GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 5, 1236, doi:10.1029/2002GL015382, 2003

Correction published 8 July 2003

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

F. T. São Sabbas and D. D. Sentman

Geophysical Institute, University of Alaska, Fairbanks, Alaska, USA

Received 25 April 2002; revised 15 July 2002; accepted 25 November 2002; published 12 March 2003.

[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 2–3°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 ~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 ~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

0094-8276/03/2002GL015382

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

Size	**A** - Contiguous Cloud shield with $T_{IR} \leq -32°C$, area $\geq 10^5$ km^2
	B - Interior clouds with $T_{IR} \leq -52°C$, area $\geq 5 \times 10^4$ 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 h
Max. extent	Cloud shield defined in A reaches maximum size
Shape	Eccentricity $\geq$ 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 ($-72°C \leq T_c \leq -69°C$) that lasts for ~2 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 ($-72°C \leq T_c \leq -69°C$) 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 $T_c \geq -70°C$, in particular $-65°C \leq T_c \leq$

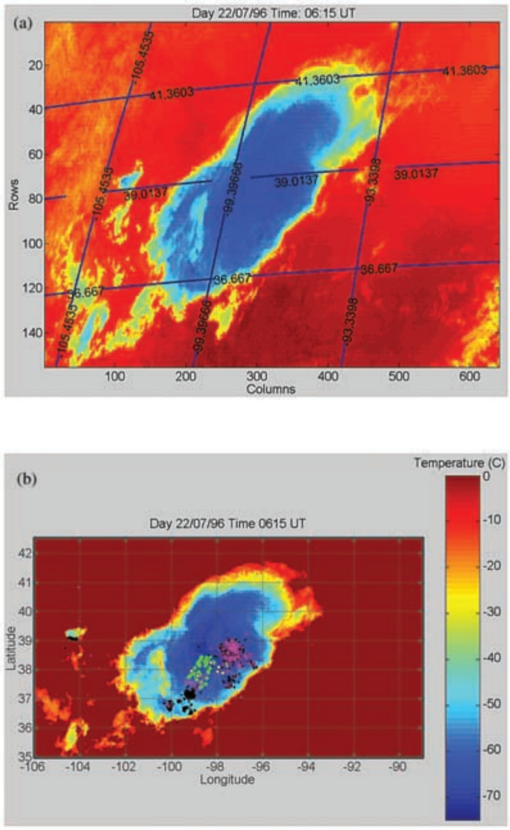

Figure 1. Images of the sprite producing thunderstorm of 22 July, 1996, observed by the GOES-8 satellite at 0615 UT. Panel (a) is the raw data utilized, i.e., the satellite view. Panel (b) is a cloudtop temperature map (T_c) as a function of latitude and longitude. The map also show the location of +CGs (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 ±15 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].

