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Research Paper

Lightning response during Forbush Decrease in the tropics and subtropics

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ABSTRACT

Galactic cosmic rays (GCRs), modulated by the heliospheric magnetic field (HMF), are speculated to provide a possible link between solar activities and the earth's lightning variation. To test this hypothesis, we investigate the correlation between the sudden decrease of GCR in a few hours to one day, known as Forbush Decrease (FD), and the lightning incidence in the tropics and subtropics. During the operating period of the TRMM Satellite, 28 FD events are identified with their decrease amplitudes (DAs) greater than 4%. For a typical FD event occurred on January 10, 2002, the daily cosmic ray (CR) intensity presents an intense decline from 5830.33 counts/min to 5675.96 counts/min in one day. Correspondingly, the daily lightning count decreases right after the FD's onset without any obvious time delay, specifically from 3474 day^{-1} to 672 day^{-1} in one day, and reaches its minimum of 355 day^{-1} another day later. Based on the superposed epoch analysis (SEA), similar statistical correlation is further confirmed. On average, the adjusted daily lightning anomaly decreases from 0.33 to −0.31 in three days after the FD's onset. The result of the Monte Carlo test indicates that such positive relevance between the CR intensity and the lightning incidence during a FD event is statistically significant.

1. Introduction

The possible influence of solar activities on the earth's lightning incidence has long been studied. Early researches mainly focused on the secular relationship between sunspot numbers and thunderstorm/lightning frequencies. Using data from 22 stations distributed around the world, Brooks (1934) found that in most cases relative sunspot numbers and annual thunderstorm frequencies were weakly positively correlated, but the correlation coefficients varied from place to place. Stringfellow (1974) demonstrated the positive relevance between annual sunspot numbers and lightning incidences in Britain based on 44 years of meteorological data from 1930 to 1973. Similar result was also found in middle Europe by Schlegel et al. (2001).

Recent studies suggested that the lightning incidence may be modulated by the rapid variation of solar wind condition as well. Owens et al. (2014) showed that the polarity reverse of the heliospheric magnetic field (HMF) was responsible for a 40–60% change in the occurrence rate of the thunderstorm/lightning in UK. Besides, lightning flash rates presented an intense increase at the heliospheric current sheet (HCS) and at 27 days before/after (Owens et al., 2015). Scott et al. (2014) showed that the daily lightning rate in summer Europe significantly increased when high speed solar wind streams arrived at the earth.

In addition to considering the response of the lightning incidence to solar parameters, researchers also attempted to link the atmospheric ionization, which contributed to the initiation of lightning by providing necessary ionization sources, to cosmic rays (CRs) as early as 1933 (Tandberg, 1933). Ney (1959) demonstrated that as CRs varied with the geomagnetic latitude, the percentage change in the atmospheric ionization also showed a latitude effect. Markson and Muir (1980) further proposed a plausible mechanism, suggesting that the solar wind influenced the earth's atmospheric electric field by the modulation of cosmic radiations on the atmospheric ionization. It was later shown that the ionospheric potential was positively correlated with the cosmic radiation (Markson, 1981). Similar correlation was also found between the galactic cosmic ray (GCR) ionization and the current density of the global electric circuit (Harrison and Usoskin, 2010).

Gurevich et al. (1992, 1999) first proposed the mechanism now known as relativistic runaway electron avalanche (RREA), which suggested that the combination of cosmic ray air showers (CRASs) and runaway breakdown (RB) on thunderstorm atmosphere led to the initiation of lightning. Lethbridge (1981) showed that the thunderstorm

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Table 1
List of 28 FD events. [1] DA represents the decrease amplitude of a FD event.

year	UTC t_0			UTC t_{min}			DA[1] (%)	branch	latitude zone (°)
	month	day	hour	month	day	hour			
1998	8	26	1	8	26	22	8.04	1	[0, 20]
	9	24	21	9	25	5	7.07	1	[−30, −10]
1999	1	22	21	1	23	17	6.35	0	[0, 20]
	6	26	5	6	26	23	4.12	0	[−30, −10]
	12	12	16	12	12	22	6.77	0	[0, 20]
2000	2	11	23	2	12	15	4.50	0	[−40, −20]
	6	8	9	6	8	16	7.98	1	[20, 40]
	11	6	11	11	7	7	6.58	0	[−20, 0]
2001	4	28	11	4	28	18	5.52	0	[20, 40]
	11	6	1	11	6	14	10.49	0	[0, 20]
	11	24	5	11	25	1	10.42	1	[−40, −20]
2002	1	10	15	1	10	23	4.70	0	[−30, −10]
2003	5	29	11	5	30	4	7.71	0	[10, 30]
2004	1	6	22	1	7	13	5.29	1	[20, 40]
2005	1	2	16	1	3	10	5.33	0	[−30, −10]
	5	15	1	5	15	7	10.20	0	[0, 20]
	5	29	8	5	29	18	4.18	1	[−40, −20]
	8	24	8	8	24	17	6.47	0	[−40, −20]
2010	4	5	9	4	5	16	4.11	0	[20, 40]
	8	3	18	8	4	15	4.46	1	[−40, −20]
2011	2	18	1	2	18	12	4.46	1	[−20, 0]
	6	23	1	6	24	1	4.19	0	[-10, 10]
	8	5	7	8	5	23	5.03	0	[0, 20]
2012	1	31	12	1	31	22	4.21	0	[20, 40]
	6	16	14	6	17	0	4.91	1	[20, 40]
2013	4	14	7	4	14	20	4.53	0	[−10, 10]
2014	2	27	23	2	28	15	4.66	0	[20, 40]
	4	18	10	4	18	22	4.08	0	[20, 40]

