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ON THE VARIABILITY OF LIGHTNING CHARACTERISTICS OVER THUNDERSTORM LIFECYCLES

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1. INTRODUCTION

Overall cloud-to-ground (CG) lightning parameters for different regions were studied by several authors in the past (Kitagawa et al., 1962, Rakov et al., 1994, Cooray and Perez, 1994, Cooray and Jayarante, 1994, Saba et al., 2006, Saraiva et al., 2010). Some differences among the lightning parameters were found for different regions, but the cause may rely on the use of different techniques to analyze some characteristics of CG lightning (Rakov et al., 1994). In Saraiva et al. (2010), lightning properties have been measured using the same instrumentation in different geographic locations in an attempt to determine if the key lightning parameters depend on the location and/or the meteorological environment. The study showed that the basic parameters were very similar in Arizona (USA) and São Paulo (Brazil), when averaged over a large number of storms. However, individual storms showed wide variation in lightning parameters both within and between regions. Other works like Orville et al. (2002), Steiger et al. (2002) and Kitterman (1980) showed possible variations of flash multiplicity and thunderstorms type or geographical location, although the authors did not arrive to any conclusions about what the effect could be.

The objective of this work is to quantify how selected lightning parameters, such as flash duration and multiplicity, and the duration of the continuing current (CC), evolve over the lifecycles of thunderstorm cells in different geographic locations. The lightning data were acquired using high-speed cameras (up to 8000 frames per second) and Lightning Location System (LLS) reports. Radar imagery was used to identify cells, measure the horizontal extent of the reflectivity at the -10° C level and estimate the total duration of the storms. The LLS's provide estimates of the 5-minute interval flash rates along with estimates of peak current, multiplicity and stroke locations which are used to characterize the overall cell behavior. The camera data are used to provide more precise measurements of the multiplicity, as well as the flash duration and CC, for a subset of flashes in each cell.

2. DATA AND ANALYSIS METHODS

Two sites were used to make the lightning observations. In the US, the data were acquired during July/August (summer) 2007 in Tucson, AZ (Cummins et al, 2008). In Brazil, all flashes were recorded in São José dos Campos, during the summer of 2008 (e.g. Ferraz, 2009). Two high-speed cameras were used to observe lightning flashes. For the same periods, data from closer Doppler weather radars and the LLS were also used.

The high-speed cameras were the Redlake MotionScope 8000S and the Photron Fastcam 512 PCI. The main difference between each one is the time and space resolutions. The MotionScope was set up to 1000 frames per second (1 millisecond time resolution) and spatial resolution of 240x210 pixels. The Fastcam 512 was set up to 4000 fps (250 μs of time resolution) and spatial resolution of 512 x 256 pixels, some flashes were also observed in 8000 fps (125 μs of time resolution). All video data have a total recording time of 2 seconds. A total of 250 flashes were recorded in Tucson and 197 were recorded in Brazil. The video frames of both high speed cameras are GPS time stamped to an accuracy of 1 ms. The synchronization allowed the comparison of each flash with the local LLS.

The LLS data used are from BrasilDAT, in Brazil and NLDN, in the US. A total of 3100 flashes were located by NLDN in 21 thunderstorm cells, and 7232 flashes were located by BrazilDat for 17 thunderstorms. Differences in detection efficiency (DE) (Biagi et al., 2007, Ballarotti et al., 2006) and sensors type made a direct comparison between the LLS results difficult. This issue was addressed by using a compensation factor of 1.4 (calculated from the stroke DE of both networks) was applied to the Tucson data in order to reduce the flash multiplicity to more-accurately relate to BrasilDat data. Also, for both networks, all data were filtered to exclude lightning in the range of 0 – 10 kA and with semi-major axis greater than 5 km to avoid IC lightning (e.g. Cummins et al., 1998; Wacker and Orville, 1999a, b).

Radar images from Brazil are from the Meteorological Radar of São Paulo, located in the city of Biritiba Mirim, approximately 50 km from the observation site. In the US, the radar used is part of the NEXRAD (Next-Generation Radar) network, KEMX level-II WSR-88D from the National Climatic Data Center (NCDC), located in Tucson, less than 40 km from the observation site. CAPPIs (Constant Altitude Plane Position Indicator) were extracted from both radars, discussed further in the next.

