_{\max}$ , reduction in  $Th_n$  and lightning flash count over WR

with respect to ER during April–September and correlation coefficients between these parameters.

The mean cooling of  $0.6^{\circ}\text{C}$  suggests that for  $1^{\circ}\text{C}$  cooling of  $T_{\max}$ , the reduction in  $Th_n$  works out to be 3.5 and reduction in flash count corresponds to 73 flashes. We note that the  $1^{\circ}\text{C}$  cooling in the  $T_{\max}$  and associated reduction in number of thunderstorms and lightning flash counts are closely related with each other and are highly significant. The actual range of temperature over which this reduction is based is between  $30^{\circ}$  and  $36^{\circ}\text{C}$  and the land region corresponds to the complete land-mass of WR. This result is in agreement with the results of previous studies mentioned earlier. It is to be noted here that the validity of above result may vary with geography of the location of study, but the generality remains that  $Th_n$  and lightning flash count variation is linked with surface maximum air temperature. The changes in the occurrence of thunderstorms dominate or control the variation in lightning activity. This result strongly supports the early results of Williams *et al* (2000) and signifies the important role of thunderstorms in development of lightning over the tropics.

### 3.4 Comparison of monthly mean flash count at different geographic locations representing different climate regimes

The locations of stations Jaisalmer (JSM), Ahmedabad (AHM), Agartala (AGT), and Guwahati (GHT) are shown in figure 1. JSM and AHM are the two land stations to the NW of India and these two stations represent semi-arid zone climate regime. AGT and GHT are the two land stations in the NE India and these stations represent hilly climate regime. This pair of land stations is chosen for the study because they are situated within  $23^{\circ}$ – $27^{\circ}\text{N}$  latitude belt, and their arial distance from the Gulf of Khambhat and

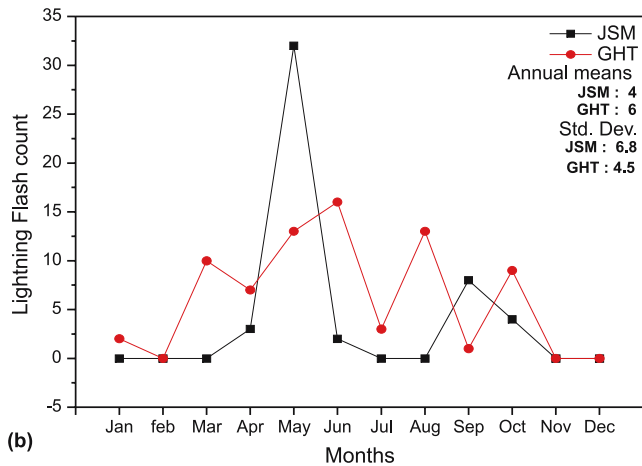
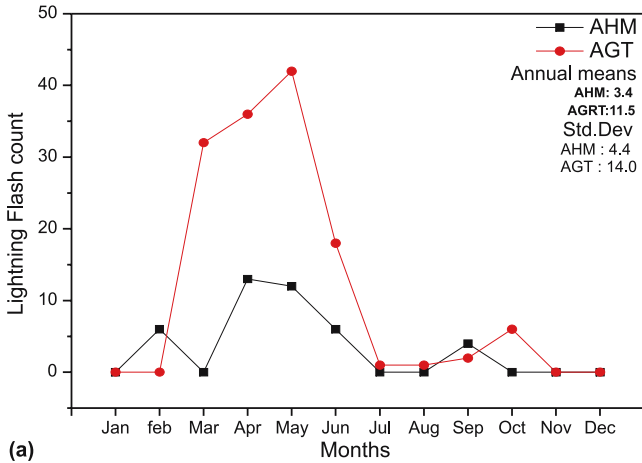


Figure 5. Monthly variation over (a) AHM and AGT (b) JSM and GHT.

Bay of Bengal respectively is nearly the same, i.e., ~350 km. The mean wind direction in the monsoon season from the above-mentioned two sources of water up to these stations is nearly southerly (Rao 1976). An important point of information is that the mean elevation of the semi-arid and hilly regions represented by this pair of stations is much different, and these pairs of stations are ~1100 km east-west apart from each other.

