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IC to CG Lightning Relationships over the Tallahassee CWA

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IC TO CG LIGHTNING RELATIONSHIPS OVER THE TALLAHASSEE CWA

By

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ABSTRACT

The formation of and the relationship between intra-cloud (IC) and cloud-to-ground (CG) lightning flashes have not been thoroughly studied. Understanding how these flash types interact in different types of thunderstorms can lead to a better understanding of lightning characteristics and how these characteristics can be applied to operational forecasting practices. Results of this study show that the IC:CG ratio varies greatly each day throughout the summer season over the County Warning Area (CWA) of the Tallahassee National Weather Service Forecast Office. The summer season is dominated by daily thunderstorms that form due to sea breeze fronts and their resulting outflow boundaries. Eleven case study storms reveal how IC and CG flash counts and rates in non-severe thunderstorms differ from those of severe storms such as those examined by Williams et al. (1999). Results of the present study reveal that the timing of CG lightning and the frequency of its strikes differ from those of severe storms. This is most likely due to severe storms producing stronger updrafts for longer periods of time than those of non-severe storms. The IC:CG ratios varied greatly among these case studies indicating that further studies must be done to determine a statistically significant understanding of how flash rates change and how the relationship between IC and CG flashes relate to the ratios they produce.

1. INTRODUCTION

Lightning is a dangerous weather phenomenon that on average accounts for 51 deaths per year in the United States (averaged from 1984-2013) (National Weather Service cited 2014). The number of deaths per year has decreased recently due to improved knowledge about how lightning forms and where it is likely to strike. Further research that aims to better understand lightning characteristics and their relationships to severe weather will continue to help educate the public about severe weather events and will bring about opportunities to better protect the public from such events.

Many studies have examined lightning flash rate, i.e., the number of flashes that occur within a given time interval (Gatlin and Goodman 2010, Goodman et al. 2005, MacGorman 1989, Metzger and Nuss 2013, Rudlosky and Fuelberg 2013, Schultz et al, 2011, Steiger et al. 2007, Wiens et al. 2005, Williams et al. 1999). Most studies of flash rate have considered total lightning, meaning the combination of cloud-to-ground (CG) and intra-cloud (IC) flashes. These studies have strived to better understand the relationship between lightning and the severity of a storm. For example, Williams et al. (1999) analyzed the behavior of total lightning in severe thunderstorms in central Florida. The Lightning Imaging Sensor Demonstration and Display (LISDAD) sensor was used to record the flash rate of specific thunderstorm cells. Results showed that lightning jumps, i.e., quick and major increases in the lightning flash rate, occurred when the cell's intensity increased rapidly. Studies have shown that this increase in flash rate corresponding to an increase in cell intensity is related to the formation and intensification of the storm's updraft (Baker et al 1995; 1999, Deierling and Petersen 2008, Goodman et al. 1989). As the updraft strengthens, collisions between ice crystals and graupel in the presence of supercooled water increase, producing the charge necessary to enhance lightning formation. This widely accepted mechanism for electrification is known as the non-inductive charging mechanism (Takahashi 1978).

Williams et al. (1989) found that storms generally are dominated by IC lightning before the storm reaches maximum intensity. The IC lightning tends to form before CG lightning because IC flash formation is largely dependent on the formation and strength of the updraft. The formation of an updraft creates the vertical depth necessary for ice particles to grow and collide. According to the non-inductive charging mechanism, as these particles collide, positive charge is transferred to smaller ice crystals while negative charge is transferred to larger graupel particles. The ice crystals are lofted up to higher parts of the cloud through the updraft, creating an area of positive charge. The graupel becomes suspended lower in the cloud, creating a negatively charged area. As ice particles grow larger and as the updraft eventually weakens, these ice particles will begin to fall. As ice particle fall, they pull positive charge down below the negatively charged portion of cloud, enhancing the opportunity for CG lightning formation (Saunders 1993, Williams et al. 1989). This relationship may have implications about storm development that can be used to improve the forecasting of severe weather.

Multiple studies have shown that total lightning flash rates increase quickly before the onset of severe weather (Williams et al. 1989; Williams et al. 1999; Goodman et al. 2005; Metzger and Nuss 2013). Fewer studies have shown how IC and CG relationships relate to severe weather. Metzger and Nuss (2013) attempted to do this by comparing IC and CG counts in individual storms to the type of severe weather that occurred. They found that when hail formed, there was usually a jump in IC flash rate, while the CG rate decreased or stayed the same. Severe wind events exhibited a lightning jump in CG while IC either increased or stayed the same. Their study did not prove that lightning jumps always occur before the onset of severe weather, but they did show an overall tendency for the jumps. Some tornadoes have been found to occur after a jump in IC lightning alone (not the total lightning) (e.g., MacGorman et al. 1989). Further research into these tendencies can potentially help meteorologists use these trends to better predict severe weather and what type of severe weather events will occur.

Recent studies have begun to compare the ratio of IC lightning counts to CG lightning counts to better understand the relationship between these two types of flashes. Boccippio et al. (2001) produced a climatological mean distribution of this ratio over the United States. They found that the ratio does not depend on latitude, contradicting previous studies (Pierce 1970, Prentice and Mackerras 1977). Rather, they suggested that larger IC:CG ratios occur in regions where mesoscale convective systems (MCSs) are more likely to occur. The average ratio of IC to CG lightning was approximately 2:1

over the continental United States, with anomalies occurring in areas that have a large number of MCSs and over areas where mountains affect storm development. MacGorman et al. (1989) explained that IC:CG ratios become much greater than average during severe storms.

There is still a great deal to be learned about how IC and CG flashes relate to one another and how this relationship can be used to describe thunderstorm formation on a regional scale. Most studies that have examined IC and CG flashes focused on severe thunderstorms. However, it is important to focus on how these flashes relate in all types of storms so that a more complete understanding of lightning flash characteristics can be found. The present study examines IC and CG flashes in the County Warning Area (CWA) of the Tallahassee National Weather Service Forecast Office. During the summer, the CWA experiences daily thunderstorms due to the sea breeze and resulting outflow boundaries (Arritt 1993). These storms generally remain weak but they do have the potential to become severe if there is enough forcing and instability to strengthen them.

2. OBJECTIVES

The main objective of this study is to analyze the relationship between IC and CG lightning over the Tallahassee CWA. Focusing on the summer season, a daily IC to CG ratio is calculated so that averages for the season can be determined. This is done for three years to compare how the ratios change each summer season. Next, a more in depth analysis of how IC and CG lightning varies during a storm's life cycle is determined through case studies of non-severe thunderstorms. By studying how lightning acts during the non-severe thunderstorms that generally form each day, a better understanding of IC and CG lightning can be gained and compared to previous studies that have used lightning to now-cast severe weather.

3. METHODOLOGY

This study first analyzed how the ratio of IC to CG flashes varies during the summer months of three consecutive years. The study area was a box defined by 29.0 to 32.05 deg North latitude and 86.45 to 82.8 deg West longitude. This box encompasses the entire Tallahassee National Weather Service Office CWA. Fig. 1 shows the outline of the CWA (blue) with the study region box (red) superimposed. A box was defined instead of using the exact land area of the CWA for computational simplicity.

STUDY REGION

Fig. 1. Display of study region (red box) and its location relative to the Tallahassee National Weather Service Forecast Office CWA (blue outline).

Lightning data were acquired from the Earth Networks Total Lightning Network (ENTLN)(Earth Networks). The ENTLN utilizes over 150 sensors over the continental United States and over 800 sensors worldwide. Each sensor can detect lightning produced radio emissions from 1Hz to 12 MHz. This makes it possible for the sensor to detect both IC and CG flashes. A lightning flash that contains at least one return stroke is classified as CG, with all other flashes recorded as IC (Lui and Heckman 2012). The national detection efficiency for CG return strokes exceeds 95%, while for IC it is approximately 50% (Fierro 2012). Areas where there is a greater density of sensors have a greater IC detection efficiency than the national average and vice versa. The average

IC detection efficiency over the Florida panhandle is about 65-70% (Liu and Heckman 2012). The detection efficiency of CG and IC flashes was assumed to be the same for the purpose of this study. I did not attempt to correct for the differing IC and CG detection efficiencies. Thus, the computed ratios probably are smaller than occur in nature.

