

Dynamical relationship of infrared cloudtop temperatures with occurrence rates of cloud-to-ground lightning and sprites

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[1] We correlated cloudtop temperatures obtained from GOES-8 infrared images, lightning data from the National Lightning Detection Network, and triangulated nadir positions of sprites from a 22 July 1996 Mesoscale Convective System (MCS) over Kansas. The maximum sprite production of the MCS occurred during the transition between growth and decay phases of the system, and when the occurrence rate of negative cloud-to-ground (−CG) flash activity maximized. The −CG flash rate was maximum when the overlying cloudtop temperatures T_c were minimum, -69° to -72°C . During the MCS growth phase, the −CG occurrence rate increased smoothly with decreasing T_c , and declined with increasing T_c during the decay phase. By way of contrast, the +CG rate remained associated with approximately constant T_c (-69° and -72°C) during the growth phase, and then also declined with increasing T_c during the decay phase. The sprite-generating +CGs occurred in regions with cloudtop temperatures $2\text{--}3^\circ\text{C}$ warmer than the rest of the +CG population. **INDEX TERMS:** 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** São Sabbas, F. T., and D. D. Sentman, Dynamical relationship of infrared cloudtop temperatures with occurrence rates of cloud-to-ground lightning and sprites, *Geophys. Res. Lett.*, 30(5), 1236, doi:10.1029/2002GL015382, 2003.

1. Introduction

[2] Sprites are optical after-effects induced in the middle and upper atmospheres by lightning discharges, first documented in 1989 [Franz *et al.*, 1990]. Boccippio *et al.* [1995] were the first to identify that a positive cloud-to-ground lightning (+CG) preceded $\sim 85\%$ of the sprites using +CG signatures identified by the National Lightning Detection Network (NLDN) and/or “Q-bursts” signatures identified by ELF/VLF sensors. Subsequent observational studies have generally supported those results [Lyons, 1996, Cummer and Inan, 1997; Bell *et al.*, 1998]. São Sabbas [1999], studying 746 sprite events from 7 days from the Sprites96 Campaign, found that only 65% of sprites were preceded by a +CG. About 11% were preceded by a −CG and 24% did not have any CG signature recorded by the NLDN. A detailed study of one of these days, 22 July, 1996, using NLDN and VLF data showed that this percentage could be increased to $\sim 75\%$, where the extra 10% would account for

+CGs that NLDN would not have registered [São Sabbas *et al.*, 2003]. About 25% of events remained without preceding +CGs, suggesting that −CGs and intracloud discharges might also produce sprites, a possibility that is not ruled out by current theories [Pasko *et al.*, 1997, 1998, and references therein].

[3] Although most sprite measurements have been performed in the central region of the US, sprites are global phenomena, as was first documented during the space shuttle Mesoscale Lightning Experiment (MLE) [Boeck *et al.*, 1995]. Between 1989 and 1991, 17 sprites were recorded above thunderstorms over Australia, Africa, South Pacific and South America. Aircraft observations over Central and South America [Sentman *et al.*, 1995], ground campaigns in Japan [Fukunishi *et al.*, 2001] Australia [Dowden *et al.*, 1996], more recent aircraft [Taylor *et al.*, 2000] and ground-based observations [Neubert *et al.*, 2001] over Europe and over Asia [Su *et al.*, 2002] have confirmed these results.

[4] In the Midwest US, most sprite observations have been made between May–August, where Mesoscale Convective Complexes (MCC) are somewhat common occurrences [Lyons, 1996]. MCCs are a particular type of MCS. They are meteorological systems with strong convective activity, dimensions between 250 and 2500 km and duration greater than or equal to 6 hr (meso- α scale definition based upon physical characteristics observed in infrared (IR) satellite images [Maddox, 1980], *cf.* Table 1). MCCs are also common in oceanic and continental tropical regions, especially in the intertropical convergence zone (ITCZ), and over South America [Conforte, 1997]. In South America, the MCCs are, on average, about 60% larger in area and persist over longer intervals than similar systems in the US [Velasco and Fritsch, 1987], thus making this region the most active in the Western Hemisphere. Sprite observations over different regions of the globe, e.g., Peru [Sentman *et al.*, 1995; Moudry *et al.*, 1997], Europe [Neubert *et al.*, 2001; Taylor *et al.*, 2000], and Japan [Fukunishi *et al.*, 2001], reveal that sprites can also be generated over small thunderstorms, suggesting that the type and size of thunderstorms that generate sprites may actually depend on local meteorology.

