Lightning Ground Flashes Associated with Summer 1990 Flash Floods and Streamflow in Tucson, Arizona: An Exploratory Study

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ABSTRACT

Eight flash flood events occurred in the Tucson area of southeastern Arizona during the 1990 summer when a high-resolution lightning detection network was operated in the region. A total of 3479 cloud-to-ground lightning flashes was composited with respect to times and locations of these flash floods. The analysis region was a square of 40 km on a side that nearly coincided with a small hydrologic region that drains runoff from high mountains around Tucson and results in streamflow near and through the city.

Most lightning in the 40-km-square area occurred between 10 h before the flood and the reported time of the flood. Flashes were most frequent around 2 h prior to the flood, but advance timing was not consistent. The most important factor in determining whether a flash flood report followed lightning was the number of consecutive 5-min periods with two or more flashes in the 40-km-square area. Intensity of the maximum flash rate was not systematically related to the amount of flooding, except that the 2 days with highest lightning frequencies were associated with the most widespread flood effects of the summer in the Tucson area. No precursor was found in positive flashes. While lightning data identified many of the flash flood events and avoided most false detections, the sample size was very small and there were no other cases for an independent test.

Streamflow increased abruptly after the occurrence of lightning for two flood periods on 19–20 July and another flood on 24 July. About 2 h after the maximum flash rate, streamflow gauges at three locations in the hydrologic region measured rapid rises in runoff that were indicative of the arrival of flash floods. Additional studies with flashes from an operational lightning detection network need to take into account additional factors, such as different locations, seasons, storm types, and precipitable water in low to midlevels, in order to more fully explore the possibility of lightning strikes providing useful precursors of flash flood events, particularly in rugged semiarid terrain.

1. Introduction

Flash flooding is a difficult forecasting problem in the western United States. Mountains can initiate localized storms that have enough precipitation to result in rapid runoff although rainfall amounts are often not as large as in more humid regions of the United States (Hill 1993). Furthermore, after the deployment of WSR-88D radars is completed, radar coverage will continue to be less complete in the western states than in other portions of the country due to mountainous terrain (Klazura and Imy 1993). For these reasons, cloud-to-ground (CG) lightning data from detection networks have been utilized operationally for over a decade at field stations in the National Weather Service’s (NWS) Western Region to identify possible flash floods in mountainous regions using graphics and time series for a range of time periods and areas (Mielke 1990).

There have not, however, been any multistorm studies of lightning related to flash floods, although lightning during several individual flash floods has been described (Holle and López 1993). A considerable amount of lightning activity was seen during the Big Thompson, Colorado, flash flood of 31 July 1976 (Maddox et al. 1977), but lightning network technology was in an early stage of development at that time. Lightning network data were used by Kane (1990) to study an Ohio flash flood associated with a mesoscale convective system; flashes gave the location, movement, redevelopment, merging, and propagation of convective cells and clusters. A case study by Cylke (1992) used NWS lightning detection graphics to locate a maximum in flash counts.


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that preceded flash flooding in Las Vegas, Nevada, by about 1 h. Henz (1996) estimated the timing and amount of rainfall leading to a flash flood in rugged western Colorado terrain with CG lightning data through a conceptual model of radar reflectivity–flash relationships; no radar or rain gauge information was available in the flood area.

An opportunity to relate lightning to several flash floods arose during the 1990 Southwest Area Monsoon Project (SWAMP). The program was held during July and August to study the environments of central Arizona thunderstorms (McCollum et al. 1995), the structure and moisture fluxes associated with the monsoon (Stensrud et al. 1995), and convective rainfall in northwest Mexico (Douglas et al. 1993). A special lightning detection network with high resolution and detection efficiency was operated during SWAMP 1990 over southern Arizona. The region of analysis (Fig. 1) is the shaded 40-km-square area that includes most of Tucson [altitude of 760 m above mean sea level (MSL)] in the semiarid Sonoran Desert, which is hot and dry until the monsoon arrives about 1 July (Bryson and Lowry 1955). Several isolated mountain ranges rise from the desert to exceed 2 km, and some are higher than 2.5 km, such as the Santa Catalina and Rincon Mountains north and east of Tucson (Fig. 2).

