AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL068924

Key Points:

- A stroke multiplicity of one is most prevalent in thunderstorms with compact charge
- Charge pockets are not needed for multiple strokes in a flash
- The return stroke peak currents are about half the mean value for these compact storms

Correspondence to:
E. R. Williams,
earlew@ll.mit.edu

Citation:
Williams, E. R., E. V. Mattos, and L. A. T. Machado (2016), Stroke multiplicity and horizontal scale of negative charge regions in thunderclouds, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL068924.

Received 29 MAR 2016
Accepted 4 MAY 2016
Accepted article online 7 MAY 2016

Stroke multiplicity and horizontal scale of negative charge regions in thunderclouds

Earle R. Williams[1], **Enrique V. Mattos**[2], **and Luiz A. T. Machado**[2]

[1]Massachusetts Institute of Technology-Parsons Laboratory, Cambridge, Massachusetts, USA, [2]Instituto Nacional de Pesquisas Espaciais, Centro de Previsão de Tempo e Estudos Climáticos, Cachoeira Paulista, Brazil

Abstract An X-band polarimetric radar and multiple lightning detection systems are used to document the initial cloud-to-ground lightning flash in a large number (46 cases) of incipient thunderstorms, as part of the CHUVA-Vale field campaign during the 2011/2012 spring-summer in southeast Brazil. The results show an exceptionally low stroke multiplicity (87% of flashes with single stroke) in the initial ground flashes, a finding consistent with the limited space available for the positive leader extension into new regions of negative space charge in compact cells. The results here are contrasted with the behavior of ground flashes in mesoscale thunderstorms in previous studies. Additionally, we found evidence for a minimum scale (radar echo >20 dBZ) for lightning initiation (>3 km in radius) and that the peak currents of initial cloud-to-ground flashes in these compact thunderstorms are only half as large as return stroke peak currents in general.

1. Introduction

This study was undertaken to shed further light on a problem in lightning physics that is still not well understood: the physical mechanism for multiple strokes in a flash to ground with negative polarity. Nor is it well known why some lightning flashes can transfer most of their charge by continuing current, following the initial stroke. Discussions on mechanisms for discrete strokes in lightning can be found in *Heckman* [1992], *Mazur and Ruhnke* [1993], *Williams* [2006], *Williams and Heckman* [2012], and *Ngin et al.* [2014]. Fortunately, the sequence of events that make up a lightning flash is well documented on the basis of time-resolved measurements with field change antennae and very high frequency (VHF) lightning mapping arrays. A negative cloud-to-ground (CG) flash is initiated by a bidirectional leader that itself is initiated in the strong field region between the main negative charge and the lower positive charge. The weakly VHF-radiating positive leader invades the negative charge region, while the opposite negatively charged and strongly radiating negative leader forges its way toward ground. When the negative leader with large negative potential nears ground, streamers are launched from points on the ground and their thermalization constitutes the "final jump," initiating the return stroke current that proceeds at near light speed back up the leader channel [*Rakov and Uman*, 2003, pp. 137–143]. Within a few milliseconds of the return stroke onset, the current in the channel to ground cuts off near the ground [*Krehbiel*, 1981] and the return stroke channel there becomes optically dark [*Rakov and Uman* 2003, p. 172]. All the while, the positive leader continues its extension into negative space charge aloft at a typical speed of $5 \times 10^4\ \mathrm{m\,s^{-1}}$ [*Williams and Heckman*, 2012], giving rise to the quasi-steady change in electric field at the ground in the interstroke interval known as the "J-process" [*Schonland*, 1938; *Malan*, 1963]. This action continues for typically 60–70 ms until a dart leader is initiated aloft to activate another leader-return stroke sequence toward the second stroke. This process can repeat several times (known as the "stroke multiplicity" of the flash) until the flash terminates. The field change antenna measurements [*Krehbiel et al.*, 1979; *Krehbiel*, 1981] have shown systematic stroke-to-stroke horizontal displacements of the negative charge centers as the flash proceeds. More recent analyses with interferometers [*Shao et al.*, 1995; *Mazur et al.*, 1995] and lightning mapping arrays [*Pilkey et al.*, 2013; *van der Velde and Montanya*, 2013] show similar behavior but with the lateral extension depicted more conspicuously by recoil leader propagation in previously formed but VHF-weak positive leader channels. The resulting horizontal displacements are on the order of kilometers and are generally consistent with the invasion distances possible during typical interstroke intervals by positive leaders at speeds on the order of $5 \times 10^4\ \mathrm{m\,s^{-1}}$ [*Williams and Heckman*, 2012]. This general picture is also supported by the evidence that flash duration increases systematically with the number of strokes in a flash [*Saraiva*, 2010]. For example,