Along with the development of this work, some assumptions were made as follow: the horizontal extent of the negative charge layer is more important than the vertical extent, one example occurred in Brazil of this behavior is showed in Figure 1, the flash on that figure is from a multiple stroke flash from 02/13/2008, and the strokes showed are numbers 7, 11, 14 and 16, note the horizontal development with increasing of stroke order; the negative charge layer did not move vertically over the thunderstorm lifecycle; and the leader velocity inside the cloud moves in a constant velocity. Even if these considerations do not completely represent the real phenomena, they are good estimates of it, and necessary steps to have this work done.

3. ANALYSIS AND RESULTS

Several works in the literature tried to relate lightning occurrence to radar parameters. It is not clear, however, what is the best radar echo to represent lightning occurrence. MacGorman (1978) and MacGorman et al. (1983) observed that the horizontal extents of lightning channels were related to the contours of the 36 dBz levels of the radar echoes. Mishimoto (1991) observed that lightning initiates after the 30 dBz levels show up in winter thunderstorms in Japan. Proctor (1991) studied lightning initiation region and found out two major layers of lightning formation, but also shows other studies that observed only one layer. Lund et al. (2009) observed that lightning initiation usually occurs within and on the boundaries of the 35 dBz contours inside the cloud at altitudes of 3 – 6 km, 7 – 10 km and some at 10 – 12 km, with most of the lightning occurring at 7 – 10 km during the mature stage of the thunderstorms analyzed. Although other works suggest different reflectivity levels for lightning initiation, 35 dBz was chosen in this work based on the data analysis. This level is also considered as indicative of strong convection as the echoes originate from graupel particles (e.g. MacGorman and Rust, 1998, Roberts, 2002, Takahashi et al. 1998). According to the tripolar model of charge distribution (Simpson and Scrase, 1937, Simpson and Robinson, 1941), it is known that the main negative charge layer is located roughly at the -10º C level (e.g., Williams, 1989; MacGorman and Rust, 1998), and its height can be determined using Skew-T diagrams. In this work we will assume this model in our considerations. To estimate the horizontal area of the thunderstorm (and, consequently, the extension of the main negative charge layer), CAPPIs were extracted from both radars in 5 km, in Brazil, and 7 km, in the US. For the days of observations in both places, these heights best represent the overall location of the -10º C (examples shown in Figures 2 and 3).

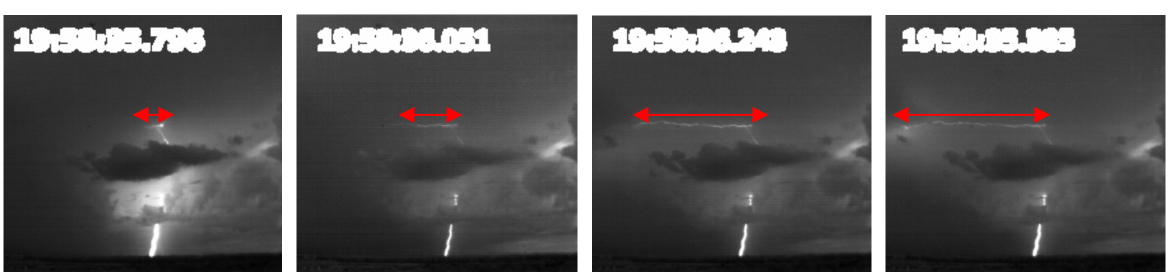

Figure 1 – Example of lightning channel propagating horizontally in the cloud, on 02/13/2008.

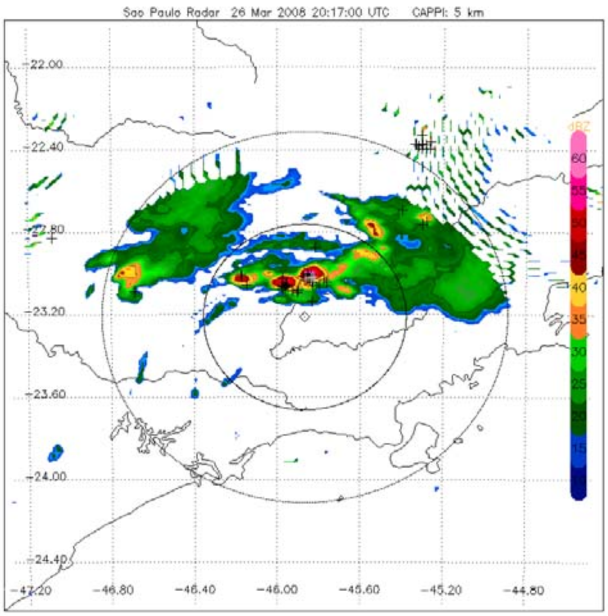

Figure 2 – Example of radar image (5 km CAPPI) from 03/26/2008 in Brazil. The black crosses are flashes occurred in the five minutes after the first scan of the radar.