frequency observed in the eastern United States would reach its maximum three days after the monthly maximum in CRs. Chronis (2009) again found a positive correlation between GCR fluxes and monthly lightning incidences in America and its surrounding waters in winter seasons.

However, the effect of the CR intensity on the lightning incidence remains controversial. On one hand, the probability of lightning initiated by CRASs was questioned and found to be less than 5% in 74 days' data in north central Florida (Hare et al., 2017). On the other hand, as the interplanetary magnetic field (IMF) modulates CRs in an anti-correlation way (Cane, 2000), the concurrence of both positive solar-lightning and positive CR-lightning correlations in the above-mentioned studies leads to contradiction. In addition, Siingh et al. (2013, 2014) studied the response of total lightning flashes towards solar parameters including sunspot numbers, Ap index, solar radio flux and CR flux both in South/Southeast Asia and in India, and found no significant responses. Kulkarni and Siingh (2014) showed that CR fluxes and lightning flash counts were correlated only when the former was related to the regional meteorological parameters, such as the period of ENSO (El Nino/La Nina Southern Oscillations) with IOD (Indian Ocean Dipole) in South/Southeast Asia. Kudela et al. (2017) also suggested that the secondary CR rates had no obvious correlation with lightning flashes.

The present situation mainly results from the limitation of the temporal and spatial resolutions of lightning data, as well as the complicated causes of the formation of lightning itself. Studies on the correlation between the CR intensity and the lightning incidence during a Forbush Decrease (FD) event may provide a good chance to improve this situation. As a sudden decrease in CR intensity observed on a global scale (Forbush, 1937), a FD event could highlight lightning's response to CRs rather than other meteorological factors. Kristjansson et al. (2008) found no statistically significant correlations between FD events and parameters of clouds, which are the essential elements in the formation of lighting, including cloud cover, cloud droplet size, cloud water content and cloud optical depth over southern hemisphere ocean regions. However, Chronis (2009) showed that the lightning incidence would reach its minimum 4–5 days after FD events in the United States and its surrounding waters.

In this study we focus on the relation between the CR intensity and the lightning incidence during a FD event in the tropics and subtropics. We use the neutron count rate data from the Oulu Cosmic Ray Station (Usoskin et al., 2001) and the lightning data from the Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) Satellite from 1998 to 2014 (Christian et al., 1992). Section 2 introduces the selection of FD events and the preprocessing of lightning data. Section 3 shows the results of case study, statistical study and Monte Carlo test. Section 4 briefly summarizes our work.

2. Data sets and methods

2.1. Selection of Forbush Decreases

The hourly neutron count rates observed at the Oulu Cosmic Ray Station are used to present the variation of GCRs and identify FD events. The Oulu station provides continuous CRs observation in Finland (65.05° N, 25.47° E) with high time resolutions since 1964 (Usoskin et al., 2001). It has a local vertical geomagnetic cutoff rigidity of about 0.8 GV. Note that the earth's magnetic field presents a selective effect on CRs, i.e. the local CR intensity is restricted by the cutoff rigidity which varies in phase with the geomagnetic latitude. Thus, the variation amplitude of a FD event observed in the tropics and subtropics is less than that observed at the Oulu station. However, the variation trend of the FD event stays the same on a global scale. That is, the CR-lightning relation would not be qualitatively changed by the selection of CR stations.