Figure 5(a and b) shows monthly variation of flash count over AHM, AGT and JSM, GHT. The arid zone locations in both figures represent lower score of lightning than that of the NE hilly region of India. In case of AHM and AGT the pattern of monthly variation is quite comparable. The pattern of monthly variation between JSM and GHT is quite different. Over hot but dry land regions marked by arid-zones, lightning activity is much reduced because the conditions are not favourable for the growth of convective storms. In this comparison, hilly regions, in the vicinity of large source of water, tend to show marked increase in lightning activity. This increase in activity is attributed to the effect of orography in the development of

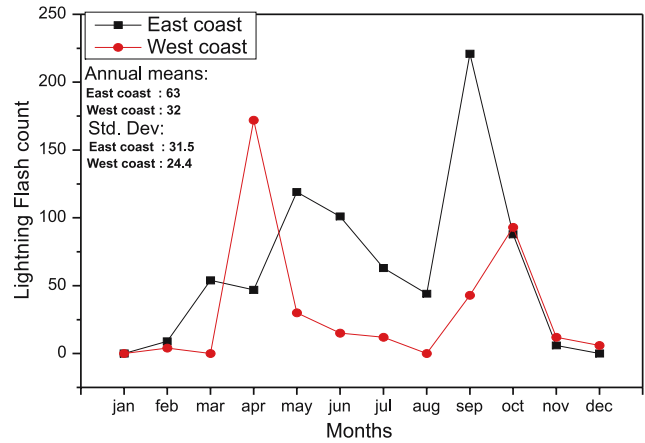
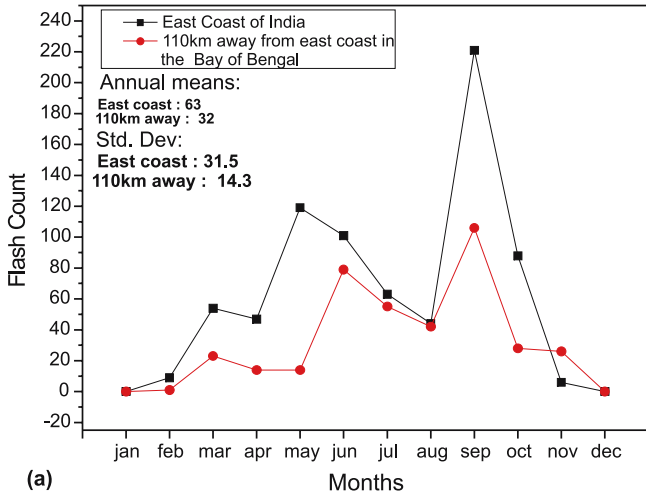


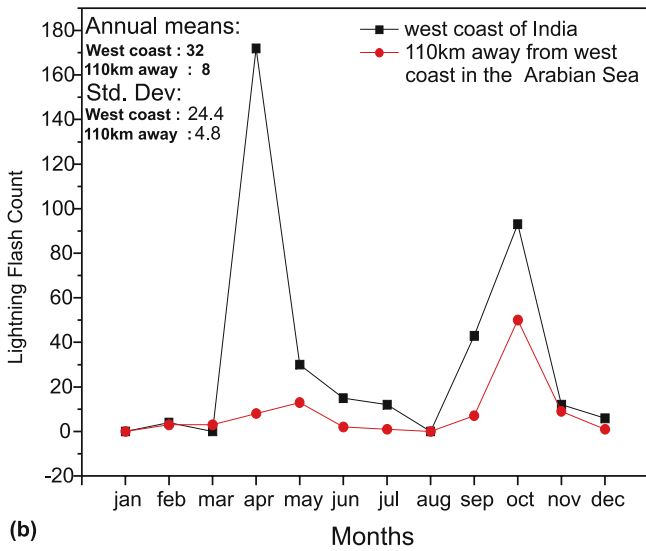
Figure 6. Monthly variation over East and West coasts.

thunderstorms. Irrespective of the fact that there is some similarity and difference in the monthly pattern of lightning flash count between the two pairs of stations: AHM, AGT, and JSM, GHT, the difference found in their annual count over the arid-zone and hilly regions is more alarming. This difference may be explained as follows: Annual frequency of the number of thunderstorm days over a region during a particular year may be a variable number around its climatological mean. But the climatological mean provides a reasonably steady picture of the parameter. We have, therefore, examined the results of recent studies of thunderstorm climatology over India by Pant and Rupakumar (1997) and Manohar and Kesarkar (2004). Their results indicated that the annual frequency of number of thunderstorm days over the arid-zone and hilly regions of NE India varied in the range of 20–30 and 60–80 respectively. Since the best known source of lightning is a thunderstorm cloud, it is reasonable to expect that the difference in lightning flash count will be controlled by the difference in the frequency of thunderstorms (Williams *et al* 2000).