In this section the analysis of 17 thunderstorm cells in São José dos Campos and 21 cells in Tucson will be presented. A total of 10332 negative CG flashes occurred and 447 were

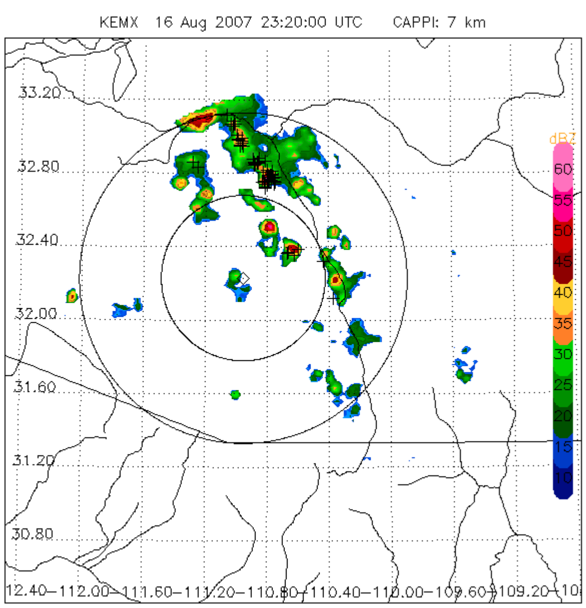

Figure 3 – Example of radar image (7 km CAPPI) from 08/16/2007 in Tucson, AZ. The black crosses are flashes occurred in the five minutes after the first scan of the radar.

recorded by high speed cameras. For these cells, the area of the 35, 45 and 55 dBz contours, at an estimated -10°C height, were calculated and all lightning inside each cell was identified. The radar data have time resolution of 5 – 10 minutes in Brazil and 4 – 10 minutes in the US. From them, the areas for the reflectivity contours for each interval were measured. The CAPPI generation and cell tracking were performed by a composition of IDL® and MapInfo® routines. All plots shown here include data sets from both Tucson and São José dos Campos, except when the contrary is specified in the plots.

3.1 Flash multiplicity

High-speed camera and LLS data were used to study the flash multiplicity. It is know that flash multiplicity given by the LLS an underestimation of the true flash multiplicity in general. However, due to the quantity of flashes measured, any trends that relate this parameter with the area in 35 dBz will be more reliable than those obtained with the limited camera dataset.

Figure 4 shows a bi-dimensional histogram of the flash multiplicities measured by the LLS versus the area of the contours at 35 dBz, where the number of observations is represented by the color scale. A tendency line was plotted on the Figure and shows a limit between higher multiplicities and the area, which suggests that higher multiplicities tend to occur in bigger areas. To produce this Figure, both datasets containing São José dos Campos and Tucson LLS data were used, and a correction factor mentioned before was applied. A separate analysis showed that Tucson dataset has considerably smaller areas in 35 dBz, since most of thunderstorms were isolated, short living cells, while São José dataset presented wider frontal systems, and also higher flash multiplicity. In Figure 5 a similar plot is made, but now with camera recorded multiplicities. 447 negative CG flashes were used to make this plot and the trend is still visible. Unlike Figure 4, we can show individual events (rather than counts), due to the small population. This also allows us to separately identify events from Brazil and the U.S. The black line shows the same tendency line of Figure 4, and the orange line is the same line shifted to the right due to a factor applied to the LLS data to compensate the difference between the multiplicity observed by the camera and the LLS. The mean multiplicity found for these datasets were 3.5 and 5, for LLS and high-speed cameras, respectively, in Brazil, and 2.8 and 4 for Tucson, and for both cases, the correction factor was surprisingly the same (1.42). As can be noted, the orange line fits 99% of the camera data except to 4 cases that occurred in Tucson that presented high multiplicities.

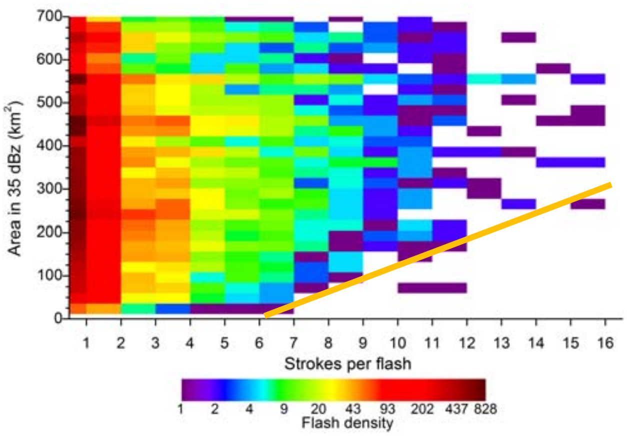

Figure 4 – Bidimensional histogram showing the relationship between the area of the contours in 35 dBz level and flash multiplicity observed by the LLS's in Tucson and São José dos Campos. The color gradients show the flash density for each multiplicity in intervals of 25 km^2.

