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Suitable regions for assessing long term trends in lightning activity

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ABSTRACT

The efficiency and stability of global lightning data are not yet sufficient to provide accurate estimates of long term trends in lightning activity. In contrast, regional lightning networks are generally both efficient and stable. Regions with a low level of interannual variability are well suited to the identification of trends in lightning activity. Satellite lightning data are used to identify countries in South America which display only mild interannual variability. These countries are candidates for regional studies of long term trends in lightning activity. These trends can be linked to climate change.

1. Introduction

The relationship between lightning activity and temperature is highly non-linear (Williams, 1992, 2005): small temperature differentials can have a large effect on the occurrence and intensity of thunderstorms. This suggests that observations of lightning activity could be used as a sensitive indicator of long term changes in climate (Reeve and Toumi, 1999). Despite this, the rate of climate change is relatively slow, so that the effects on lightning activity will still be comparatively small.

Climate change is a regional phenomenon: the rates of change over various regions of the Earth can differ significantly from each other and from the average rate of change for the Earth as a whole (Christensen et al., 2007). This is one reason why a study of the relationship between lightning and climate change should be conducted on a regional scale. The other reason is the fact that regional lightning networks have superior efficiency to global lightning detection systems. A larger fraction of the lightning discharges are detected by these networks, so that they yield a more accurate indication of absolute lightning rates.

Global lightning detection by terrestrial networks is not yet efficient or stable enough to gauge long term trends in lightning activity. Satellite lightning data require extensive temporal and spatial averaging, and are thus not sufficiently sensitive to reveal small interannual changes. By contrast, regional lightning data, which do not require averaging and have relatively high efficiency, are well suited to quantifying interannual variability.

In order to objectively assess the influence of climate on lightning, it is important to establish first a detailed baseline for the distribution of lightning in both space and time. This will allow variations in lightning activity associated with climate change to be separated from those caused by other influences like the seasons and the solar cycle. The first stage in establishing a lightning baseline is to derive a lightning climatology which reflects the average seasonal cycle of lightning activity. Both global (Christian et al., 2003) and various regional (Williams, 2005, and references therein) lightning climatologies already exist.

Lightning activity in a given region can be represented as a time series composed of three components: a trend, regular seasonal variations, and irregular random fluctuations. In general, the seasonal component is readily identified and removed. The trend, if present, is normally weak. If the irregular component is relatively strong then it can obscure the presence of the trend. Therefore, in order to isolate a trend, one requires that the irregular component be small. Regions with mild interannual variability are therefore suitable for monitoring long term trends. Collier and Hughes (2011), using lightning data for countries in Africa, demonstrated that regional climatologies were well described by

$$\alpha+\gamma_1 \cos 2\pi(t-\phi_1)+\gamma_2 \cos 4\pi(t-\phi_2) \tag{1}$$

which consists of a constant component and two sinusoids representing annual and semi-annual variations. The parameters

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α, γ_1, and γ_2 have units of flashes km^{-2} yr^{-1}, while t, ϕ_1, and ϕ_2 are given as fractions of a year.

The model (1) applies to an annualised climatology and does not cater for interannual variations. Some regions do not exhibit an appreciable interannual variation in lightning activity and conform well to the climatology from year to year. These are good candidates for extracting a long term trend since external influences do not appear to affect the yearly cycle. Other regions display a significant degree of interannual variability and only match the climatology in an average sense. For these it would be difficult to identify a trend in the midst of strong irregular fluctuations.

Although interannual variations may encumber the identification of a trend, they are also of inherent interest. The residuals formed between the interannual data and the climatology can facilitate the rigorous examination of the relationship between lightning and other phenomena like hurricanes (Price et al., 2007), cosmic rays, and aerosols.

