Cloud-to-Ground Lightning Flash Parameters Associated with Heavy Rainfall Alarms in the Denver, Colorado, Urban Drainage and Flood Control District ALERT Network

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ABSTRACT

Rainfall data from the Denver, Colorado, Urban Drainage and Flood Control District Automated Local Evaluation in Real Time (ALERT) network were used to identify heavy rainfall alarms for the period 1999–2003. Twenty-nine heavy rainfall-rate alarms were identified. Cloud-to-ground (CG) lightning flash data from the National Lightning Detection Network (NLDN) were analyzed for the 90 min prior to each heavy rainfall alarm. Spatial patterns from NLDN data were extracted using a point-polygon topology developed with basic Geographic Information System procedures. The information extracted from the polygons was used to calculated summary statistics for rainfall rates, CG flash rates, and CG flash duration. Heavy rainfall episodes were divided into two groups based on latitude, longitude, and elevation. Heavy rainfall episodes in the higher elevations of the study area produced an average of 29 mm of rainfall per episode and 1095 CG flashes in the 90 min prior to the rainfall-rate alarm. Only five polygons, all closely proximal to the alarm sites, produced significant CG flash rates prior to the rainfall alarms, and areas with CG flash durations greater than 25 min were clustered near the rainfall-rate alarm sites. In the second group (the lower elevation stations) the mean event produced a total of 33 mm of rainfall and 1182 CG flashes during the 90 min prior to the rainfall alarm. Four polygons saw consistent CG flash rates in the 90 min prior to the heavy rainfall alarms and CG flash duration was at its greatest in areas just west of the ALERT stations.

1. Introduction

Frequent intense rainfall can lead to a persistent flash flooding hazard as a basin experiences rapid urbanization (Smith et al. 2002). A basin's size, shape, land use, vegetation, and drainage density contribute to deliver runoff to the stream channel, with the temporal variability of the delivery playing a pivotal role in generating flash floods. In urbanized basins rainfall storage capacity is substantially diminished thereby leading to reduced infiltration, increased runoff volume, increased peak flow, and reduced time of concentration (Cheng and Wang 2002). The diminished storage capability in an urbanized area is related to the percentage of impervious surface in the basin. Modeling results suggest that doubling the area of impervious surface in a drainage basin increases peak flow by nearly 20% (Ng and Marsalek 1989). Additionally, the increased use of artificial channeling, curbing, guttering, and storm drainage–collection systems increase the flow velocity of storm runoff (Chow et al. 1988).

The heavy rainfall events that lead to urban flash flooding in the urban environment require a unique set of meteorological processes coinciding in space and time. This somewhat simple statement is made complex in reality when one entertains the various processes that can combine to produce heavy rainfall (Doswell et al. 1996). In the southwestern United States, for example, ingredients for heavy rainfall include seasonal weather systems such as the North American Monsoon (NAM), orographic enhancement of rainfall systems, and embedded convection in frontal systems. In the southwestern United States these ingredients often combine to produce thunderstorms. These thunder-
storms may produce heavy rainfall and produce numerous cloud-to-ground (CG) lightning flashes. In the past, CG lightning flashes have been shown to be correlated in space and time with heavy rainfall in the southwestern United States (Petersen and Rutledge 1998; Holle and Bennett 1997). This study will analyze the spatial and temporal relationship between CG lightning flashes and heavy rainfall in an urbanized drainage basin in the southwestern United States. More precisely the focus of the study is to produce a regional analysis that indicates the location and time of CG flashes that precede heavy rainfall in the Denver, Colorado, metropolitan area.

2. The UDFCD ALERT network

A number of municipalities that have experienced urban flash flooding in the past have taken steps to monitor their meteorological and hydrological environments with the aim of providing flash flood guidance for urbanized basins. One such community is Denver where the Urban Drainage and Flood Control District (UDFCD) operates an Automated Local Evaluation in Real Time (ALERT) system (more information available online at http://alert.udfcd.org/), which monitors the flash flood hazard. The network includes rain gauges, stream gauges, and complete weather stations designed to provide nested warnings and give decision makers the needed data for producing the appropriate watches and warnings.

