Observation of sprites over the Asian continent and over oceans around Taiwan

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Received 5 July 2001; revised 11 December 2001; accepted 14 December 2001; published 27 February 2002.

[1] Sprites were observed over thunderstorms in the southern China and in oceans around Taiwan. The observation sites were on the Ali Mountain of Taiwan's Central Ridge area with an altitude of 2413 m and in the campus of National Cheng Kung University with an altitude of 50 m. For the observed land sprites, 90% of them were either carrots or columniforms and 64% of the sprites occurred in groups. Among the observed oceanic sprites, 89% of them were carrots but only 22% of the sprites occurred in groups. We define a sprite active system as a thunderstorm that continuously produces at least one sprite in a 10-minute interval. The active sprites generating periods for the observed thunderstorms were typically shorter than 30 minutes. The sprite production rates for these Asian thunderstorms are estimated to be between $I \approx 2 \times 10^{-4}$ events/km^2/hr and $I \approx 1 \times 10^{-3}$ events/km^2/hr. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335)

1. Introduction

[2] The scientific evidence of sprites was accidentally recorded using a low light level camera by *Franz et al.* [1990] on the night of 22 September 1989. The first color television image of sprites was obtained in the summer of 1994 by *Sentman et al.* [1995] from a platform aboard a NASA research jet aircraft. This historical observation provided scientists with first quantitative range and absolute brightness of sprites. Through efforts of various research groups over the years, several lightning-related luminous phenomena have been identified, including blue jets, elves and and sprites [*Mende et al.*, 1995; *Winckler et al.*, 1996; *Barrington-Leigh et al.*, 2001].

[3] Sprites are categorized according to their morphological appearance. The most commonly reported sprites are the "carrot sprites" which have a strong, luminous center regions tapering towards lower altitudes while showing a diffuse "hair" region above the body. Near the bottom, the 'carrots' are often accompanied by thin-hairline discharges or tendrils [*Sentman et al.*, 1995]. *Wescott et al.* [1998] reported another type of sprite consisting of relatively thin uniform vertical columns. This second most common type of sprites is called the columniform or "C" sprite. Carrot and C sprites account for 90% of the sprites observed in the American continent [*Wescott et al.*, 1998]. Some other minor types of sprite, with the suggestive names firework, ghost fire, and troll, also exist, but they account only for a small fraction of the sprites observed. Most sprites are largely elongated in the vertical direction, indicating that the discharges line up with the predominantly vertical electric field.

[4] Geographically, past sprite campaigns have discovered sprites over thunderstorm systems in North and South America, Africa, Australia, Sea of Japan, and European continent [*Franz et al.*, 1990; *Boeck et al.*, 1995; *Hardman et al.*, 2000; *Fukunishi et al.*, 1999; *Neubert et al.*, 2001]. The distribution and morphology of sprites in the other geographical locations have yet to be confirmed and studied. In this paper, we report ground observations of sprites over the Asian continent and over oceans around Taiwan. The characteristics of the observed sprites and the sprite production rates of the parental storms will also be presented.

2. Instrumentation and Observation Sites

[5] The 2001 sprite campaign in Taiwan was conducted between April and August of 2001. The two observation locations for this campaign were the Ali Mountain Weather Station (AMWS, 2413 m) and the campus of National Cheng Kung University (NCKU, 50 m). The camera systems used in this campaign consisted of WAT-902H/Neptune CCDs, Sigma 20 mm/f1.8 lens, Nikon 50 mm/f1.4 lens, and SONY DCR-PC5 digital recorders. When equipped with a 20 mm lens, the field of view (FOV) of the camera is 18.5°(H) by 13.8°(V). With a 50 mm lens, the FOV is 7.5° by 5.6°. The cameras were operated at interlaced frame mode with standard video rates at 30 frames per second.

[6] The internal clocks of the digital recorders, after being synchronized to the GPS time, were used to generate the time codes for the images. In the SONY DCR-PC5 digital recorder, the time codes are stored in a separated memory buffer, so they will not interfere with the sprite images and can be inserted as needed.