[5] In the present paper we investigate the cloud-top temperature characteristics of an intense sprite-producing thunderstorm system and the inter-relationships with associated lightning and sprite activity. The meteorological system is classified according to the Maddox [1980] definition. The analysis examines the occurrence rate and location of sprites and lightning with respect to the thunderstorm features and temporal development. The objective of the study is to create a methodology based on satellite

Table 1. MCC definition [adapted from *Maddox*, 1980]

Size	A - Contiguous Cloud shield with $T_{IR} \leq -32^{\circ}\text{C}$, area $\geq 10^5 \text{ km}^2$ B - Interior clouds with $T_{IR} \leq -52^{\circ}\text{C}$, area $\geq 5 \times 10^4 \text{ km}^2$
Initiation	Size definitions A and B are first satisfied
Duration	Size definitions A and B must be met for a period $\geq 6 \text{ h}$
Max. extent	Cloud shield defined in A reaches maximum size
Shape	Eccentricity ≥ 0.7 at time of maximum extent
Termination	Size definitions A and B no longer satisfied

imagery that could be used in studies of global sprite production.

2. Data Set

[6] We used GOES-8 satellite 10–12 μm IR images over the period 0015–1545 UT containing the meteorological system over Kansas that produced the sprites observed on the night of July 22, 1996. Forty events from the set of sprites observed on this night have previously been studied in a detailed report presented by *São Sabbas et al.* [2003]. The sprite positions were triangulated (see *São Sabbas et al.* [2003] for details) and the lightning information used here was provided by the NLDN.

[7] The GOES-8 data were provided by the National Climatic Data Center (NCDC), Asheville, North Carolina. The 10 bit/pixel images had a spatial resolution of approximately 4 km, temperature resolution 0.1 K, and were spaced at 30 min intervals. We isolated the part of the image corresponding to the sprite-producing MCC and environs (Figure 1a) and remapped it to an isometric latitude and longitude grid. The count values were converted to cloudtop temperature (T_c) using the procedures of *Weinreb et al.* [2001]. Figure 1b shows the resulting color-coded temperature map as a function of latitude and longitude (lat/lon) for 0615 UT. On these maps were also plotted the location of +/-CGs detected by the NLDN and triangulated locations of sprites that occurred within +/-15 min of the image, e.g., from 0600–0630 UT in Figure 1.

3. Analysis

[8] We matched the lat/lon of the lightning and triangulated positions of sprites to the lat/lon matrices of the images and identified the pixels with the temperatures of the correspondent cloudtop region. For each image we assembled histograms of lightning flashes and sprites versus temperature. Comparing the histograms with the T_c maps, we find that as the storm grows, compact regions of very cold cloudtops develop and the lightning discharges, -CGs more than +CGs, have the tendency to concentrate on those regions. Not all regions with very cold cloudtops exhibited lightning activity, even though cold cloudtops are strong evidence of vigorous convection. Generally, we expect that charge separation, hence lightning, follows convection, leading to an intensification of the lightning activity associated with cold cloudtops.

[9] The histograms were combined into temperature-time spectrograms (Figure 2) that reveal the evolution of T_c associated with lightning and sprites over the lifetime of the storm. There is some smearing in the histograms from samples obtained near sharp temperature gradients, due to the thunderstorm movement northeastward at a rate of

several tens of km between the 30 min image intervals. This motion corresponded to several pixels in the IR images, but the overall effect is minor.

