Warm Season Cloud-to-Ground Lightning–Precipitation Relationships in the South-Central United States

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ABSTRACT

This study examines the relationship between cloud-to-ground (CG) lightning and surface precipitation using observations from six regions (each on the order of 10 000 km^2), April through October (1989–93), in the south-central United States. The relationship is evaluated using two different methods. First, regression equations are fit to the data, initially for only the CG lightning flash density and precipitation, and then with additional atmospheric and lightning parameters. Second, days are categorized according to differences in the precipitation-to-CG lightning ratio; the same additional parameters are then examined for differences occurring within each category.

Results show that the relationship between CG lightning and surface precipitation is highly variable; r^2 coefficients range from 0.121 in Baton Rouge to 0.601 in Dallas. A measure of the positive CG lightning flash density is the best addition to the model, statistically significant in all regions. When days are categorized, the percentage of lightning that is positive shows the most significant differences between categories, ranging from <4% on days with a ''low'' precipitation-to-CG lightning ratio, to 12%–36% on days with a ''high'' ratio. Other lightning parameters give less significant results; however, three atmospheric parameters (CAPE, lifted index, and Showalter index) do show a significant trend suggesting that there is much less instability in the atmosphere on ''high'' ratio days than on ''low'' ratio days.

1. Introduction

It has long been acknowledged that lightning and precipitation are related phenomena as written observations of their coexistence date back to the Roman Empire (Lucretius 58 B.C.). However, few studies have examined temporal relationships between cloud-to-ground (CG) lightning and surface precipitation. The majority of these studies are based on relatively short time periods or on relatively small geographical areas.

a. Recent studies

Battan (1965) examined data collected from the Santa Catalina Mountains in Arizona from 1957 to 1962; rainfall totals were gauge averaged, and lightning counts were recorded visually from a lookout tower. He discovered a statistically significant correlation between mean rainfall and the number of CG lightning flashes. Further, it was found that approximately 0.03 mm of rainfall occurred per flash during both ''heavy'' (defined as days with mean rainfall of 2.54 mm or greater) and ''light'' rain days (mean rainfall of less than 0.25 mm).

Shih (1988) examined CG lightning and precipitation observations recorded at the Kennedy Space Center in Florida during the summers of 1977 and 1978. He discovered a coefficient of determination (r^2) of 0.67 when comparing gauge-average total rainfall to average flash rate. Using radar-derived precipitation estimates from Alabama and Tennessee during July 1986, Buechler et al. (1990) found a poorer correlation between rain volume and total CG flashes ($r^2 = 0.45$).

An investigation of CG lightning in Sweden was performed by Murty et al. (1983), who compared the percentage of CG lightning that was positive to gauge-averaged precipitation in the vicinity of Uppsala. While their results are based on limited data, there is a clear trend toward lower precipitation amounts as the percentage of positive CG flashes increased. When the average precipitation exceeded 4 mm, no positive CG lightning was observed.

Analyses of CG lightning in the form of seasonal climatologies have been produced for several regions: the Florida peninsula, Oklahoma, and eastern Colorado (López and Holle 1986; López et al. 1991; MacGorman et al. 1993; Reap 1994). López et al. (1991) studied east-central Florida, grouping days from June to September 1983 by the prevailing wind flow over the region, and examining correlations between radar-derived rain volume and CG lightning. On nearly all days, a

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ratio on the order of 10^7 to 10^9 kg of water flash^{-1} was observed.

Williams et al. (1992) studied the deep tropical convection in the vicinity of Darwin, Australia, using radar and a lightning detection network. They observed an order-of-magnitude contrast in land–ocean lightning activity associated with modest differences in wet-bulb potential temperature measured over the land and over the ocean.

b. Climatology of precipitation and convection in the south-central United States

For the portion of the United States between the Rocky Mountains and the Appalachian Mountains, the source of moist air from which precipitation ultimately forms is almost exclusively the Gulf of Mexico. The south-central United States is on the western side of the subtropical high that lies in the western North Atlantic for the majority of the year. The clockwise flow around this high produces net south-to-north transport of moisture from the gulf into the plains.

There are several ways in which precipitation forms in the south-central United States. The majority of the precipitation in this region is formed when a maritime (mT) air mass, advected inland, encounters a continental polar (cP) air mass that has migrated southward from Canada. It is the interaction of these two air masses, typically along a surface cold front, that forces the less dense mT air over the cP air, providing the necessary lifting mechanism and resulting precipitation.

In Lubbock, and to a lesser degree Dallas, a different forcing mechanism may also be responsible for significant precipitation, and this is the dryline. This barrier separates the mT air mass from the continental tropical air mass situated over the southwestern United States and the Sonoran Desert of Mexico. Again, it is the mT air that is less dense and, thus, is forced to ascend. Dryline convection may, at times, be more severe than frontal convection. Yet, unlike a front that is a transient, long-lived (>4 days) and large- (synoptic-) scale (>1000 km) storm system, a dryline is generally limited to the mesoscale (<1000 km) and is quasi-stationary.