Despite a number of studies which examined lightning in Brazil (Petersen and Rutledge, 2001; Petersen et al., 2002; Williams et al., 2002; Lay et al., 2004; Pinto and Pinto, 2008; de Souza et al., 2009), the incidence of lightning over other countries in South America has received relatively little attention and a complete climatology of South American lightning is still absent. Even the spectacular and novel lightning activity associated with the eruption of the Chaitén volcano in Chile has warranted only paltry coverage (Carn et al., 2009). In this paper we use satellite lightning data to derive regional lightning climatologies for countries in South America. These climatologies are used to assess the degree of interannual variability. It should be noted that the climatologies are constructed using averaged satellite lightning data. Averaging was necessary to remove the aliasing effects associated with the asynoptic sampling pattern in the satellite data. Consequently a significant proportion of the spatial and temporal variability in the data has already been smoothed out prior to this analysis. Temporal smoothing was applied with a 110 day window so that the sensitivity of this technique to variations with shorter periods is reduced. Sensitivity to interannual variability, however, was not compromised.

2. Data, analysis, and results

The data employed in this analysis are from the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) satellite instruments. OTD was operational from May 1995 until March 2000 and provided lightning data between 75° S and 75° N. LIS has been operational since November 1997 in a 35° inclination orbit.

Annualised data were derived from the composite LIS/OTD $0.5^\circ \times 0.5^\circ$ gridded High Resolution Annual Climatology (HRAC) (Boccippio et al., 2002; Christian et al., 2003). Interannual variations were obtained from the LIS/OTD $2.5^\circ \times 2.5^\circ$ gridded Low Resolution Time Series (LRTS). The HRAC and LRTS data were partitioned using national boundaries to yield regional time series.

Fig. 1 presents annualised lightning climatologies for a selection of South American countries. It is apparent that there is significant variety in the forms of the climatologies. For example, while Argentina presents a simple sinusoid with a period of 1 yr, Uruguay is more complicated, with evidence of a strong semi-annual component.

The parameters obtained by fitting (1) to these climatology data are recorded in Table 1. The average amplitudes of both the annual and semi-annual components over South America, 6.6 km^{-2} yr^{-1} and 1.7 km^{-2} yr^{-1} respectively, are appreciably smaller than those for Africa (Collier and Hughes, 2011). This is consistent with the fact that Africa is more continental in character than South America (Williams and Sátori, 2004), possibly due to its greater average elevation.

To place the data from Table 1 into a larger context, we compared them to the parameters derived for regions of geographic significance in South America. The Andes Mountains, which run down the western edge of South America, are characterised by high altitudes and associated with low lightning activity (Christian et al., 2003). The Andes Mountains have an average lightning intensity of $\alpha = 11.0$ km^{-2} yr^{-1}, while the amplitudes of the annual and semi-annual variations are $\gamma_1 = 3.5$ km^{-2} yr^{-1} and $\gamma_2 = 0.7$ km^{-2} yr^{-1} respectively. The parameters derived for the Andes Mountains are not really representative of the entire region. The largest contribution to lightning activity over the Andes Mountains comes from Colombia, with progressively smaller contributions arising further south. An appreciable level of lightning activity occurs over the Brazilian Highlands (Christian et al., 2003). For this region our analysis yields $\alpha = 17.1$ km^{-2} yr^{-1} with $\gamma_1 = 11.0$ km^{-2} yr^{-1} and $\gamma_2 = 1.4$ km^{-2} yr^{-1}. Here the contribution of the semi-annual cycle is relatively insignificant, probably due to the concentration of thunderstorm activity in the southern extremes of this region. Lightning activity in the Brazilian Highlands peaks around 1 December. The Amazon Basin has $\alpha = 16.9$ km^{-2} yr^{-1} with $\gamma_1 = 10.2$ km^{-2} yr^{-1} and $\gamma_2 = 2.8$ km^{-2} yr^{-1}. The contribution of the annual variation is significantly larger than that from the semi-annual cycle and they are phased in such a way as to give a sharp peak in lightning activity around 6 October. This peak occurs at about the time that air temperature in the Amazon Basin reaches a maximum, prior to the onset of the monsoon. This is a period associated with high concentrations of Cloud Condensation Nuclei (CCN), although Williams et al. (2002) found that CCN concentration did not have a direct link to lightning activity.

3. Discussion

The data in Table 1 are ordered according to the centroid latitude, $\overline{\lambda}$, of each country. With the exception of Uruguay, Argentina, and Chile, $\overline{\lambda}$ lies within the tropics. The semi-annual component for Argentina is negligible, with $\gamma_2/\gamma_1 \ll 1$. This is reflected in Fig. 1, which clearly contains only an annual variation. There is essentially no lightning over Chile, so that the statistics for the annual and semi-annual components are not meaningful. Despite being sub-tropical, Uruguay has a significant semi-annual variation: it has the largest value of γ_2/γ_1 and Fig. 1 clearly displays annual and semi-annual components with comparable amplitudes.