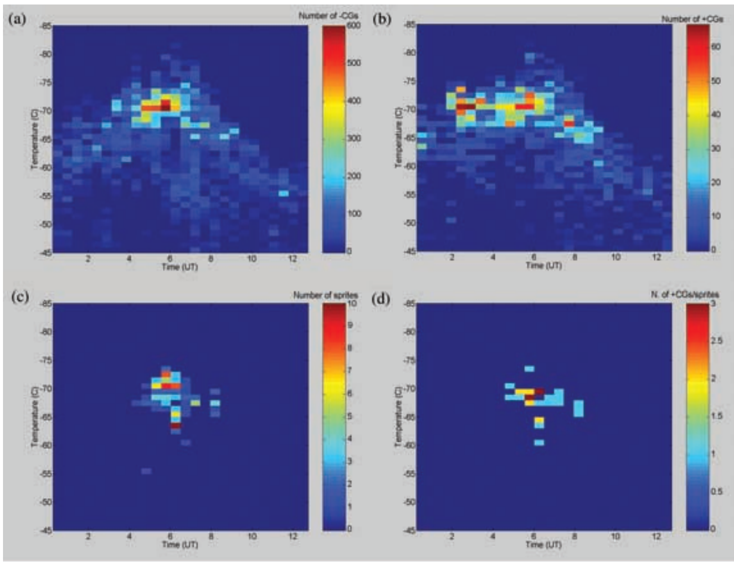

Figure 2. Temporal development of the relationship between GOES-8 IR cloudtop temperatures and the occurrence rate of lightning and sprites throughout the lifetime of the thunderstorm. Each pixel covers 30 min by 1°C, so that each column is the histogram of occurrences vs temperature. The thunderstorm 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 2–3°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 $T \leq -52$°C reaches the maximum area of $\sim 1.4 \times 10^5$ km^2, after which the storm starts to decay, even as the total area of the thunderstorm, as defined by the warmer $T_c \leq -32$°C, continues to expand. The maximum extent of the storm $\sim 2.32 \times 10^5$ 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 $T \leq -52$°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

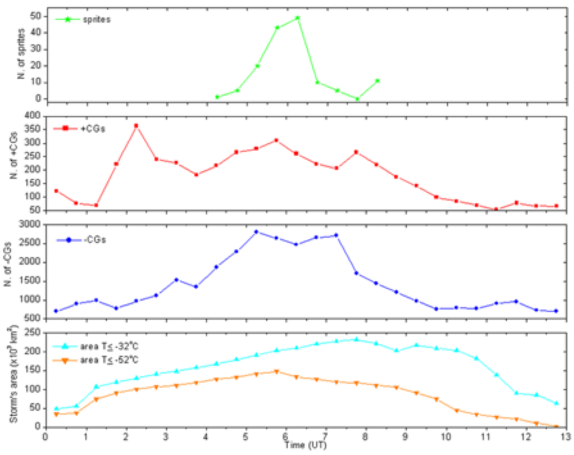

Figure 3. Temporal development of sprite rate (first row), +CG rate (second row), −CG rate (third row) and contiguous area of cloud cover with $T_c \leq -32$°C and $T_c \leq -52$°C during the thunderstorm lifetime.

(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 ∼2hr 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 ∼9h. The MCS moved northeastward and reached a maximum extent of $\sim 2.3 \times 10^5$ km^2 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 $T_c \leq -52°C$, ∼ 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 ($-72°C \leq T_c \leq -69°C$), 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 ($-72°C \leq T_c \leq -69°C$, 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°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]).

[18] **Acknowledgments.** We acknowledge useful discussions with W.A. Lyons, M. Stanley and Earle Williams. Lightning data from the National Lightning Detection Network were kindly provided by Ken Cummins from Global Atmospherics. We thank Michael Taylor for providing the USU sprite date used in the triangulation. This work was developed with the support of CNPq, a Brazilian Government agency dedicated to scientific and technological development, and partially supported by NASA Grant NAG5-0131 and the Geophysical Institute of University of Alaska Fairbanks.

References

Bell, T. F., S. J. Reising, and U. S. Inan, Intense continuing currents following positive cloud-to-ground lightning associated with red sprites, *Geophys. Res., Lett.*, *25*, 1285–1288, 1998.

Boccippio, K. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, and R. Boldi, Sprites, ELF transients, and positive ground strokes, *Science*, *269*, 1088, 1995.

Boeck, W. L., O. H. Vaughan, R. J. Blakeslee, B. Vonnegut, M. Brook, and J. McKune, Observations of lightning in the stratosphere, *J. Geophys. Res.*, *100*, 1465, 1995.

Conforte, J. C., "A study of Mesoscale Convective Complexes over South America and Neighboorood" (in Portuguese), Ph.D. Dissertation, National Institute of Space Research (INPE), S. J. dos Campos, Brazil, 1997.

Cummer, S. A., and U. S. Inan, Measurements of charge transfer in Sprite-producing lightning using ELF radio atmospherics, *Geophys. Res., Lett.*, *24*, 1731–1734, 1997.

Dowden, R. L., J. B. Brundell, W. A. Lyons, and T. Nelson, Detection and location of sprites by VLF phase scattering of subionospheric transmissions, *Geophys. Res. Let.*, *23*, 1741–1744, 1996.

Franz, R. C., R. J. Nemzek, and J. R. Winckler, Television image of a large upward electrical discharge above a thunderstorm system, *Science*, *249*, 48–51, 1990.