Figure 6 shows monthly variation in flash count over the east coast and west coast of India. The pattern of monthly variation for both locations indicates bimodal variation but with a difference in the months of their occurrence. In case of west coast, the first peak is pronounced while in the case of east coast the second peak is more pronounced. It is noted here that the annual mean of lightning flash count of east coast is nearly twice higher than that of the west coast. We note that the bimodal variation of lightning flash count over the two coastal belts of India, which lie within the tropics, is analogous with the bimodal oscillation of the number of thunderstorm days (Manohar and Kesarkar 2005). Variations in the incoming shortwave radiation from the sun are attributed to be ultimately responsible for variations in global meteorological parameters on the



(a)



(b)

Figure 7. Monthly variation over (a) East coast and a strip of oceanic stations, and (b) West coast and a strip of oceanic stations.

seasonal timescale. From figure 6, we note that during the period June–August, the east coast lightning activity decreases step-wise, and becomes minimum in the month of August. This observation appears to be consistent with the fact that east coast region around the latitude of 15°N and south of it, is less dominated by the southwest monsoon. In the months of September and October, lightning activity is picked up. This increase in lightning activity around the months of September and October is believed to be associated with the mark of the postmonsoon season over the stretch of east coast south of 15°N. In this period, tropical cyclones are formed over the Bay of Bengal. The maximum lightning activity noted may be due to the formation of thunderstorms due to retreating ITCZ and synoptic scale systems (Sikka and Gadgil 1980; Manohar *et al* 1999; Kandalgaonkar *et al* 2005).

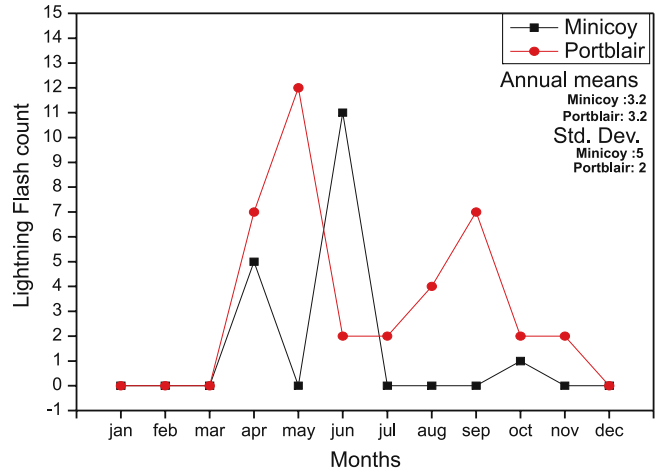


Figure 8. Monthly variation over two island stations (MNC and PBL).

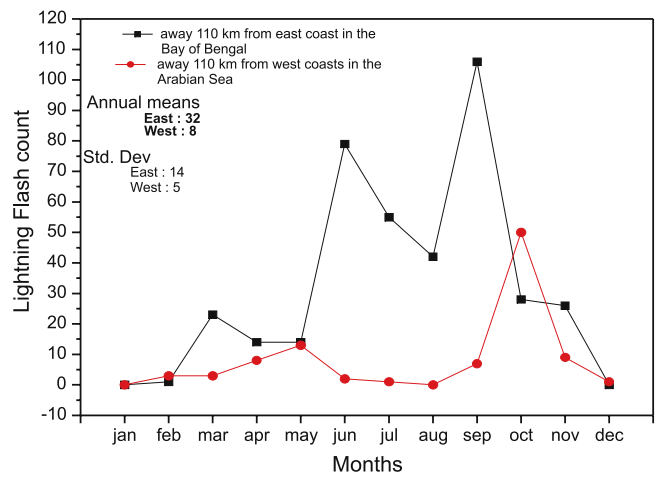


Figure 9. Monthly mean variation of flash count at six pairs of locations representing different climate regimes.

Figure 7 (a and b) displays monthly variation in flash count over east and west coasts and over a strip of oceanic stations 110 km away from them. Two curves in both the figures represent identical pattern of variation but with a clear difference such that east and west coasts score nearly twice or higher activity than that over the oceanic strip 110 km inside the ocean. An important and notable inference that could be drawn from these observations is that the lightning activity declines by a factor of 2–4 as we move away from the landmass and enter the oceanic climate.