The original ENTLN data acquired spanned from 0000 UTC 1 November 2011 to 0400 UTC 2 September 2014 for a land area that ranged in latitude from 20 to 32.05 degrees North and from 86.45 to 82.80 degrees West longitude. Data for each individual flash included the date and time displayed in UTC out to nine decimal places in seconds. The latitude and longitude were recorded out to five decimal places in degrees. Each flash was either classified as IC or CG. The data also included the peak current, IC height, the multiplicity of each flash, as well as the number of sensors that detected the flash.

The data received from ENTLN was sorted into monthly files. I first wrote a program in Python to sort through each flash of each file and save only those that occurred within in the study region. This was done to make sure that no miscellaneous flashes corrupted the analysis. A program then converted the times recorded in UTC to Eastern Standard Time (EST). This was done so that diurnal variations in lightning could be examined more easily. After the times were corrected, the flashes were then sorted into daily files.

The daily files that occurred during the months of June, July, and August were analyzed for the three-year time span. For each daily file used, a daily ratio was created using a Python program that counted the number of IC flashes and the number of CG flashes that were listed in the file. The program then calculated a ratio by dividing the IC count by the CG count. The ratio was set to zero when there were zero CG flashes during a day. If there were fewer than 10 total flashes on a day, that day was not used. This was done so there would be a sufficient number of flashes to create an accurate representation of how IC and CG counts vary per day. Averages, maxima, and minima were determined for the flash counts, flash rates, and ratios of each year analyzed and a combination of all three years analyzed. Seasonal IC:CG ratios were determined by counting all the IC flashes that occurred within a season and dividing this number by the total number of CG flashes that occurred that season. Average IC:CG ratios were determined by averaging the daily ratios that were calculated from each daily file.

After determining the daily lightning ratios during the summer months and plotting the results, a more in depth analysis of lightning characteristics in the CWA was desired. Case studies were performed on 11 storms throughout the summer months of 2014. The storms were chosen by analyzing WSR-88D radar data using GR2Analyst software (http://www.grlevelx.com/gr2analyst/). Examples of the images produced by GR2Analyst can be seen in Fig. 2a and 2b. Each storm was analyzed throughout its life cycle to determine how the IC:CG ratio changed as the storm grew and matured. The 11 storms were either a single cell or two to three adjoining cells that each appeared to be in the same stage of their lifecycles. This selection allowed the stages of a storm's life to be compared to its production of lightning. The storms were isolated from nearby storms. That is, each storm's radar reflectivity was clearly separated from surrounding storms so that other storm cells did not interact and cause lightning to form that did not relate to the growth and decay of the cells being studied. Storms with more than one cell were isolated from other storms, but the multiple cells within the storm were not isolated from one another. None of these storms were associated with severe weather reports.

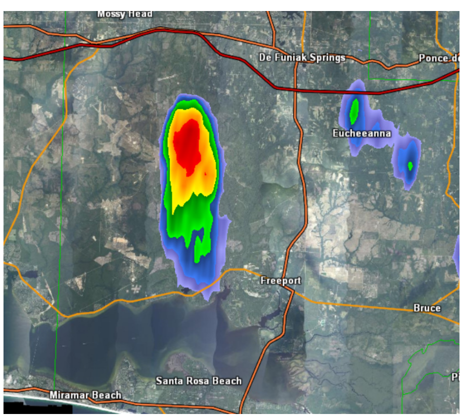

Fig. 2a- Example of radar reflectivity analyzed on GR2Analyst for Storm 10

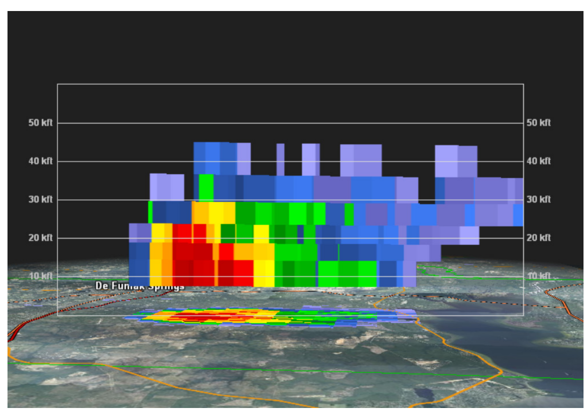

Fig. 2b- Cross section of Fig. 2a, used to analyze structure of Storm 10

Selected storms were tracked by monitoring the storm as it formed, grew, matured, and dissipated. A box defined by latitude and longitude values was placed around each storm as it went through its lifecycle. This box was made large enough to encompass the entire storm, but small enough so that it did not include another nearby storm producing lightning. The box cut through the stratiform region of the cell in a few cases so that other storms could be avoided. This was assumed to have no effect on the results of the study because this region of non-severe thunderstorms rarely produces lightning. As the storms moved, it was necessary to change their box coordinates so that the box followed the storm and still avoided surrounding storms. The box was changed anywhere from one to five times for each storm. Fig. 3 shows what these boxes would look like if they were plotted on top of the radar reflectivity.

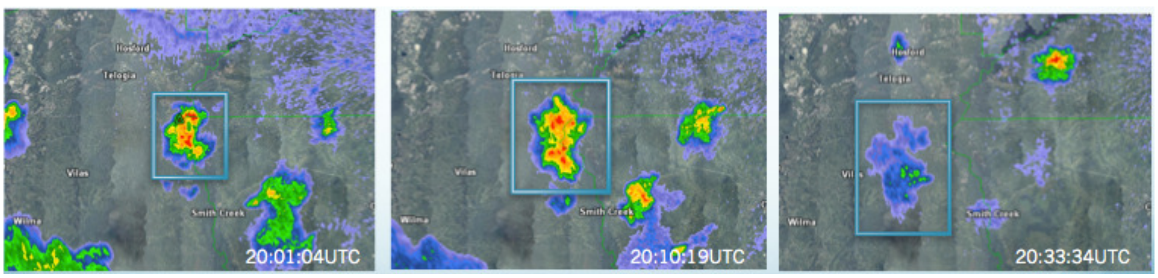

Fig. 3 Example of storm boxes changing over time in Storm 1

Once the boxes and times were determined, IC and CG flashes were recorded and the lightning ratio was calculated for each storm. This was done by creating a Python program to define each box that tracked the storm and the time associated with it. The program analyzed each original monthly ENTLN file because these files were received in UTC. This was done so that the UTC times of these data files could be compared to the UTC times displayed in the WSR-88D radar files. The program recorded flashes that occurred within the time frame and bounds of each box. Another program then sorted each flash of a storm into 1 min increments so that flash rates (flashes min^{-1}) could be calculated for each minute of the storm's lifecycle. That is, the total flash rate, the IC flash rate, the CG flash rate, and the IC:CG ratio were computed at 1 min increments starting at the time of a storm's first flash and ending when the storm produced its last flash. This time period will be referred to as the storm's "lightning life."

4. RESULTS

a. Seasonal Average Studies

Daily IC:CG lightning ratios for the months of June, July, and August were determined for the years of 2012, 2013, and 2014. The average values for these ratios and lightning counts are displayed in Table 1.

Table 1. Averages, maxima, and minima of lightning flashes, lightning flash rates, and IC:CG ratios for each year and a combination of all three years.