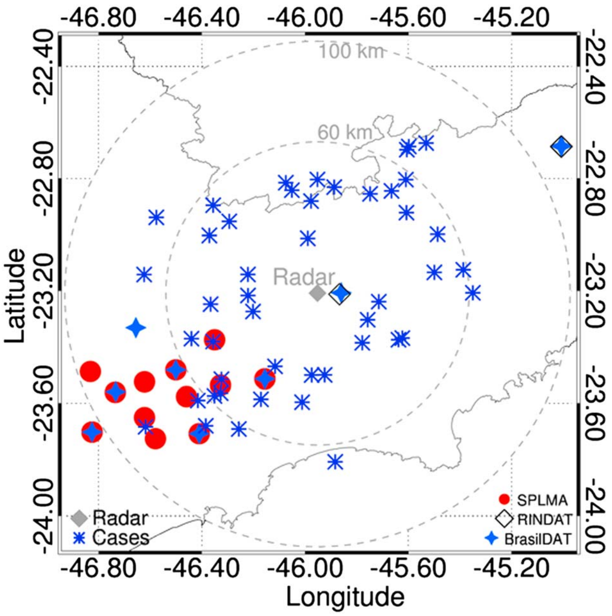

Figure 1. Location of the XPOL radar in São Jose dos Campos, Brazil, together with the lightning sensor locations for SPLMA (red filled circles), BrasilDAT (blue filled stars), and RINDAT (black open diamond) networks used to characterize IC and CG lightning in incipient thunderstorms. Also shown with blue asterisks are the locations of all the incipient thunderstorms in this study.

Saba et al. [2006] have measured flash durations with high-speed video and have constructed an empirical "best" relationship between duration D (ms) and multiplicity M expressed by

$$D = 72M - 100 \qquad (1)$$

with the implication that the mean duration of the interstroke interval is 72 ms.

The main goal in the present study is to find isolated thunderclouds on radar as they first appear and whose lightning activity is well documented with special detection systems. In this way it is possible to study initial cloud-to-ground lightning flashes with a minimum in horizontal extent of the main negative charge region. The working hypothesis is that if the horizontal extent of the negative charge region is sufficiently small, then multiple-stroke flashes will not be possible. In contrast, the literature is replete with evidence that stroke multiplicity can be large in multicellular storms at the mesoscale [*Kitterman*, 1980; *Saraiva*, 2010].

2. Radar and lightning observations during the CHUVA-Vale campaign

The portable X-band polarimetric radar (XPOL) acquired for the CHUVA field experiment (Cloud processes of tHe main precipitation systems in Brazil: A contribUtion to cloud resolVing modeling and to the GlobAl Precipitation Measurement) [*Machado et al.*, 2014] in Brazil was used in this study to identify and characterize a large number (46 cases) of incipient thunderstorms. This fourth campaign of the CHUVA project was called CHUVA-Vale do Paraíba (CHUVA-Vale). From 1 November 2011 to 31 March 2012, this campaign was held in São José dos Campos in the state of São Paulo and multiple lightning networks and ground instrumentation were available.