[10] Figure 2a shows that, throughout the lifetime of the thunderstorm, the -CG occurrence rate increases in association with decreasing T_c during the growing phase, reaches a maximum associated with the coldest T_c ($-72^{\circ}\text{C} \leq T_c \leq -69^{\circ}\text{C}$) that lasts for $\sim 2 \text{ h}$, and then decreases in association with increasing T_c during the decay phase of the storm. The +CG rate (Figure 2b) remains associated with approximately constant T_c ($-72^{\circ}\text{C} \leq T_c \leq -69^{\circ}\text{C}$) during the growth of the thunderstorm and also decreases with increasing T_c during the decay phase. The +CGs produced during the growth phase occur in association with the same T_c range that -CGs are associated with during the -CGs maximum production.

[11] The sprite observation period was 0323–0856 UT, and sprites were recorded from 0428 UT to 0829 UT. Figure 2c shows that during the period of most intense sprite activity, between 0545 UT and 0615 UT, sprites concentrated over regions with $T_c \geq -70^{\circ}\text{C}$, in particular $-65^{\circ}\text{C} \leq T_c \leq$

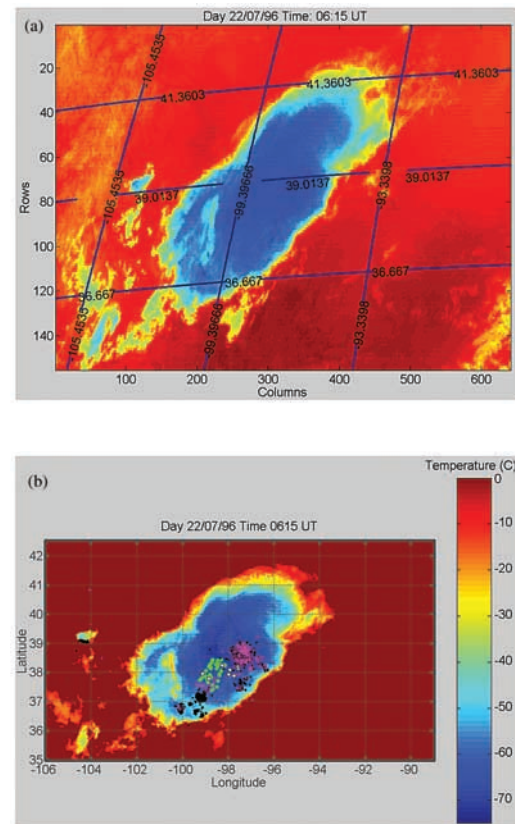


Figure 1. Images of the sprite producing thunderstorm of 22 July, 1996, observed by the GOES-8 satellite at 0615 UT. Panel (a) is the raw data utilized, i.e., the satellite view. Panel (b) is a cloudtop temperature map (T_c) as a function of latitude and longitude. The map also show the location of +CGs (pink crosses), -CGs (black dots), sprites (green circles), +CGs associated with sprites (white circles), and -CGs associated with sprites (white squares). The CGs and sprites occurred within $\pm 15 \text{ min}$ of the image time. A similar map showing the association of lightning with cloudtop temperatures have been previously presented by *Lyons et al.* [2000].