	2012	**2013**	**2014**	**Combined**
Days with ≥ 10 Total Flashes	80	91	83	254
Days with < 10 Total Flashes	12	1	9	22
Seasonal IC:CG Ratio	1.69	3.50	6.56	3.46
Average IC:CG Ratio	1.63	3.64	7.12	4.14
Min IC:CG Ratio	0.69	1.12	1.49	0.69
Max IC:CG Ratio	3.23	8.28	26.50	26.50
Average Total Lightning Count	18040	16716	27645	20704
Min Total Lightning Count	44	15	72	15
Max Total Lightning Count	97928	109763	141879	141879
Average IC Lightning Count	11326	12300	23988	16063
Min IC Lightning Count	18	13	44	13
Max IC Lightning Count	63715	90897	133202	133202
Average CG Lightning Count	6714	3716	3656	4641
Min CG Lightning Count	13	2	28	2
Max CG Lightning Count	37529	24068	20640	37529

It is clear the number of flashes and the IC:CG ratio vary greatly between summers. Each summer produced at least 80 days (out of a possible 92) with more than 10 flashes. This provided the present study with a large distribution of days throughout each summer period. From 2012 to 2014 the average IC:CG ratio increased from 1.63 to 7.12. This increase with each subsequent year remained true in the minimum and maximum values of the ratios as well. In 2012, the minimum ratio was 0.69 and the maximum ratio was 3.23. There was an increase in both these values in 2013 and once again in 2014. It is interesting to note that the increase in ratios did not correspond to an increase in average lightning flash counts among the three time periods. The summer of 2012 exhibited a greater average flash rate than the summer of 2013, but the average IC:CG ratio was larger in 2013. The average IC flash count increased with each year. The average CG flash count decreased each year. This inverse relationship between the average IC and CG flash counts corresponds to how the average IC:CG ratios changed with each year. Larger IC and smaller CG flash counts lead to larger IC:CG ratios. The summer of 2014 had the largest IC counts and smallest CG counts, and thus the largest ratio. The summer of 2012 had the smallest IC and largest CG flash counts, creating the smallest average ratio.

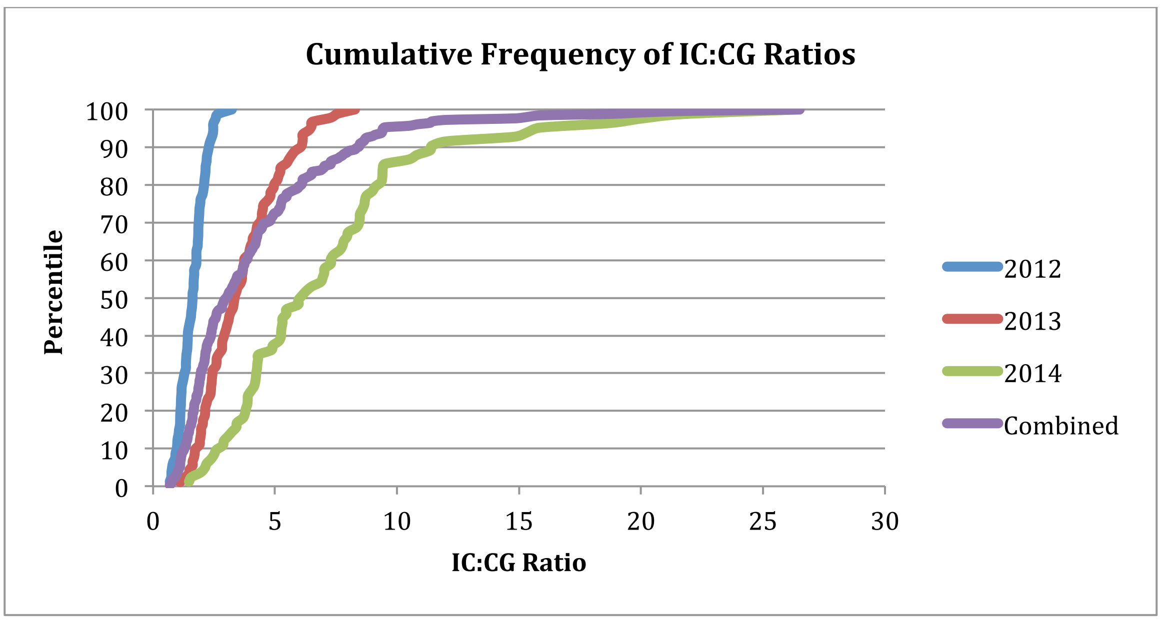

Fig. 4. Cumulative frequency of IC:CG ratio over each time period and time periods combined.

Fig. 4 shows how the IC:CG ratios were distributed each year through a cumulative frequency chart. The summer of 2012 (in blue) showed the smallest range in ratio values with each daily ratio reaching a value less than five. 2013 (red) showed a slightly larger range, starting at about the same minimum ratio as 2012, but increasing to values greater than six. 2014 (green) showed an even greater range, starting at a ratio slightly larger than the minimum ratios for 2012 and 2013, but reaching a maximum value greater than 25. This increase in ratio range and increase in ratio values could be due to a number of factors. ENTLN has enhanced its IC detection efficiency by installing additional lightning sensors in recent years. According to ENTLN, the average IC detection efficiency over Florida has increased from about 78% to 82% from 2012 to 2013 (Sloop et al. 2014). If this trend continues through 2014 and if this trend is true of the Tallahassee CWA, the IC detection efficiency would increase during 2014. With an improved IC detection efficiency comes a greater ability to detect IC lightning. Since IC lightning is in the numerator of the IC:CG ratio, greater IC detection efficiencies result in larger ratios. Environmental factors also may have played a roll in producing the increasing ratios. In 2012 Tropical Storm Debby crossed Florida, largely affecting the CWA. This tropical storm moved slowly across central Florida, directly impacting the CWA coastlines for at least four days and influencing synoptic patterns for an even longer period. In 2013, Tropical Storm Andrea followed a similar track, also influencing weather patterns in the CWA. This storm was not as long lived, only directly impacting the Florida coast for about two days, but this large system may have changed typical synoptic patterns for a much longer period of time. In 2014 there were no tropical storms that directly affected the CWA.

The daily lightning ratios did not take into account what types of storms formed the lightning each day or the environmental conditions associated with them. Future studies that only use sea breeze related storms in the calculation of ratios might show a more consistent ratio. Climatologically, these types of thunderstorms occur most frequently over the CWA.

It is apparent by the large differences among the yearly ratios that there is still a great deal to be learned about IC:CG ratios and how they change. Boccippio et al. (2001) showed that the average climatological value of this ratio is about 2.64-2.94 over the continental United States. The non-severe storms in the Tallahassee CWA had a ratio of ~4.1 (Table 1). This study shows that IC lightning almost always outnumbers CG lightning, but it does not show how these ratios change with seasons or in specific regions of the Southeast. Further research must be done to better understand IC and CG flash relationships and how these relationships lead to differing IC:CG ratios.

b. Case Studies

Eleven case studies were performed on isolated thunderstorms during the summer of 2014 in order to better understand why ratios vary during the lifecycle of non-severe Southeastern United States storms. It is expected that the ratios are dependent on the strength of the thunderstorm. Based on the idea that severe weather is preceded by a large lightning jump associated with IC flashes from an intensifying updraft, this study theoretically should show that flash rates increase as a storm forms due to the updraft development, even when the storm is not severe. Each thunderstorm chosen was analyzed during its entire lifecycle. The IC and CG flashes were recorded for each storm and flash rates per minute created. Table 2 shows the greatest flash rate determined for each storm, the total IC and CG flash count of each storm, and the overall ratio.

Table 2. Peak flash rates, IC and CG flash counts, and total storm IC:CG ratios for each case study storm.

Storm #	Peak Total Flash Rate	Total IC Count	Total CG Count	Storm IC:CG Ratio
1	3	21	2	10.5
2	9	32	3	10.7
3	6	48	3	16.0
4	6	18	2	9.0
5	5	28	1	28.0
6	7	59	6	9.8
7	12	22	8	2.8
8	15	224	10	22.4
9	15	160	17	9.4
10	13	127	18	7.1
11	11	162	36	4.5

The flash counts, ratios, and peak flash rates vary greatly during these storms (Table 2). The overall ratio of these storms ranges from 4.5 to 28. The peak total flash rates range from 3 to 15. Fig. 5 and 6 show how the flash rates were distributed throughout the lightning life of each storm. This distribution was displayed on a normalized time scale. That is, each storm was displayed so that "0" represents the point at which each storm had not produced any flashes and "1" represents the point in time at which each storm produced its last flash. This means that 0.5 would represent half of the storm's lightning life. Each storm was set to this scale so that the occurrence of flashes relative to the lightning lifetime could be compared among the case studies. Fig. 5 shows the distribution for storms that had total flash rates less than 10 flashes per minute (fpm) while Fig. 6 shows the distribution for storms with peak total flash rates greater than 10 fpm. The storms were divided into these two cases to better analyze how storm strength relates to ratio variability.

