

Spatial and temporal variations of thunderstorm activities over Sri Lanka

Upul Sonnadara¹

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Abstract Spatial and temporal variation of frequencies of thunderstorms over Sri Lanka using thunder day data is presented. A thunder day is simply a calendar day in which thunder is heard at least once at a given location. Two sets of data were collected and analyzed: annual totals for 10 climatological stations for a period of 50 years and monthly totals for 20 climatological stations for a period of 20 years. The average annual thunder days over Sri Lanka was found to be 76. Among the climatological stations considered, a high number of annual thunder days was recorded in Ratnapura (150 days/year), followed by Colombo (108 days/year) and Bandarawela (106 days/year). It appears that there are no widespread long-term increasing or decreasing trends in thunderstorm frequencies. However, Colombo, the capital of Sri Lanka which has over two million people shows an increasing trend of 0.8 thunder days per year. Although there is a high variability between stations reporting the number of thunder days, the overall pattern within a year is clear. Thunderstorm frequencies are high during two periods: March–May and September–November, which coincide with the first inter-monsoon and second inter-monsoon periods. Compared to the dry zone, the wet zone, especially the southwestern region, has high thunderstorm activity. There is a clear spatial difference in thunderstorm activities during the southwest and northeast monsoon seasons. During both these seasons, enhanced thunderstorm activities are reported on the leeward side of the mountain range. A slight reduction in the thunderstorm activities was found in the high elevation areas of the hill country compared to the surrounding

areas. A lightning ground flash density map derived using annual thunder days is also presented.

1 Introduction

Thunder days or thunder events recorded from very early days in climatological stations have been used to study the characteristics of thunderstorms worldwide. For example, Changnon (1988a; 1988b) described the temporal and spatial aspects of thunderstorms in the USA using thunder events recorded in 152 first-order stations during the period 1948–1977. In a subsequent study, thunder day occurrences during a 100-year period based on data from 86 first-order stations were used to investigate the long-term fluctuations in thunderstorm activities in the USA (Changnon and Changnon 2001). In Japan, the long-term variations of thunder day frequencies in various regions have been investigated by using 100-year thunder day records (Kitagawa 1989). The long-term variability of thunderstorm occurrence in Poland was investigated by using thunder day observations from 56 stations in the period 1951–2000 representing all geographical regions (Bielec-Bakowska 2003). Kuleshov et al. (2002) studied the distribution and frequency of thunderstorms in Australia using thunder day data from 300 sites over a period of 10 years. Although improved techniques to monitor activities in thunderstorms over large regions such as lightning locating systems (Orville et al. 2002) and more recently satellite-based optical sensors (Christian et al. 2003) are now available, long-term variations of thunderstorm activities (20 years or more) related to change in climate are still derived through the thunder day observations.

Sri Lanka has a warm and tropical climate with frequent thunder activities due to its position between 5° and 10° North latitudes. However, studies are not yet available in literature

✉ Upul Sonnadara
upul@phys.cmb.ac.lk

¹ Department of Physics, University of Colombo, Colombo 3, Sri Lanka

that could provide an insight into the climatology of thunderstorm activities over Sri Lanka. In the past, there have been several attempts to study the cloud to ground flash activities in thunderstorms over Sri Lanka and in the surrounding areas by using the data provided by an experimental scale implementation of a lightning locating system (Sonnadara et al. 2000; Weerasekera et al. 2001; Liyanage et al. 2002). Frequent interruptions caused by power failures, insufficient coverage due to a limited number of sensors, and serially complete quality data are not yet available for sufficiently long periods. Although thunder day data is available at climatological stations scattered around the country with a reasonable coverage for many years, systematic studies have not been carried out to investigate the distribution and frequency of thunderstorm activities. Thus, the main purpose of this work is to present for the first time, the thunderstorm activities over Sri Lanka using thunder day observations. The results are presented for the occurrence of thunderstorm activities in relation to spatial and temporal variations. A ground flash density map was also produced based on the thunder day data from 1991 to 2010.