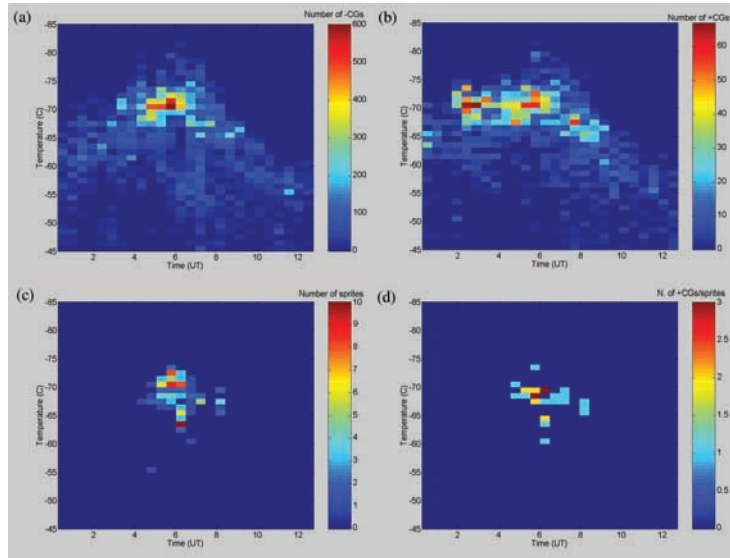


Figure 2. Temporal development of the relationship between GOES-8 IR cloudtop temperatures and the occurrence rate of lightning and sprites throughout the lifetime of the thunderstorm. Each pixel covers 30 min by 1°C , so that each column is the histogram of occurrences vs temperature. The thunderstorm growth phase is 0015–0545 UT. Panel (a) is for $-$ CGs, (b) is for $+$ CGs, (c) is for sprites, and (d) is for sprite producing $+$ CGs.

-63°C (0615 UT). The peak in sprite activity occurred during the period when the $-$ CGs occurrence rate reached a maximum associated with minimum T_c . Even though sprites are predominantly generated by $+$ CGs [Boccippio *et al.*, 1995; Lyons, 1996, Cummer and Inan, 1997; Bell *et al.*, 1998; São Sabbas *et al.*, 2003], this result shows that the total $-$ CG activity is more tightly correlated with sprite activity than has previously been reported. Whether the total $-$ CG activity plays a role in determining the sprite occurrence rate, or this result reflects a particular characteristic of the specific thunderstorm studied, is presently unknown.

[12] The rate of occurrence of sprite generating $+$ CGs remains associated with approximately constant T_c (Figure 2d), following the behavior of the total $+$ CGs rate (Figure 2b). The difference is that the distribution of the sprite-generating $+$ CGs (2d) is centered between -67° and -69°C , about $2\text{--}3^{\circ}\text{C}$ warmer than for $+$ CGs taken as a whole (2b). The bulk of $+$ CGs of the storm tend to occur in the strong convective regions associated with the coldest cloudtop temperatures, while sprite producing lightning tend to occur in warmer stratiform regions.

[13] The development of the thunderstorm area is shown in the last row of Figure 3 together with the sprite, $+$ CG, $-$ CG and total $+/-$ CG occurrence rates during the lifetime of the thunderstorm. The sprite producing storm is “born” between 0045 and 0115 UT, as a result of the coalescence of two relatively small thunder cells (not shown). At 0115 UT it satisfies Maddox’s initiation criteria for MCCs (*cf.* Table 1). The storm grows until 0545 UT when the contiguous cloudtop region with $T \leq -52^{\circ}\text{C}$ reaches the maximum area of $\sim 1.4 \times 10^5 \text{ km}^2$, after which the storm starts to decay, even as the total area of the thunderstorm, as defined by the warmer $T_c \leq -32^{\circ}\text{C}$, continues to expand. The maximum extent of the storm $\sim 2.32 \times 10^5 \text{ km}^2$ is reached at 0745 UT. The eccentricity of the storm at this point is less than 0.7, so this MCS cannot be classified as an MCC according to the Maddox criteria. The MCS terminates at 1015 UT.

[14] The ~ 9 hr lifetime of the system studied here is lower than the 14.3 hr mean MCCs duration reported by Goodman and MacGorman [1986] in a study of 10 MCCs over the Midwest US. During these ~ 9 hr a total of 40,605 cloud-to-ground flashes were produced, of which 10.9% (4,412) were $+$ CGs and 89.1% (36,193) were $-$ CGs. The average flash rate 75.2 min^{-1} was more than 2 times greater than the maximum 32.7 min^{-1} average flash rate reported by Goodman and MacGorman [1986].