3. Results

[7] In spring and summer seasons, the weather in Taiwan usually is heavily influenced by local convection systems and typhoons. During the four month campaign period, only 27 nights had good local conditions and good visibility that allowed ground observations to be carried out, and sprites were observed on 5 evenings. Sprites were recorded over southern China on 30 April and 17 August 2001, and over oceans around Taiwan on 7 June, 20 July, and 22 August 2001. In all, 42 land sprites and 18 oceanic sprites were recorded, as shown in Table 1.

3.1. Land Sprites

[8] On 30 April 2001, 40 sprite events were recorded over two moderate thunderstorms in the eastern Guandong Province, China,

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0094-8276/02/2001GL013737$05.00

Table 1. List of Observed Land and Oceanic Sprites in 2001[a]

30 April	
S_1 storm (land)	
15:56:41	CA
16:00:46	gCA(2) + C
16:20:16	C
16:42:44	gCA(2)
16:46:25	CA, CA
16:49:35	U
16:50:57	gCA(4)
16:52:00	CA
16:58:51	gC(5)
16:59:45	gCA(6)
17:03:12	gCA(6), CA
17:05:16	gCA(8)
17:07:21	gCA(2), gCA(4)
17:11:03	C, U, gCA(2) + U
17:13:07	gC(7)
17:18:03	gCA(3), gCA(3)
17:38:49	gCA(2) + C
17:57:02	CA + C
18:14:36	gCA(3)
18:59:55	C + CA, gCA(4), C
19:03:45	gC(4), U
20:14:02	gCA(4) + C
S_2 storm (land)	
15:47:40	CA, CA
15:55:33	gCA(2) + gC(5)
15:58:51	gCA(3) + U
16:02:03	gCA(4)
16:03:33	U
18:59:17	gC(4)
19:41:37	gU
20:02:45	gU(2)
7 June (ocean)	
13:24:00	gCA(2), CA
13:27:28	CA
13:59:20	gU
14:23:14	CA
14:44:14	CA
20 July (ocean)	
17:22:03	CA
17:24:41	CA
17:29:12	CA
17:35:56	CA
17 August (land)	
13:46:19	CA
13:53:41	gC(9)
22 August (ocean)	
12:59:08	CA
13:53:10	gCA(2)
14:01:50	C
14:03:42	CA
14:13:49	CA, gCA(2)
14:18:04	CA
15:31:20	CA

[a] Sprites occurring in the same video frame are classified as a group and counted as a single event. Sprites appearing in different video frames are counted as separated events. Notations used in categorizing the forms of the sprites are CA for carrots, C for columiform, U for un-recognizable. Additional notations are gCA(#) for the number of carrot sprites appearing in a group, gC(#) for the number of C sprites appearing in a group, "+" for different type of sprites occurring in the same frame, and "," for dancing sprites. All times are in UT.

~600 km west of the AMWS. Figure 1a contains the satellite infrared map for the surrounding area of Taiwan at 17:00 UT. This storm system in the eastern Guandong Province actually consists of two smaller systems, S_1 and S_2 as shown in Figure 1a. At 17:00 UT, these two storms sat right next to each other. The S_1 storm gradually moved along the front line in the northeast direction. At 20:14:02 UT, when the front edge of the S_1 storm was approximately 450 km from the AMWS and its size was reduced to ~100 km × 100 km, it produced the sprite shown in Figure 2d. The image clearly shows that the bottom of the carrot sprite contains thin-hairline discharges, similar to the carrot sprites observed over the American continent.