The monsoon was found by Hirschboeck (1987) to account for 77% of southern Arizona floods, and 40% of these southern Arizona monsoon floods were due to localized rather than widespread monsoon precipitation. Maddox et al. (1980) found that most western U.S. flash floods occurred during the afternoon and early evening in summer, resulted from less than 10.2 cm (4 in.) of rain, and may have been produced by only 2–3 cm (0.8–1.2 in.) of rain over rugged terrain with a small drainage basin. In the dry western states with under 20 cm of annual rainfall, M. Winchell (1995, personal communication) found that 6 of 13 severe flash flood events had reported rainfall of 2.5–5 cm (1–2 in.), often in less than

![Fig. 1. Region of study, with counties and major cities in southern Arizona. Shaded area is 40-km-square area around Tucson.](image1)

![Fig. 2. Hydrologic region (solid curved lines), 40-km-square area, lightning network direction finders (triangles), mountain ranges, streams and rivers, stream gauges used in analysis (bold letters next to squares), and urban locations (italics) mentioned by Storm Data near Tucson. Shaded altitudes are 915 m (3000 ft) and 1525 m (5000 ft); highest peaks indicated by x.](image2)
1 h. The focus of the following study is on the frequent floods from convection during the Arizona monsoon that may initially be undetected in mountainous areas with few people and relatively small amounts of rain.

2. Data

a. Lightning

Cloud-to-ground lightning data were available from 30 June through 12 August 1990 from a network of three direction finders (DF) in the Tucson area. The DFs were of the type described by Krider et al. (1976, 1980) and manufactured by Lightning Location and Protection, Inc. The critical feature of this dataset was the short distance between DFs (baseline) of 43 km compared to the national lightning network’s typical distance of several hundred kilometers. For the current study, 3433 negative and 46 positive flashes were detected by the special lightning network over the 40 km × 40 km square area within 12 h of the time of the eight flood reports in Storm Data (NOAA 1990).

Within the area enclosed by the three DFs (Fig. 2), the median accuracy of flash locations was estimated to be 1 km. Within one baseline beyond any DF (80–100 km from the network’s center), the median accuracy was 1–2 km. Accuracy was 2–4 km from one to two baselines beyond any DF. Site errors were regularly determined for this network through a combination of the methods of Hiscox et al. (1984), Passi and López (1989), and López and Passi (1991).

System detection efficiency is the ratio of flashes detected by the network to the number of CG flashes that actually occurred. Detection efficiency of a DF network is not considered to be affected by rugged terrain. The highest efficiency is near the center of the network, since detection efficiency is influenced by signal attenuation with range (López et al. 1991). Detection efficiency was estimated to be on the order of 80% within the 1990 Tucson network and one baseline length beyond any DF, and 60%–80% beyond one to two baselines. These estimates were based on similar networks in the Kennedy Space Center region (Holle and López 1993), but no direct measurements have been made in southern Arizona.

b. Flash floods

Information on the eight flash floods during the data collection period was extracted from Storm Data, a monthly National Oceanic and Atmospheric Administration (NOAA) publication that describes damaging and severe weather. Local NWS offices collect storm reports and send them to NOAA’s National Climatic Data Center in Asheville, North Carolina; original information from the Tucson NWS office was not saved. Reports contain day, month, year, location, type of casualty or damage, age and gender of the victims, and a verbal description of the weather and its estimated economic impacts.

The descriptions of the eight flash flood events in Table 1 include all information on the damages and casualties given by Storm Data. Every Storm Data entry listed the impacts as due to a flash flood, although there was a wide variety of intensities. Thunderstorm winds were also listed as impacts on 20 July and 3 August. There were two deaths, two injuries, minor to significant damage, and numerous rescues and other disruptions due to the flash flooding. Nearly all impacts were related to urban or transportation factors, particularly from flooded streets and rescues from vehicles. The floods on 15 and 20 July, listed as occurring in early morning in Storm Data, were assigned the time of 0300 MST for this study. The flood event on 24 July (all morning in Storm Data) was assigned the time of 1200 MST.

In order to focus on the flash floods, a 40-km-square area was located around the floods (Fig. 2). This 40-km square was chosen because it is 1) nearly coincident with the hydrologic region for the area of northeast Tucson that is prone to flash floods, 2) large enough to include most areas affected by the eight flash floods although there was sometimes limited information, 3) large enough to obtain an adequate sample size of flashes in 5-min increments, 4) small enough to focus on the flood events without other significant storms in the sample, and 5) easy to analyze in a square with latitude–longitude flash positions. Relevant hydrologic features are also included in Fig. 2.

c. Streamflow

The Pima County Flood Control District supplied hydograph data for June, July, and August at three locations identified with bold letters and squares in Fig. 2. Streamflow on the two days with the largest flash floods in the Tucson area were chosen for detailed analysis in this exploratory study. Data were supplied in a format that indicated time, stream height or depth in feet, and streamflow $Q$ in cubic feet per second. Each data point represented a rate of change or differential streamflow $dQ$ in either positive or negative values. Since data points were dependent on $dQ$, they were not equally spaced in time. Data were interpolated to a 5-min time series to make them comparable to flash data.