2 Data sample

The only records related to thunderstorm activities maintained by the Department of Meteorology, Sri Lanka, are the thunder day data. A thunder day is defined as a 24-h period during which at least one thunderstorm occurred. However, since thunderstorm occurrences at a climatological station are recorded purely based on hearing thunder, careful screening of data is required (Changnon 2001). For the present analysis, two sets of high-quality thunder day data were obtained from the Department of Meteorology. The first set consisted of monthly totals of thunder days for 20 stations for a 20-year period (1991–2010). The second set consisted of annual totals of thunder days for 10 stations for a 50-year period (1961–2010). These stations are located in different geographical regions and cover different climatic conditions that are experienced in Sri Lanka. Unfortunately, data from stations in the northern and eastern part of Sri Lanka such as Jaffna, Mannar, Vavunia, and Pottuvil consisted of missing values from 1980 to 1993 due to social unrests and hostilities in the region. The data from Jaffna are available only after 2000. Thus, the lengths of the time series had to be truncated for those stations.

The thunder day data were carefully evaluated prior to the analysis. In the 50-year data set, one of the stations, Ratnapura, had an unusual increase in thunderstorm frequencies after 1990. It was found that the location of the station had been changed from a lower elevation of 34.45 m to a higher elevation of 86.29 m in August 1993. In addition, in May 1994, the two-men observation at the same station had been changed to a 4-men observation. Thus, the data from the station was not used in the trend analysis. In January 2001, the

observations at the Galle station were also changed from a 2-men observation to a 4-men observation. In November 1983, the Trincomalee station had been shifted from Fort Frederick to a nearby Navy Base. No apparent shift in the data was observed for both stations. In relation to the 20-year data set with more recent observations, the location of only one station, Mannar, had been changed in June 2007 to a new location not too far from the previous location. Except for Ratnapura, there were no changes in the observational procedures for the 20-year data set. However, since 8 out of the 20 stations used in this work had 2-men observations (which limits the usual 8 observations per day to 6), the results presented in this work can be considered as a lower limit for thunder day frequencies in Sri Lanka.

The list of stations used in this work together with their geographical details and the length of thunder day data records used in the present analysis are given in Table 1.

3 Results and discussion

3.1 Temporal variations

3.1.1 Frequency of thunderstorms

In order to study the short-term variations in the average frequency of thunderstorm activities over Sri Lanka, annual average thunder days were calculated by combining data from all the stations. The annual variability of the number of thunder days is shown in Fig. 1a. The error bars in the figure indicate the error of the mean computed with data from all available stations for a given year (i.e., σ/\sqrt{n} where σ is the standard deviation and n is the number of stations). During the period from 1991 to 2010, there were 1525 days with thunderstorms or about 76 thunder days per year on average over the island. The highest number of days with thunderstorms per year is 103 days and the lowest is 61 days. The data show that there is no high inter-annual variability or significant increasing or decreasing trends in the average number of thunderstorms during the last 20 years over Sri Lanka.

In Fig. 1b, the monthly distribution of days with thunderstorms is shown. Although there is a considerable variation in the thunderstorms reported by each station in different months, a general pattern is quite clear. Two peaks in the figure correspond to the start of the first inter-monsoon (April) period and the second inter-monsoon period (October). Traditionally, frequent lightning strikes are known to occur during the month of April which is the Sinhala/Tamil New Year season which is known as “Bak Maha Akunu.” Loss of human life due to lightning strikes is high during this month. High thunderstorm activities are observed during two periods annually, March–May and September–November. This pattern agrees very well with the bimodal pattern of

Table 1 List of stations selected for the study, their geographical information, and the period of thunder day data used

No.	Station name	Latitude N°	Longitude E°	Elevation (m)	Period	Length (years)
1	Anuradhapura	8.35	80.38	93	1961–2010	50
2	Badulla	6.95	81.05	670	1991–2010	20
3	Bandarawela	6.83	80.98	1248	1991–2010	20
4	Batticaloa	7.72	81.72	8	1991–2010	20
5	Colombo	6.90	79.87	7	1961–2010	50
6	Galle	6.03	80.22	13	1961–2010	50
7	Hambantota	6.12	81.13	16	1961–2010	50
8	Jaffna	9.65	80.02	4	2001–2010	10
9	Kandy	7.33	80.63	417	1961–2010	50
10	Katunayake	7.17	79.88	9	1961–2010	50
11	Kurunegala	7.47	80.50	116	1991–2010	20
12	Maha Illukpallama	8.08	80.38	117	1991–2010	20
13	Mannar	8.83	79.92	4	1994–2010	17
14	Nuwara Eliya	6.97	80.77	1895	1961–2010	50
15	Pottuvil	6.88	81.83	8	1994–2010	17
16	Puttalam	8.03	79.83	2	1961–2010	50
17	Ratmalana	6.82	79.88	5	1991–2010	20
18	Ratnapura	6.68	80.40	86	1961–2010	50
19	Trincomalee	8.58	81.25	24	1961–2010	50
20	Vavunia	8.75	80.50	106	1992–2010	19