[9] Figure 2 shows four representative land sprites observed on 30 April 2001. According to their forms, these sprites are classified as carrot and columniform sprites. Since the locations and other detailed characteristics of the parental CG strokes for these sprites are unavailable, accurate ranges of the observed sprites cannot be determined. Fortunately, the light from the west coastal cities of Taiwan formed a diffused band across the bottom of each image which served nicely as a local horizon for visually gauging the altitude of the sprites, and hence the distance to the sprites. Assuming that the vertical extension of sprites over the Asian continent is similar to that over North America, the distances between the sprites and the AMWS can also be estimated from the observed vertical FOV. The approximated distances of these sprites range from 450 to 900 km. In all, the S_1 storm was observed to produced 31 sprites in four hours and, in the same time interval, 9 sprite events originated from the S_2 storm. The horizontal spatial distribution of these sprites is consistent with the extension of the storm system along the line-of-view as shown in Figure 1a.

[10] Among the 42 land sprites observed on 30 April and 17 August 2001 (Table 1), 64% of them occurred in groups. 55% of the events are carrot sprites, 21% are C sprites, mixed groupings of carrot and C sprites account for 14%, and the rest of them have forms too ill defined to be properly classified. Morphologically, carrot and C sprites accounted for 90% of sprites observed. The occurrence frequencies for these two types of sprites are similar to those observed over the American plain.

3.2. Oceanic Sprites

[11] Oceanic sprites were observed over a thunderstorm in the Pacific Ocean near eastern Taiwan on 7 June 2001, and over thunderstorms in the northern region of the South China Sea on 20 July and 22 August 2001, as shown in Figures 1b–1d. The observation locations were the AMWS and the NCKU campus. The parental thunderstorms for these oceanic sprites were all mesoscale convection systems. They formed and dispersed in less than 10 hours, and the sprites appeared about four hours before the dismissal of these thunderstorms.

[12] The events shown in Figure 3 exemplify the oceanic sprites recorded in this campaign. Among the 18 oceanic sprites recorded in this campaign, 89% of the events are carrot sprites and only one event is a C sprite. Furthermore, only 4 events (22%) were sprites appearing in groups as shown in Table 1, in sharp contrast to the observed land sprites.

3.3. Sprite Production Rate

[13] If we sort the sprite events of a storm into 10-minute bins, the resulting distribution resembles a Gaussian-like curve. Assuming a thunderstorm system that continuously produces at least one sprite in a 10 minute interval is a sprite active system, the active period for the thunderstorms shown in Figure 1 was typically less than 30 minutes. During our ground observations, the camera was usually directed at the center of the most active region of a thunderstorm. If Δt is the sprite active duration of the storm, N is the number of events observed in this time span, and ΔA is the observed area of the storm, one can define the production rate of sprite events as $I = N/(\Delta t \cdot \Delta A)$. The sprites production rate I is a fair indicator of the sprite generating power of a storm.

[14] For the sprites producing thunderstorm systems on 7 June and 17 August, only a small portion of the system was observed either due to the elongated shape or the closeness of the systems. Thus they are excluded from the calculation of the sprites production rate. For the sprite active storm S_1 shown in