The majority of meteorological and hydrological instruments in the Denver UDFCD ALERT system are located across six counties (Adams, Arapahoe, Boulder, Denver, Douglas, and Jefferson). The flood history for these counties as reflected by entries in the National Climatic Data Center (NCDC) publication Storm Data for the past 10 yr (1994–2003) indicates a total of 79 flash floods for the period. The temporal distribution of flash floods in this region of Colorado is highly concentrated in the summer months. More than 93% of floods were reported between 1 June and 30 September. This clustering of flash floods in the warm season, especially mid-to-late summer, suggests that storms generating heavy rainfall are likely convective and may be linked to moisture advection from the NAM circulation (Weaver and Doesken 1990; Maddox et al. 1980). If this is the case, it is also likely that these storms produced moderate-to-high CG lightning flash totals in concert with the heavy rainfall (Watson et al. 1994; Battan 1965). The CG lightning flashes that accompany heavy rainfall may prove valuable to forecasters, as observations made by the National Lightning Detection System (NLDN) show potential for providing increased lead times for heavy rainfall in specific circumstances (Underwood and Schultz 2004; 2003).

3. Cloud-to-ground lightning and heavy rainfall

A number of studies have demonstrated the relationship between CG flash parameters and heavy convective rainfall in space and time (Soriano et al. 2001; Grecu et al. 2000; Sheridan et al. 1997; Reap and MacGorman 1989; Piepgrass and Krider 1982). Using monthly data Petersen and Rutledge (1998) identified geographic variability in the correlation between CG flashes and rainfall rates across the United States, with the arid southwestern portion of the country producing correlation coefficients of 0.90. Soriano et al. (2001) confirmed this relationship between CG flashes and heavy convective rainfall in continental environments. Their analysis concluded that CG flashes and rainfall rates in the semiarid region of the Iberian Peninsula were significantly related with a correlation coefficient of 0.75, compared to a correlation coefficient of 0.67 in the more humid reaches of the peninsula. Tapia et al. (1998) analyzing 22 thunderstorms in Florida suggest a temporal and spatial relationship between rainfall flux and CG flash frequency. The authors also propose a model for estimating convective rainfall using CG flash parameters. Cheze and Sauvageot (1997) reported spatial agreement between CG flash density and radar-derived rainfall intensity during a thunderstorm that produced a flash flood in the Spanish Pyrenees.

Williams et al. (1992) discussed the connection between CG flashes and rainfall in terms of continental versus open-ocean convection, pointing out that continental rainfall systems produce 10 times more lightning per unit area than storms over open ocean. The dissimilarity in CG flash production between continental locations and humid ocean was argued to be related to the more vigorous and deeper vertical lifting in continental environments and the greater proportion of humid ocean rainfall that forms from coalescence rather than ice phase processes. In many regions, heavy rainfall and copious CG lightning flashes tend to be linked physically. Strong updrafts through the mixed phase region initiate charge separation and lightning activity in clouds dominated by ice phase hydrometeors. Continued strong convection and the subsequent formation and descent of precipitation typically produce the electrical conditions needed for flashes to reach the ground. This dominant ice phase also preconditions the atmosphere for precipitation as the solid phase hydrometeors melt and fall to the surface as rain (Williams and Renno 1993).

This study will utilize data generated by the Denver
UDFCD ALERT network and the NLDN to investigate the spatial and temporal relationships between regional CG lightning flashes and heavy rainfall in the urban ALERT network. Recently NLDN datasets have been used to examine the relationship between CG flashes and precipitation. For example, NLDN data were used by Hunter et al. (2001), to indicate bands of heavy snowfall in the southeastern United States and by Underwood and Schultz (2003) to indicate heavy rainfall leading to flash floods and debris flows in mountain areas in the southwestern United States. In a study of 12 post-wildfire flash floods in Colorado, Underwood and Schultz (2004) calculated a mean lead time of 41 min from peak CG flash rate to peak rainfall rate. Holle and Bennett (1997) found that continuous CG flashes, especially those episodes exceeding 100 min were spatially and temporally related to urban flash flooding in Tucson, Arizona.