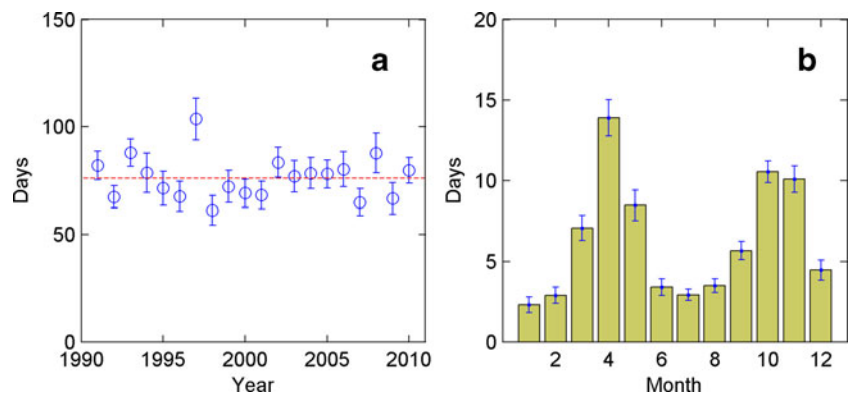
rainfall or rainy days observed over the island for most locations particularly in the wet zone which is in the southwestern part of the island (Suppiah 1989).

During the month of April, for the highest number of thunder days, 30 was recorded at the Ratnapura (80.40° E, 6.68° N) climatological station in the wet zone while the lowest number of thunder days, and 8 was recorded at the Pottuvil (81.83° E, 6.88° N) climatological station in the dry zone. On average, the distribution of frequency of thunderstorm days during the commonly identified four seasons are as follows: first inter-monsoon (March to April)—11 days/month, southwest monsoon (May to September)—5 day/month, second inter-monsoon (October to November)—10 days/month and northeast monsoon (December to February)—3 days/month.

Clearly, the frequency of thunderstorms dominates during the inter-monsoon periods.

The high percentage of thunderstorms associated with inter-monsoons is due to the fact that the Inter Tropical Convection Zone (ITCZ) is positioned over Sri Lanka during these two periods. The ITCZ is a region where trade winds from the southern hemisphere and northern hemisphere converge and appear as a band of clouds that encircle the globe near the equator. The ITCZ induces semi-persistent low-pressure conditions causing heavy rain and lightning. During the first inter-monsoon period, the ITCZ migrates from south to north over Sri Lanka, with moisture-laden air accumulated through the long track over the Indian Ocean. The energy released from latent heat due to condensation is high during

Fig. 1 Mean number of days with thunderstorms observed during the period 1991–2010 computed using data recorded in 20 stations. The error bars indicate the errors in the mean value. **a** Annual variation; **b** monthly variation