Mesoscale convective complexes (MCCs) are the largest and longest lived organized convective systems that occur throughout the south-central United States (Maddox et al. 1986). They do not exhibit the diurnal convection cycle but rather exhibit a persistence through the local overnight hours. While the entire south-central United States is affected by MCCs, they occur most commonly in the northern half of this region. In a given year, it is possible for these systems to produce the majority of the total precipitation.

Storms of tropical origin are the least consistent, but still significant, source of precipitation in the south-central United States. The influence is much greater near the Gulf of Mexico, but significant precipitation totals have been observed inland on occasion.

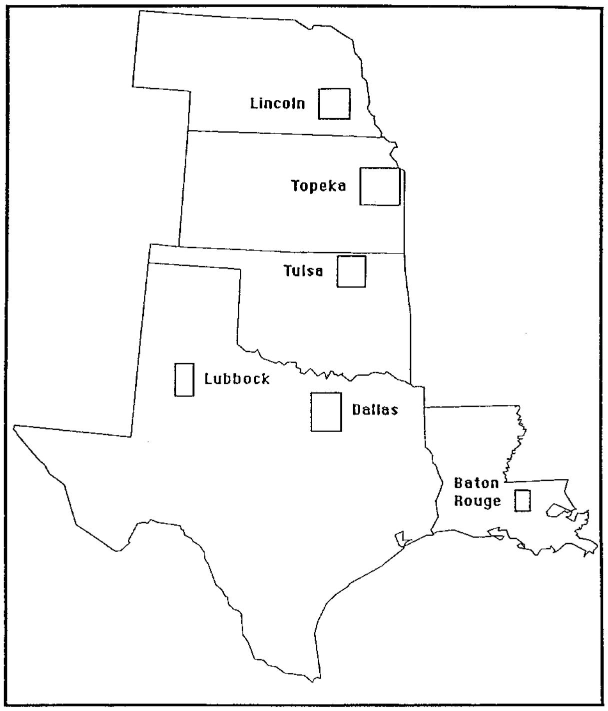

FIG. 1. The south-central United States and the six regions used in this study.

A final source of precipitation is from thunderstorms whose geneses do not fall into any of the above classifications. They result from a differential daytime heating at the surface, such as the sea breeze at Baton Rouge. They occur typically when a region is in an mT air mass and is conditionally unstable.

During the period from April to October, distinct patterns of precipitation are discernible throughout the south-central United States. There is a primary peak during May and June in all areas except Baton Rouge, corresponding to the peak in convective activity that occurs from the year's strongest air mass contrast. A secondary maximum is observed in September.

c. Analysis approach

We use the daily timescale for all comparisons. We do this in two ways. First, we examine the correlations between CG lightning and precipitation, other atmospheric and lightning parameters, and their variability from month to month and from region to region. Second, we examine the differences in measured lightning parameters and atmospheric parameters between sets of days that are grouped according to a precipitation-to-CG lightning ratio.

The regions studied are six different rectangular-shaped areas in the states of Nebraska, Kansas, Oklahoma, Texas, and Louisiana. These regions are shown in Fig. 1 and relevant data are presented in Table 1. Each individual region has been chosen based on a com-

TABLE 1. Dimensions and precipitation-recording station densities for each of the six regions used in this study.

Region	Longitudinal extent (km)	Latitudinal extent (km)	Total area (km^2)	Stations	Avg. station density (km^2 per station)
Baton Rouge	39	67	2579	17	151
Dallas	93	111	10 405	24	434
Lincoln	94	84	7883	24	328
Lubbock	56	89	4967	11	452
Topeka	118	111	13 090	30	436
Tulsa	81	89	7183	16	449

paratively dense network of precipitation-recording stations and a relatively homogenous climate (i.e., without appreciable orographic influence or immediate coastlines) within its boundaries. These regions are representative of the different climate zones present in the central United States; normal annual precipitation ranges from approximately 500 mm in Lubbock to greater than 1500 mm in Baton Rouge.

This study includes data from the ‘‘warm season’’ (defined here as April through October) of 1989 through 1993. As little or no CG lightning occurs in much of the south-central United States from November through March, these months are excluded from our analysis. The analysis starts with 1989, the first year for which CG lightning data were available with full nationwide coverage.