Considering the operating period of the TRMM Satellite, 17 years of CR data from 1998 to 2014 are analyzed in this study. According to Cane (2000), a FD event generally happens when the coronal mass ejections (CMEs) reach the earth, cover it with plasma clusters and the IMF, and finally shield it from GCRs. A FD event observed by neutron monitors (NMs) on the ground appears as a sudden decrease in the CR intensity from a few to even 20% in less than 24 hours, followed by a gradual

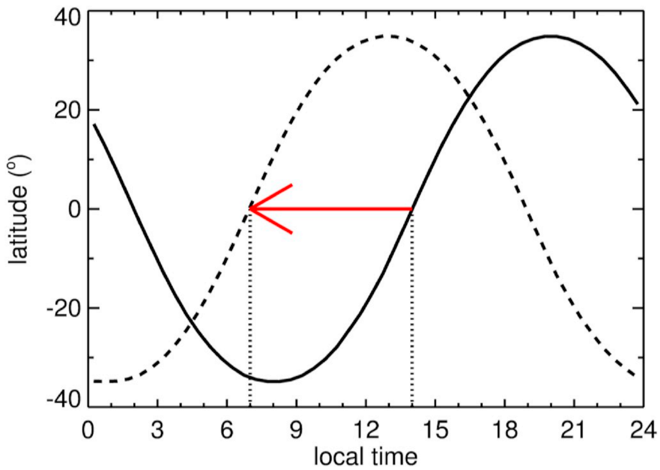

Fig. 1. The first orbit on Jan 7, 2002 (black solid line) and the last orbit on Jan 20, 2002 (black dashed line) are projected to the local time (LT)-latitude plane. The red arrow indicates that the LT at which the ascending branch of the TRMM Satellite passes the equator transfers from 14:00 to 07:00.

recovery to its initial level lasting for a week or so. Here t_0 in the Universal Time Coordinated (UTC) is used to denote the onset of a FD event when the CR intensity begins to decrease. The 3 days before t_0 plus the 11 days after that form the 14-day FD period. Note that the "day" mentioned here refers to 24 successive hours instead of the calendar day. In addition, t_{min} in the UTC denotes the time when the sudden decrease in the CR intensity stops. The percentage change of the CR intensity at t_{min} relative to that at t_0 is defined as the decrease amplitude (DA) of a FD event.

According to the criteria mentioned above, the hourly neutron count rate data from 1998 to 2014 are checked manually. A total of 112 FD events are initially identified with their DAs greater than 4%. Then some of the FD events are excluded considering the following situations:

(1) No gap of the lightning data during a FD period.
(2) No sharp sparks, e.g. Ground Level Enhancements, during a FD period.
(3) No successive FD events within 10 days.
(4) Standard FD events with a recovery phase of 7–10 days are considered.

Thus, 28 typical isolated FD events are selected, as shown in Table 1.

2.2. Lightning data preprocessing

Launched in November 1997 and ended mission in June 2015, the TRMM Satellite provides over 17 years of rainfall data for weather and climate researches from 1998 to 2015 (Christian et al., 1999). As operating in a non-sun-synchronous circular orbit with an inclination of 35° to the equator, the TRMM Satellite observed the tropical and subtropical regions between the latitudes 35° north and south with a periodic precession from east to west (Palmer et al., 2011). In addition, as undergoing an orbit boost in August 2001, the average operating altitude of the TRMM Satellite was elevated from 350 km of pre-boost to 403 km of post-boost (Bitzer and Christian, 2014), resulting in the corresponding change of the precession period from 46-47 days to 47–48 days. Fig. 1 presents a 14-day precession of the TRMM Satellite in January 2002. For illustration, the orbital branch at which the TRMM