4. Research design

a. Study area

The observation area for CG lightning flashes from the NLDN is centered on the Denver metropolitan area but is extensive in its coverage of the north-central portion of Colorado (Fig. 1). The CG flash analysis area is much larger than the area of the urbanized basin where the rainfall data are collected. The different scales for CG flashes and rainfall observations takes into consideration the regional scale of storms that produce rainfall in the Denver metropolitan area. This study will identify CG flash patterns regionally that coincide with heavy rainfall in the urban basin. The northwest corner coordinates for the CG flash analysis area are 42°N, 106.5°W, and southeast corner coordinates are 38°N, 103.5°W. The area is subdivided into 0.25° × 0.25° polygons that will capture CG flash data at a more refined scale. This spatial resolution (0.25° × 0.25°) was found to capture greater than 93% of NLDN flashes within the polygon boundaries, given NLDN spatial accuracy resolution of 1 km. Smaller polygon sizes tend to misplace upward of 10% of NLDN flashes, and polygons larger than 0.25° are so large that aggregated flash parameters loose spatial relevance (Schultz et al. 2005).

The UDFCD ALERT network provided rainfall data for this study. A map of the area shows the locations of rainfall gauges in the network (Fig. 2).

b. Data

The ALERT network data to be used in this research are the rainfall-rate “alarms,” which represent the most intense local rainfall episodes for the study period (June–September 1999–2003). The alarms are triggered when a rainfall-rate thresholds is exceeded. The rainfall-rate thresholds are 12.7 mm/10 min, 25.4 mm/1 h, 76.2 mm/2 h, or 127 mm/5 h (more information available online at http://alert.udfcd.org/). To guard against false alarms generated by a single faulty observation, an event was selected for inclusion when two or more stations reported an alarm on the same calendar date. If a single station reported the first alarm more than 2 h prior to subsequent reports at multiple stations the second alarm of the day was used to identify the event. Additionally, the study’s focus on CG lightning flashes required that the rainfall alarms result from convective weather systems. The seasonal nature of heavy rainfall in the region signaled that many of the alarms were likely triggered by thunderstorms, but to ensure that the rainfall-rate alarms were indeed produced by thunderstorms the “present weather descriptions” from the Denver/Boulder National Weather Service (NWS) Forecast Office (FO) were used to identify thunderstorm activity. Rainfall-rate alarms, identified from the ALERT network, were only used if the Denver/Boulder NWS FO concurrently reported thunderstorms (TS) in the hourly description of present weather on the date in question (NWS 2005).

In developing the dataset for this project a problem was noted in the UDFCD historic alarm database. In some instances the date of an alarm was misreported in the “historic database,” however, the correct alarm information was reported in the “individual station database.” In this case the dates for the 1999 alarms were all two days askew in the historical record. The data used in this analysis, and confirmed with NWS TS reports, were taken from the individual station database.

The CG lightning flash data for days with a rainfall-rate alarm were acquired from Vaisala, Inc. The data consist of the following: time of flash, location of flash, amperage, and polarity of CG flashes. The flash data were collected over the study area as described above and include the time of the rainfall-rate alarm and the 90-min period prior to the alarm.

Maps and geographic information system (GIS) data for the analysis area were provided by the Denver UDFCD ALERT system coordinator. The files include county boundaries, urban areas, and rainfall-observing stations in the network.

c. Methods

The focus of this research is to investigate the spatial and temporal relationship between regional CG flash parameters (NLDN data) and heavy rainfall in a highly instrumented mesonetwork (UDFCD ALERT network). To this end the following methodology was de-
veloped. The NLDN data were analyzed on a grid system using basic GIS software. Point-polygon topology was developed by identifying each 0.25° × 0.25° grid cell as a unique polygon. The grid arrangement allowed each cell (polygon) in the grid to capture CG flash and rainfall (point) information and further allowed for the calculation of spatial statistics at the resolution of a single polygon.

For each rainfall event in the network the time of first rainfall-rate alarm was set as the “alarm time” and given the temporal distinction of $t_0$ for that event. The NLDN and ALERT data for each event were then di-

![Fig. 1. Full extent of study area. The northwest corner coordinates are 42°N, 106.5°W, and southeast corner coordinates are 38°N, 103.5°W. Each 0.25° × 0.25° cell in the grid acts as an individual polygon for compiling information and calculating statistics.](image-url)
vided into 5-min intervals from \( t_0 \) to \( t_{-90} \) minutes. The time tags \( t_n \) label the last minute in the time interval. The use of 5-min intervals for analysis of CG flash and rainfall parameters follows methods set out in Watson et al. (1994), Holle and Bennett (1997), and Underwood and Schultz (2004).

With the grid in place, rainfall and CG flash data from the heavy rainfall events were used to calculate summary statistics over both time and space using the point-polygon topology. The parameters to be discussed in this study include the following:

1) Mean CG flash frequency, which represents the number of CG flashes per unit time;
2) Mean CG flash duration, which describes the number of consecutive 5-min intervals with one or more CG flashes; and
3) Total event rainfall, calculated at ALERT stations reporting rainfall-rate alarms.