2. Data sources and processing

All CG lightning data used in this study were collected by the National Lightning Detection Network. For each of the regions shown in Fig. 1, the following daily (beginning and ending at 1300 UTC) lightning parameters were computed: total CG flashes, the percentage of flashes of positive polarity (PP), the mean multiplicity of both negative (MNM) and positive flashes (MPM), and the mean first stroke peak current for both negative (MNC) and positive flashes (MPC). Total CG flashes are standardized to *measured ground flash density* (MGFD), defined as the number of measured CG flashes per 100 km^2. It should be noted that the CG lightning data in this research are not multiplied by a scaling factor to account for unrecorded flashes, hence, the adjective *measured.*

The precipitation data used were collected and archived by the National Climatic Data Center. This study uses data from first- and second-order stations, as well as cooperative observers. For comparisons with the regional total MGFD defined above, a corresponding regional mean precipitation (PCPN) is needed. For this, the method of Thiessen polygons was used (Manning 1987) and areal weights derived from these polygons were used to determine PCPN.

TABLE 2. Values of r^2, b_0, and b_1 for the simple linear regression model PCPN = b_0 + b_1MGFD.

Region	r^2	b_0	b_1
Baton Rouge	0.121	3.12	1.04
Dallas	0.601	0.79	1.37
Lincoln	0.504	1.35	1.09
Lubbock	0.331	0.91	0.63
Topeka	0.535	1.66	0.93
Tulsa	0.317	1.96	0.85

The sounding parameters studied included the following: convective available potential energy (CAPE), precipitable water (PW), lifted index (LI), Showalter index (SI), K index (KI), and total totals (TT). They are calculated for the nearest available National Weather Service morning sounding (1200 UTC) in the region. For three regions—Topeka (sounding site: Topeka), Lincoln (Omaha), and Dallas (Stephenville)—a sounding site is within 70 km of the region; for the other three, sounding sites are much farther (140–180 km) away: Lubbock (Amarillo), Tulsa (Norman), and Baton Rouge (Lake Charles).

As mentioned above, the 24-h period used throughout this research is from 1300 to 1300 UTC. Cooperative stations with daily observation times of both 1300 and 1400 UTC (0700 and 0800 CST) are included in this study. While including both groups in the study greatly increases the station density, it also results in the need to eliminate some days from the study. Specifically, this requires days during which 15% of the daily total precipitation occurred between 1300 and 1400 UTC to be eliminated, as the precipitation would be included in one day for one group of stations and the following day for the other group. The number of days eliminated in each region ranges from 28 to 78 (2.6% to 7.3%).

3. Correlations between CG lightning and precipitation, and other parameters

a. Regression model including MGFD and PCPN

Simple linear regression equations (of the form PCPN = b_0 + b_1MGFD) were applied to precipitation and MGFD values on a daily basis. The large number of days included (~1000) affords the opportunity to compare regression equations for each of the seven calendar months in addition to one that includes all months.

For the equations that include days from all months (Table 2), values of r^2 range from 0.121 at Baton Rouge to 0.601 at Dallas. The relatively low value of 0.33 in Lubbock may be due to the strong variance in the percentage of precipitation that evaporates in its descent. In Baton Rouge, where numerous cases of heavy precipitation without significant cloud-to-ground lightning activity are observed, the linear regression equation is not very useful. It is uncertain why Tulsa’s r^2 value is significantly lower than the others in the plains.

Although variable, monthly patterns of r^2 values are

TABLE 3. Partial r^2 (r^2_{part}) values for other atmospheric parameters. Correlations are with PCPN when MGFD is already included in the regression equation. A dash indicates a value of less than 0.01.

	Region					
Parameter	Baton Rouge	Dallas	Lincoln	Lubbock	Topeka	Tulsa
CAPE	—	—	—	—	—	—
PW	0.037	—	—	0.022	—	0.012
LI	—	—	—	—	—	0.011
SI	0.027	—	—	—	—	0.022
KI	0.042	—	—	0.016	0.015	0.025
TT	0.020	—	—	—	—	0.021
PGFD	0.161	0.293	0.181	0.214	0.290	0.313
MNC	—	—	—	—	—	—
MPC	—	—	0.011	—	—	—
MNM	—	—	—	—	—	0.015
MPM	—	—	0.013	—	0.018	—

TABLE 4. Values of r^2, b_0, b_1, and b_2 for the multiple linear regression model PCPN = b_0 + b_1MGFD + b_2PGFD.

Region	r^2	b_0	b_1	b_2
Baton Rouge	0.262	2.52	0.245	25.7
Dallas	0.716	0.65	0.564	22.8
Lincoln	0.594	1.05	0.713	10.5
Lubbock	0.475	0.75	0.203	16.5
Topeka	0.670	1.27	0.357	16.3
Tulsa	0.530	1.43	0.062	22.0

discernible at all locations. At all regions except for Baton Rouge, the higher r^2 values are generally observed during more ''active'' months, that is, months in which a greater amount of CG lightning and/or precipitation occurred. (Baton Rouge's pattern is quite random.) Peak values thus shift north as the year progresses: the highest r^2 at Dallas is in May (0.7), at Tulsa in June (0.6), and at both Topeka and Lincoln in July (0.7). The month of September is an interesting exception. In five of the six regions, the poorest correlation is observed during September. This is perhaps connected to the relatively high number of distinct precipitation geneses (tropical, airmass, frontal) that can occur in September, compared to other months.