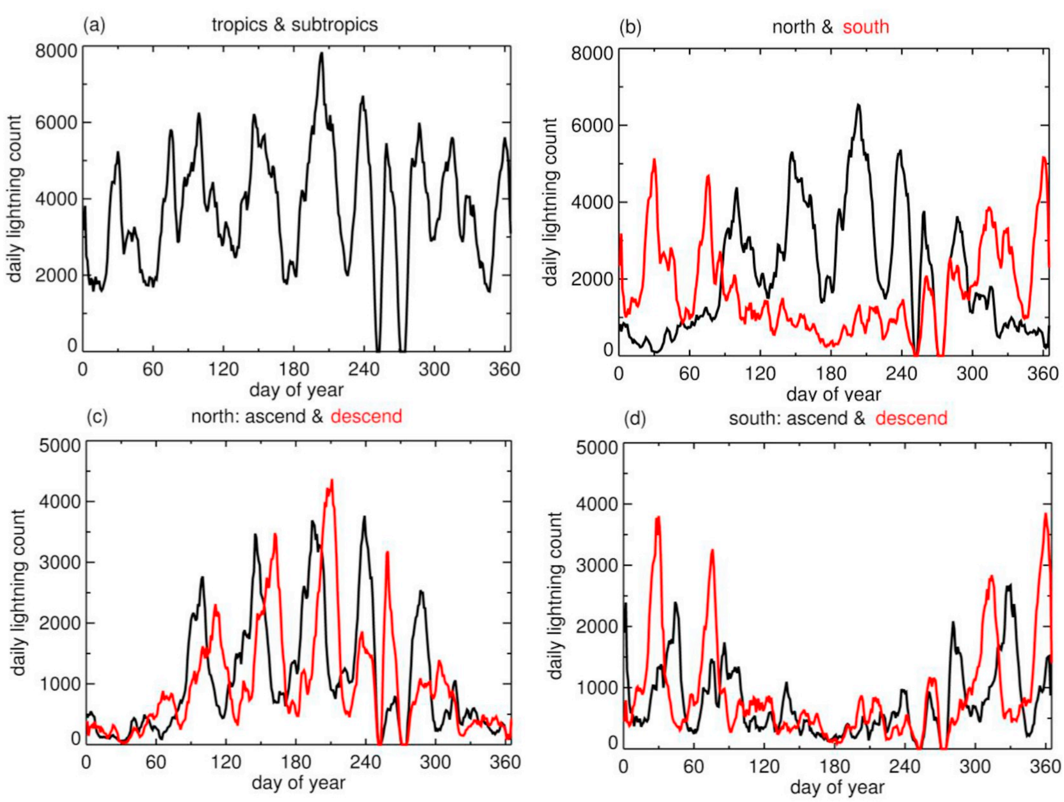

Fig. 2. The variation of the daily lightning counts observed: (a) in the tropics and subtropics. (b) respectively in the northern hemisphere (black line) and the southern hemisphere (red line). (c) respectively at the ascending branches (black line) and the descending branches (red line) in the northern hemisphere. (d) respectively at the ascending branches (black line) and the descending branches (red line) in the southern hemisphere. Note that: (1) The daily lightning counts are 5-day average smoothed. (2) The abnormal data during the period of the 240th to 300th day are excluded, which results in zero values of the corresponding daily lightning counts.

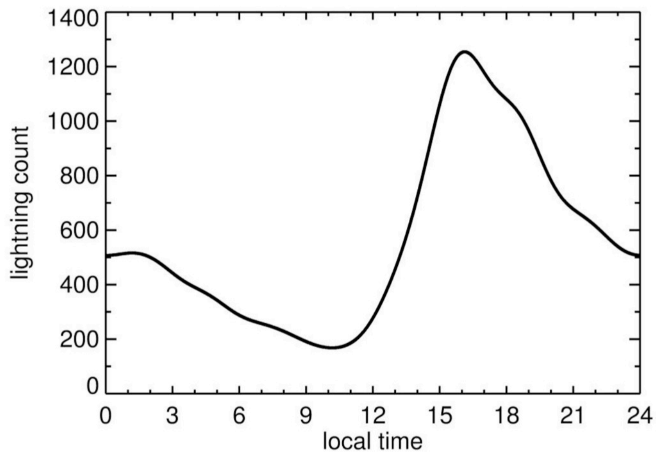

Fig. 3. Lightning's diurnal variation as a function of LT in the tropics and subtropics in 2002. The lightning data are 3-min average smoothed.

Satellite operated from south to north geographically is defined as the ascending branch (represented by "1" in Table 1), and the one with the opposite direction is defined as the descending branch (represented by "0" in Table 1). As shown in Fig. 1, the local time (LT) at which the ascending branch passes the equator transfers from 14:00 to 07:00 in 14 days. That is, the TRMM Satellite passes the same observation area with about 0.5-hour advance in daily LT.

The LIS on board the TRMM Satellite detected and located both day and night cloud-to-ground, cloud-to-cloud and intra-cloud lightning and its distribution in the tropics and subtropics (Boccippio et al., 2002). Based on a tree or a parent-child relationship between the individual levels of the clustering, the LIS classifies lightning signals into 4 categories including events, groups, flashes and areas (Mach et al., 2007). Here we use flashes which are close to the physical lightning "flash", i.e. a collection of nearby channels which may illuminate and re-illuminate multiple times.

The lightning data obtained by the LIS present unique fluctuations due to the operation mode of the TRMM Satellite. Changes in the daily lightning counts in 2002 are used to demonstrate these fluctuations, as shown in Fig. 2. Fig. 2(a) presents the variation of the daily lightning counts in the tropics and subtropics, which is relatively chaotic and disorganized. With the northern and southern hemispheres separately considered in Fig. 2(b), lightning shows its seasonal anti-phase distribution - occurs more in summer than in winter - in terms of both hemispheres. Meanwhile, lightning presents a periodic fluctuation of about 50 days. In Fig. 2(c) and 2(d), the lightning observed at the ascending branch is further distinguished from that observed at the descending branch. The phase difference between the two kinds of branches exists in both hemispheres. Also, the periodic fluctuation becomes more evident, which is actually in agreement with the 47–48 days' precession period of the TRMM Satellite.