In calculating mean CG flashes and mean CG flash duration, each polygon represented an individual data unit for each time interval \( t_0 \) to \( t_{-90} \). To ensure that the summary statistics from the polygons were representative of a majority of events and to remove the influence of outliers on measures of central tendency a threshold of one-half of the event population was set. Only those polygons that experienced rainfall and CG flashes from one-half (or more) of the event population were included in calculations of mean CG flashes and mean duration. For example, if the population consisted of 20 heavy rainfall events then at least 10 of the 20 events were required to have produced CG flashes in a particular polygon before that polygon’s summary statistics were included in the analysis.

Twenty-nine heavy rainfall events were identified in the UDFCD ALERT network using the criteria set out above. A k-means clustering algorithm was used to divide the 29 heavy rainfall events into two populations based on location (latitude–longitude) and elevation. The clusters separated along a northwest–southeast divide and at an elevation of approximately 1900 m. The two populations of heavy rainfall events will be referred to as group A, the northwesterly events with elevations greater than 1900 m, and group B, those events occurring in the southeasterly portion of the study area and having elevations below 1900 m. The reader will note that group B does contain a member with an elevation of 1978 m (11 August 2003), the extreme southeasterly location of this station was the factor that placed the event in this group. Figure 3 shows the locations of the ALERT stations that reported heavy rainfall episodes for both group A and B. The groups are divided along 105.25°W and those stations that are members of group A are located in the complex topography of the Front Range and those members of group B are located on the more uniform topography of the High Plains as they extend to the base of the Front Range.

5. Findings

a. Rainfall and CG flash characteristics

Table 1 provides the summary information for the nine events composing group A. The mean elevation for this group was 2411 m and the mean rainfall totals from the events was 29 mm. The mean 90-min CG flash total for the group was 1095 with a range from 285 to 3423. The median time of event initiation was 1555 Mountain Standard Time (MST). The upper quartile of events began after 1655 MST, and the latest event began at 1940 MST and the earliest at 1215 MST. Table 2 summarizes the events that make up group B. In this group of 20 heavy rainfall events the mean elevation was 1720 m and the mean event total rainfall was 33 mm. The mean 90-min CG flash total for group B was 1182 with a range from 253 to 2556. The median event start time for this group was 1530 MST, with the upper quartile of events beginning after 1740. The earliest
event began at 1235 MST and the latest event initiation time was 2015 MST.

b. CG flash rates (group A)

Figure 4 displays the polygons that recorded CG flashes during at least five of the nine group-A events over the 90-min analysis period. There were 192 total polygons in the analysis extending across a large portion of central Colorado but the location of these 5 polygons in close proximity to the rainfall alarm sites strengthens the hypothesis that heavy rainfall and CG flashes are often spatially collocated in this region. Since the polygons with CG flashes are concentrated around the ALERT network the grid will be cropped and given alphanumeric identifiers A-1 through J-10. With the exception of polygon D-2, the common flash polygons are all very near the group-A ALERT network stations and all are west of 105.25°W in the more complex terrain of the Front Range.

To examine the temporal CG flash characteristics prior to heavy rainfall events in group A, a time series of each of the five polygons is presented. Figure 5 illustrates the CG flash time series at polygon D-2 (northwest at 40.75°N, 105.75°W and southeast at 40.50°N, 105.50°W). The only period with more than half of the nine events producing CG flashes was $t_{-25}$. During this period five events were observed to produce a mean CG flash (cgf) rate of 2.2 cgf/5 min with a standard deviation of 1.6. The maximum flash rate for a single event was 5 cgf/5 min.

Polygon D-4 (northwest at 40.25°N, 105.75°W and southeast at 40.0°N, 105.5°W) produced a mean CG flash rate of 2.8 cgf/5 min at $t_{-80}$, and a mean of 2.6 cgf/5 min, which was 50 min prior to the composite rainfall-rate alarm (Fig. 6). The standard deviations for these two time intervals were 3.5 and 1.1, respectively.