The presence of an appreciable semi-annual component for countries located outside the tropics, most notably Uruguay, is interesting. In a harmonic analysis of climatological data, Hsu and Wallace (1976) found a pronounced semi-annual modulation of precipitation over Uruguay. A strong connection also exists between South American precipitation and the South American Low Level Jet (SALLJ) (Wang and Fu, 2004). Penalba and Vargas (2004) found that precipitation over the La Plata Basin exhibited both annual and semi-annual cycles, with the former connected to warming and the latter linked to the advection of humidity. The semi-annual variation in precipitation thus appears to be driven by the SALLJ although a semi-annual oscillation in sea-level pressure (van Loon, 1967; Meehl, 1991), caused by disparate heating and cooling rates at different latitudes, may also play a role.

Fig. 2 compares the interannual variations in lightning activity to the corresponding climatologies. Such a comparison must take into account the fact that the interannual activities were derived

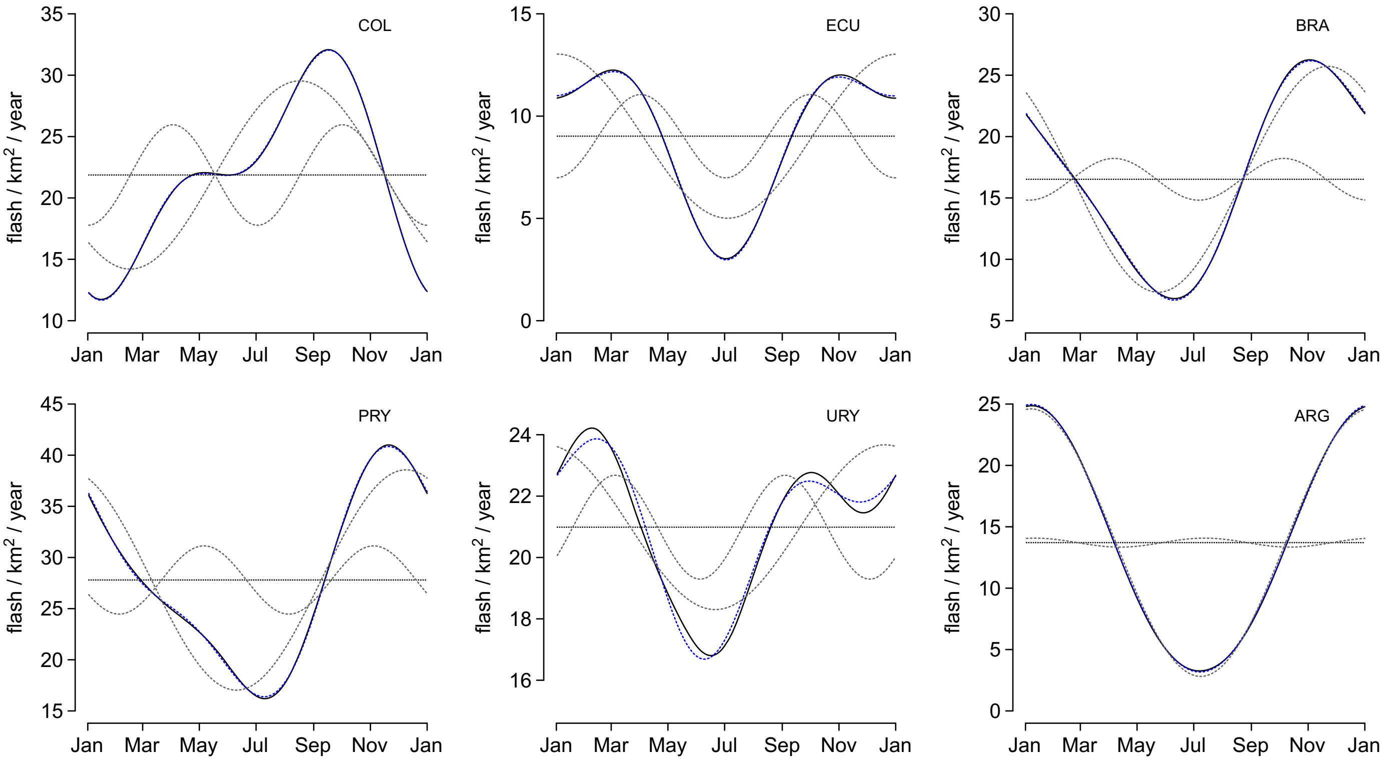

Fig. 1. Annualised total flash rate constructed from 10 yr LIS/OTD data for Colombia (COL), Ecuador (ECU), Brazil (BRA), Paraguay (PRY), Uruguay (URY), and Argentina (ARG). The climatologies are plotted as a solid black curve; the annual and semi-annual components of a sinusoidal fit are dashed in grey, while their sum is dashed in blue. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table 1

Parameters describing the variation of lightning flash rate. The rows are ordered according to the centroid latitude, $\overline{\lambda}$, of each country. The parameters α and γ have units of flashes km^{-2} yr^{-1} while the phase ϕ is given as dd/mm [jjj], where dd is day in month, mm is month, and jjj is day in year. The quality of the fit is indicated by σ, the residual standard error based on 360 degrees of freedom.

Country		Area [Mm^2]	$\overline{\lambda}$ [°]	α	γ_1	ϕ_1	γ_2	ϕ_2	γ_2/γ_1	σ
VEN	Venezuela	0.91	7.04	15.3	11.5	03/09 [246]	3.4	29/09 [272]	0.30	0.138
GUY	Guyana	0.21	4.82	6.7	7.1	01/09 [244]	1.4	10/09 [253]	0.20	0.049