The other key factor in the formation of the above-mentioned periodic fluctuation is speculated to be the diurnal variation of lightning, as shown in Fig. 3 by using the lightning counts accumulated at each 0.01 LT hour in 2002. It can be seen that the lightning count is closely related to the LT at which it is observed. The minimum and maximum appear around 10:00 and 16:00 respectively, which is similar to the variation of the Carnegie Curve of the fair-weather electric field (Harrison, 2013). This diurnal variation in lightning basically remains the same either on a global or a regional scale.

Considering the above two factors, the daily lightning observed by the LIS presents a self-owned variation trend which has no concern with FD events. How this trend goes depends on the LT span during which the daily lightning is observed. To be specific, as the TRMM Satellite precesses from east to west, the LT of lightning varies in the direction of 24:00 to 00:00, that is, the daily lightning counts obtained during 16:00–24:00, 10:00–16:00 and 00:00–10:00 respectively show an intense increasing trend, an intense decreasing trend as well as a gentle increasing trend.

This self-owned variation trend in the LIS lightning data, which is named as "precession effect" in our study, should be previously eliminated in case it shields the actual relation between the CR intensity and the lightning incidence during a FD event. Thus, the lightning data are preprocessed in the following two steps:

(1) The lightning data obtained during 00:00–10:00 LT are selected for each FD event. As limited to 00:00–10:00 LT, the daily lightning presents only a gentle increasing trend under less influence of the "precession effect". Meanwhile, the selected data automatically lie in either the ascending or the descending branch due to the limitation of the LT span. In a few cases when the selected data lie in the junction, the branch which is close to

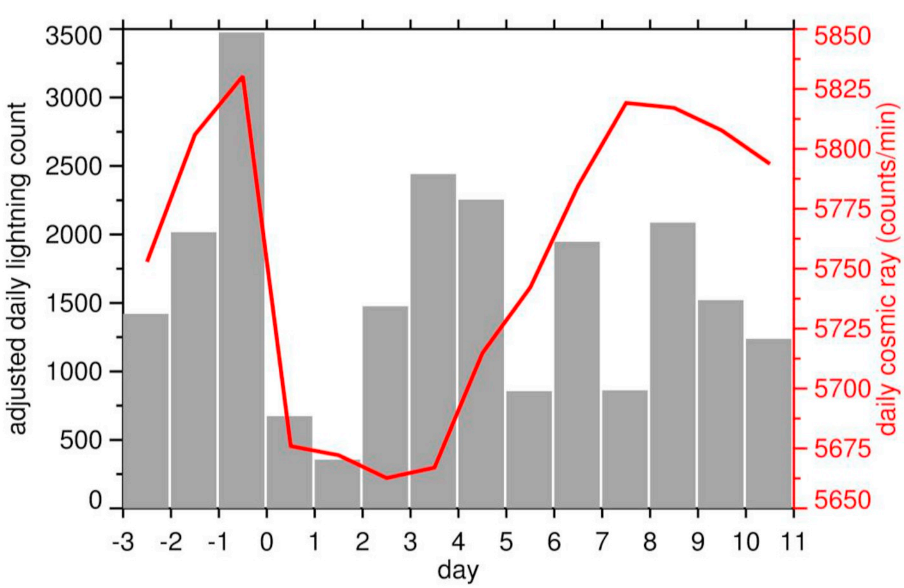

Fig. 4. The correlation between the daily cosmic ray (CR) and the adjusted daily lightning count during the FD event occurred on Jan 10, 2002. The red line represents the daily CR. The grey bars represent the adjusted daily lightning counts. Time t = 0 represents the FD's onset.