[15] Figure 3 shows that the maximum production of sprites, from 0545 UT to 0615 UT, occurs at the time of maximum area of the region of $T \leq -52^{\circ}\text{C}$, spanning the transition from growth to decay phases of the MCS. The same behavior also occurs for the $-$ CG (third row) and total $+/-$ CG (fourth row) occurrence rates. The $+$ CG rate

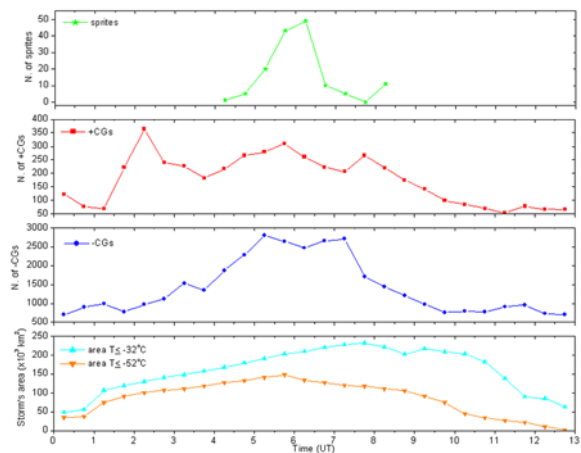


Figure 3. Temporal development of sprite rate (first row), $+$ CG rate (second row), $-$ CG rate (third row) and contiguous area of cloud cover with $T_c \leq -32^{\circ}\text{C}$ and $T_c \leq -52^{\circ}\text{C}$ during the thunderstorm lifetime.

(second row) remains high (>170 flashes/30 min) and exhibits a relative maximum during this period, but its absolute maximum occurs at 0215 UT, approximately 1 hr after merging of the two cells that initiated the MCS. The total $+/-$ CG occurrence rate peaks ~ 2 hr before maximum extent, agreeing with the 2.6 hr reported by *Goodman and MacGorman* [1986]. By the time of maximum extent of the storm (cf. Table 1) the total $+/-$ CG occurrence rate starts to decrease. *Goodman and MacGorman* [1986] suggest that this occurs because the convective precipitation regions are replaced by widespread stratiform precipitation.

4. Summary of Results

[16] The sprite producing system over Kansas on 22 July 1996 was an MCS that originated from the merging of two thunderstorm cells between 0045 UT and 0115 UT. The total lifetime of the system was ~ 9 h. The MCS moved north-eastward and reached a maximum extent of $\sim 2.3 \times 10^5$ km² at 0745 UT, approximately 6 hr after its initiation. The maximum sprite and $-$ CG production of the system were simultaneously achieved at the time of maximum contiguous cloud cover of the coldest region with $T_c \leq -52^\circ\text{C}$, ~ 2 hr before the system reached its maximum extent. The $-$ CG rate increased during the growth phase of the thunderstorm in association with decreasing T_c , it reached a maximum associated with the coldest T_c ($-72^\circ\text{C} \leq T_c \leq -69^\circ\text{C}$), and then, in the decay phase of the MCS, it decreased in association with increasing T_c . We suggest that the total $-$ CG activity and dynamical development of the thunderstorm may be more tightly correlated with sprite activity than has previously been reported. The $+$ CG rate remained high during the sprite-recording period, and remained associated with approximately constant T_c ($-72^\circ\text{C} \leq T_c \leq -69^\circ\text{C}$, same as $-$ CGs) while the system was growing, subsequently decreasing with increasing T_c during the decay phase. Sprite-generating $+$ CGs occurred in regions about $2-3^\circ\text{C}$ warmer than the bulk population of $+$ CGs.

[17] The techniques reported here to correlate sprite occurrence with the spatial and temporal topology of cloud-top temperatures are the initial steps towards developing a robust methodology based on satellite imagery that could be used to study sprite-generating thunderstorms wherever they might occur in the world. The present analysis was for a single storm. To be most useful and to bound the variance of the results, additional studies would need to be made across many thunderstorms and a variety of latitudes, longitudes and seasons. Candidate regions and satellites suitable for such studies include South America (GOES-8; *Velasco and Fritsch* [1987]), equatorial and Southern mid-latitude Africa (Meteosat-7; *Fuellekrug* [2001]) South-, Southeast Asia, and the Malay Archipelago (GMS-5 and InSat; *Sentman and São Sabbas* [2001]).

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