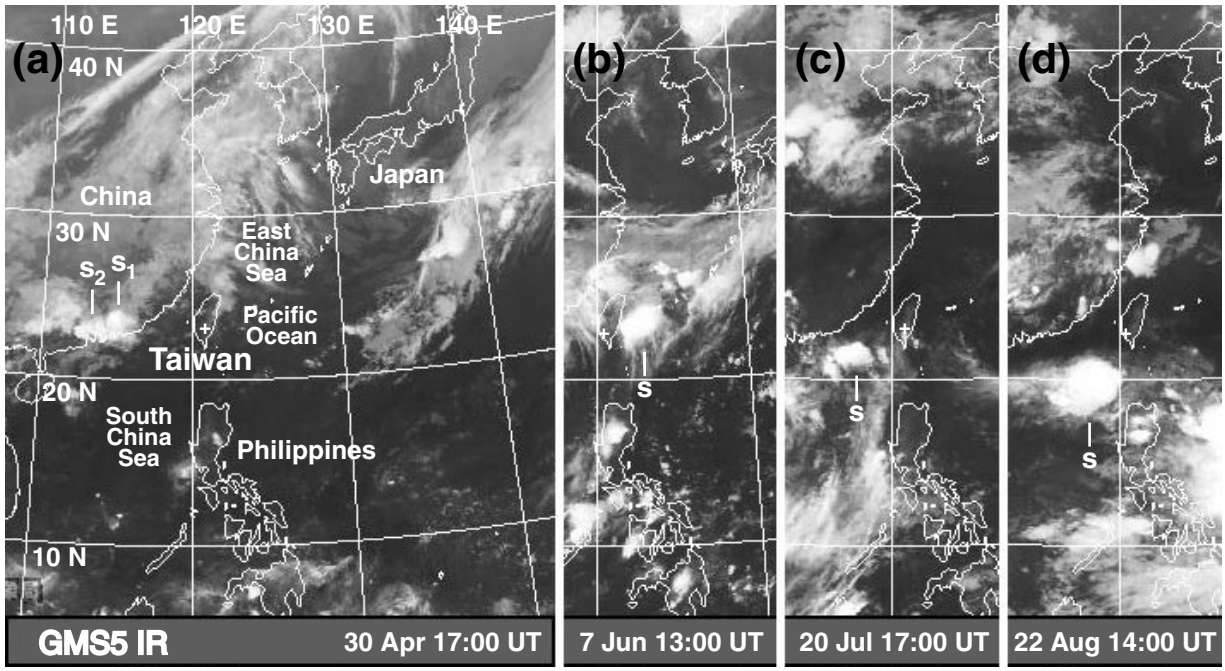

Figure 1. Infrared maps for the area around Taiwan on 30 April (a), 7 June (b), 20 July (c), and 22 August 2001 (d) at the sprites producing periods. The white crosses (+) mark the locations of the AMWS and the NCKU campus.

Figure 1a, the observed area is $\Delta A \sim 23{,}000$ km^2 the active time span is $\Delta t \sim 40$ minutes, and N is 19. As for the S_2 storm, the observed area is also $\sim$23,000 km^2, the active time span is 20 minutes, and N is 6. The sprite production rates of these storms are estimated to be

$$I = \frac{N}{\Delta t \cdot \Delta A} \approx \begin{cases} 1 \times 10^{-3} \text{ events/km}^2\text{/hr (S}_1\text{ storm over land)} \\ 5 \times 10^{-4} \text{ events/km}^2\text{/hr (S}_2\text{ storm over land)} \end{cases} \quad (1)$$

[15] The oceanic thunderstorm on 20 July has an observed area $\Delta A \sim 25{,}000$ km^2, has an active time span $\Delta t \sim 20$ minutes, and has N = 4. For the oceanic storm on 22 August, the observed area is $\Delta A \sim 60{,}000$ km^2, the active time span is $\Delta t \sim 30$ minutes, and N is 6. Using the same definition in Equation (1), the sprite production rates for these oceanic thunderstorms are estimated to be

$$I \approx \begin{cases} 5 \times 10^{-4} \text{ events/km}^2\text{/hr (20 July storm over ocean)} \\ 2 \times 10^{-4} \text{ events/km}^2\text{/hr (22 August storm over ocean)} \end{cases} \quad (2)$$

4. Discussion and Summary

[16] The S_1 storm system, which was observed to produce 31 sprites on 30 April 2001, had another very interesting attribute. This system started as a mesoscale thunderstorm. But by 20:00 UT, the area of this storm had been reduced to 100 km by 100 km and the storm was still capable of producing the sprites shown in Figure 2d. Thunderstorms with a similar or smaller size appear