In this study, three independent lightning detection networks were utilized to locate and characterize the CG lightning flashes in these incipient thunderstorms during the CHUVA-Vale campaign. The SPLMA (São Paulo Lightning Mapping Array, set up and operated by NASA Marshall Space Flight Center, as discussed by *Bailey et al.* [2014], and shown in Figure 1) is a multistation VHF time-of-arrival system with 12 sensors whose station cluster is concentrated to the west southwest of the XPOL radar. VHF radiation sources associated with impulsive events, probably dominated by the negative leaders in both intracloud (IC) and CG lightning, are located three dimensionally. The Brazilian Lightning Detection Network (BrasilDAT) network for CHUVA-Vale (see also Figure 1), set up and operated by Earth Networks, is based on detections with a network of wideband flat plate electric field sensors with bandwidth 5 kHz to 10 MHz. With this system, the times of lightning strokes (in both CG and IC flashes) can be determined accurately in time, and the peak currents associated with the return strokes estimated. Based on a preliminary evaluation of BrazilDAT with video camera [*Naccarato et al.*, 2012], the detection efficiency for CG flashes was found to be 88%. The same study also reported detection efficiency versus stroke order for a small number of flashes, with values 79% (first stroke), 91% (second stroke), and 96% (third stroke). Finally, the Brazilian Integrated Lightning Detection Network (RINDAT) was also used to detect ground flashes and their peak return stroke currents. RINDAT's limited number of sensors available during the CHUVA-Vale campaign is also shown in Figure 1. Only two RINDAT stations are available in the area served by 8 BrasilDAT sensors and 12 SPLMA sensors. This configuration probably reduces the detection efficiency of RINDAT below its value at the time of an earlier study

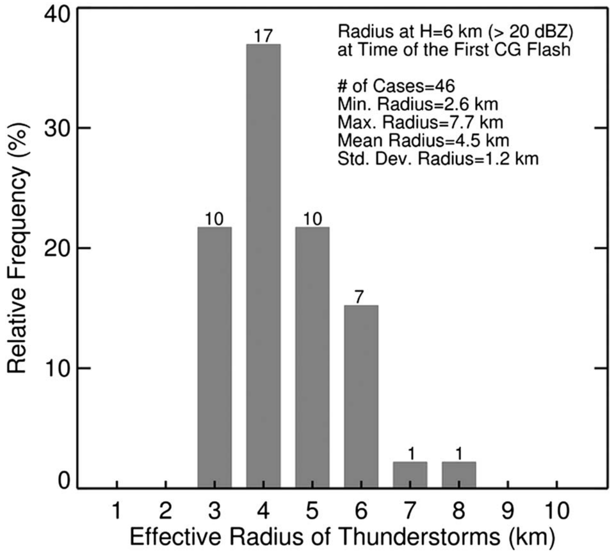

Figure 2. Distribution of effective radii (km) associated with reflectivity greater than 20 dBZ cell areas at 6 km altitude at the times of first CG lightning for 46 incipient thunderstorms. The XPOL radar observations were used for these estimates.

[*Pinto et al.*, 2006]. The return strokes from BrasilDAT and RINDAT were grouped into flashes using a temporal and spatial criterion of 0.5 s and 20 km, respectively. While the time threshold utilized here (0.5 s) is similar to those applied by *McCaul et al.* [2009] and *Goodman et al.* [2005] (0.3 s) and *Nelson* [2002] (0.5 s), the spatial threshold (20 km) is consistent with the small diameters of the precipitating cells in this study.

The location of the XPOL radar on the Universidade do Vale do Paraíba campus in São Jose dos Campos with respect to the various lightning sensors used in this field program is also shown in Figure 1. Full radar volume scans of reflectivity were undertaken continuously every 4 min. Movies of the archived data were used to find initial radar echoes that evolved to thunderstorm stage as isolated convective cells. In poststorm analysis, IC and CG flashes were accumulated within each radar volume scan and assigned to the appropriate storm cell considering area boundaries as a constraint.

The most typical behavior for the initial flashes in these specially selected thunderstorms is for the SPLMA sources to precede the BrasilDAT and RINDAT stroke times for individual lightning flashes [*Mattos*, 2015], consistent with the notion that bidirectional leader activity precedes the return stroke in CG lightning flashes, as discussed in the Introduction. Despite the SPLMA's sensitivity to earlier radiation sources in a flash, this network did not achieve a sensitivity sufficient to follow the full development of the bidirectional leader in individual lightning flashes.