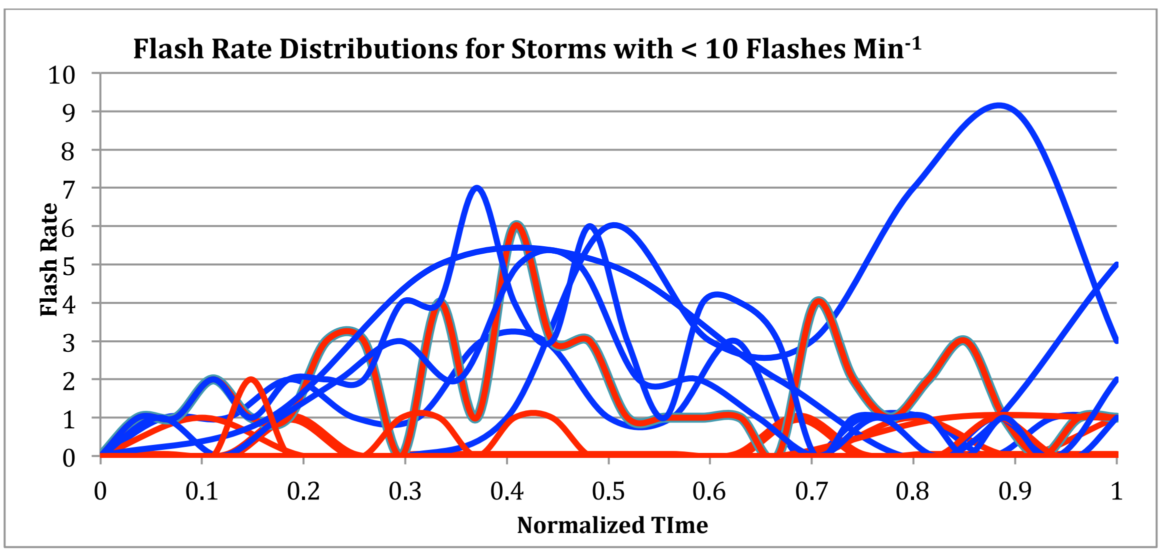

Fig. 5. IC (blue) and CG(red) flash rate distributions over a normalized time frame of storms with peak total flash rates less than 10 fpm.

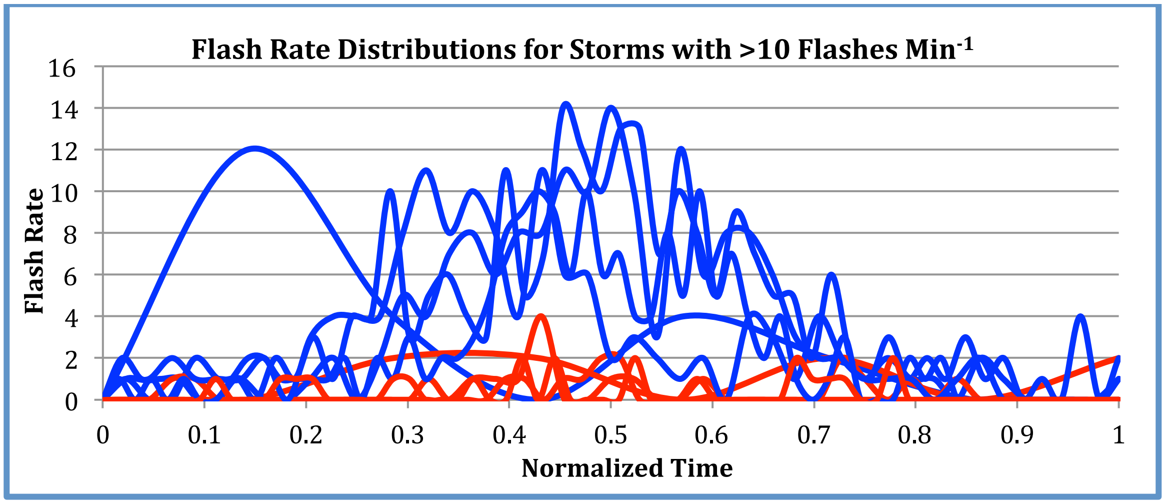

Fig. 6. IC (blue) and CG (red) flash rate distributions over a normalized time scale of storms with peak total flash rates greater than 10 fpm.

i. Storms with Total Flash Rates < 10 fpm:

Fig. 5 and 6 show that storms with peak total flash rates less than 10 fpm do not show as organized a pattern in IC and CG flash distribution as storms with peak total flash rates greater than 10 fpm. However, Fig. 5 does show peak flash rates generally occurring between 0.3 and 0.5 on the normalized time axis. This means that once the first flash of a storm had occurred, the majority of the storms studied experienced their peak flash rate about 30 to 50% of the way through their lightning life span. This figure also shows that IC flashes generally outnumber CG flashes with a few exceptions. The following figures show the relationship of IC and CG flashes for each individual storm. The first six examples produced peak total flash rates less than 10 fpm.

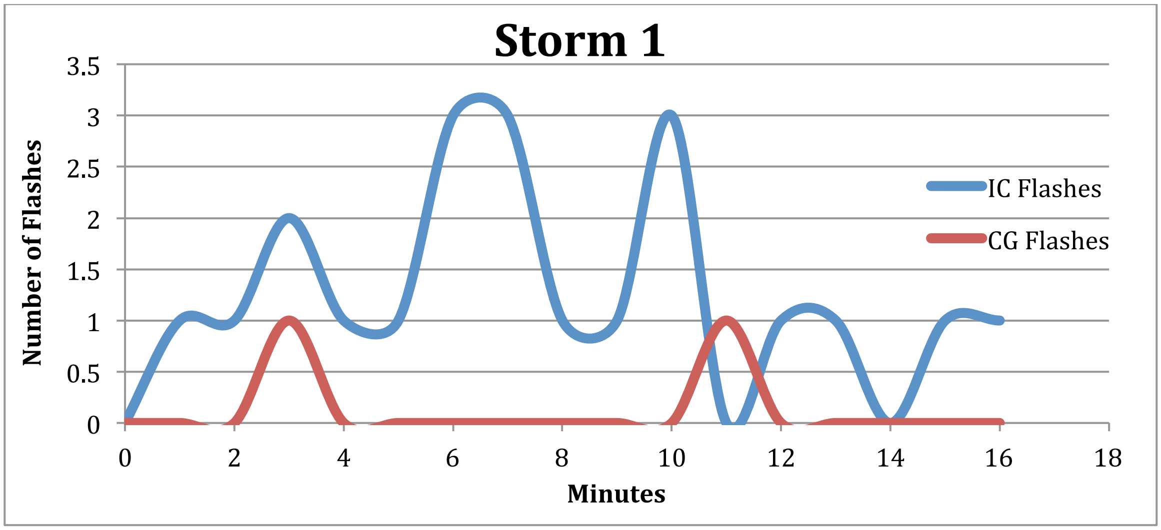

Fig. 7. IC and CG flash distributions for Storm 1

Storm 1 (Fig. 7) was a small multicellular system with each cell appearing to be within the same stage of life. Storm 1 had a total of 23 flashes. 21 of them were IC, and 2 were CG. Its peak flash rate was 3 fpm. The storm reached 3 fpm four times. The storm produced two IC flashes during the first two minutes of the storm's lightning life before experiencing a slight jump reaching 3 fpm within the third minute. Two of the flashes within this third minute were IC and one was CG. The storm then produced a great deal of IC lightning for the next seven minutes before producing its last CG flash. IC flashes then occurred about once every minute for the remainder of the storm. Each CG flash occurred during a rise in IC flash rate or shortly after.