Figure 8 shows variation in flash count over two island stations, one in the Bay of Bengal (PBL) and the other in the Arabian Sea (MNC). We note that the score of both the island stations is same, but the standard deviation of MNC is higher. Shown in figure 9 is the comparison of variation in flash count over the two off-coast oceanic strips. It is very critical and important to note that amongst

Table 5. Annual mean and standard deviation of lightning flash count at various locations representing different climate regimes.

Climate regime	Annual mean lightning flash count and no. of stations on which these means are based			Normalized value of flash count, i.e., for 100 stations
	Flash count	Standard deviation	No. of stations	
Continental (ER)	361	173	40	903
Continental (WR)	240	132	40	600
Coastal (East coast)	63	32	6	1050
Coastal (West coast)	32	24	6	533
Off East coast	32	14	6	533
Off West coast	8	5	6	133
Hilly region of NE India (GHT)	6	4	1	600
Hilly region of NE India (AGT)	11	14	1	1100
Semi-arid zone of NW India (AHM)	3	4	1	400
Semi-arid zone of NW India (JSM)	4	7	1	400
Oceanic (MNC)	3	5	1	320
Oceanic (PBL)	3	2	1	320

the two oceanic strips, the strip situated 110 km off the east coast located within the Bay of Bengal has a higher score than that over the strip located within the Arabian Sea. Thus the present study points out that lightning activity tends to increase over tropical moist and hot extensive land regions and as we move out away from the land region into the seas, lightning activity decreases. This property of response of lightning is termed as land–ocean contrast.

For summarizing the contrast in lightning flash count over land and oceanic areas, we provide mean values of key physical parameters which favour strong and weak electrification of the thunderstorms over continents in the tropics and over oceans. From a comprehensive study by Williams and Stanfill (2002), these values are reproduced in the following contingent table:

Parameter	Average value	
	Land	Ocean
Surface relative humidity (%)	20–60	80
Cloud base height (m, amsl)	1000–4000	500
Bowen ratio (sensible heat/latent heat)	0.2–1.0	0.1
Updraft width (km)	1–3	0.5–1.0
Updraft ( $\text{ms}^{-1}$ )	> 10	~ 3

### 3.5 Lightning flash count over different climate regimes

In the previous section of this study, we have presented results of monthly (January–December) values of lightning flash count at various geographic locations of India. A comparative study of the lightning activity over such locations is presented in this section. Table 5 shows the annual mean and standard deviation of lightning flash count at different climate regimes, and the number of stations on which these means are based. Provided in the last column are the normalized values of flash count at each location.

The normalized annual mean values of flash count are plotted in figure 10 in their ascending order and given serial numbers 1, 2, 3, . . . , 12. At each point of the plot the name of the corresponding climate regime is labelled. A straight line of best fit is drawn through the points. It is clear from the plot that most points lay close to the line on its either side, which implies that there exists a prominent relation between the climate regime and intensity of lightning activity. A close and inquisitive look at the figure indicates that lightning flash count over continents and hilly regions in the tropics is high and its relative measure tends to remain near the upper end of the scale. Lightning activity over areas influenced by dry and marine climatic conditions (semi-arid and island) tends to remain along the central and lower end of the scale. It is felt that long term observations of lightning

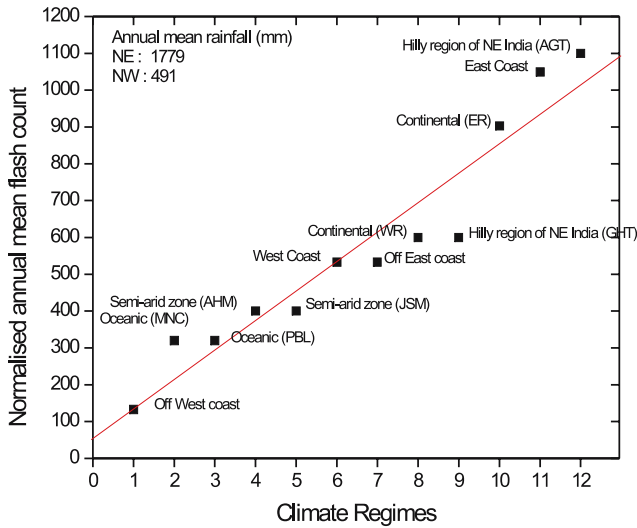


Figure 10. Normalized annual mean values of flash count at locations representing different climate regimes.