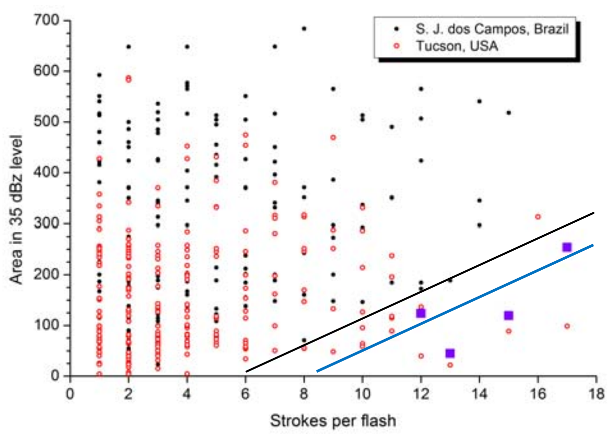

Figure 5 – Scatterplot of the areas in 35 dBz and flash multiplicities observed by high-speed cameras in São José dos Campos (black circles) and Tucson (red circles).

Figure 6 shows the multiplicity as seen by the LLS in both locations, with the required compensation factor applied versus the flash count at each 5 minutes interval, also called here as the electrical activity of the storm. As shown in Figure 4, there is a very clear trend concerning the occurrence of higher multiple stroke flashes with higher periods of electrical activity. These two tendencies can be separate effects or may just reflect of a linear relationship between the area in 35 dBz and the electrical activity. Again, in Figure 7, the same plot shown in Figure 6 was made, but now with high-speed camera data. After applying the correction factors, the same 4 high-multiplicity cases occurred outside the boundaries of the tendency line.

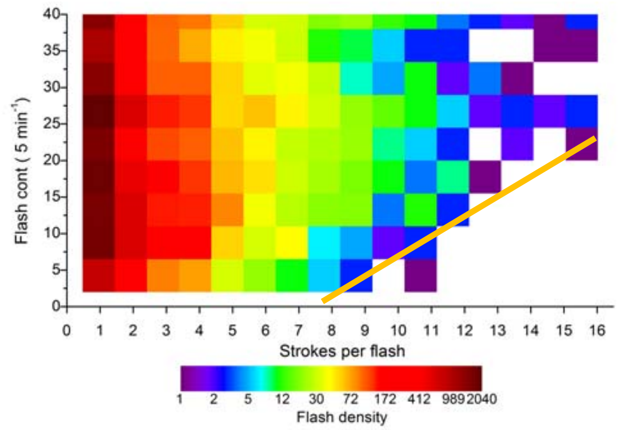

Figure 6 - Bidimensional histogram showing the relationship between the flash counts per 5 minutes and flash multiplicity observed by the LLS's in Tucson and São José dos Campos. The color gradients show the flash density for each multiplicity in intervals of 25 km^2.

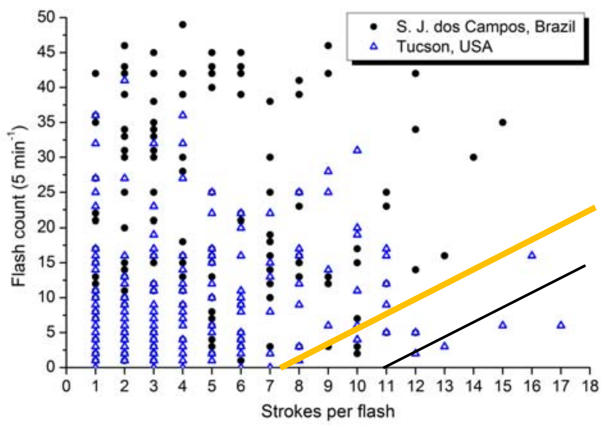

Figure 7 – Scatterplot of the flash count and flash multiplicities observed by high-speed cameras in São José dos Campos (black circles) and Tucson (blue triangles).