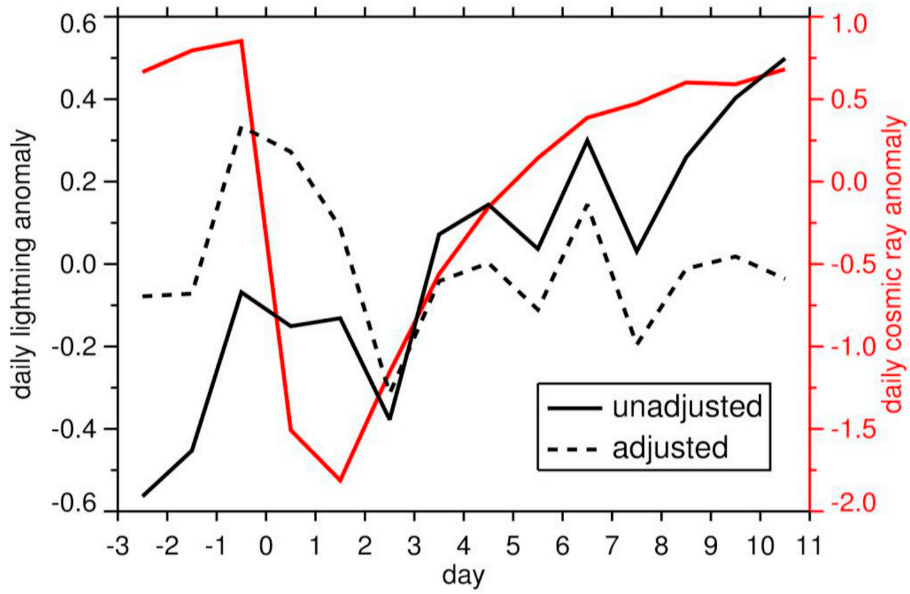

Fig. 5. The superposed epoch analysis (SEA) of the correlation between the daily CR anomaly and the unadjusted/adjusted daily lightning anomaly of the 28 FD events. The red line represents the daily CR anomaly. The black solid line represents the unadjusted daily lightning anomaly and the black dashed line represents the adjusted daily lightning anomaly.

16:00–24:00 LT is chosen. In addition, to make the LT span approach to 00:00–10:00 LT as much as possible, the selected data are limited to a 20-degree latitude zone manually. The selected branch and latitude zone for each FD event are listed in Table 1. This step is named as the "00:00–10:00 LT rule".

(2) The LT-adjusted lightning is calculated for each FD event. To further eliminate lightning's increasing trend during 00:00–10:00 LT, the lightning counts observed at each 0.01 LT are normalized by the unit value, which is defined as the lightning count obtained at 16:00 LT, to get the adjusted lightning counts. That is, the adjusted daily lightning counts could be regarded as being observed at the same LT, and they are comparable with each other during a FD event. This step is named as the "LT adjustment".

3. Results

3.1. A typical case

The variation in daily lightning counts during a typical FD event occurred on Jan 10, 2002 is studied in Fig. 4. The daily CR (the red line) presents an intense decline from 5830.33 counts/min to 5675.96 counts/min right after the FD's onset, followed by two days of slight drops and a gradual recovery to its initial level. The corresponding adjusted daily lightning count (the grey bar), which is limited to the descending branch within 10-30°S by the "00:00–10:00 LT rule", also presents a big drop specifically from 3474 day^{-1} to 672 day^{-1} right after the FD's onset, and finally to its minimum of 355 day^{-1} another day later, giving a lightning decrease percent of 89.8%. As the daily CR gradually turns back, the adjusted daily lightning count presents a similar recovery in spite of some fluctuations. Thus, this typical case preliminarily shows that the CR intensity and the lightning incidence are positively correlated in the tropics and subtropics during a FD event.

3.2. Superposed epoch analysis

To further verify the positive CR-lightning correlation demonstrated by the typical case, a statistical study of the 28 FD events listed in Table 1 is carried out by using the superposed epoch analysis (SEA). The selected branch and latitude zone for each FD event are listed in Table 1. As the actual fluctuation level of the CR/lightning varies with each FD event, the inconsistent weights of the absolute daily CR/lightning during different FD periods would affect the result of SEA. To reduce such interference, the anomalies of the daily CR/lightning are calculated, as shown in Fig. 5. The anomaly value is specifically described by the Zero-Mean (Z-Score) Normalization, which is

$$x' = \frac{x - \mu}{\sigma} \tag{1}$$

where x is the absolute value of the daily CR/lightning during a FD event, μ and σ represent the mean and the standard deviation of the x values respectively. To illustrate the effect of "LT adjustment", both the unadjusted (black solid line) and the adjusted daily lightning anomalies (black dashed line) are presented. According to the "00:00–10:00 LT rule", the unadjusted daily lightning anomaly shows an overall increasing trend under the "precession effect" as expected. This trend is eliminated when using the adjusted daily lightning anomaly. As the daily CR anomaly decreases from 0.85 to −1.51 right after the FD's onset and reaches its minimum of −1.81 another day later, the adjusted daily lightning anomaly correspondingly declines from 0.33 to −0.31 in three days after the FD's onset, followed by a recovery which is basically consistent with the variation trend of the daily CR anomaly in spite of some fluctuations. Thus, it is further demonstrated that the CR intensity and the lightning incidence are positively correlated in the tropics and subtropics during a FD period. But unlike the case study, the statistical result shows that the daily lightning anomaly does not respond so rapidly nor it reaches the minimum until three days after the FD's onset. Note that the lightning decrease intensity of the 28 FD events, which is defined as the difference between the adjusted daily lightning anomaly of the day before the FD's onset and that of the third day after the FD's onset, is 0.65 as shown in Fig. 5.

