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Solar 27-day rotational period detected in wide-area lightning activity in Japan

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Abstract. A signal of the 27-day solar rotational period is often observed in cloud and lightning activities over the globe. Here we provide evidence of the 27-day periodicity of lightning activity in Japan using daily observational records of lightning for AD 1989–2015. The 27-day period is detected with 4.2 standard deviations, but only in wide-area lightning activity covering more than a 10^5 km^2. The 27-day signal is more prominent around the maxima of solar decadal cycles.

Keywords. Meteorology and atmospheric dynamics (lightning)

1 Introduction

Possible connections between solar cyclic activity and climate variations have been detected over a wide range of timescales such as millennial (Bond et al., 2001; Obrochta et al., 2012), centennial (Agnihotri et al., 2002; Fleitmann et al., 2003), decadal to multidecadal (Camp and Tung, 2007; Miyahara et al., 2008; Yamaguchi et al., 2010), and monthly scales (Takahashi et al., 2010; Hong et al., 2011). This mechanism is under debate, but several possible pathways have been suggested, including total solar irradiance (TSI; Foukal, 2004, 2006), ultraviolet (UV; Hood, 1986; Shindell, 1999; Kodera and Kuroda, 2002), and galactic cosmic rays (GCRs; Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000; Svensmark et al., 2016).

The emergence of sunspots on the surface of the Sun causes magnetic activities such as solar flares and coronal mass ejections (CMEs). As the Sun rotates, both TSI and UV vary with the 27-day period due to the nonuniform longitudinal distribution of sunspots and coronal holes. The typical lifetime of a group of sunspots or coronal holes is a few weeks to a few months. Sunspots and coronal holes tend to persistently appear and disappear at a particular longitude for several months; hence, the quasi-27-day periodicity is often maintained in solar-related parameters for a long period of time. GCRs incident to the Earth show quasi-27-day variability associated with the recurrent CME activities heading toward the Earth from the "active longitude."

Takahashi et al. (2010) and Hong et al. (2011) detected a significant signal of the 27-day solar rotational period in tropospheric cloud activity around the Indian Ocean and over the western Pacific in the past 30 years, but only around the maxima of 11-year solar cycles. Using the same data set as used by Takahashi et al. (2010), Hong et al. (2011) also suggested a possible modulation in the 27-day signal in the equatorial region associated with the stratospheric quasi-biennial oscillation. Other possible signals of the 27-day solar rotational period have been detected in global lightning activity as monitored by Schumann resonance for AD 1990 (Füllekrug and Fraser-Smith, 1996) and for AD 2000–2002 (Sato and Fukunishi, 2005), both corresponding to the solar cycle maxima. A possible signal associated with solar rotation has also been found in the lightning data obtained by the

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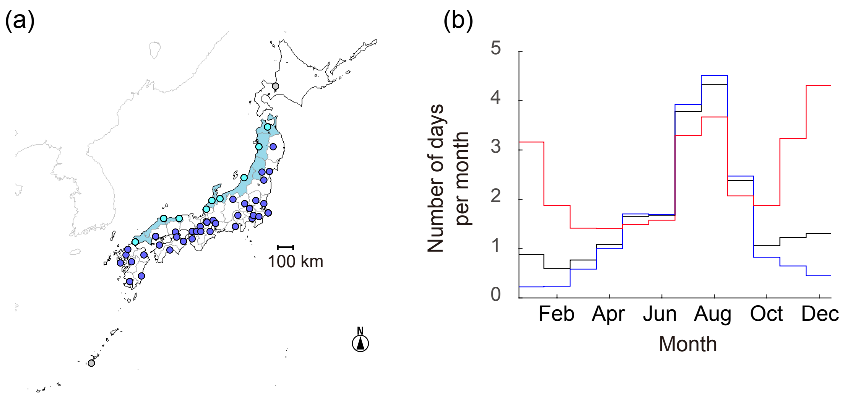

Figure 1. (a) Locations of meteorological stations monitoring lightning activity. Borders between prefectures are shown by thin curves. The area of the Sea of Japan side is indicated by blue shading. Data from Okinawa and Hokkaidō stations (gray circles) were excluded from the histogram analysis. **(b)** Monthly lightning days averaged over the 45 prefectures. The black line indicates the monthly averages for the 45 prefectures, the red line is for the 10 prefectures at the Sea of Japan side, and the blue line is for the rest of the prefectures.