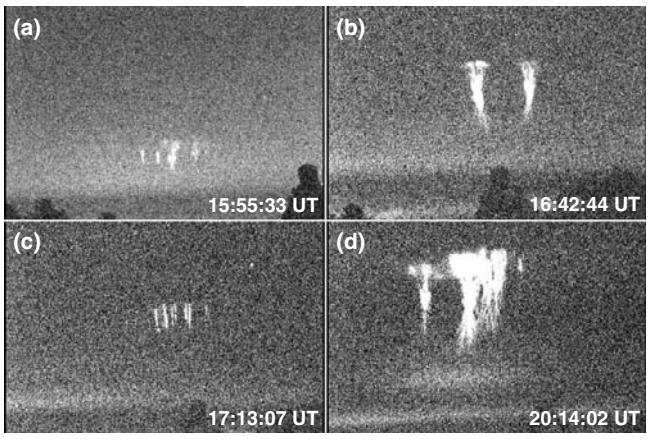

Figure 2. Representative land sprites observed on 30 April 2001, an event produced by S_2 storm (a), and three events produced by S_1 storm, (b)–(d).

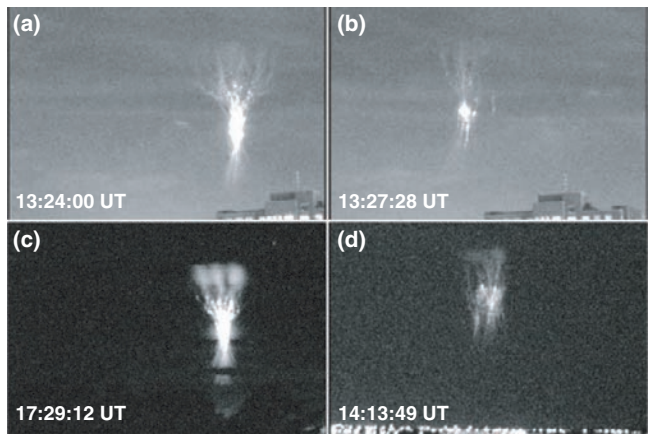

Figure 3. Representative oceanic sprites observed on 7 June, (a) and (b), on 20 July (c), and on 22 August 2001 (d).

very frequently around Taiwan and they will be interesting targets for future observations.

[17] One of the observation sites in this campaign was the Physics Building II in the NCKU campus, which is located in the center of the Tainan metropolitan area. However, on 7 July and 22 August 2001 we were able to recorded 14 oceanic sprites from this highly light-polluted site, as shown in Figures 3a, 3b and 3d. Another observation site is the AMWS with an altitude of 2413 m. The AMWS site offers better observation conditions and is only a three-hour drive from Tainan City. Hence sprite observations can be carried out year-round in Taiwan. We can observe storm systems within a radius of 1000 km from the AMWS, covering areas in the northern Luzon Island of the Philippines, southern China, eastern China and the western edge of the Pacific Ocean. Future observations may provide data to identify more characteristic differences between land sprites and oceanic sprites, and differences between sprites observed in different seasons.

[18] In summary, sprites over southern China and over oceans around Taiwan have been observed. For the land sprites observed on 30 April and 17 August 2001, carrot and C sprites account for 90% of the events and 64% of the sprites appear in groups, similar to those observed in North America. The sprite production rates for the two thunderstorms observed on 30 April are $I \approx 1 \times 10^{-3}$ events/km^2/hr and $I \approx 5 \times 10^{-4}$ events/km^2/hr, respectively. Among the oceanic sprites recorded on 7 June, 20 July and 22 August 2001, 89% of the events are carrots but only 22% of them appear in groups. The sprite production rates for the oceanic thunderstorms observed on 20 July and 22 August are estimated to be $I \approx 5 \times 10^{-4}$ events/km^2/hr and $I \approx 2 \times 10^{-4}$ events/km^2/hr, respectively.

[19] **Acknowledgments.** This work was sponsored in part by the National Space Program Office, Taiwan, under contract number NSC90-NSPO(B)-ISUAL-FA09-01. The technical assistance of C. K. Chang is highly appreciated. We thank the logistic support of the Ali Mountain Weather Station and the Central Weather Bureau in Taiwan.

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