Overall b_0 and b_1 values are also listed in Table 2. The high b_0 value at Baton Rouge shows the large number of days there in which heavy precipitation occurred without significant CG lightning. At Lubbock, the coefficients are comparatively low, indicative of the drier climate. In the other four cities, it is interesting that while the lines in themselves are somewhat diverse, they all converge near a middle point [2 CG flashes (100 km^2)$^{-1}$, 3.6 mm]. Much of the difference in the lines' slopes (b_1) can be attributed to the presence of several days of extreme amounts of precipitation and/or CG lightning. Seasonally, the b_1 coefficient in most cases is highest in spring (April, May) and autumn (September, October) (~1–3) and lowest in the summer months (June–August) (~0.6–1). Since the relative increase in CG lightning during the summer is nearly an order of magnitude larger than the relative increase in precipitation, a lower b_1 should be observed in the summer. There is no obvious monthly pattern to the b_0 values.

b. Correlations with other parameters

The usefulness of adding more parameters to the simple linear equation was checked. For each region, for the regression model containing all daily data, partial r^2 values (which are equal to the proportionate drop in sum of squared error terms for a model when a new variable is added) were calculated for the other 11 parameters mentioned above. A summary of these r^2_{part} values is given in Table 3. We note that the positive ground flash density (PGFD) shows significant promise in being a useful addition to the model. This is consistently true in all six regions, producing between 16% and 31% reduction in the sum of squared error terms when added to the model that already contains MGFD. None of the other parameters produced r^2_{part} values of greater than 0.042 in any region, and no other parameter produced values above 0.01 in all regions. Next we tested a model with MGFD and PGFD as independent variables.

Results of adding the MGFD and PGFD as independent variables are shown in Table 4. The r^2 values range from 0.262 at Baton Rouge to 0.716 at Dallas, an increase of 0.090 to 0.213 over the r^2 values presented in Table 2. Increases are generally larger in the regions that have lower r^2 values in the model with only MGFD. In Baton Rouge and Tulsa, PGFD has a higher correlation to PCPN than MGFD. An examination of b_1 and b_2 values revealed that a significantly higher amount of precipitation is associated with each positive CG flash. The b_2 to b_1 ratio is highly variable, although it is generally on the order of 10 to 100. These results are not in themselves surprising, since typically MGFD is on the order of 10 to 100 times PGFD. However, these results contradict the study by Murty et al. (1983), whose results imply that a negative value of b_2 would perhaps be expected. This discrepancy is discussed further in section 4e.

Tests on the b_2 coefficient show that it is statistically significant in all regions. Also, the variance inflation factor, a test of multicollinearity (Neter et al. 1989), or correlation between the independent variables, has been applied to each of the models. In none of the six regions does the test conclude that multicollinearity is a problem, despite obvious inherent correlation between MGFD and PGFD.

The model using MGFD and PGFD is next applied to the dataset for each month for each region. The tendency for b_2 to be on the order of 10 to 100 times greater than b_1 is fairly consistent from month to month (when b_1 does not have a negative value). Moreover, the influence of PGFD in the equation is often so strong in determining precipitation that in 14 out of 42 equations the coefficient for MGFD (b_1) is either statistically in-

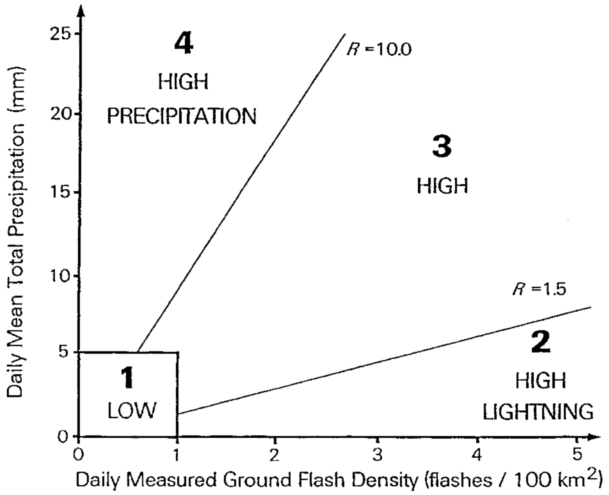

FIG. 2. Schematic of the categorization of days.

significant or even negative. In only 2 of the 42 equations does this occur with the coefficient for PGFD (b_2). As a result, the trend to lower b_1 values in the summer in the simple regression model is mirrored in the multiple regression model by the b_2 coefficient: April and October both have values mostly above 20. The July values average around 10. In the multiple regression model, b_1 shows no appreciable monthly pattern.

The r^2 values are quite variable. They also conform to the same pattern with the highest value occurring in the southern part of the area of interest in May and shifting northward to Topeka and Lincoln by July. Interestingly, very low r^2 values are again observed in September.