Polygon E-4 (northwest at 40.25°N, 105.5°W and southeast at 40.0°N, 105.25°W) was the polygon with the most ALERT network alarms in group A. At 30 min prior to the composite rainfall-rate alarm polygon E-4 had five events that produced a mean CG flash rate of 6.9 cgf/5 min with a standard deviation of 8.1. At $t_{-15}$ the mean CG flash rate was 7.2 cgf/5 min with a standard deviation of 6.6. The mean value at the $t_{-15}$ inter-

<table>
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<tr>
<th>Event date</th>
<th>ALERT station No.</th>
<th>90-min analysis period (MST)</th>
<th>Elev (m)</th>
<th>Tot event rainfall (mm)</th>
<th>90-min CG flash totals</th>
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<td>2477</td>
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<td>29 Aug 2003</td>
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<td>1940–2110</td>
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<td>1095</td>
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val was 10.4 cgf/5 min with a maximum single-episode flash rate of 27 cgf/5 min. The $t_{-10}$ flash statistics consisted of a mean rate of 4.1 cgf/5 min, a standard deviation of 5.4. At 5 min prior to the composite rainfall-rate alarm polygon 4-E produced a mean CG flash rate of 14.2 cgf/5 min, with a standard deviation of 11.5. The maximum single event flash rate at $t_{-05}$ was 29 cgf/5 min (Fig. 7).

Figure 8 illustrates the CG flash time series for polygon D-5 (northwest at 40.0°N, 105.75°W and southeast at 39.75°N, 105.5°W). In this particular region there were a total of five events from the population of nine events that commonly produced CG flashes 90 min prior to the composite heavy rainfall alarm. The mean flash rate for this period was 4.0 cgf/5 min. At time interval $t_{-55}$ the mean flash rate in polygon D-5 was very high at 14.4 cgf/5 min; however, there was great variability in the flash rates of the five events contributing to this statistic (standard deviation = 16.8). The highest single event flash total at $t_{-55}$ was 42 cgf/5 min. At 15 min prior to the rainfall-rate alarm the mean flash rate for polygon D-5 was 6.8 cgf/5 min.

Polygon E-5 (northwest at 40.0°N, 105.5°W and southeast at 39.75°N, 105.25°W) also saw CG flashes in conjunction with heavy rainfall events. The first time interval to record CG flashes from five or more events was $t_{-10}$ where the mean flash rate was 3.7 cgf/5 min. Here $t_{-05}$ also had five events contribute to the calculation of a mean flash rate of 3.6 cgf/5 min and a standard deviation of 3.2 (Fig. 9).

### Table 2. Summary information for the group-B rainfall-rate alarms.

<table>
<thead>
<tr>
<th>Event date</th>
<th>ALERT station No.</th>
<th>90-min analysis period (MST)</th>
<th>Elev (m)</th>
<th>Tot event rainfall (mm)</th>
<th>90-min CG flash totals</th>
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**Fig. 4.** The shaded polygons are those with more than half of group-A events producing CG flashes at a common time interval. The dark triangles are the ALERT sites that reported the group-A rainfall-rate alarms.
Fig. 5. The CG flash time series for polygon D-2. The dark points represent the mean CG flash rate at the time interval indicated on the bottom axis. The wires extending from the points represent the standard deviation around the mean. Only the time intervals with more than half of the group-A population of events producing CG flashes are included.

Fig. 6. Same as in Fig. 5, but for polygon D-4.
c. CG flash rates (group B)

Group-B events generated four polygons that met the event threshold for calculating the summary statistics. Each of the four polygons were in close proximity to the ALERT stations that recorded heavy rainfall alarms and the polygons were to the southeast of the group-A region (Fig. 10).

Figure 11 shows the CG flash time series for polygon G-5 (northwest at 40°N, 105.0°W and southeast at 39.75°N, 104.75°W). The CG flashes from 11 events produced a mean flash rate of 6.2 cgf/5 min, a standard deviation of 6.9, and a maximum flash rate of 22 cgf/5 min at $t_0$.

At polygon E-6 (northwest at 39.75°N, 105.5°W and southeast at 39.5°N, 105.25°W) two time intervals saw at least 10 events producing CG flashes. At $t_{-65}$ 11 events produced a mean flash rate of 2.2 cgf/5 min with a standard deviation of 1.5. At 15 min prior to the composite heavy rainfall alarm, 11 of the 20 group-B events produced CG flashes at polygon E-6. The mean CG flash rate was 5.6 cgf/5 min and the standard deviation was 5.7 (Fig. 12).