SUR	Suriname	0.15	4.14	5.3	4.8	20/08 [232]	0.8	30/08 [242]	0.17	0.035
GUF	French Guiana	0.08	4.06	3.5	2.9	19/08 [231]	0.4	13/08 [225]	0.13	0.030
COL	Colombia	1.14	3.95	21.9	7.7	16/08 [228]	4.1	01/10 [274]	0.53	0.052
ECU	Ecuador	0.25	−1.42	9.0	4.0	02/01 [002]	2.0	01/04 [091]	0.51	0.060
PER	Peru	1.30	−9.14	10.9	6.2	19/11 [323]	1.8	23/09 [266]	0.30	0.058
BRA	Brazil	8.51	−10.78	16.5	9.2	21/11 [325]	1.7	05/10 [278]	0.18	0.090
BOL	Bolivia	1.09	−16.72	12.7	8.0	26/11 [330]	1.3	18/10 [291]	0.16	0.060
PRY	Paraguay	0.40	−23.27	27.8	10.8	08/12 [342]	3.3	03/11 [307]	0.31	0.134
URY	Uruguay	0.18	−32.85	21.0	2.7	19/12 [353]	1.7	04/03 [063]	0.63	0.264
ARG	Argentina	2.78	−35.37	13.7	10.9	06/01 [006]	0.4	10/01 [010]	0.03	0.063
CHL	Chile	0.70	−36.94	0.6	0.7	26/01 [026]	0.2	31/01 [031]	0.28	0.013

from LRTS data with lower spatial resolution. This distinction accounts for any systematic differences between the two sets of data. For a large country like Brazil, the majority of the LRTS cells lie completely within its borders. However, for smaller countries like Venezuela and Paraguay, an appreciable number of the cells include parts of adjacent countries or the ocean. The difference between the interannual data and the corresponding climatology is quantified by the relative median absolute deviation (RMAD) which is normalised to the peak-to-peak amplitude of the climatology.

The interannual variations in lightning activity over Venezuela (RMAD=9.5%) and Brazil (RMAD=9.9%) conform consistently to the climatology with some minor anomalies. Peru (RMAD=12.9%) is slightly more variable. Although the lightning cycle changes from year to year, it generally conforms to the climatology. Peru is roughly unimodal, with a small shoulder or second peak developing during some years. This feature is also evident in the climatology, which has a weak shoulder following the main peak. Ecuador (RMAD=23.0%) displays a bimodal pattern in which the relative importance of the two peaks varies considerably from year to year. Paraguay (RMAD=23.2%) exhibits major departures from the climatology. Although some years do indeed resemble the climatology, most are conspicuously different.