at such locations are necessary to arrive at a reasonable and steady picture of this parameter. Some explanation for this observation may be sought in the surface properties such as; lower heat capacity of land, immobile nature of rock-soil, vegetation and topography of a region. As explained by Williams and Stanfill (2002), the land or deep continents in the tropics are systematically hotter and more moist, and hence the lower atmosphere is more unstable to cause vertical air motions. These vertical air motions are usually in excess of 10 m/s and are vital for the generation of deep convection or the development of thunderstorms. The effect of mountain ranges (Garo-Khasi and Arakan Yoma to Patkai hills) on the development of thunderstorms in the NE region of India is profound. The Garo-Khasi hills are 300 km in length and 70 km in width running east to west. The highest peaks in these ranges of hills are  $\sim 2$  km (amsl). The effect of orographic structure, nearness to the Bay of Bengal, and southerly-southwesterly mean wind flow during March–September, on the development of thunderstorms in this area is well known and well described by Rao (1976) and documented in a recent study by Manohar and Kesarkar (2005). Results of a recent study (Chaudhari 2006) concerning the development of thunderstorms over north eastern part of India are important. Their study summarized that CAPE should attain the threshold values of 7000 J/kg and CINE (Convective Inhibition Energy) should not exceed 100 J/kg respectively for the occurrence of severe thunderstorms. This situation is witnessed quite frequently over NE regions of India during the pre-monsoon season. In the hot but dry environment of the NW India, occupied by deserts and semi-arid zone, annual frequency of thunderstorms is low (less than

50% that of the NE region). Storms under such conditions have usually high cloud bases and produce little electrification and precipitation at the ground (Reap 1986). Annual mean rainfall, averaged for the five-year period, 1995–1999 over NE and NW regions of India is also furnished (source: www.tropmet.res.in) in figure 10 to represent the relevance between lightning and rainfall amount. Many studies are devoted to the understanding of oceanic thunderstorms (Zipser 1994; Zipser and Lutz 1994). They suggest that absence of strong ( $> 10$  mps) updrafts in the mixed phase region is responsible for the low or near absence of lightning activity in oceanic storms.

### 3.6 Sources of errors in lightning flash count and the probable correction

There could be probable few sources of errors in lightning flash count in this study. A brief discussion on these sources of errors is desirable here. It is felt that due considerations of these errors should be made while taking into account the results of this study. We note that the inbuilt detection efficiency of the OTD system, as mentioned in the literature, is in the range 40–65% (Christian *et al* 1996) and 46–69% (Boccippio *et al* 2000a). This large range of variation of efficiency depends on various factors such as: external brightness conditions, small-scale nature of weather system, and the polar orbit of the satellite and the simultaneity of the weather event. In this study, we have focused our attention to the comparison of monthly (seasonal) variations of lightning flash count over extended regions of India. Therefore, the overhead absence of the satellite when lightning occurs and the external brightness conditions are the two pertinent causes of worry for the loss of data. Over these causes of loss of data, we do not have any control. In the absence of exact information about the source of error and the correction to be applied, we have not been able to allow for any corrections to our results. It is hard to fix the proper range of correction to the results of this study. However, it is felt that the correction of about 50% to the results of this study may be appropriate.

## 4. Conclusions

The monthly mean variation of lightning activity,  $T_{\max}$ , and  $Th_n$  over the two largest adjacent land regions (ER and WR) of India showed remarkable matching between the three parameters. Our analysis showed that as we move out of winter season and enter the monsoon season (May–September); via pre-monsoon season: the WR

undergoes cooling relative to the ER in the range 0.1 to 1.2°C. As a consequence, WR experiences reduction in the number of thunder days as well as lowering of flash count. This decrease in  $T_{\max}$ ,  $Th_n$ , and flash count over WR may also be associated with relatively small values of  $T_{\max}$  and CAPE in comparison with similar values over ER during the monsoon season. Thus the present study reveals that for cooling of 1°C in surface air maximum temperature results in the reduction of ~3.5 thunderstorms per station and 73 flashes. Summary of the comparison of lightning flashes between pairs of coastal, oceanic, arid-zone, and hilly, and island stations suggests possible relationship between climate regime and intensity of lightning activity. The hilly and deep inland tropical locations are usually placed at the top of the scale than the oceanic and arid-zone areas. Surface properties such as orography, site location, and deep inland placement and nearness to source of water, etc., are primarily responsible for the observed differences noted in the study. We may conclude the results of this study by saying that the overhead lightning activity is a clear reflection of the status of the underlying ground-earth properties. A close and continuous monitoring of lightning activity may be considered as a need of present day scientific studies. More studies are planned for future research to elucidate the observed association between flash count and various meteorological/geographical parameters.

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