Fuellekrug, M., Estimation of sprite occurrence densities in central Africa by infrared satellite imagery, *Proceedings of IAGA-IASEI Joint Scientific Assembly*, Hanoi, Vietnam, p. 99, Aug. 2001.

Fukunishi, H., Y. Takahashi, T. Adachi and R. Miyasato, Characteristics of sprites and Elves observed in winter above Japan, *Proceedings of IAGA-IASEI Joint Scientific Assembly*, Hanoi, Vietnam, p. 98, Aug. 2001.

Goodman, S. J., and D. R. MacGorman, Cloud-to-Ground Lightning Activity in Mesoscale Convective Complexes, *Monthly Weather Review*, *114*, 2320, 1986.

Lyons, W. A., Sprite observations above the U. S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, *101*, 29,641, 1996.

Lyons, W. A., R. A. Armstrong, E. R. Williams, and E. A. Bering, The Hundred Year Hunt for the Sprite, *EOS, Trans. AGU.*, *81*(33), 373–377, 2000.

Maddox, R. A., Mesoscale convective complexes, *Bull. Am. Meteorol. Soc.*, *61*, 1374–1387, Nov. 1980.

Moudry, D. R., M. J. Heavner, D. D. Sentman, and E. M. Wescott, Sprites over small storms, *EOS Trans. Am. Geophys. Union*, *78*(46), F83, 1997.

Neubert, T., T. H. Allin, H. Stenbaek-Nielsen, and E. Blanc, Sprites over Europe, *J. Geophys. Res. Lett.*, *28*, 3585, 2001.

Pasko, V. P., U. S. Inan, and T. F. Bell, Sprites produced by Quasi-electrostatic heating and ionization in the lower ionosphere", *J. Geophys. Res.*, *102*, 4529, 1997.

Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko, Spatial structure of sprites, *Geophys. Res. Lett.*, *25*, 2123–2126, 1998.

São Sabbas, F. T., D. D. Sentman, E. M. Wescott, O. Pinto Júnior, O. Mendes Júnior, and M. J. Taylor, Statistical analysis of space-time relationships between sprites and lightning, *J. Atmos. Solar-Terr. Phys.*, in press, 2003.

São Sabbas, F. T., "Estudo da relação entre Sprites e os relâmpagos das tempestades associadas" (Study of the relationship between Sprites and lightning from the associated storms). *Master dissertation*, *Instituto Nacional de Pesquisas Espaciais (INPE)*, São José dos Campos, SP, Brazil, Feb. 1999.

Sentman, D. D., and F. T. São Sabbas, Comparison of South American and African diurnal signatures in the Schuman resonances with satellite infrared Images", *Proceedings of Vietnam 2001 IAGA-IASPEI Joint Scientific Assembly*, paper G2.01[2624], p. 100, Hanoi, Vietnam, August, 2001.

Sentman, D. D., E. M. Wescott, D. L. Osborne, M. J. Heavner, and D. L. Hampton, The Peru95 Sprites Campaign: Overview, *EOS Trans. AGU*, May 1995.

Su, H. T., R. R. Hsu, A. B. Chen, Y. J. Lee, and L. C. Lee, Observations of sprites over the Asian continent and over oceans around Taiwan, *Geophys. Res. Lett.*, *29*, 1–4, 2002.

Taylor, M. J., L. C. Gardner, and C. Siefring, Image measurements during the 1999 Leonids-MAC Airborne Campaign: High-resolution meteor ablation signatures and longitudinal gravity wave study", *2nd Leonids-MAC workshop*, Tel Aviv, April, 2000.

Velasco, I., and J. M. Fritsch, Mesoscale convective complexes in the Americas, *J. Geophys. Res.*, *92*, 9591, 1987.

Weinreb, M. P., J. X. Johnson and D. Han, "Conversion of GVAR Infrared Data to Scene Radiance or Temperature", *NOAA NESDIS Office of Satellite Operations*, Boulder, Colorado, Revised, June 2001.

D. D. Sentman and F. T. São Sabbas, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320, USA. (fssabbas@gi.alaska.edu)