Fig. 3 presents the residuals for Brazil and Paraguay formed by subtracting the climatology from the interannual data. These two countries represent two opposing extremes: whereas the interannual lightning data for Brazil conforms closely to the climatology, Paraguay exhibits an appreciable variation in lightning activity from year to year, only occasionally agreeing with the climatology. The residuals for Brazil are ~ 1 km^{-2} yr^{-1} while for

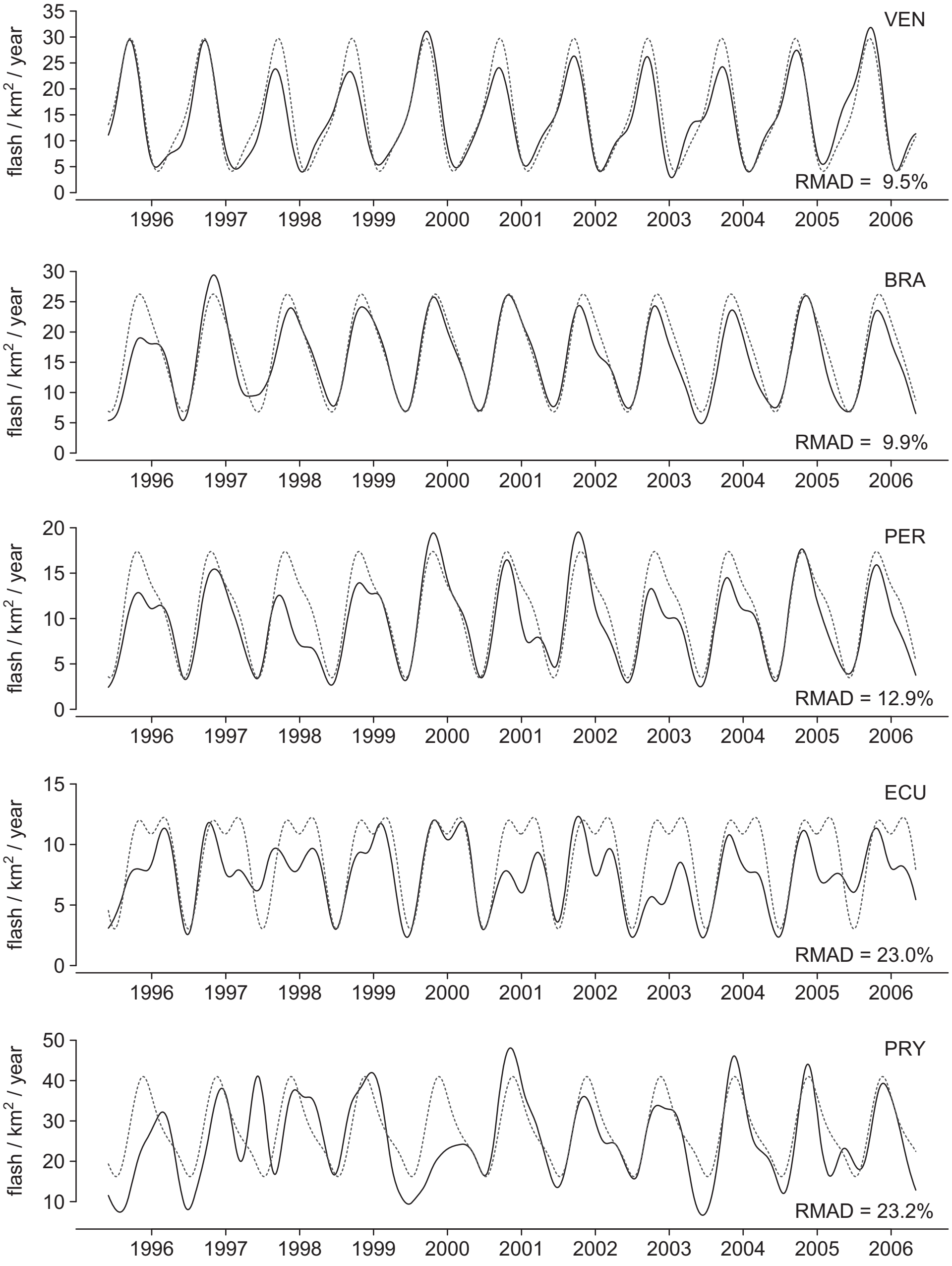

Fig. 2. Comparison of the climatology (dashed grey) to the interannual variations (black) in lightning activity for Venezuela (VEN), Brazil (BRA), Peru (PER), Ecuador (ECU), and Paraguay (PRY). The RMAD is displayed at the bottom right of each panel.