As showed by Lund et al. (2009), a large percentage of flashes originates in the decaying phase of the storm are produced at lower altitudes 3 – 7 km (in their cases), probably reflecting that the whole charge regions are displaced downwards and the initiation occurs in those regions. Although in this study this effect was not computed, some cases with high multiplicities related to small areas occurred during the decaying phase of the thunderstorms. Since at lower altitudes the areas in 35 dBz were bigger (not shown here), it is possible that those flashes initiated and propagated through lower regions. Curiously the effect of charge region displacement seems to be more important in Tucson than in São José dos Campos, however there is no similar

Table 1 – Flashes that occurred outside the tendency lines of multiplicity and flash count vs area in 35 dBz

Date	Time (UTC)	Multiplicity	Long CC?	Duration (s)	Flash count	Area in 35 dBz, at 7 km height	Area in 35 dBz at 3 km height
08/16/07	03:38:22	17	y	1.06	6	98.55 km^2	253.9 km^2
08/11/07	00:53:00	15	n	0.773	6	88.47 km^2	119.3 km^2
07/31/07	22:19:05	13	y	0.818	3	21.94 km^2	44.72 km^2
07/31/07	02:32:39	12	y	0.703	2	39.77 km^2	123.8 km^2

studies like one did by Lund et al. (2009) for this region. Summarized in Table 1 are the 4 flashes that happened outside the tendency lines and the suggested area of the contour of 35 dBz in lower regions.

Figure 8 shows the correlation between multiplicity and reflectivity of the radar on the coordinate of the ground strike point of the flash, detected by the LLS. As it can be seen, at the height of 5 km, in S. J. dos Campos, and 7 km in Tucson, most of the lightning flashes occur within 30 – 50 dBz, and the higher multiple flashes tend to occur in that range also. This result will be discussed later on the text.

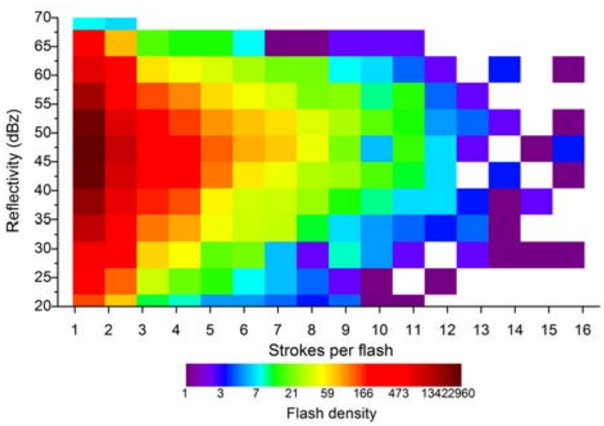

Figure 8 – Bidimensional histogram showing the relationship between the reflectivities associated to each multiple stroke flash observed by the LLS's in Tucson and São José dos Campos. The color gradients show the flash density for each multiplicity in intervals of 25 km^2.

3.2 Flash duration

The flash duration is defined here as the time between the first stroke and the end of the luminosity of the last subsequent stroke, or the end of the continuing current (if present). Figure 9 shows a plot of flash duration versus multiplicity, using both datasets. Two tendency lines were plotted, one to represent the minimum flash durations for each multiplicity and other to represent the maximum duration for multiplicities. The results plotted in Figure 9 will be discussed later.

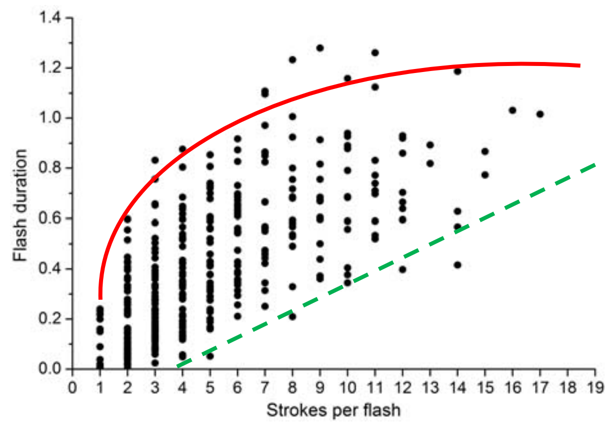

Figure 9 – Scatterplot showing the relation between the total flash duration and the number of strokes per flash. The tendency line in red fits the maximum durations for each multiplicity and the dashed green line fits the minimum durations for each multiplicity.