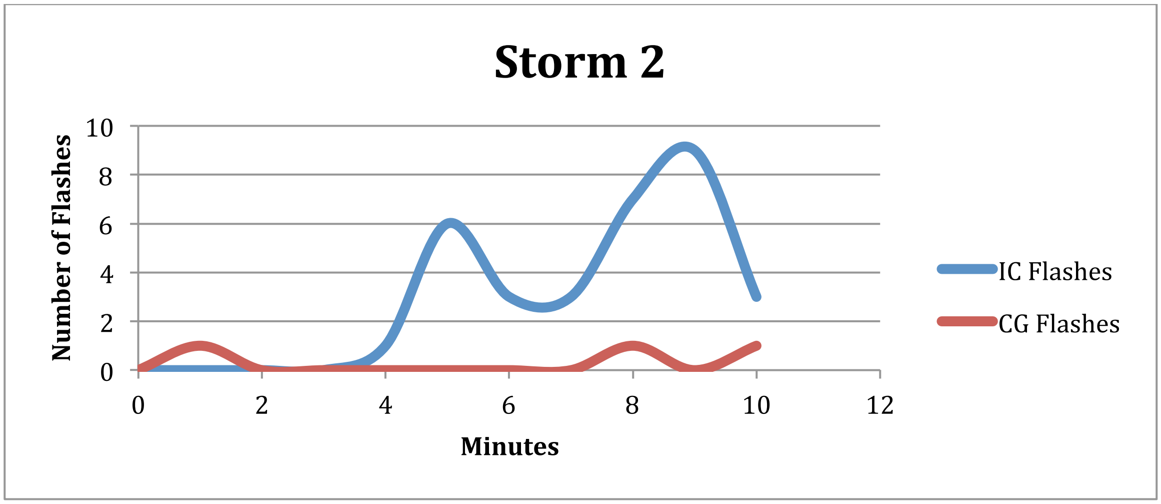

Fig. 8. IC and CG flash distribution for Storm 2

Storm 2 (Fig. 8) produced lightning for 10 min. Unlike most storms, its first flash was CG. The storm produced one CG flash and then produced no lightning for 2 min. It then produced mainly IC flashes, only producing two more CG flashes towards the end of the storm's life. The storm produced a total of 35 flashes. 32 flashes were IC and 3 were CG. Its peak flash rate was 9 fpm, which occurred toward the end of the storm's lightning life. The storm produced secondary peak flash rates of 6 and 7 fpm in the middle of its lightning life.

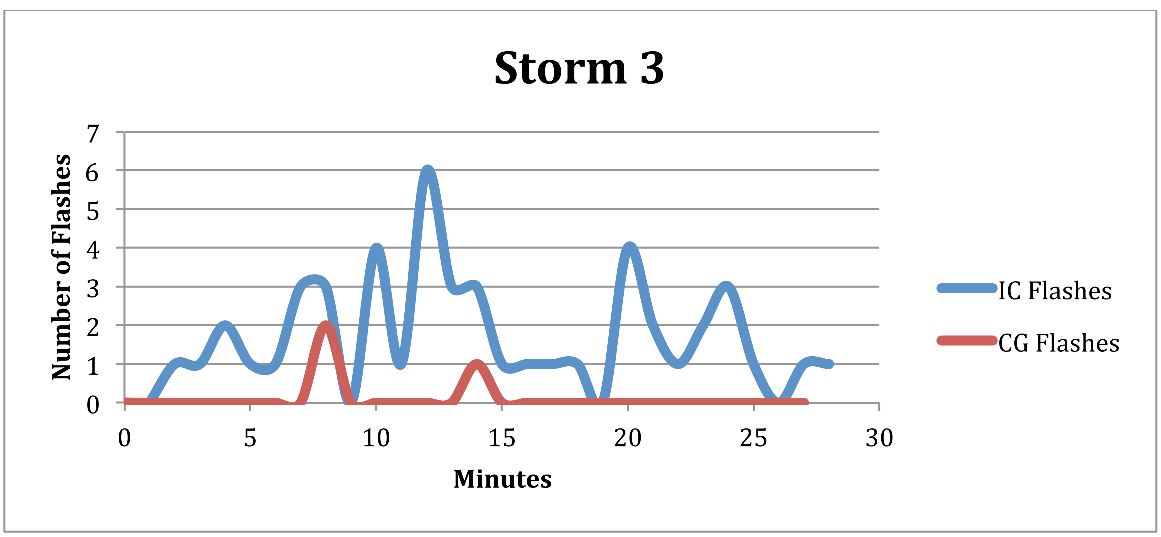

Fig. 9. IC and CG flash distribution for Storm 3

Storm 3 (Fig. 9) produced 51 total flashes; 48 were IC, and 3 were CG. It produced lightning for 27 min, beginning with large amounts of IC. For the first 7 min the storm produced IC lightning with flash rates reaching 3 fpm. It then produced two CG flashes within a minute and returned to mainly IC flashes thereafter. One more CG flash was produced halfway through the storm's lightning life. This storm was clearly IC dominated with CG flashes always following multiple IC flashes. The peak flash rate of this storm was 6 fpm.

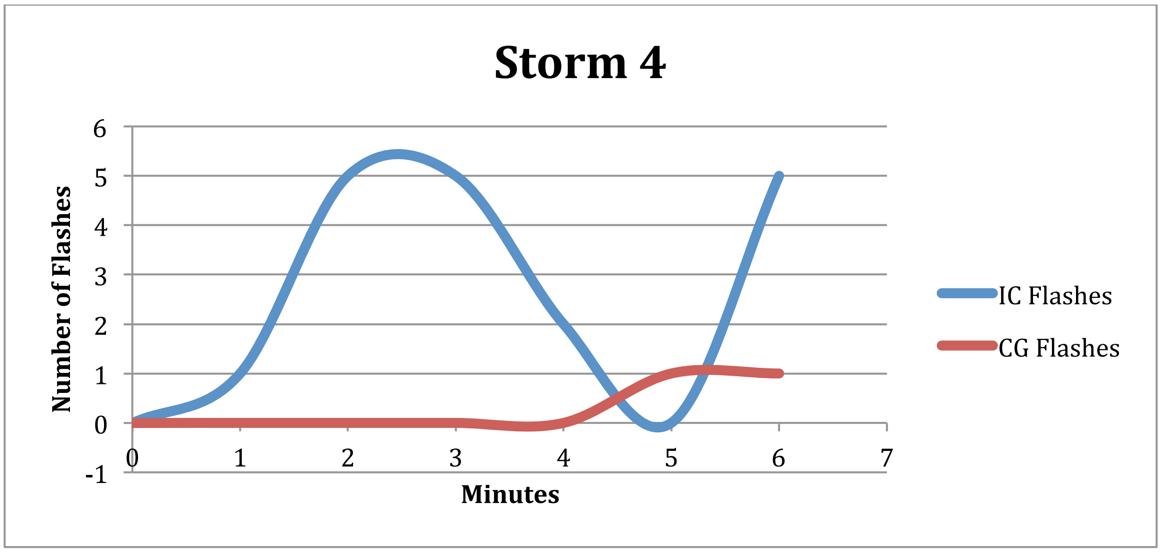

Fig. 10. IC and CG flash distributions for Storm 4

Storm 4 (Fig. 10) was a small, but potent storm that had cloud tops reaching near 30 kft. The storm produced lightning for only 6 min, with total flash rates reaching 6 fpm at the end of the storm. There were 20 total flashes, only 2 of those being CG. The first 4 min consisted only of IC flashes with rates reaching 5 fpm. The storm then produced two CG flashes within the last two minutes of the storm's lightning life. This storm was IC dominated with IC occurring for a long period of the storm's life before CG flashes occurred.