Paraguay they are $\sim 10\,\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$. As a result, any long term trend in the data for Brazil should be discernible, while for Paraguay it would be lost in the interannual variation.

4. Conclusion

We have used global satellite lightning data to derive lightning climatologies for countries in South America. These climatologies can be used to predict the seasonal variation in lightning activity. For those countries which do not exhibit a significant interannual departure from the climatology, this may be sufficient for reliable prediction of future activity. However, for those countries which have an appreciable interannual variation, the climatology can only act as a low order indication and a more sophisticated model is required which will take into account the interannual variability.

The lightning climatologies have been used to identify countries in South America for which the interannual variation does not differ appreciably from the regular seasonal variation. The lightning time series for these countries have only a relatively small irregular interannual component and are thus well suited to the identification of long term trends. However, in practice, global lightning data are not sufficiently stable nor efficient to yield evidence of a secular trend in lightning activity. By contrast, regional lightning detection networks are both stable and efficient, and are thus well suited to this purpose. The only South American countries which have a regional network are Brazil, Venezuela, and Colombia.

The interannual variation of lightning activity over Brazil closely follows the climatology. Since Brazil is also covered by a

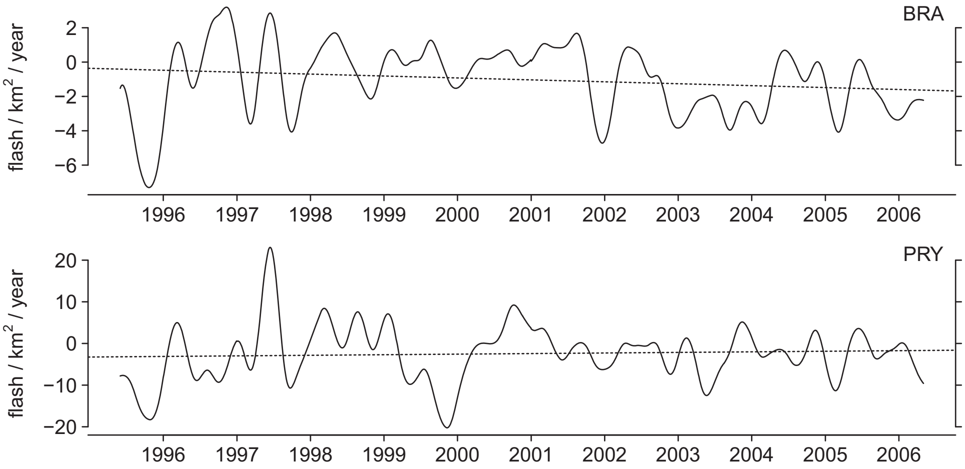

Fig. 3. Residuals for Brazil (BRA) and Paraguay (PRY) formed by subtracting the climatology from the interannual data. The dashed line is a linear fit to the residuals.

regional lightning network (Naccarato and Pinto, 2008), it is a good candidate for monitoring longer term changes in lightning activity and diagnosing a possible link with climate change. Similarly, Venezuela might also be suitable.

The primary objective of this paper is to identify regions which are suitable for gathering detailed lightning data with the objective of determining flash rate trends due to climate change. In order to accomplish this, the lightning data would necessarily have to be derived from a regional lightning network. Since such networks are normally operated by an institution within a single country, our data were analysed according to national boundaries.

Our results thus characterise the annual variation in lightning activity over entire countries and are comparable with other national climatologies such as those for temperature and precipitation. However, for large countries like Brazil which encompass a range of different topographic and atmospheric conditions, the results fail to capture local variability. This work is currently being extended to apply the same analysis technique on a global grid. This will yield parameters which capture the finer spatial variations in seasonal lightning activity.

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