The r^2_{part} values calculated for the other 10 variables, based on an equation that already includes MGFD and PGFD, are largely insignificant. Except for Baton Rouge, no value exceeds 0.023. In Baton Rouge, it is possibly a function of the regression model functioning so poorly overall as there are three variables with r^2_{part} values between 0.03 and 0.05. Since no additional parameter would be statistically significant in more than three regions, no further additions to the regression model were made.

4. Comparisons between days grouped by precipitation to CG lightning ratio

The results discussed above suggest that the relationship between CG lightning and precipitation cannot be summarized solely by regression equations. Further, plots of the two parameters in many cases yield distinct clusters of data points. This leads to an interesting question of whether there are significant differences in atmospheric parameters or other lightning parameters between days whose points appear in one region of the plot as distinct from another. For this purpose, all available days for each station were divided into four categories, subjectively created based on the plots made. Category 1, LOW, is defined to include all days during which less than 5 mm of precipitation fell *and* less than 1 flash (100 km^2)$^{-1}$ was recorded. All other days are then placed in one of three categories, based on the ratio of PCPN to MGFD, R, in units of millimeters per flashes per 100 km^2: category 2, HIGH LIGHTNING, $R \leq 1.5$; category 3, HIGH, $1.5 < R < 10.0$; and category 4, HIGH PRECIPITATION, $R \geq 10.0$. These categories are depicted graphically in Fig. 2.

TABLE 5. The number of days that fall into each category.

	Region					
Category	Baton Rouge	Dallas	Lincoln	Lubbock	Topeka	Tulsa
1	730	810	835	858	778	800
2	107	88	55	103	101	92
3	112	65	62	50	86	75
4	92	29	43	27	53	55

a. Classification of days

Several observations regarding the classification of days should be noted. Table 5 contains a list of the total number of days that fit into each of the four categories for each region. The three active categories (2, 3, and 4) contain the same order of number of days. There is in most regions a decrease in the number of days as the category number increases.

b. Percent positive

Of all the parameters discussed in this section, it is the percent positive (PP) that exhibits the most significant intercategory differences. This follows logically from the results presented in section 3, in which PGFD is shown to be the most significant addition to the simple linear regression model. Results for the entire warm season are listed in Table 6. In all regions, there is a significantly higher PP associated with days that featured a higher precipitation-to-CG lightning ratio, R. On category 2 ($R < 1.5$) days, between 2.4% and 3.9% of the CG flashes were positive. This increased to 5.3%–9.6% positive on category 3 ($1.5 < R < 10$) days and 12.5%–36.4% on category 4 ($R \geq 10$) days. The intercategorical differences are statistically significant in all regions, using a binomial test on the respective proportions; in each of the comparisons, the p value is less than 0.0001.

On a monthly basis, PP values in this study show a trend similar to that observed by Silver and Orville (1995): the lowest values occur in the summer months and increase toward the winter months. The average PP of the six regions, for the months April through October, is highest in April at 10%, declines to 4% in July and August, and rises again to 8% by October.

This monthly PP pattern, in light of the monthly pat-

TABLE 6. The mean values of each of the lightning parameters by category number. A bold value indicates it is statistically significantly different [using the *t* test, the binomial test, or the Wilcoxon rank sum (parametric) test] from the other two categories' values.

	Region category								
	Baton Rouge			Dallas			Lincoln		
Parameter	2	3	4	2	3	4	2	3	4
PP (%)	**3.3**	**5.3**	**20.3**	**2.7**	**6.0**	**18.1**	**3.2**	**9.6**	**36.4**
MNM (strokes)	**2.67**	**2.57**	**2.15**	2.81	2.77	**2.34**	**2.83**	**2.54**	**1.98**
MPM (strokes)	**2.80**	**2.30**	**1.45**	1.49	1.66	1.48	1.97	1.58	**1.37**
MNC (kA)	45	44	**41**	**34**	36	40	34	32	38
MPC (kA)	105	106	90	**49**	68	77	66	65	71
	Lubbock			Topeka			Tulsa		
Parameter	2	3	4	2	3	4	2	3	4
PP (%)	**2.4**	**6.8**	**12.5**	**3.1**	**8.2**	**26.4**	**3.9**	**7.8**	**28.0**
MNM (strokes)	**2.82**	**2.46**	**2.07**	**2.66**	**2.45**	**2.03**	**2.59**	**2.40**	**1.99**
MPM (strokes)	1.70	1.53	1.33	**1.87**	**1.69**	**1.39**	1.73	1.74	**1.44**
MNC (kA)	29	30	34	33	35	**37**	33	35	36
MPC (kA)	60	68	76	65	75	78	59	78	75

tern of day categorization described above, likely explains some of the large PP differences among the three categories. That is, the typical peak occurrence of category 2 days, the category with the lowest PP, is during July and August, and synchronous with the time of year with the lowest PP. Category 3 and category 4 are similarly coincident. However, if this were responsible for much of the variability, the magnitude of the day categorization patterns would have been much stronger than they were. Also, the monthly variations in PP are not nearly large enough to account for the 5- to 12-fold differences seen between categories 2 and 4.