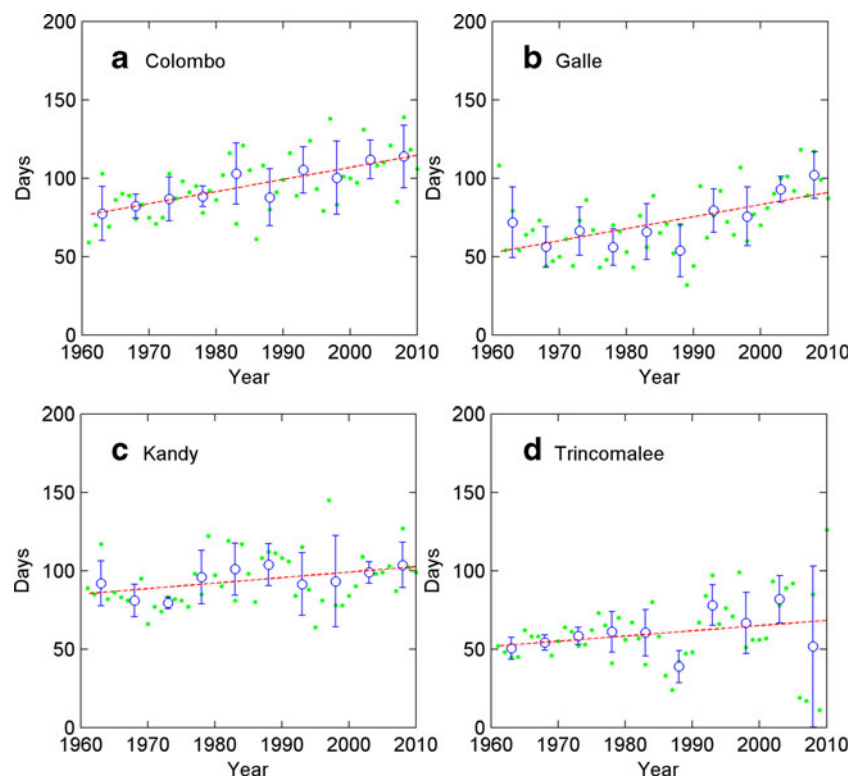
this season, which is favorable for vigorous thunderstorms. Therefore, strong thunderstorm activities with lightning are frequent during this season. During the second inter-monsoon period, ITCZ migrates from north to south. During this period, since the air is comparatively cooler, although thunderstorm activities with lightning are high, it is less pronounced compared to first inter-monsoon period. Even during the southwest monsoon period, the influence of the ITCZ is felt because its location is closely related to the summer monsoon trough over South Asia (Suppiah 1989).

3.1.2 Long-term variations

The long-term variations of annual thunderstorms were studied using the 10 selected climatology stations having data from 1961 to 2010. The stations were selected with the intention to capture the variations in thunderstorm frequencies in the low-lying areas of the wet zone (Colombo, Katunayake, and Galle), the hill country region (Kandy, Nuwara Eliya and Ratnapura), and the dry zone (Puttalam, Trincomalee, Anuradhapura, and Hambantota) which accounts for about 60 % of the total land area of the island. Initial screening of the data showed that an unusual shift in the thunder day frequencies after the 1990s in one of the selected stations in the hill country (Ratnapura). This was attributed to a change in location and observation procedures. Thus, it was excluded from the trend analysis. Linear trends based on 5-year average thunder day values for the remaining nine stations revealed

positive trends in five stations and unchanged trends in four stations. Of the five stations which showed positive trends, Colombo (+0.77 days/year), Galle (+0.76 days/year), Kandy (+0.35 days/year), and Trincomalee (+0.33 days/year) show trends which are significant at 95 % level while Puttalam (+0.22 days/year) showing a trend significant at 90 % level (see Fig. 2a–d). The highest increasing trend was observed at Colombo, the capital of Sri Lanka which has more than two million people and is located in the western coast of the island. However, Katunayake where the international airport is located and the closest station to Colombo did not show any significant increasing or decreasing trend in thunderstorm activities during last 50 years. Similarly, although Kandy and Trincomalee show significant increasing trends, stations in similar geographical regions such as Nuwara Eliya and Anuradhapura did not show any trends. From the stations in the dry zone, the highest increasing trend was observed at Trincomalee which is in the eastern coast of the island. The detrended time series data for the selected stations showed that the standard deviations of the thunder day frequencies are in the order of 11–21 days. The local influences including localized unstable air masses, topographical effects, and coastal effects may cause differences in thunderstorm frequencies in adjacent stations. We conclude from the analysis that there is no clear indication of any widespread increasing or decreasing trends in thunderstorm frequencies in Sri Lanka.

Fig. 2 Linear trend of days with thunderstorms for the period 1961–2010. **a** Colombo, **b** Galle, **c** Kandy, and **d** Trincomalee. Open circles represent the 5-year average of thunder days while the dashed line represents the linear fit to the data



3.2 Spatial variations

3.2.1 Annual variations

Figure 3 shows the geographical locations of the stations selected in this work along with the pattern of thunderstorm activities based on average annual thunder days over Sri Lanka in the period 1991–2010. The pattern indicates that the thunderstorms are most frequent in the wet zone (southwestern part) of the island and generally decrease when moving from the hill country high-elevation areas towards the dry zone (eastern part) low-land areas with the lowest frequencies in the northwestern coast and the southeastern coast. The maximum storm frequency exceeding 140 thunder days per year is observed in the region of Ratnapura (80.40° E, 6.68° N) which is at an elevation of 34 m from sea level. This finding is consistent with the earlier observations carried out with a limited data set taken from a lightning locating system consisting of two direction finders (Weerasekera et al. 2001). Ratnapura shows a clear bimodal pattern for thunderstorm activities with