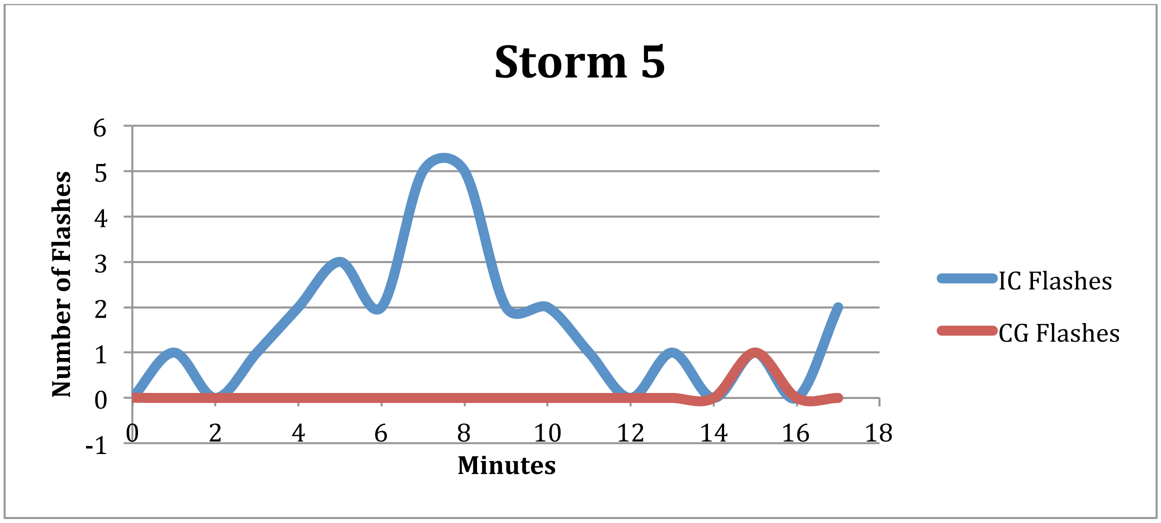

Fig. 11. IC and CG flash distributions for Storm 5

Storm 5 (Fig. 11) produced lightning for 17 min. It had a total of 29 flashes, 28 being IC and one being CG. The storm was dominated by IC lightning. This storm produced CG lightning within the last 3 min of its lightning life and had total flash rates reaching 5 fpm. The only CG flash occurred well after this peak in IC flash rate.

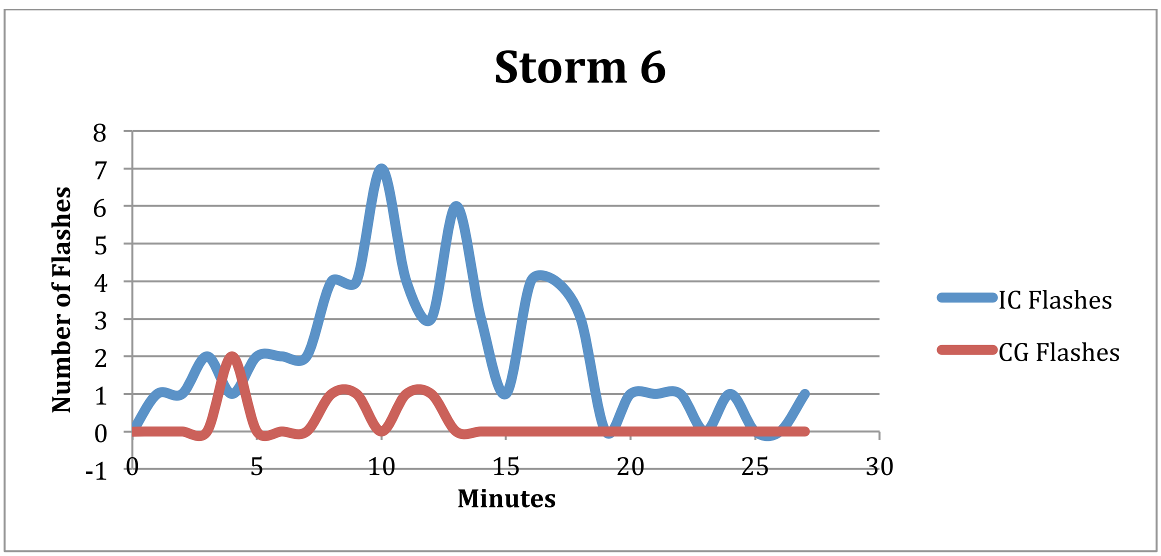

Fig. 12. IC and CG flash distributions for Storm 6

Storm 6 (Fig. 12) produced more lightning than any of the other small peak total flash rate storms. There were 65 total flashes, 59 being IC and 6 being CG. The storm produced lightning for 27 min. It produced IC lightning for the 3 min before producing

CG flashes. A majority of the CG lightning occurred beginning 8 min after the first IC flash. These CG flashes were accompanied by many IC flashes. The peak rate of 7 fpm was reached during this time period. The storm was clearly IC dominated with CG flashes forming after IC flashes. The CG flashes appeared to occur at the same time or even before the IC flash rate was greatest.

ii. Conclusions for Storms with Total Flash Rates < 10 fpm:

Each of the six case study storms was dominated by IC lightning. In five out of six cases, the IC lightning formed before CG lightning occurred. This is consistent with the study by Williams et al. (1989) that showed IC lightning dominates a storm and tends to form before CG lightning. The majority of the CG lightning did not occur during the peak in IC flash rates. Many of the storms produced a CG flash before the peak of IC flashes and then produced another CG flash after the peak. These findings suggest that CG lightning is not confined to forming after updrafts reach their maximum intensity and large ice and graupel particles begin to fall inside a cloud. This may be due to the fact that these storms were very weak in comparison to the severe storms analyzed in previous studies. The case study storms did not have the vertical depth of severe storms. This means there was less cloud depth through which ice particles can fall and most likely less charge separation overall. Also, there was potentially less time between the formation of an updraft (along with the initial formation of IC lightning) and the time at which particles began to fall, leading to the charge necessary to create CG lightning. The IC:CG ratios of these storms ranged from 9.8 to 28. This large range in ratios does not show a consistent trend for how small lightning rates affect the IC:CG ratio. This is most likely because there are very few total flashes in general for these storms, making each ratio highly dependent on each individual flash that occurred.

iii. Storms with Total Flash Rates > 10 fpm:

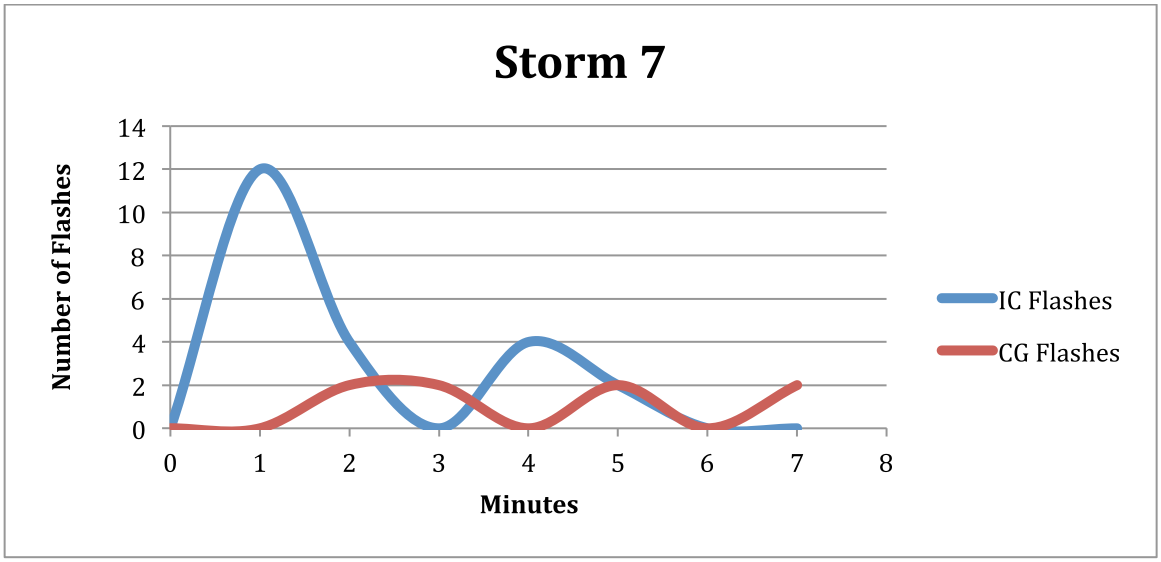

Fig. 13. IC and CG flash distributions for Storm 7

Storm 7 (Fig. 13) was unique for the group of storms with total flash rates greater than 10 fpm because it had a very small number of flashes. The storm produced only 30 total flashes, 22 being IC and 8 being CG. The greatest total flash rate was 12 fpm, which occurred within the first minute of the storm's lightning life. Each flash during this peak was IC. CG flashes began in the next minute and occurred along with IC lightning throughout the remainder of the storm's lightning life. This storm only produced lightning for 7 min. The peak lightning flash rate most likely occurred due to an explosive short-lived updraft. Since this was a very small, single cellular storm, it dissipated soon after the explosive updraft. This most likely led to the smaller values of flash rates and the increase in CG lightning.