3. Results

The radar first echoes associated with developing moist convection were identified and followed in volume scan observations to the times of first IC flash and first CG flash for 46 incipient thunderstorms. For the large majority (98%) of thunderstorms, an initial IC flash preceded the first CG flash. Only one thunderstorm exhibited a CG flash as its first flash. The XPOL radar data were examined in the plan position indicator scan that most closely coincided with the 6 km mean sea level altitude at the time of the first CG flash, and the area covered by radar samples with 20 dBZ and greater in that scan was used as a proxy measure for the size of the negative charge region at that time. This assumption is consistent with the idea that the negative charge-carrying particles are radar-detectable graupel particles. This reflectivity threshold was selected close to the minimum detectable reflectivity. The results on cell area are not particularly sensitive to the selection because the reflectivity gradients are sharp in this stage of cell development. Those areas were equated with a circular area of radius R, and the distributions of those storm radii are shown in histogram form in Figure 2. The mean radius is 4.5 km. Some estimated radii are as small as 3 km. These results suggest that a minimum size ($>$3 km radius) for the negative charge center is necessary for the first CG flash in incipient thunderstorms, thereby demonstrating some potential for lightning nowcasting.

Stolzenburg et al. [2015] have studied the radar structure of New Mexico thunderstorms at the time of the initial intracloud flash. The cell diameters at 6 km altitude and within 20 dBZ radar contours are in the 5–7 km range. Corresponding radii (2.5–3.5 km) are consistent with the findings in Figure 2 if it is remembered that these measurements pertain to the first IC flash rather than the first CG flash in the storm.

BrasilDAT lightning data were used to determine the stroke multiplicity for all initial CG flashes in these developing thunderstorms. That distribution is shown in Figure 3. No multiplicity greater than two was found, and

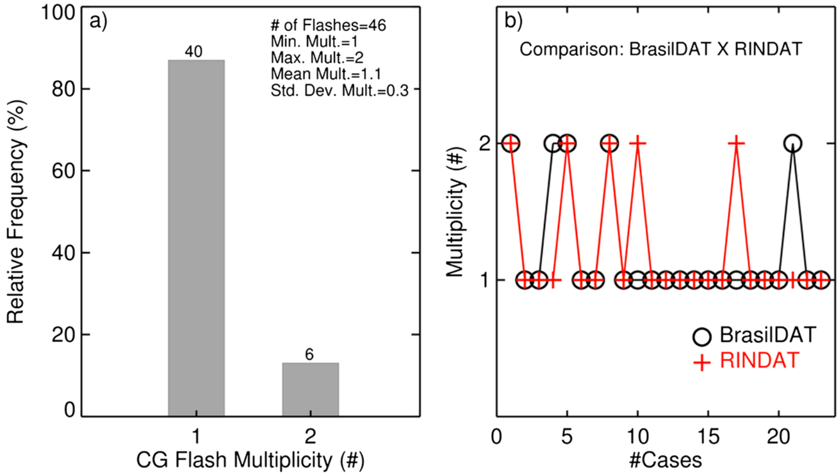

Figure 3. (a) Distribution of stroke multiplicities for all initial CG lightning flashes in the 46 incipient thunderstorms. BrasilDAT observations were used for these determinations. (b) Comparison of stroke multiplicity for the 23 flashes detected by BrasilDAT and RINDAT networks.

the great majority (40 of 46 flashes or 87%) of flashes showed single-stroke behavior. The RINDAT archive was also examined for stroke multiplicity, and the comparisons for a subset of 23 CG flashes detected both by BrasilDAT and RINDAT are shown in Figure 3b and demonstrate good agreement with BrasilDAT results. The poor relative detection efficiency of RINDAT is consistent with the small number of sensors available in the region of interest shown in Figure 1. But 18 of 23 (78%) of RINDAT flashes show single-stroke multiplicity. To investigate the effects of increasing thunderstorm horizontal scale on stroke multiplicity, the distribution of values in BrasilDAT was examined for the second CG lightning flash in the thunderstorms. Some flashes with multiplicities up to 5 were encountered (not shown). Further trends with time were not clear, maybe because the size of these thunderstorms did not increase substantially following the initial lightning flashes.