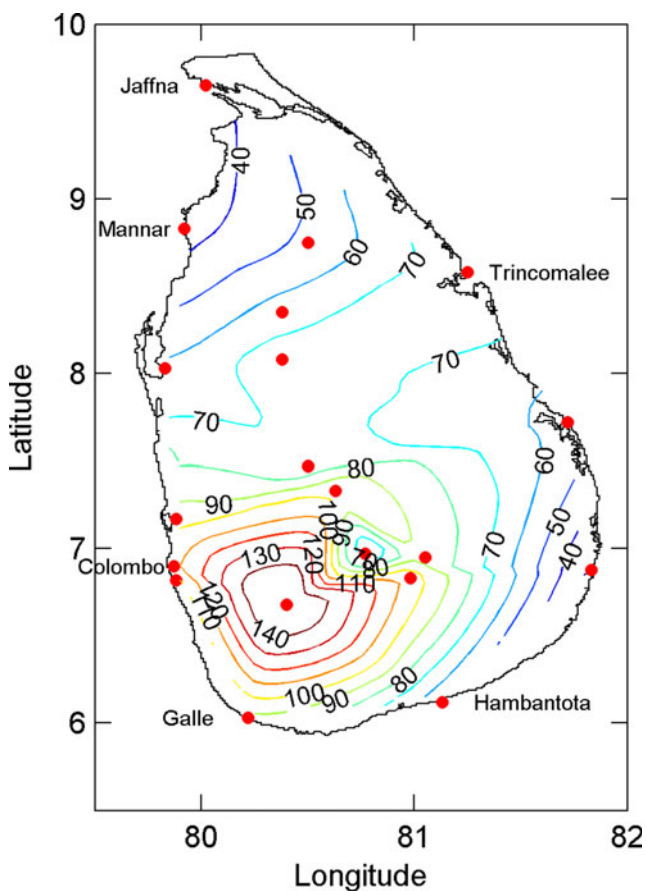


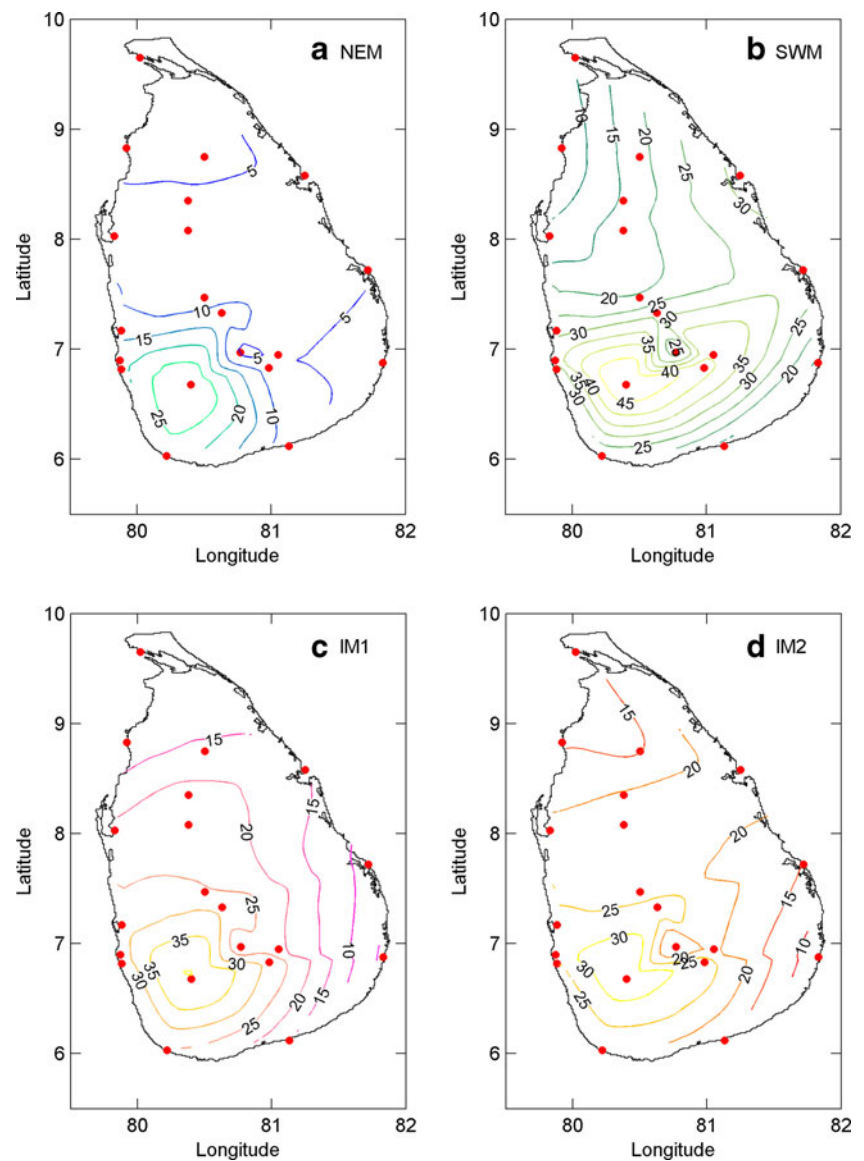
Fig. 3 Spatial distribution of the annual thunderstorm activities. Geographical locations of the weather stations used in this work is also shown (closed circles). The highest number of thunderstorm days exceeding 140 thunder days is observed in the region of Ratnapura in the wet zone