The monthly PP values, when categorized, show seasonal trends that are generally similar to the overall pattern. In 35 of the 41 category months (October for Lubbock is excluded since there were zero CG flashes in category 4), the pattern of [PP (category 2) $<$ PP (category 3) $<$ PP (category 4)] was observed. Statistical tests were not performed on the monthly data since, in several cases, the total number of CG flashes that occurred in one or more categories was small ($<$100).

It is also a possibility that the marked difference in PP between categories could be due to a correlation between PP and either PCPN and/or MGFD, instead of the ratio *R*, the parameter whose value initially determined the categorization of each day. Both PCPN and MGFD show significant differences from category to category, as would be expected by the nature of the categorization. To test this possibility, three linear regression models were fit comparing the PP values to their corresponding *R*, MGFD, and PCPN values. Days from category 1 and days with less than 10 measured CG flashes were excluded. The resulting r^2 values are low in all cases, which should be expected due to the volatility of the binomial parameter PP. Still, as shown in Table 7, in all six regions the r^2 values from the model with *R* are much greater than the r^2 values for the models with only PCPN or MGFD. These results suggest further the correlation between percent positive and the ratio of precipitation-to-CG lightning.

TABLE 7. Values of r^2 for a simple linear regression model applied to PP individually against *R*, MGFD, and PCPN.

Region	PP vs *R*	PP vs MGFD	PP vs PCPN
Baton Rouge	0.170	0.130	0.035
Dallas	0.097	0.032	0.040
Lincoln	0.186	0.070	0.003
Lubbock	0.125	0.022	0.021
Topeka	0.278	0.069	0.020
Tulsa	0.427	0.058	0.043

c. Other lightning parameters

1) MULTIPLICITY

The warm season MNM and MPM values are shown in Table 6. The widely observed disparity between the two (with higher mean multiplicities for negative flashes) is apparent (Reap and MacGorman 1989; MacGorman et al. 1993). For MNM, statistically significant differences are observed for all regions between categories 2, 3, and 4, except for Dallas's categories 2 and 3. Mean values range from 2.59 to 2.83 in category 2; these are between 0.52 and 0.85 higher than the mean values in category 4 for each region.

However, it has been observed that MNM is positively correlated with total CG lightning flashes (Reap and MacGorman 1989; Studwell and Orville 1995). A test of correlation of MNM individually against *R*, MGFD, and PCPN (similar to the one described above for PP) supports this observation, since the r^2 values are higher for the correlation of MNM with MGFD than with either PCPN or *R* in all regions except Topeka. By definition of the regions, much greater CG lightning activity took place on category 2 days than on category 4 days (on average a factor of 25). Thus, the interca-

Table 8. Same as Table 6 except for the atmospheric parameters.

	Region category								
	Baton Rouge			Dallas			Lincoln		
Parameter	2	3	4	2	3	4	2	3	4
CAPE (J kg^{-1})	**3060**	**2641**	**1522**	**1794**	1144	801	1009	719	**307**
LI (°C)	−7.1	−6.4	**−4.0**	**−5.1**	−3.7	−1.5	−1.8	−0.8	**2.7**
SI (°C)	−0.4	−0.7	0.6	**−2.0**	−1.0	0.5	0.2	0.6	**4.2**
PW (cm)	4.9	4.8	4.6	3.8	3.6	3.8	3.0	3.3	**2.3**
KI (°C)	30	29	30	31	29	30	25	28	**19**
TT (°C)	46	46	**45**	50	48	**46**	48	46	**43**

	Lubbock			Topeka			Tulsa		
Parameter	2	3	4	2	3	4	2	3	4
CAPE (J kg^{-1})	822	855	**463**	**1141**	**987**	**297**	**2021**	**1529**	**649**
LI (°C)	−2.6	−2.6	**−0.8**	**−3.4**	**−1.6**	**3.0**	**−5.2**	**−4.0**	**−1.1**
SI (°C)	−1.1	−0.6	**1.3**	**−1.6**	**−0.2**	**3.5**	−2.3	−1.7	**0.3**
PW (cm)	2.7	2.8	2.8	**4.1**	**3.7**	**3.0**	3.7	3.6	3.5
KI (°C)	29	31	29	32	30	**24**	30	31	29
TT (°C)	49	47	**45**	49	47	**43**	49	49	**47**

tegorical differences have no discernible basis in differences in *R.*

MPM values depict a pattern similar to MNM, although smaller in magnitude and less consistent. In around half of the cases the differences are statistically significant. An interesting side result of the analysis is the very high MPM for Baton Rouge in categories 2 and 3. It is unclear why these values are much higher for Baton Rouge than for all other regions. One possible explanation is the lack of nearby lightning detection equipment (Orville 1994), which potentially could result in only the higher peak current flashes being detected by the network. This would explain the higher mean peak current discussed below, although it does not explain why only certain categories are affected.