BrasilDAT observations were also used to determine the distribution of interstroke intervals in the initial CG flashes in the incipient thunderstorms. That distribution of time intervals is shown in Figure 4. For the minority set of flashes with multiplicity greater than one values range from 40 to 130 ms, with a mean of 72 ms. These interstroke intervals are similar to ones recorded in thunderstorms that are not spatially compact, presented by *Rakov and Uman* [2003] (60 ms), *Schulz et al.* [2005] (80–95 ms), and *Saba et al.* [2006] (61 ms).

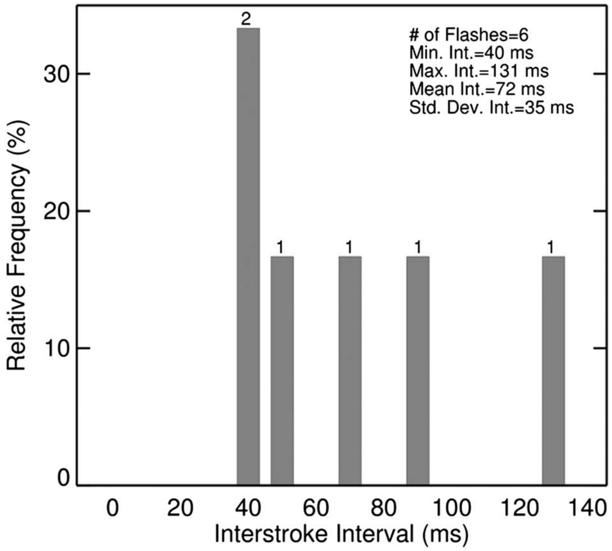

Figure 4. Distribution of interstroke time intervals for initial multistroke CG lightning flashes in the set of 46 incipient thunderstorms. BrasilDAT observations were used for these determinations.

The return stroke peak current for initial ground flashes in incipient thunderstorms has also been studied, with findings shown in Figure 5. The mean peak current for 45 first negative CG flashes in incipient thunderstorms (−11 kA) is less than half the mean peak current for negative CG flashes recorded by RINDAT in "climatology" [*Pinto et al.*, 2006]. The reliability of RINDAT prior to this 2006 study was substantially better than during this CHUVA-Vale campaign (O. Pinto Jr., personal communication). Nevertheless, the peak current estimates by RINDAT and BrasilDAT for the CHUVA campaign show excellent agreement. One possible interpretation for this finding follows results in *Chronis et al.* [2015] that CG peak current is proportional to cloud potential and that this quantity at the time

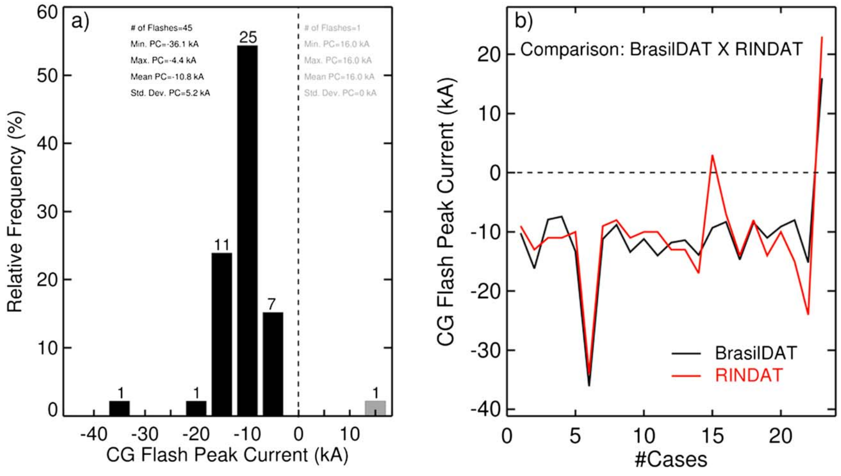

Figure 5. (a) Distribution of return stroke peak current for 46 initial ground flashes and (b) comparison of BrasilDAT and RINDAT estimates of CG peak current for the 23 flashes detected by both networks.

of the initial ground flash is systematically less than its values during other stages of thunderstorm development. This suggestion is however difficult to verify because cloud potential measurements are scarce [*Stolzenburg and Marshall*, 2008], and those available at the time of first CG flashes are scarcer still.