At $t_{-20}$ 10 events produced a mean flash rate of 10.7 cgf/5 min with a standard deviation of 12.9. The maximum single event flash rate at this time interval was 39 cgf/5 min. At $t_{-10}$ 11 events were observed to produce a mean of 11.1 cgf/5 min with a standard deviation of 13.6. At $t_0$ the mean flash rate at polygon F-6 was 8.4 cgf/5 min with a standard deviation of 8.4.

The flash sequence for polygon G-6 (northwest at 39.75°N, 105.0°W and southeast at 39.5°N, 104.75°W) is shown in Fig. 14. At 25 min prior to the composite rainfall-rate alarm 10 group-B events combined to produce a mean CG flash rate of 5.9 cgf/5 min with a standard deviation of 4.2. Again at $t_{-10}$ the mean flash rate was just above 4 cgf/5 min. At $t_{-5}$ a total of 13 events produced a mean of 6.1 cgf/5 min and a standard deviation of 7.8. Finally at $t_0$ 14 events were observed to produce a mean flash rate of 10 cgf/5 min and a standard deviation of 13.3.

d. CG flash duration (group A)

The calculation of CG flash duration captures the number of consecutive 5-min intervals with at least one CG flash within the same polygon. This flash parameter was found to be positively related with rainfall episodes leading to flash flooding in the arid southwestern United States by Holle and Bennett (1997). In discuss-
ing this flash parameter the primary statistic will be the mean number of consecutive time intervals, for example a mean duration of three refers to three consecutive 5-min intervals (15 total min).

In group A a total of seven polygons in the western portion of the UDFCD ALERT network were found to have at least one-half of the total population of events producing continuous flashes during heavy rainfall epi-

Fig. 8. Same as in Fig. 5, but for polygon D-5.

Fig. 9. Same as in Fig. 5, but for polygon E-5.
sodes. The longest CG flash durations were recorded in the region bounded on the northwest by coordinates 40.25°N, 105.75°W and to the southeast at 39.75°N, 105.5°W (polygons 4-D and 5-D). In polygon 4-D the mean CG flash duration over seven contributing events was 7.4 suggesting that prior to the rainfall-rate alarm there was a period of more than 35 min with a flash rate of at least 1 cgf/5 min. In polygon 5-D the mean continuous CG flash duration was calculated over five events with a mean duration of 5.8 prior to the rainfall-rate alarm. Polygons 4-C and 5-E had mean CG flash durations of 4.2 and 4.8, while polygons 4-E, 5-C, and 6-D recorded mean duration statistics of 3.6, 3.0, and 3.8, respectively (Fig. 15).

e. CG flash duration (group B)

Areas of continuous CG flashes were more numerous and more spatially dispersed over the group-B events (Fig. 16). A total of 10 polygons saw at least one-half (10 out of 20) of the group-B events producing CG flashes in consecutive time intervals. However, the longest durations, those greater than five consecutive intervals, were confined to a two-polygon region bounded on the northwest at 40.0°N, 105.5°W and on the southeast at 39.5°N, 105.25°W. Polygons 5-E and 6-E make up this area west of the group-B heavy rainfall observation sites. Both polygons had a mean flash duration of 5.7. Six polygons had mean flash durations between 4.0 and 5.0. Two of the polygons are collocated with the majority of heavy rainfall reports in group B. Polygons 6-G and 7-G observed mean flash durations of 4.4 and 4.5, respectively. Polygons 6-C and 6-D west of the group-B ALERT stations had mean duration statistics of 4.3 and 4.6. Polygon 9-E to the south of the group-B observation sites produced a mean consecutive duration of 4.1 while the mean duration at polygon 7-E (south of the core of highest durations) was 4.8. The area exhibiting the longer CG flash duration statistics therefore extends southward from polygon 5-E to 7-E. This area is much higher in elevation that the group-B ALERT stations reporting heavy rainfall, suggesting a topographic influence on consecutive periods of CG flash activity, and a more spatially remote signal between continuous CG flashes and heavy rainfall in group B.