2) First stroke peak current

The mean values of the first stroke peak current for both positive (MPC) and negative (MNC) flashes (Table 6) suggest in both cases that the peak current values are generally higher in category 4 than in category 2. This supports previous observations of higher peak currents associated with lower CG flash totals (Silver and Orville 1995). The high variance in the peak current data (the majority of the MNC datasets had standard deviations of greater than 8 kA; for MPC datasets this value was greater than 30 kA) resulted in very few of the statistical tests yielding significant results. In Baton Rouge, overall peak currents for both polarities are higher than in the other regions and the intercategory differences also trend in the opposite direction from the other regions. That is, higher mean peak current occurs in category 2 than in category 4. This may be an instrumentation effect resulting from a greater spacing of the lightning direction finder sites in this region during the years in which data used for this analysis were recorded.

d. Atmospheric parameters

1) CAPE

Mean values of CAPE are shown, with all of the other atmospheric parameters, in Table 8. In general, the CAPE on category 2 days is larger than it is on category 3 days, which in turn is larger than it is on category 4 days. The mean CAPE value on category 2 days is from 2 to 4 times the mean value on category 4 days. In most cases, these differences are statistically significant.

The monthly pattern for CAPE values is similar in all regions: there is a broad peak from June to August with values decreasing sharply winterward. In Baton Rouge, the range is from 575 J kg^{-1} in October to 2800 J kg^{-1} by July. In Lubbock, which had the lowest mean CAPE of all regions, the corresponding figures are 100 J kg^{-1} and 900 J kg^{-1}. However, unlike what is observed with PP, there is no consistent monthly pattern to the data when it is categorized. While this is likely in part due to a relatively small sample size of a parameter that has high variance, it still does suggest that on days that fall into categories 2, 3, and 4 the seasonal dependence of the CAPE values is weak.

Correlation coefficients from the regression of CAPE individually on *R*, MGFD, and PCPN show results similar to those with PP; that is, the correlations are highest with *R*. This suggests that the CAPE parameter, as well as PP, could have some sort of association with the precipitation-to-CG lightning ratio as was first shown by Williams et al. (1992) in their studies near Darwin, Australia.

2) Lifted and Showalter indices

The intercategorical differences in the mean values of the LI and SI are similar. Furthermore, they both resemble the pattern of differences observed in the

CAPE values, as can be seen in the bold values in Table 8. The trend in mean values is for higher values (greater atmospheric stability) in category 4 than category 2.

The monthly pattern of these two parameters is as expected, that is, algebraically highest in April (LI: 1° to 7°C, SI: 4° to 7°C) and lowest in July (LI: −7° to −1°C, SI: −1° to 1°C). Unlike CAPE, in most cases the categorized days do exhibit the same LI and SI patterns as the overall data, likely a result of lower variability in these datasets.

3) PRECIPITABLE WATER, K INDEX, AND TOTAL TOTALS

Unlike the previous atmospheric parameters discussed, trends in PW from category to category exhibit a regional dependence. In the southern portion of the area studied (including Baton Rouge, Lubbock, Tulsa, and Dallas), there are no significant differences between categories. In Topeka and Lincoln, meanwhile, the mean PW in category 4 is significantly lower than the mean in both categories 2 and 3. Also, PW in category 2 is significantly less than it is in category 3 in Topeka.

The PW values, calculated from the 1200 UTC sounding, form a monthly pattern similar to the CAPE values. The mean PW is lowest in April, ranging from 1.3 cm in Lubbock to 2.7 cm in Baton Rouge, and highest in July, ranging from 3.0 cm to 4.7 cm. Some of the intercategory differences observed in Lincoln and Topeka can be attributed to the monthly pattern of the categorization of days. Yet unlike the other regions, where categories 2, 3, and 4 all feature nearly identical mean PW values each month, the mean monthly category 4 PW is consistently 0.5–1.0 cm lower than the mean monthly category 2 *PW* throughout the entire warm season in Topeka and Lincoln. The result seems paradoxical at first: a significantly *lower* amount of water in the atmosphere occurring on days with a *higher* precipitation-to-CG lightning ratio. However, this suggests that perhaps in the northern tier of the area studied heavy precipitation with little corresponding CG lightning activity occurs more often when significant moisture is not present at the start of the day and, thus, must be advected in during the day.