3.3. Monte Carlo test

A Monte Carlo test is conducted to verify the reliability of the statistical result shown in Fig. 5. A control sample of 28 time intervals during 1998 and 2014 is randomly selected with the length of each time interval same as that of a FD period. Note that the time intervals

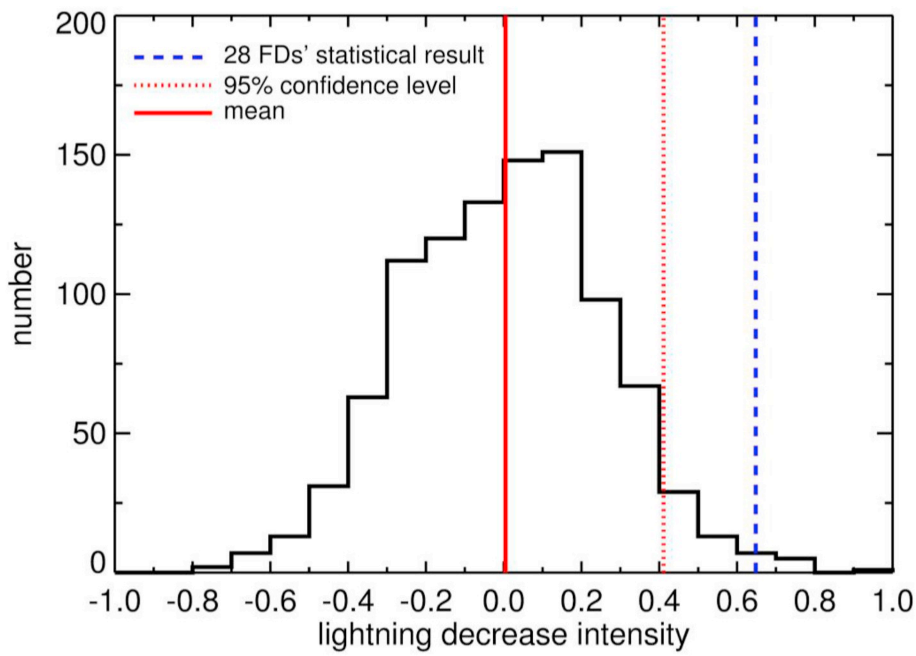

Fig. 6. The Monte Carlo test of 1000 groups of randomly selected assumptive FD events between 1998 and 2014, with each group including 28 time periods serving as 28 assumptive FD events. The red solid line represents the mean of 1000 values of lightning decrease intensity. The red dotted line represents the 95% confidence level. The blue dashed line represents the lightning decrease intensity of the SEA result of the 28 FD events shown in Fig. 5. The black line represents the number of the corresponding lightning decrease intensities of the control samples.

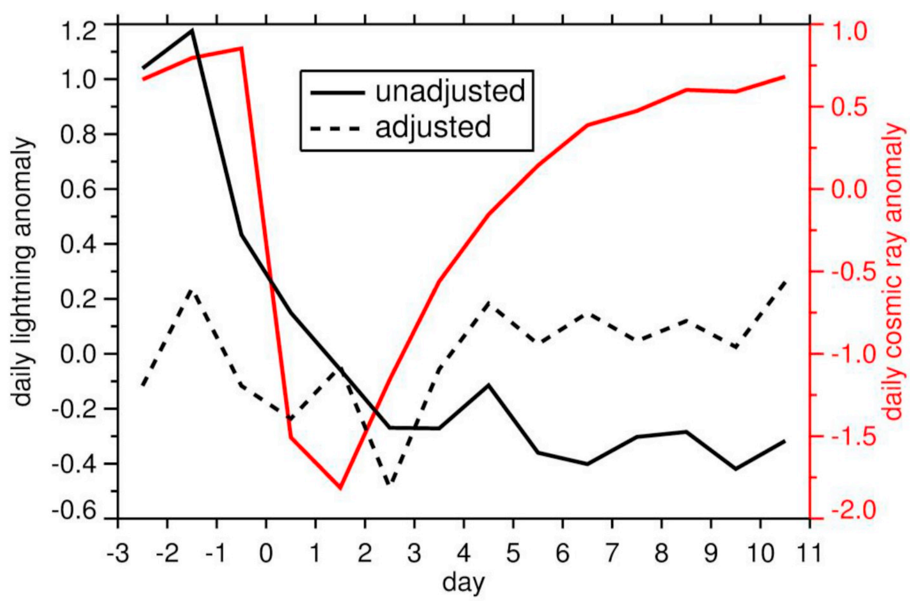

Fig. 7. The SEA of the correlation between the daily CR anomaly and the unadjusted/adjusted daily lightning anomaly of the 28 FD events, of which the lightning data are mainly observed during the LT span of 10:00–16:00 LT.

including either lightning data gaps or previously identified FD events are excluded. The above-mentioned process is repeated 1000 times to give the distribution of 1000 values of lightning decrease intensity, as shown in Fig. 6. The 95% confidence level (red dotted line) of the Monte Carlo test is 0.41, which is surpassed by the lightning decrease intensity of the 28 FD events shown in Fig. 5, specifically 0.65, to a large extent. Thus, it can be concluded that the positive response of the lightning incidence to the CR intensity in the tropics and subtropics is of significance during a FD period.