the first peak in the month of April and the second peak in the month of November closely following the mean monthly distribution of thunderstorm days (Fig. 1b). The highly populated coastal regions of the southwestern region of the island also show high thunderstorm activities with over 100 thunder days per year. The areas of least frequent thunder events with less than 40 thunderstorm days per year are seen in the semi-arid regions around Mannar (79.92° E, 8.83° N) and Pottuvil (81.83° E, 6.88° N) which are basically situated in the two opposite corners of the island. The high-elevation areas in the central hills in the region of Nuwara Eliya (80.77° E, 6.97° N) also show less thunderstorm activities compared to its surrounding areas. The eastern coastal region close to Trincomalee (81.25° E, 8.58° N) showed relatively high thunder activities with over 70 thunder days per year.

3.2.2 Seasonal variations

The seasonal variation of thunderstorm frequencies is shown in Fig. 4a–d, for four seasons, namely the northeast monsoon (winter monsoon), the southwest monsoon (summer monsoon), the first inter-monsoon and the second inter-monsoon. During the northeast monsoon season (December–February), although the rainfall is predominantly received in the northeastern region of the island, the thunderstorm activities are recorded in the southwestern region in the leeward side of the central hills which is quite unexpected. During this season, thunderstorms are less frequent in the whole of the dry zone with less than 5 thunder days per season. In contrast, the wet zone reports about two to five times more thunder activities. During the southwest monsoon season (June–September), the thunder activities are more or less comparable in the southwestern region and the northeastern region of the island. This is also unexpected since the rainfall is received in the southwestern region, and the northeastern region is located on the leeward side of the central hills. It appears that during the southwest and northeast monsoon seasons, the thunder activities are enhanced on the leeward side of the mountain range while most of the rainfall is received on the windward side of the mountain range. Although not specifically discussed or noted, this observation confirms the reconstructed strike locations of lightning ground flashes recorded during the northeast and southwest monsoon periods in an earlier published work (Weerasekera et al. 2001). During the first inter-monsoon season (April–May) and the second inter-monsoon season (October–November), thunderstorm activities are distributed throughout the island with the southwestern sector having roughly two times more activities compared to the rest of the island. Thus, the geographical location and seasonality are important factors to be considered in the estimation of thunderstorm frequencies.

Fig. 4 Spatial distribution of thunderstorm activities by season. **a** Northeast monsoon. **b** Southwest monsoon. **c** First inter-monsoon. **d** Second inter-monsoon