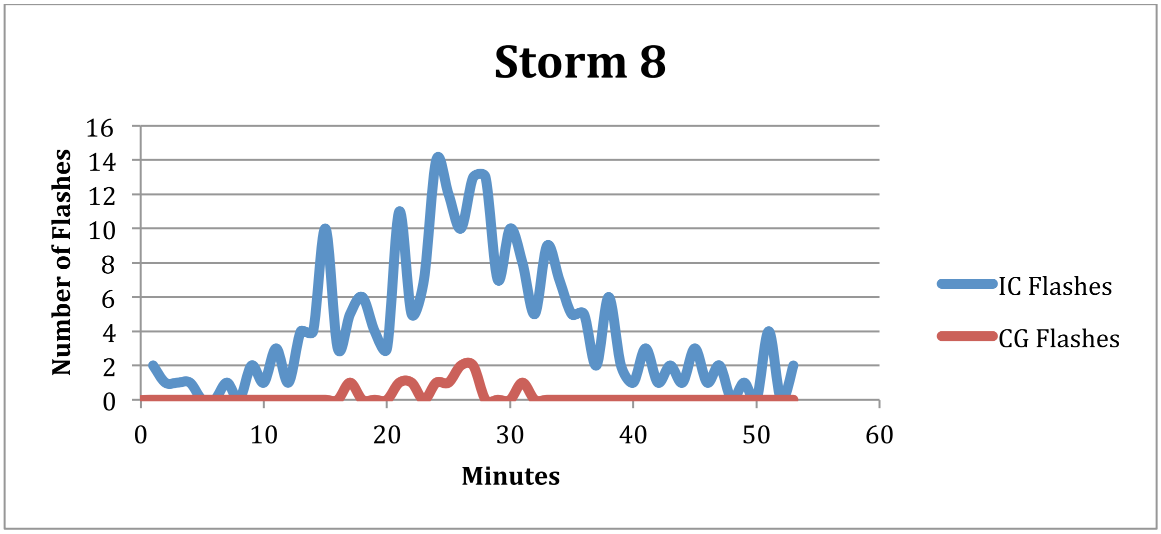

Fig. 14. IC and CG flash distributions for Storm 8

Storm 8 (Fig. 14) produced 234 total flashes over a 53 min period. 224 flashes were IC and 10 were CG. The storm was clearly dominated by IC flashes. IC flashes initially were produced at a small rate of 1-2 fpm during the first 10 min of the storm's lightning life. The flash rate then began to increase and maintained relatively steady, large flash rates ranging from 3 to 15 fpm for 22 min. The greatest total flash rates reached 13-15 fpm. The CG flashes generally occurred within the peak of IC flashes.

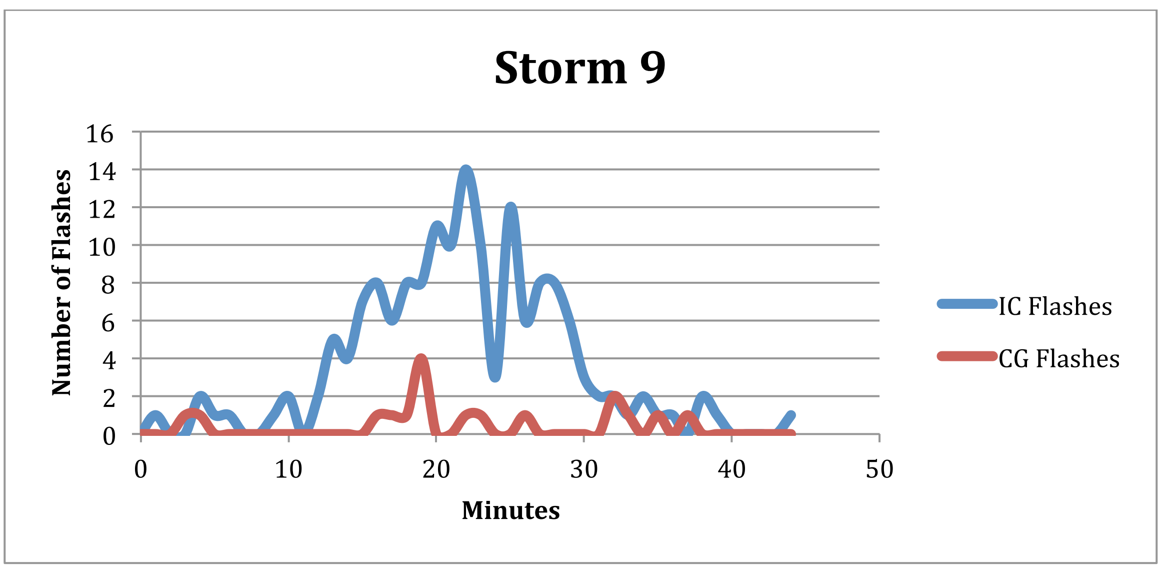

Fig. 15. IC and CG flash distributions for Storm 9.

Storm 9 (Fig. 15) produced 177 total flashes over a time period of 44 min. There were 160 IC flashes and only 17 CG flashes. This storm was clearly IC dominated. The storm began by producing one IC flash within the first minute and then one CG flash in the third minute of the storm's lightning life. The storm then produced virtually all IC flashes, with flash rates increasing to values ranging from 7 to 15 fpm by minute 14. The flash rates remained large for the next 15 min. Within this peak in flash rates, CG flashes began to occur once again, continuing to be produced well past the time of the IC flash rate maximum.

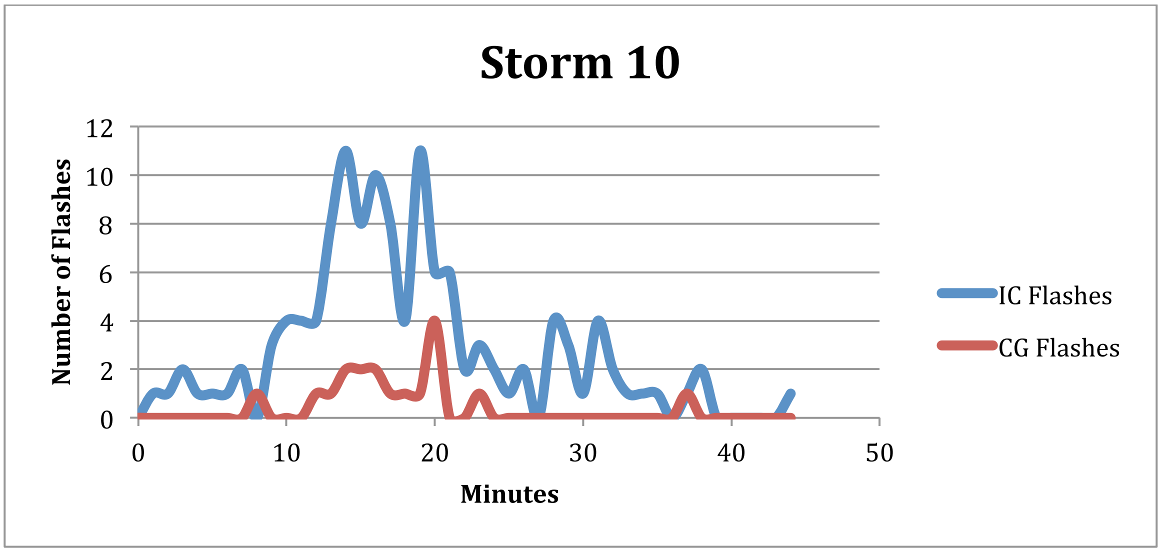

Fig. 16. IC and CG flash distributions for Storm 10

Storm 10 (Fig. 16) produced 145 total flashes over a 44 min time period. 127 flashes were IC, and 18 flashes were CG. The first 7 min of the storm's lightning life produced only IC flashes at rates of 1-2 fpm. A CG flash was produced at minute 8, followed quickly by a rapid increase in IC flash rates. The majority of the CG flashes formed after the peak of IC flash rates that occurred between minutes 10 and 20. After this peak, flash rates weakened and the majority of the flashes were IC, with only one CG flash occurring near the end of the storm's lightning life.