The KI shows results essentially identical to those of PW. Total totals is similar, yet with larger weighting on atmospheric stability than KI, TI does show some tendency toward stratification between categories.

e. Discussion

There are two explanations for the strong association between the precipitation-to-CG lightning ratio and the percentage of lightning that is positive. One involves the trailing edge of thunderstorms. Stratiform clouds with steady moderate precipitation characterize this section of the thunderstorm. Observations also show that a greater PP occurs in this region (Rutledge and MacGorman 1988). Since quantities of CG lightning are less in this region than in the core of the thunderstorm (Rutledge and MacGorman 1988), were a thunderstorm to enter the edge of the region in its dying stages (when the stratiform region is dominant), or ‘‘clip’’ the region so that the stratiform part of the storm was all that was present within the region's boundaries, then a comparatively high PP and high *R* would occur simultaneously.

While it is likely this did occur on occasion, it seems unlikely this is the full explanation. Another possibility includes consideration of the positive CG flashes that are initiated from the positively charged region of the cloud. It has been observed (Engholm et al. 1990) that a greater percentage of CG flashes is positive in shallower convective clouds. This concurs with the previous observations of higher PP values in comparatively colder atmospheres and at more northerly latitudes. However, it could also be hypothesized that a greater PP would occur in thunderstorms when the vertical velocity is comparatively weak. That is, since it has been observed (Marshall and Rust 1991; Marshall et al. 1995) that higher vertical velocities in severe thunderstorms tend to shift the charge regions higher in the atmosphere, then over the long term, on days when a higher vertical velocity is observed, the corresponding PP would be lower.

This is one model in which the significantly higher CAPE values and significantly lower PP values in category 2 (relative to category 4) can be linked. CAPE is theoretically proportional to the square of the vertical velocity. The higher CAPEs observed in category 2 would imply a greater vertical velocity; this would push the charge regions to greater heights and result in a lower percentage of positive lightning, which is what occurs. It would also generally result in a higher amount of CG lightning activity, since higher vertical velocity would make the charge separation process more efficient. Conversely, on a day with a lower CAPE value, the vertical velocity would generally be weaker, thus providing less efficient charge separation, and less CG lightning. The CG lightning that does occur though is more likely to be positive since the upper positively charged region is closer to the ground. This is precisely what has been observed on average in category 4.

5. Conclusions

In this study we examined various aspects of the relationship between CG lightning and precipitation, in order to improve the general knowledge of their connection. The principal conclusions are as follows:

- On the daily timescale, there appears to be a definite linear correlation between the total number of CG lightning flashes occurring in a region and its mean precipitation. There is great variability in the strength of this correlation, however, from region to region and month to month. Correlations generally increase farther away from the Gulf of Mexico. Within a region, the highest r^2 values generally occur in the months with relatively high CG lightning counts.

- A measure of the amount of positive CG lightning cannot be overlooked in any examination of the relationship between CG lightning and precipitation. This is apparent in both sections of this research.
    1) Of the atmospheric parameters examined, only PGFD shows significant improvement to a regression model that already contains PCPN and MGFD. In several equations, PGFD actually is better correlated with PCPN than MGFD.
    2) When days are split by category, it is the PP that shows the most consistently significant differences between categories.
- These two points imply a positive correlation between the percentage of CG lightning that is positive and the precipitation-to-CG lightning ratio. This contradicts the implications of a prior study (Murty et al. 1983).
- Neither first stroke peak current nor multiplicity show any correlation with the precipitation-to-CG lightning ratio, although a positive correlation between MGFD and multiplicity supports earlier work (Reap and MacGorman 1989; Studwell and Orville 1995).
- In most cases, the atmospheric parameters and indices whose values are strongly influenced by the stability of the atmosphere (CAPE, LI, SI) show statistically significant differences from category to category (Table 8, categories 2, 3, and 4). On days when a higher precipitation-to-CG lightning ratio is observed, there is a tendency for greater atmospheric stability (i.e., lower CAPE values, higher LI and SI values) than on days with a lower ratio.
- Conversely, the atmospheric parameters and indices whose values are strongly influenced by the moisture in the atmosphere (PW, KI, TT) show little difference from category to category in the southern half of the region of study. In the northern half, the results suggest that there is significantly less moisture present at the start of days that ultimately yield a high precipitation-to-CG lightning ratio than on days that yield a lower ratio.
- The intercategorical differences that are observed in PP are likely explainable by differences in CAPE. Higher CAPE values in theory signify stronger vertical velocities. This can be related to both greater lightning activity with higher vertical velocities more efficiently separating charge (Zipser 1994) and a lower PP (the positive charge region being shifted to higher elevations).

Differences between the categories defined above need to be further assessed by analyzing more independent parameters, including the synoptic conditions. A preliminary examination of two years' data in Topeka and Lincoln shows that the frequency of a frontal system being in the area is approximately the same in categories 2, 3, and 4. However, in category 4 the relative occurrence of a 500-hPa trough affecting the area is five times (0.50 vs 0.10) more likely than the occurrence on category 2 days. This could help explain the high precipitation and the correspondingly small amount of CG lightning on category 4 days (occurring from large-scale rising air that may or may not promote vigorous convection).

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