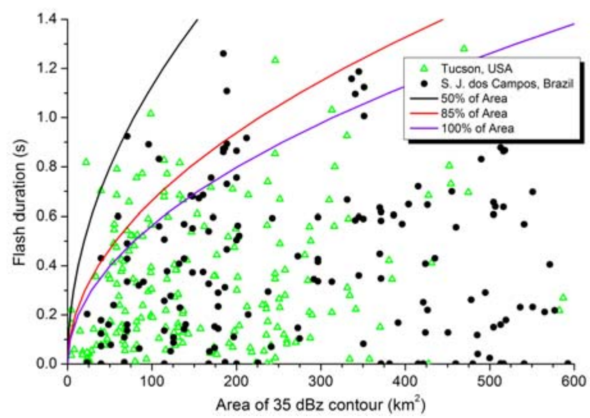

Figure 10 – Scatterplot of flash durations measured by the high-speed camera versus the area in 35 dBz for S. J. dos Campos and Tucson. The 3 curves plotted are idealized minimum areas for the related to each flash duration.

Figure 10 shows a scatterplot of flash durations observed by the high-speed cameras on São José dos Campos and Tucson. The tendency here is more complicated to see, and the colored curves will help understanding some of the behavior of the durations of the flashes. This result will also be part of the discussion on the last section.

3.3 Continuing current

The duration of the continuing current (CC) can be inferred from the duration of the continuing luminosity in the channel following the return stroke. The CC can last from a few to hundreds of milliseconds, and it can be classified as long (duration greater than 40 ms) [Brook, et al., 1962; Kitagawa, et al., 1962], short (between 10 and 40 ms) [Shindo and Uman, 1989] and very short (between 4 and 10 ms) [Ballarotti, et al., 2005].

Figure 11 and 12 show a histogram of number of short and long CCs, respectively, as a function of the ratio of the areas of the 45 and 35 dBz CAPPI contours. This ratio is related to the convective strength of the cell at a given time; from these analyses it is possible to say that small ratios are associated to the decaying phase of the cell and the higher ratios to the initial and mature phases. More than 50% of the short and long CCs occur in the decaying phase (ratio < 0.05), and more than 80% when the ratio is below half of the maximum value.

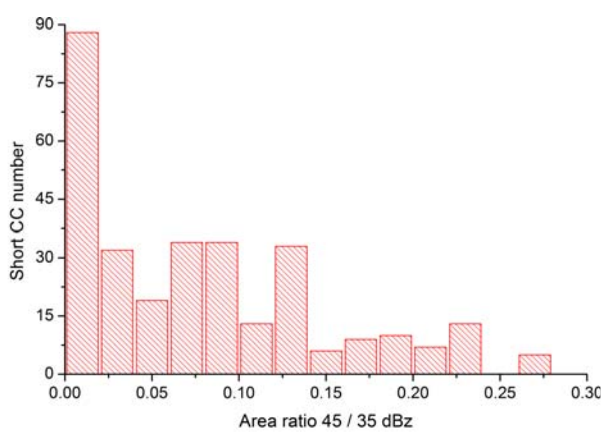

Figure 11 – The histogram shows distributions of the number of short CC for ranges of ratio between 45 and 35 dBz levels.

4. DISCUSSIONS AND CONCLUSIONS

This paper presented comparisons of lightning parameters obtained by Lightning Location Systems and high-speed cameras with radar data, in Brazil and the US. The parameters presented here, flash multiplicity and duration showed a good correlation with the horizontal extent of the 35 dBz level in -10º C. However, continuing currents occurrences seemed to be more related to the ratio between reflectivity levels of 45 and 35 dBz. The reduction in this ratio is related to the decaying phase of the storms.

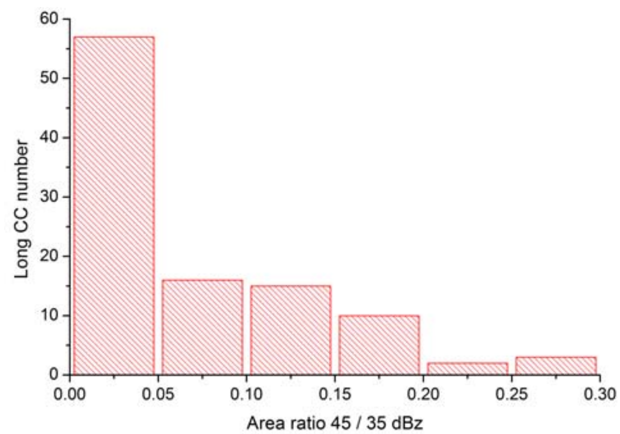

Figure 12 – The histogram shows distributions of the number of long CC for ranges of ratio between 45 and 35 dBz levels.