UK Met Office both for AD 2000–2005 (Scott et al., 2014) and AD 2000–2007 (Owens et al., 2015).

For local lightning activity, a significant 27-day signal has been detected for AD 1991–1992 and AD 1999–2001, corresponding to the solar cycle maxima, in the data obtained at Norikura-dake in Japan (Muraki et al., 2004). In this paper, we statistically investigate the spatial scale of the 27-day signal in lightning activity in Japan and discuss the possible origin of the local response to the solar rotational period.

2 Methods

We used lightning data distributed by the Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/etrn/): continual daily data are available since AD 1989 for all of the 47 prefectures. We conducted analyses on the data for AD 1989–2015. The records are based on thunder (audio) and flash (optical) observations. We do not distinguish daytime and nighttime lightning to select and count the "lightning days". We analyzed the data for 45 prefectures: Okinawa, the southernmost prefecture that is separate from the main island, and Hokkaidō, the northernmost prefecture where rain-front activity is rare, were excluded from this study. The locations of meteorological stations monitoring lightning activity are shown in Fig. 1a. Two stations are indicated in Chiba Prefecture, because the observation of lightning was conducted at Chiba station until September 2010, after which the monitoring was taken over by Chōshi station.

Figure 1b shows the monthly lightning days averaged for the prefectures at the Sea of Japan side (10 prefectures, indicated by blue shading in Fig. 1a), for the Pacific side (35 prefectures), and for the whole area. In general, lightning activity in Japan is the highest in summer, especially in July and August, because of the high updraft. There is also intense lightning activity in winter at the Sea of Japan side because cold wind from the Siberian air mass flows southeastward toward Japan during that season and enhances lightning activity. Due to the different mechanisms, the lightning frequency at the Pacific side and at the Sea of Japan side deviates from approximately November to March. In order to isolate the effect of the cold Siberian air mass, we focused on lightning activity only from April to October in this study.

As explained in the Introduction, the 27-day period in the solar-related parameters is maintained by sunspots or coronal holes with a relatively short lifetime of a few months at most. It is therefore expected that the phase of the 27-day periodicity sometimes changes in a random manner associated with the new emergence of sunspots and coronal holes. Such frequent phase shifts can easily dilute the possible periodic signal if one uses the standard fast Fourier transform (FFT). In order to detect the periodicity by taking the unstable phase into account, we count the number of days between every combination of two lightning days to construct histograms in this study. For example, if lightning were observed on 1, 20, and 28 August, then counts would be increased by 1 for 19, 27, and 8 days. While the method allows for detecting the 27-day variations accompanied by frequent phase shifts, a disadvantage compared to the FFT is that we cannot estimate the amplitude of variations.

3 Results and discussion

Figure 2 displays the results of the histogram analysis for 45 prefectures in Japan. Each plot indicates the periodicity of wide-area lightning activity. For example, Fig. 2a shows the histogram of the number of days between every combination of two lightning days on which lightning was observed in more than nine prefectures. The counts linearly decrease for longer event intervals. There is a peak at around 27–30 days for more than 9 to more than 18 prefectures. The signifi-