4. Discussion

The stroke multiplicities of lightning flashes in this special set of cloud-to-ground events in incipient thunderstorms differ markedly from those in earlier studies in which the storm size and horizontal extent of the main negative charge center were not controlled. Figure 6 summarizes findings on stroke multiplicity in Florida [*Rakov and Uman*, 1990] and New Mexico [*Kitagawa et al.*, 1962]. Additional observations in Kansas [*Kitterman*, 1980] and in Brazil [*Saraiva*, 2010] also involved multicellular thunderstorms and mesoscale activity with large stroke multiplicity. In the case of *Kitterman* [1980], multicellular squall lines were specifically targeted.

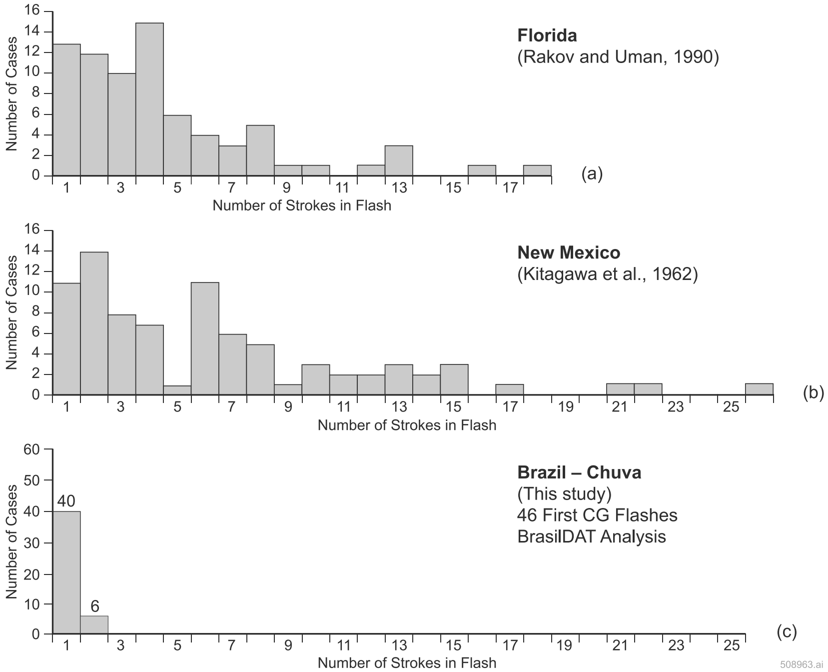

Figure 6. Comparison of distributions of stroke multiplicity for CG lightning flashes in this and other previous studies. The predominance of stroke multiplicity = 1 is unique to the present study.

In the case of *Saraiva* [2010], radar data were also used, but the character of the convection was mostly mesoscale and not isolated thunderstorms. Figure 6 shows that only in the case of the compact thunderstorms studied here is single-stroke lightning predominant.

Consistent with these findings are independent studies with lightning location networks in which CG flashes with large multiplicity (up to 15 strokes by flash) have been documented. For example, *Rakov and Huffines* [2003], *Schulz et al*. [2005], *Mäkelä et al*. [2010], and *Rudlosky and Fuelberg* [2010] observed a maximum mean value near 2.4, while *Baharudin et al*. [2014] documented flashes with mean multiplicity up to four strokes per flash. Methods based on electric field and optical measurements [*Rakov and Huffines*, 2003], judged to be more accurate than lightning network measurements, have been used to determine stroke multiplicity in Florida (FL) and New Mexico (NM). The results show that the percentages of all ground flashes with only one stroke (FL 17% and NM 14% with the improved documentation) are appreciably smaller than the percentages based on the National Lightning Detection Network measurements (FL 44% and NM 51%). But both sets of percentages stand in marked contrast to the 87% value for the special set of ground flashes studied here for incipient thunderstorms.