3.3 Lightning ground flash density

One of the parameters useful in deriving from the thunder days is the lightning ground flash density. However, how well they are related and the relationships between the two are not very well known for different geographical regions. Since many lightning flashes could occur within a given thunder day, a smaller unit such as thunder hour may show a better correlation with lightning flash densities than thunder days. In addition, while a thunder day is estimated considering all thunder events, the ratio between cloud flashes to ground flashes depends on the local conditions, season, as well as on the latitude (Prentice and Mackerras 1977). In general, the lightning ground flash density N_g can be estimated from annual thunder days T_D by using an equation of the form:

$$N_g = a \times T_D^b \text{ km}^{-2}\text{yr}^{-1}$$

where a and b are empirically derived constants that depend on the meteorological condition of a given location (Kuleshov and Jayaratne 2004). One of the early estimates derived from the above equation for Australia was carried out by Mackerras (1978) based on 26 sites where the annual thunder day level varied from about 10 to about 100. The derived values were $a=0.01$ and $b=1.4$. Anderson and Eriksson (1980) carried out a study based on 120 observations in South Africa where the annual thunder day level varied from about 3 to about 100. Their derived values were $a=0.023$ and $b=1.3$, and the corresponding equation has since become known as Eriksson's formula (Kuleshov and Jayaratne 2004).

In this work, we have used Mackerras and Eriksson's formulas to derive the annual lightning ground flash densities using the average annual thunder day data measured at 20 sites in Sri Lanka from 1991 to 2010. The results of this analysis are given in Table 2. The third and fourth columns in the table

Table 2 Average annual thunder days estimated from the 1991 to 2010 data set, their standard deviations and estimated annual lightning flash densities for the selected 20 sites. Zone simply identifies whether the selected stations belong to the wet zone or the dry zone

No.	Station name	T_D days	$\sigma(T_D)$ days	Mackerras $\text{km}^{-2} \text{year}^{-1}$	Eriksson's $\text{km}^{-2} \text{year}^{-1}$	Zone
1	Anuradhapura	64.5	14.0	3.41	5.17	Dry
2	Badulla	87.2	16.6	5.21	7.66	Wet
3	Bandarawela	105.9	17.6	6.83	9.86	Wet
4	Batticaloa	55.6	17.3	2.77	4.27	Dry
5	Colombo	107.8	17.5	7.00	10.09	Wet
6	Galle	87.5	17.1	5.23	7.69	Wet
7	Hambantota	51.1	10.8	2.46	3.82	Dry
8	Jaffna	30.7	9.1	1.21	1.97	Dry
9	Kandy	96.8	18.4	6.02	8.77	Wet
10	Katunayake	96.0	17.7	5.95	8.68	Wet
11	Kurunegala	75.4	16.9	4.25	6.34	Wet
12	Maha Illukpallama	73.5	13.4	4.10	6.14	Dry
13	Mannar	35.8	18.7	1.50	2.41	Dry
14	Nuwara Eliya	65.4	13.3	3.48	5.27	Wet
15	Pottuvil	27.5	15.1	1.03	1.71	Dry
16	Puttalam	61.7	13.5	3.21	4.89	Dry
17	Ratmalana	97.0	16.3	6.05	8.80	Wet
18	Ratnapura	149.5	23.1	11.08	15.44	Wet
19	Trincomalee	69.8	27.3	3.81	5.74	Dry
20	Vavunia	51.0	13.7	2.46	3.82	Dry

show the average annual thunder days and their standard deviations. The next two columns show the flash densities derived from Mackerras and Eriksson's formulas. The Eriksson's formula gives approximately a factor of 1.5 higher values for flash densities compared to Mackerras formula. A recent study carried out in Australia (Kuleshov and Jayaratne 2004) has observed close agreement with the values estimated from Eriksson's formula.

Due to the tropical climate and the location of Sri Lanka, the frequency of thunder activities is high. Regions with a higher number of thunder days have more lightning flashes per thunder day compared to regions with a lower number of thunder days (Mackerras 1978). Since the minimum and maximum number of thunder days measured in 20 sites selected for this work varies by a factor of 5, Eriksson's formula is preferred over Mackerras' formula which derives comparatively high flash densities when the number of thunder days is high. If we use Eriksson's formula to derive the values, the average ground flash density for Sri Lanka is 6 flashes $\text{km}^{-2} \text{year}^{-1}$. The maximum and minimum flash densities observed at Ratnapura (80.40° E , 6.68° N) and Pottuvil (81.83° E , 6.88° N) are 15 and 2 flashes $\text{km}^{-2} \text{year}^{-1}$ respectively. In the wet zone, flash densities vary from 6 to 15 flashes $\text{km}^{-2} \text{year}^{-1}$ while in the dry zone, flash densities vary from 2 to 7 flashes $\text{km}^{-2} \text{year}^{-1}$. Overall, the flash density in the wet zone is twice as much as the flash density in the dry zone. The spatial variation of