The flashes presented in Table 1 had their associated area of 35 dBz contours recalculated in 3 km height in order to verify the possibility of their initiation happened in a lower altitude, a possibility described by Lund et al. (2009). For 3 of them a significant increase in the area associated allowed them to lay within or near the expected behavior. The new locations of these points are plotted in Figure 5 as violet squares. One of these flashes did not change its location considerabily; however, as suggested before, cases outside the trend line plotted can and will happen, but not often.

Also in Figure 5 it is clear that S. J. dos Campos data related better with the trend estimated than Tucson data. This could also be due to the different thunderstorm regimes that usually happen in both places and were predominant for the overall thunderstorms.

The effect of the area or the ratio of areas in different reflectivity contour levels on the continuing current is still a question not fully understood. The histograms showed that most of the CCs occur at the end of the storm, where the ratio between the 45 and 35 dBz levels are smaller. This may be a mechanism yet unknown, which disturbs the channel, making it more unstable during the initial and mature phases, thereby inhibiting long

CC. This condition may not exist during the decaying phase, thereby allowing long CC. Alternatively, there may simply be large charge reservoirs in lower-reflectivity regions during the late phase.

To understand the variations of the flash multiplicity and duration within the 35 dBz region, some considerations could be made. The example of Figure 13 shows a small thunderstorm cell developing in Tucson, on July 31st of 2007. This is a short living cell, not connected with any other cell in any altitude. The CAPPIs on the Figure were taken in 7 km height and the crosses shows the lightning that occurred on it during 5 minutes, showed also in Table 2. As the results showed before, it was expected that most of the flashes presented very low multiplicities. However, there was an exception: the last one. Taking a closer look at the last square of Figure 13 (at 02:21) it is possible to see that the flash happened on one corner of the cell. Considering that the channel propagates inside the cloud acquiring more charges to make possible the next strokes, and also that the velocity of this leader might be comparable to the velocities of downward leaders (of about 10^4), that channel should have travelled about 8 km, which is the total extent of the cell in 35 dBz, at 7km, from one corner to the other. So, it is reasonable to assume that that flash could have more strokes if the cell was longer. Now, the question is, is there a minimum cell size for the occurrence of a given multiple stroke flash?

The answer to that question is not so simple because one must take into account the probability of the channel inside the cloud goes “in the right way” to collect more charges, and the channel propagates linearly, not in angled steps. In the example