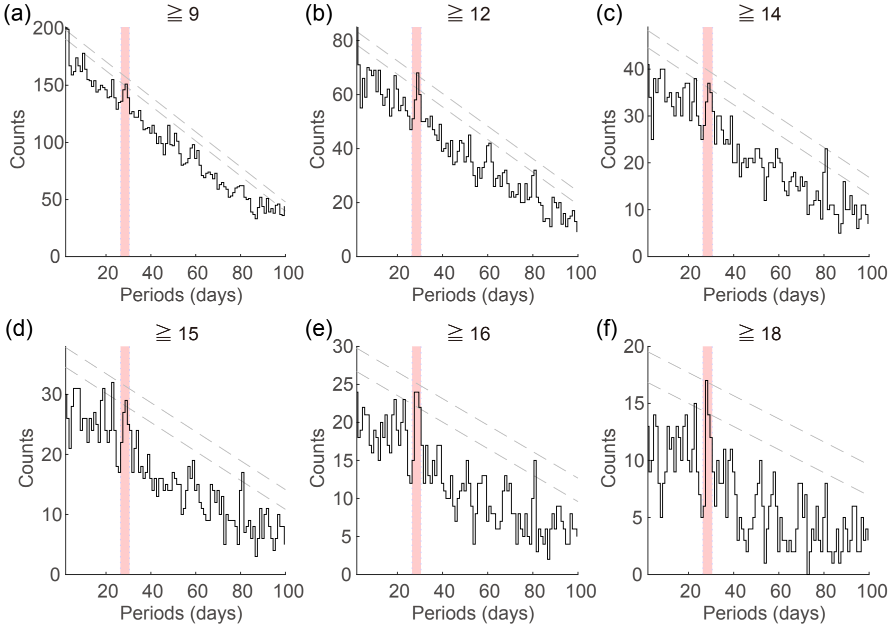

Figure 2. Histogram of number of days between every combination of two lightning days covering more than **(a)** 9, **(b)** 12, **(c)** 14, **(d)** 15, **(e)** 16, and **(f)** 18 prefectures. Gray dashed lines indicate significance levels of 2 and 3 standard deviations. Red-shaded bars indicate the 27–30-day period.

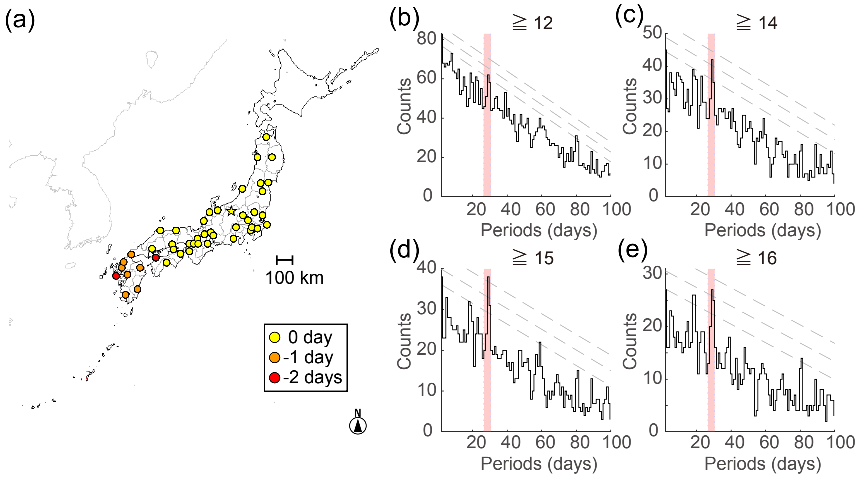

Figure 3. (a) Time lag of the 27-day component in lightning activity in each prefecture compared to that of Nagano Prefecture (indicated by a star) in central Japan. Panels **(b–e)** are the same as Fig. 2, except for considering the 1-day time lag between the area of Kyūshū and its vicinity (orange and red circles in **a**) and the rest of Japan (yellow circle in **e**). The gray dashed lines correspond to 2, 3, and 4 standard deviations. The red bars indicate the 27–30-day period.

cant peak beyond 3 standard deviations, as calculated from a random noise superposed on the linear slope, was detected for the wide-area events in which lightning was observed in more than 12 prefectures (Fig. 2b).