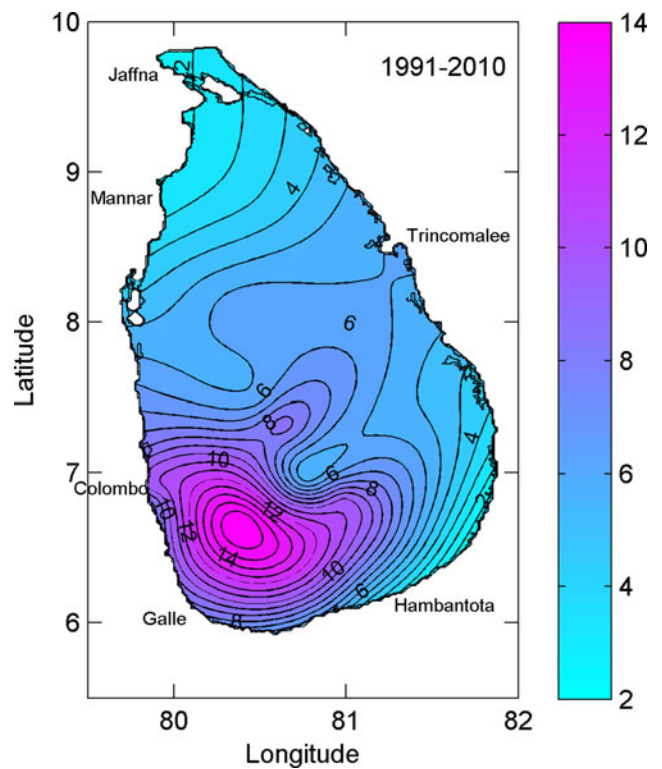


Fig. 5 Spatial distribution of the annual ground flash densities derived from Eriksson's formula based on thunder day data recorded during the period from 1991 to 2010. The highest flash density exceeding 14 flashes $\text{km}^{-2} \text{year}^{-1}$ is observed in the region of Ratnapura in the wet zone

lightning flash densities derived through Eriksson's formula is shown in Fig. 5.

4 Conclusions

This work was initiated to study the thunderstorm activities over Sri Lanka from thunder day data. Since thunder day data do not originate from a direct scientific measurement, data were limited to observations from first-order climatological stations maintained by the department of meteorology, Sri Lanka. Two data sets were used in this work; monthly thunder day data of 20 years from 20 climatological stations and annual thunder day data of 50 years from 10 climatological stations.

The average annual thunder days over Sri Lanka was 76 days. Locations such as Ratnapura, (80.40° E, 6.68° N), Colombo (79.87° E, 6.90° N), and Bandarawela (80.98° E, 6.83° N) reported high thunderstorm activities compared to other areas. Compared to the dry zone, the thunderstorm activities are high in the wet zone. The frequency of thunderstorms over the island is high during the months from March–May and September–November, which coincides with the two inter-monsoon periods. A trend analysis with a 50-year data set revealed a statistically significant increase in thunderstorm frequencies in some of the stations. Since stations in the same geographical regions do not show similar trends, any widespread increasing or decreasing trends in thunderstorm activities were ruled out.

There is a clear spatial difference between the thunderstorm activities observed during southwest monsoon and northeast monsoon periods. During the southwest and the northeast monsoon seasons, thunderstorm activities are enhanced on the leeward side of the mountain range when the rainfall is received in the windward side of the mountain range. It appears that high-elevation areas in the hill country have less thunderstorm activities compared to the surrounding areas. Further studies are required to strengthen these findings.

The lightning ground flash densities were derived using annual average thunder days with the findings from the studies carried out in Australia (Mackerras 1978) and South Africa (Anderson and Eriksson 1980). The Eriksson's formula which is widely used gives a factor of 1.5 higher flash densities compared to Mackerras formula. The average ground flash density for Sri Lanka is 6 flashes $\text{km}^{-2} \text{year}^{-1}$ based on Eriksson's formula. The highest flash density was found to be 14 flashes $\text{km}^{-2} \text{year}^{-1}$. We believe that the spatial

distribution of annual ground flash density presented in this work based on 20 years of thunder day data records adequately represents the lightning frequency contours for various regions and hence can be used in other climate related studies.

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