6. Summary and conclusions

This study analyzed 29 heavy rainfall events that occurred across the UDFCD ALERT network over a 5-yr period. The events were divided into two groups based on latitude, longitude, and elevation. Group-A events were grouped in the northwestern portion of the study area above 1900 m, while group-B events occurred in the southeastern portion of the study area below 1900 m. There were nine events in group A and 20 events in group B. The group-B events on average produced heavier rainfall (33 versus 29 mm) and more CG flashes (1182 versus 1095) than the group-A events. In analyzing the mean flash rates it was apparent that in both group A and B populations’ CG flash activity was collocated with heavy rainfall. Though the analysis covered a large portion of central Colorado it was found that CG flashes clustered in the same 0.25° × 0.25° polygons where the heavy rainfall alarms were observed. In the group-A population of heavy rainfall events polygon E-4 (northwest at 40.25°N, 105.5°W and southwest at 40.0°N, 105.25°W) saw seven of the nine heavy rainfall events produce CG flashes within the boundary of the polygon. This polygon also housed five of the nine ALERT stations that reported group-A heavy rainfall alarms. This area (polygon E-4) observed CG flashes on average 30 min prior to heavy rainfall alarms in the network.

In group B, 14 of the 20 heavy rainfall events pro-
Fig. 11. The CG flash time series for polygon G-5. The dark points represent the mean CG flash rate at the time interval indicated on the bottom axis. The wires extending from the points represent the standard deviation around the mean. Only the time intervals with more than half of the group-B population of events producing CG flashes are included.

Fig. 12. Same as in Fig. 11, but for polygon E-6.
duced CG flashes in polygon G-6 in concert with heavy rainfall. Polygon G-6 (northwest at 39.75°N, 105.0°W and southeast at 39.5°N, 104.75°W) also included the locations of 10 of the rainfall alarms in group B. This collocation of CG flashes and heavy rainfall further documents the spatial and temporal relationships found by Petersen and Rutledge (1998), Watson et al. (1994), and Underwood and Schultz (2004).

Fig. 13. Same as in Fig. 11, but for polygon F-6.

Fig. 14. Same as in Fig. 11, but for polygon G-6.
In an applied context there are two contiguous polygons in group A (E-4 and E-5) with temporal flash characteristics that could be used to aid in heavy rainfall forecasting. This combined area is bounded by the northwest coordinates 40.25°N, 105.5°W and the southeast coordinates 39.75°N, 105.25°W. This is the highest region of the study area with elevations reaching 4000 m. Polygon E-4 provided common CG flash signals at time intervals $t_{-30}$, $t_{-25}$, $t_{-15}$, $t_{-10}$, and $t_{-5}$ prior to the composite rainfall-rate alarm. The CG flash time series showed that the mean flash rates increased steadily from 30 min prior to the rainfall alarm until 5 min prior to the alarm, with the exception of $t_{-10}$. This pronounced increase in the mean flash rate from 6.8 cgf/5 min to 14.2 cgf/5 min just before the heavy rainfall alarm should encourage further exploration of this parameter’s value in forecasting heavy rainfall in this region. Polygon E-5 on the other hand produced CG flashes at intervals $t_{-10}$ and $t_{-5}$ only. The mean flash rates at these two intervals were substantially lower (3.6 and 3.7 cgf/5 min) than the more northerly polygon. Again this temporally proximal signal may be useful for extending heavy rainfall and flash flood warnings in this area of the UDFC network.

In the lower elevations of the ALERT network (group B) polygon 6-F exhibited a CG flash sequence with $t_{-30}$, $t_{-20}$, $t_{-10}$, and $t_{0}$ recording mean flash rates of 5.1 cgf/5 min, 10.7 cgf/5 min, 11.1 cgf/5 min, and 8.3 cgf/5 min, respectively. Polygon 6-G produced a temporal sequence where mean CG flash rates increased from $t_{-10}$ to $t_{0}$. The area covered by polygons 6-F and 6-G is bounded on the northwest at 39.75°N, 105.25°W and on the southeast at 39.5°N, 104.75°W.

Long periods of continuous CG flashes have also been shown to correlate with heavy rainfall and flash flooding in an urban setting, the present analysis also showed distinct collocation of regions of continuous CG flashes and heavy rainfall. An area to the immediate west of the group-A ALERT stations saw the most
extended periods of continuous CG flashes (>35 min). The same spatial alignment was observed in the group-B events with the longer CG flash durations occurring in polygons to the west of the heavy rainfall sites. In this case the longest continuous flash sequences were approximately 30 min in duration.

This study has shown the utility of using in a mesonet-work of rainfall observation stations and the NLDN to define spatial and temporal relationships between heavy rainfall episodes and CG lightning flashes in an urban setting.

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REFERENCES