3.4. *Effect of the "00:00–10:00 LT rule"*

The selection of the LT span in the "00:00–10:00 LT rule" does not qualitatively change the positive relevance between the CR intensity and the lightning incidence. The lightning data obtained during 10:00–16:00 LT are selected to recheck the statistical result in Section 3.2. As shown in Fig. 7, the unadjusted daily lightning anomaly shows an overall decreasing trend under the "precession effect" as expected. Despite fairly strong, this trend is eliminated when the "LT adjustment" is adopted. The adjusted daily lightning anomaly presents a less positive response to the daily CR anomaly compared to the result of Fig. 5. It declines from -0.12 of the day before the FD's onset to -0.49 in three days after the FD's onset, which gives a lightning decrease intensity of 0.37, but is still followed by a gradual recovery in spite of some fluctuations.

The selection of the latitude zone does not qualitatively change the positive CR-lightning correlation either. Despite expanding the width of the latitude zone from 20° to 40°, as demonstrated in Fig. 8, both the

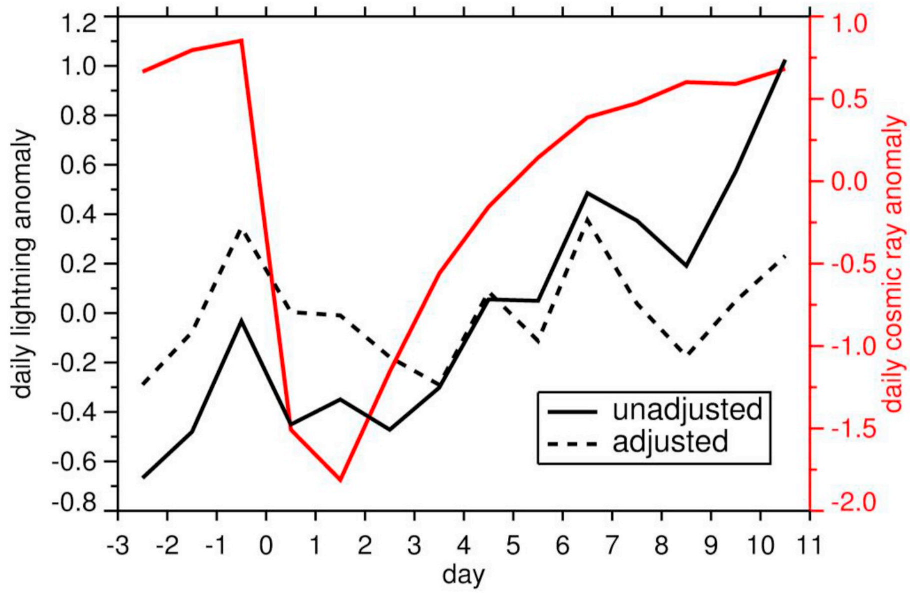

Fig. 8. The SEA of the correlation between the daily CR anomaly and the unadjusted/adjusted daily lightning anomaly of the 28 FD events, of which the lightning data are observed within the latitude zone of 40° wide.

unadjusted and adjusted daily lightning anomalies decline after the FD's onset. The overall increasing trend in the unadjusted daily lightning anomaly is basically eliminated after the "LT adjustment", which gives a lightning decrease intensity of 0.53 in the adjusted daily lightning anomaly specifically from 0.35 to −0.18. But the positive CR-lightning correlation is weakened and becomes less evident than that shown in Fig. 5.

4. Summary

To identify the possible link between the CR intensity and the lightning incidence, we study the lightning response to CRs variation during a FD event in the tropics and subtropics. A case analysis is performed by employing the FD event occurred on Jan 10, 2002, during which the daily CR declines from 5830.33 counts/min to 5675.96 counts/min one day after the FD's onset. The corresponding adjusted daily lightning count also decreases without any obvious time delay, specifically from 3474 day^{-1} to 672 day^{-1} right after the FD's onset, and finally to its minimum of 355 day^{-1} another day later. Following the gradual recovery of the daily CR to its initial level, the adjusted daily lightning count basically presents a similar variation trend in spite of some fluctuations. To verify the result of the case analysis, a statistical study is conducted by applying the SEA to the 28 FD events identified and listed in Table 1. It is confirmed that the lightning incidence is in phase with the CR intensity during a FD period, except that the unadjusted/adjusted daily lightning anomaly does not respond so rapidly nor it reaches the minimum until three days after the FD's onset. The Monte Carlo test further indicates the statistical significance of such positive relevance between the CR intensity and the lightning incidence in the tropics and subtropics during a FD event.

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