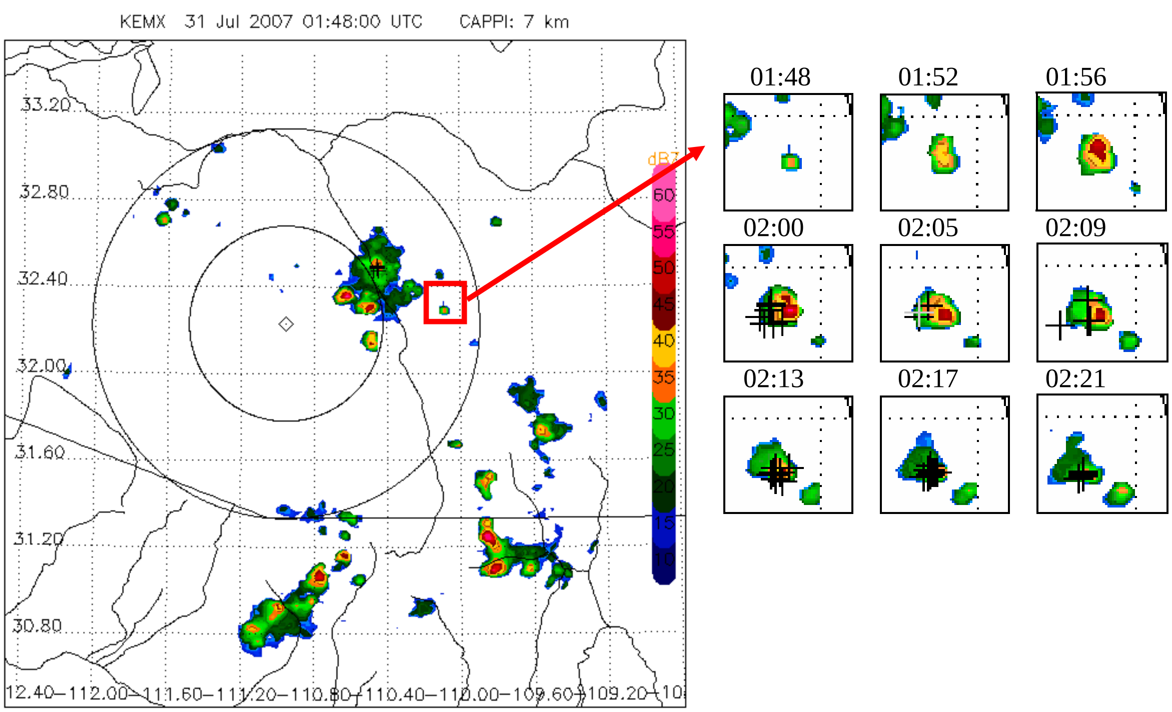

Figure 13 – Evolution of a small, isolated, short living cell in Tucson, on 07/31/2007. The main figure shows the entire figure with lat – lon limits, and gives an overall view of that day. The small figures show the evolution of the cell of interest until the last flash occurs. The crosses represent lightning strokes occured in a 4 min interval.

above, an area of only 78 km^2 was required to produce a 9 stroke flash, but what would be the most probable situation for that flash to occur? The highest probability could be that flash to occur in the middle of an hypothetical circular cell with a minimum radius of the same size of the total travel length of the channel. If we assume a circle cell of the radius of 8 km (the flash duration times the velocity of the propagating channel inside the cloud), the best scenario for this flash to occur would be within a cell of >200 km^2 of area, something similar to the values presented on Figure 4 and 5 for higher multiplicities. But this does not mean that the flash will not occur in smaller areas, just it is more unlikely. Teer and Few (1974) showed that the propagation of the lightning channel inside the cloud, in some Arizona thunderstorms, is clearly horizontally, ranging 9.8 +/- 3.6 km, values very similar to the assumptions made in this paper.

To support this hypothesis, two results must be taken into account. The first one is the Figure 9, from which is clear that there is a strong correlation between the flash duration and multiplicity (already mentioned in Saba et al. and Saraiva et al), that is, higher multiple stroke flashes require also higher durations to occur. So, they will also be produced more likely in regions with bigger areas. The other result is presented in Figure 8, when the comparison with flash multiplicity and reflectivity is made. It is shown that the higher multiplicities tend to occur near the maximum values of reflectivities, and the analysis of all images showed that higher multiplicities occur near the central regions of the cell, rather in the borders. Again this suggests that the higher multiplicity flashes occur near the center of the cells, where there is more chance for a longer channel inside the cell to produce more strokes or longer continuing current.

In Figure 10, hypothetical "circular cells" were calculated for each range of flash durations. To produce these curves, we employ an estimated "velocity" (10^4 m/s) for defining the charge-gathering radius of the cell. This is used to convert flash duration in Figure 10 to a radius. The radius is associated with a specific area assuming a circular area. The result is the blue curve plotted on the figure. It is possible to see that the majority of flashes occurred within the boundaries of the curves. Recalculating again the areas, now considering a reduction of 85% in the area gives the red curve, where more lightning lies within its boundaries, and finally the black curve shows that a reduction of 50% in the area looks like the lower limit for flash occurrence, considering that the channel walks angled and not linearly, the reduction of this area seems to be a very reasonable representation of the real area requirement.

Table 2 – Flashes occurred in a small single cell from 07/31/2007.

Thunderstorm at July, 31st 2007				
Time	Latitude	Longitude	1st stroke Peak Current	Multiplicity
02:01:22.6101	32.31	-110.143	-16.3	2
02:02:15.2317	32.28	-110.177	-18	1
02:03:32.6988	32.297	-110.147	-15.7	2
02:04:32.5791	32.273	-110.11	-12.8	2
02:05:13.7558	32.292	-110.167	-12.9	1
02:06:27.9447	32.284	-110.171	-11.5	2
02:07:2.64357	32.312	-110.141	-10	1
02:09:0.46283	32.318	-110.134	-19.5	2
02:11:41.3472	32.273	-110.131	-31.4	2
02:13:28.2023	32.282	-110.093	-10.4	1
02:15:12.9971	32.266	-110.129	-22.1	2
02:16:10.5051	32.272	-110.116	-10.3	1
02:16:53.3588	32.257	-110.129	-19.5	4
02:17:51.6030	32.278	-110.133	-16.9	3
02:19:11.3394	32.267	-110.135	-30.7	2
02:20:59.4847	32.263	-110.14	-35.9	4
02:24:32.9948	32.266	-110.147	-14	9

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