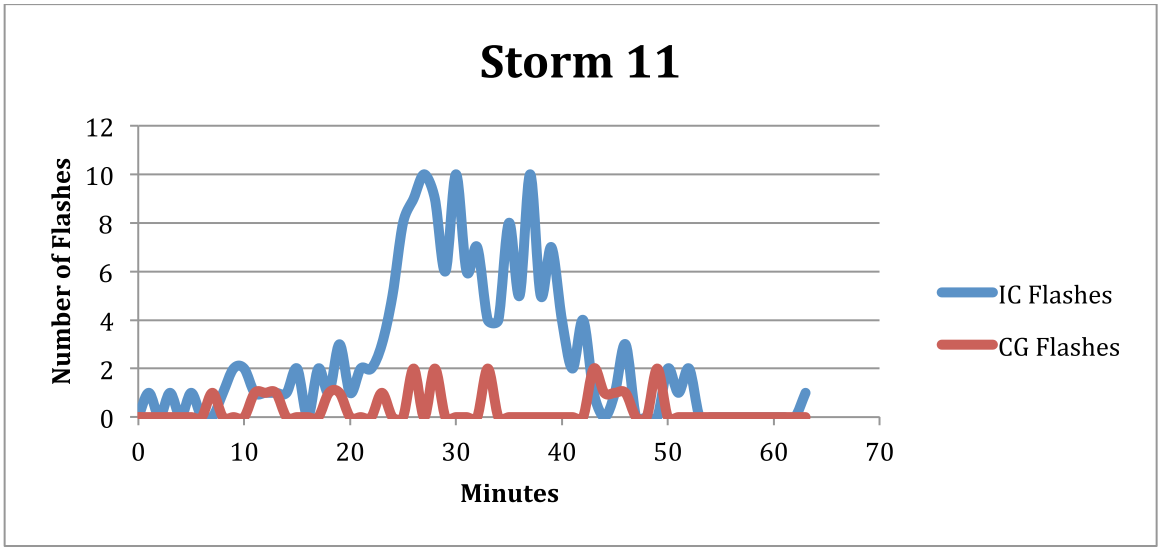

Fig. 17. IC and CG flash distributions for Storm 11

Storm 11 (Fig. 17) produced lightning for 63 min. A total of 198 flashes occurred. 162 flashes were IC and 36 were CG. During the first 6 min of the storm's lightning lifetime, IC flashes were produced about once every 2 min. One CG flash occurred at minute 7. Following this, there was a 3 min period of only IC flashes. Then, CG flashes began to occur within every minute. The flash rates increased around minute 20, with both IC and CG flashes still occurring. The IC flashes showed the greatest increase, creating large flash rates ranging from 5 to 10 fpm for nearly a 20 min period. A majority of the CG flashes occurred during this time, but CG flashes continued throughout the remainder of the storm's life. Unlike most of the previously described storms, the CG flashes constantly occurred throughout this storm rather than mainly occurring during or after the peak in IC flash rate.

iv. Conclusions for Storms with Total Flash Rates > than 10 fpm:

Four out of five of the greater total flash rate storms produced over 100 total flashes. Most of these storms were longer lived than the smaller total flash rate storms. These findings suggest that these storms were more intense than those with flash rates smaller than 10 fpm. MacGorman et al. (1989) found that flash rates tend to increase with increasing storm severity. The greater flash rates and larger number of flashes are most likely due to stronger and longer-lived updrafts. Each of these storms produced IC flashes before producing CG flashes. CG flashes were distributed throughout the entire lightning life of each storm, but the majority of the CG flashes occurred within the peak range of IC flash rates for 4 out of 5 of these cases. Storm 7 was the outlier, most likely due to its small number of flashes. Storm 7 produced CG only after the peak in IC flash rate. Having a majority of the CG flashes occur within the peak of IC flash rates does not completely support the idea that CG flashes form after a peak in updraft and IC lightning formation. This was most likely because these storms were not severe, and they did not maintain an extremely strong updraft.

5. DISSCUSSION AND CONCLUSIONS

Findings from the 11 case studies support the work of Williams et al. (1989) by showing that IC flashes dominate CG flashes in typical air mass thunderstorms. IC flashes preceded CG flashes in a majority of the storms. Although IC flashes usually occurred first, the majority of CG flashes in the weaker total flash rate storms did not occur within or after the peak in IC flash rate. The larger flash rate storms tended to produce the majority of the CG flashes during the time period in which there was a peak in IC flash rates. These trends suggest that the strength of a storm has a large role in determining when CG flashes occur compared to IC flashes. Williams et al. (1989) suggested that CG flashes occur after the peak in IC flash rate and thus after the peak in updraft intensity. In this study, the relatively strong flash rate storms with assumed stronger updrafts tended to form CG lightning during the period of peak IC flash rate, most likely because the updraft did not loft ice particles as high in the cloud as would a severe storm. This means the ice particles had a smaller distance to fall before bringing charge to an area of the cloud that made it favorable for CG formation. This would suggest that there would be less separation between the peak IC flash rate and the onset of the majority of CG flashes. This time separation would be even shorter for weaker storms. Also, there was probably a smaller charge separation overall for these storms when compared to severe storms. There was not a strong correlation between peak IC rates and the formation of CG flashes for the weaker, small total flash rate storms most likely for these reasons. The IC:CG ratios varied greatly between all storm types. Further studies are needed to determine why the ratios change so dramatically.

6. SUMMARY

The goal of this study was to investigate the relationship between IC and CG flashes in non-severe summer thunderstorms in the Tallahassee CWA. Averages of their relationship during the summers of 2012, 2013, and 2014 revealed that IC:CG ratios vary greatly from year to year and from day to day. To better understand why IC:CG ratios vary so greatly, case studies were performed on 11 storms during the summer season of 2014. These storms were analyzed to determine how many IC and CG flashes they produced and to see how the IC and CG flash rates changed during the lightning life of each storm. Results showed that each storm was dominated by IC lightning and 10 out of the 11 storms produced at least one IC flash before a CG flash occurred. These storms were divided into two groups. The first group consisted of storms producing peak total lightning flash rates less than 10 fpm. These storms were assumed to be weak due their small flash rates and small flash counts. Assuming these counts and rates are directly related to updraft strength, the storms were considered to be weak compared to the storms that exhibited peak total flash rates greater than 10 fpm. These weaker storms did not exhibit a strong pattern in IC versus CG development most likely due to the weak updraft. The storms with peak flash rates greater than 10 fpm showed a clear peak in IC flash rate during the middle of the storm's lightning life. The majority of CG flashes occurred during this time. The updraft in these storms is expected to be stronger than those in the weaker total flash rate storms, but not as strong as the severe storms described in Williams et al. (1999). The slightly stronger updraft led to a better defined region of CG lightning within the storm's lightning life, but these storms still did not follow the same pattern as the severe thunderstorms in Florida (William et al. 1999). The overall IC:CG ratio of each storm varied greatly between both groups. Research that studies a greater number of storms than this sampling would be necessary to prove that there is any significant trend in ratio. The number of flashes and size of storm varies greatly among these cases, most likely causing these discrepancies. These results show that there is definitely a change in IC and CG development with changing storm intensity, which can be useful for further improving the knowledge of lightning's relationship to severe weather. Future studies could determine a more statistically significant finding about how IC and CG lightning form in relation to each other.

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