For a careful examination of the synchroneity of lightning activity over a wide area, the typical time lag between the prefectures cannot be neglected. The time lag of a 27-day component between Nagano Prefecture (as indicated by a star in Fig. 3a) and each prefecture was therefore estimated. Note that the 27-day component of lightning activity, obtained for a range of 27–30-day periods, in Kyūshū (Fukuoka, Saga, Nagasaki, Ōita, Kumamoto, Miyazaki, and Kagoshima prefectures) and the adjoining prefectures (Yamaguchi and Ehime prefectures) precedes the rest of the area by approximately 1 day (Fig. 3a). This finding suggests that the periodic pattern of lightning migrates from southwest to northeast. This feature is consistent with the typical northeastward migration of the cloud pattern in summer in Japan. A possible reason is that the generation of wide-area thunder clouds itself possesses the 27-day modulation. Considering the 1-day time lag, the histogram shows a higher significance for the 27-day component, especially in the case in which lightning occurs in more than 15 prefectures (Fig. 3d). The significance level is 4.2 standard deviations. This result suggests that the 27-day periodic pattern is present in summertime lightning activity with a spatial coverage of more than a 10^5 km^2. The events covering smaller regions show less significance. A possible interpretation is that mesoscale events are more sensitive to solar impact than local events such as the ones caused by local updrafts.

Interestingly, we cannot find a significant 27-day rotational period at the Japan Sea side during wintertime, as shown in Fig. S1 in the Supplement. Lightning at the Japan Sea side in winter is dominantly controlled by the activities of Siberian air mass. Due to the different mechanism of cloud formation, the 27-day period may be masked.

In previous studies, it had been suggested that the 27-day signal in cloud activities is significant mainly around the equatorial region (Takahashi et al., 2010; Hong et al., 2011). The migrating pattern of lightning activity detected in this study is consistent with the idea that the periodic pattern in Japan may originate from low latitudes. This feature may also explain why there are no 27-day signals in wintertime lightning. It would be interesting for future studies to trace the migration of the summertime 27-day periodic pattern backward to the tropical region to find out which areas correspond to the short-term variations of solar-related parameters such as TSI, UV, or GCRs. It is noteworthy that the temporal scale of lightning activity in Japan and the tropical cloud activities as its possible origin overlaps with that of Madden–Julian Oscillation (Madden and Julian, 1971, 1972). In fact, lightning activity in the United States has been suggested to have connections with the Madden–Julian Oscillation (Abatzoglou and Brown, 2009). The appearance of 27-day periodicity in cloud activities and its relation to the Madden–Julian Oscillation needs further extensive examination.

In order to examine the relation of the 27-day signal in lightning activity to the 11-year solar cycle, we extracted data for periods of solar maxima and minima based on sunspot numbers (Fig. 4a). Figure 4b displays the results of the histogram analysis for solar maxima (AD 1989–1991, 1999–2002, and 2011–2014) and solar minima (AD 1993–1998 and AD 2006–2010) for lightning activity extending over more than 15 prefectures. Only the data from April to October were analyzed, as for Figs. 2 and 3. The 1-day time lag between the area of Kyūshū and its vicinity and the rest of Japan is taken into account, as in Fig. 3. The histogram illustrates that the 27-day period is more prominent during solar maxima for wide-area lightning activity and that the significance level of the 27-day period at solar maxima is approximately 3.6 standard deviations. A 27-day period is