In contrast with the stroke multiplicity, the distribution of interstroke intervals for these compact thunderstorms is not markedly different than in the other studies, including *Schulz et al*. [2005] (80–95 ms) and *Saba et al*. [2006] (61 ms) already mentioned. If the horizontal extension speed of the positive leader is 5×10^4 m s^{-1}, then in a typical interstroke interval of 72 ms (consistent with the findings in Figure 4 for compact thunderstorms and with equation (1) from *Saba et al*. [2006] for thunderstorms with large stroke multiplicity), the leader will extend by 3.6 km. That distance is already comparable to the estimated radius of the main negative charge region, based on the radar measurements in Figure 2 (mean radius 4.5 km). On that basis, compact cells may not be capable of supporting flashes to ground with multiplicities larger than 1 or 2. Based on the results of *Saba et al*. [2006] and *Saraiva* [2010], it is logical that one can estimate the maximum horizontal extent of the negative charge region by counting the largest multiplicity exhibited by lightning in that system.

Schonland [1938] had suggested similar ideas in the context of his “charge-pocket” explanation for multiple strokes in lightning, in writing “The association of multiple strokes with large and extensive cloud masses is in accord with this suggestion, for the larger thunderstorms may be expected to possess several generating centers.” The observations shown here, together with the evidence for larger stroke multiplicity in larger storms, support the role for horizontal size in promoting multiplicity. The observations on compact storms in CHUVA do not support the idea for distinct and separate charge centers as a necessity for separate strokes in a flash, given the evidence for multiple strokes within the same contiguous radar echo at 6 km altitude in these incipient thunderstorms. It should also be noted that Schonland’s original “junction streamer” idea to link the original channel with the charge pockets is unlikely to be occurring. The contemporary evidence for that assertion is that the main negative charge region is often devoid of the strong VHF radiation known to accompany the negative leaders [*Williams*, 2006], which are fundamental players in his 1938 picture of multistroke flashes.

5. Conclusion

In incipient thunderstorms of minimum possible size (<4.5 km mean radius), the time scale for leader progression in a typical interstroke interval is already comparable to or greater than the size of the main negative charge region, making multistroke flashes unlikely, consistent with observations noted here. Findings for incipient thunderstorms show marked contrast with findings for mesoscale convective systems with large horizontal extents [*Kitterman*, 1980; *Saba et al*., 2006; *Saraiva*, 2010], in which multiplicities of 10 and greater are exhibited. The finding here for compact thunderstorms is also consistent with the notion that the maximum number of strokes per flash can serve as a measure of the horizontal extent of the negative charge region in noncompact (i.e., mesoscale) thunderstorms [*Saba et al*., 2006; *Saraiva*, 2010].

Acknowledgments
This study was supported by a grant from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (2011/13673-8) that enabled the participation of the first author in the CHUVA-Vale campaign. The second author’s work at MIT in this study was supported by FAPESP grant 2013/04292-6. We would also like to thank the CHUVA project, also supported by FAPESP with the grant 2009/15235-8. Discussions with NASA MSFC (Jeff Bailey, Richard Blakeslee, and Steve Goodman) on SPLMA and Earth Networks (Stan Heckman) on BrasilDAT results and with Osmar Pinto and Kleber Naccarato on RINDAT results are much appreciated. Discussions with Antonio Saraiva on a radar experiment in his doctoral thesis with a similar conceptual goal were also of great benefit to this study. Rachel Albrecht and Ken Cummins shared their information on detection system intercomparisons. Discussions with Paul Krehbiel and Xuan-Min Shao on the interstroke interval are appreciated. Maribeth Stolzenburg provided discussion on conditions associated with the first lightning flashes in New Mexico thunderstorms. The data used in this work are freely accessible on the CHUVA project website (http://chuvaproject.cptec.inpe.br).

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