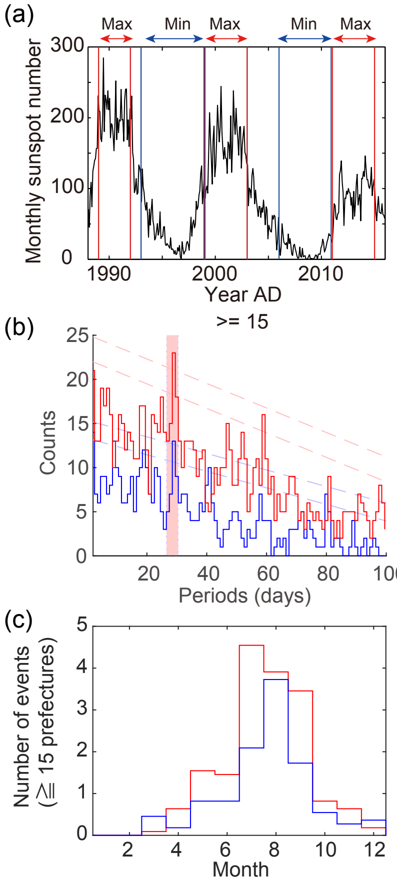

Figure 4. (a) Time series of monthly sunspot numbers for AD 1989–2015. The red and blue arrows define the periods of solar maxima and minima used for the analyses. **(b)** Same as Fig. 2 but only for the events covering more than 15 prefectures. Data were analyzed for solar maxima (red line) and minima (blue line), independently. The 1-day time lag in the Kyūshū area is considered, as for Fig. 3. Red dashed lines denote the 2 and 3 standard deviations for solar maxima; blue dashed lines are for solar minima. **(c)** Monthly average number of wide-area lightning activity instances covering more than 15 prefectures at solar maxima (red line) and minima (blue line).

also present for solar minima in the corresponding histogram, but the significance is lower than compared to solar maxima. In the previous study on lightning activity at Norikura-dake, which is located on the border between Nagano and Gifu prefectures, lightning activity did not show a significant 27-day period at solar minima (Muraki et al., 2004). It is likely that this result was obtained only because the spatial coverage was not sufficient to detect a 27-day signal. The difference in the absolute counts between solar maxima and minima itself originates from the occurrence frequency of wide-area lightning activity. For example, Fig. 4c shows that the monthly average number of wide-area events is higher at solar maxima than at minima from April to November, especially in July and September.

The excess of wide-area events at solar maxima shown in Fig. 4c implies an impact of the solar decadal cycle on lightning activity. A similar result of a positive correlation between lightning activity and the solar cycle has been also found in German data for AD 1992–2000 (Schlegel et al., 2001). Siingh et al. (2013), in contrast, show little effect of solar activity over south or southeast Asia. It is therefore important to carefully examine the spatial extent of the impact of the solar decadal cycle by studying additional regions in the future.

One might think that the monthly scale periodicity is possibly related to the lunar revolution period. However, the lunar hypothesis is less likely due to the following reasons. First, the 14.6-day periodicity evident in the tidal effect is not significant in the histogram. Second, frequent phase shifts of the lightning cycle conflict with the nature of lunar revolution.

We notice that there are weaker but significant signals at 58-day and 80-day periods in Fig. 3. These two periods are close to twice and 3 times the 27-day solar rotational period. We note that such periodicities often appear in solar-related parameters such as in GCRs since large sunspots survive for a few months, but they do not necessarily cause CMEs every time they face the direction of the Earth. Further investigations are however needed to confirm their relationship to solar activity.

4 Conclusions

A significant signal of the 27-day solar rotational period is present in summertime wide-area lightning activity in Japan for AD 1989–2015. The signal was most prominent in lightning activity covering more than 15 prefectures. The events covering smaller regions have shown the signal only with smaller significance. The significance of the 27-day period in wide-area lightning activity becomes higher at the maxima of solar decadal cycles. We found that the 27-day periodicity is also present at solar minima, although the occurrence rate is smaller than that of solar maxima. The occurrence rate of wide-area lightning activity is larger at solar maxima than at minima. A northeastward migration pattern is visible in the 27-day component of lightning activity.

Data availability. The data used in this paper are publicly accessible (see Sect. 2).

The Supplement related to this article is available online at doi:10.5194/angeo-35-583-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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