3. Flash floods

a. Single flood events

Figure 3 shows the time relationships between CG flashes in the 40 km × 40 km area and the eight flash flood events in the area during the summer of 1990. These time series of 5-min frequencies of lightning start 12 h before and end 2 h after the floods described in Table 1. The vertical lines mark times of flood reports in Storm Data. On 7 July, for example, first flashes preceded the flood by 3 h, and most lightning activity ended near the time of the flood report. The most com-
Table 1. Characteristics of eight flash flood events in southern Arizona as recorded in Storm Data (NOAA 1990) for the summer of 1990.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Time (MST)</th>
<th>Storm Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 July</td>
<td>Pima County Tucson</td>
<td>1315</td>
<td>In 3-h period ending about 1315, up to 7.7 cm (3.03 in.) rain along Cañada del Oro and Tanque Verde watersheds. Several vehicles stalled in washes; five motorists rescued.</td>
</tr>
<tr>
<td>8 July</td>
<td>Pima County Tucson</td>
<td>1800</td>
<td>Many roads closed due to heavy rains of 2.5–5.1 cm (1–2 in.).</td>
</tr>
<tr>
<td>10 July</td>
<td>Pima County Tucson area</td>
<td>1930</td>
<td>Numerous thunderstorms closed state highway in Ryan Field area. Two U.S. Border Patrol agents rescued from stranded vehicles. Flooded washes and highway dips in eastern Pima County. Wind gusts of 46 mph.</td>
</tr>
<tr>
<td>15 July</td>
<td>Pima County Avra Valley</td>
<td>Early morning</td>
<td>Many areas in eastern Pima County had flooding. One gauge had 2 cm (0.79 in.) in 30 min. Street flooding in Tucson Estates and Cañada del Oro.</td>
</tr>
<tr>
<td>16 July</td>
<td>Pima County Tucson area</td>
<td>1800</td>
<td>Minor street flooding.</td>
</tr>
<tr>
<td>20 July</td>
<td>Pima County Tucson</td>
<td>Early morning</td>
<td>Heavy flooding on some city roads; several motorists stranded while trying to cross flooded dips. Several homes and businesses flooded; damage exceeded $30,000. Apartment complex wall had $100,000 damage. Reclamation plant flooded. Man killed falling 40 ft over waterfall in Tanque Verde Falls area.</td>
</tr>
<tr>
<td>24 July</td>
<td>Pima County Tucson area</td>
<td>All morning</td>
<td>Widespread severe flooding over many areas of county. One man killed when he fell into swollen Santa Cruz River at St. Mary’s Road and was swept away; two other injuries. More than 50 river rescues in morning; up to 10.2 cm (4 in.) of rain resulted in 25 road closures in Pima County; 24 road closures in city. Automatic gauge had 9.0 cm (3.55 in.); 5.1 cm (2 in.) in 30 min. Several homes flooded in Oracle area; 150 people evacuated at 49’ers Country Club at lower end of Sabino Canyon. Public Works Department reported 21 000 cfs in Santa Cruz River—highest July discharge since 1910. Total of 1.8 m (6 ft) of water in Stone Avenue downtown underpass.</td>
</tr>
<tr>
<td>3 August</td>
<td>Pima County Tucson</td>
<td>2030</td>
<td>Total of 2.8 cm (1.12 in.) rain in 15 min. Downed power pole and flooded house in southeast Tucson. Several vehicles stuck in flood waters in Tanque Verde area; 4.6 cm (1.8 in.) rain in 15 min.</td>
</tr>
</tbody>
</table>

Common feature is that lightning usually ended at the time of the flood reports. These time frames are consistent with Maddox et al. (1980) and M. Winchell (1995, personal communication), who found that flash floods in small drainage basins in the western mountains can result from as little as 2–5 cm of rain in less than 1 h. From 2 to 12 h after the flood report, there were only 26 flashes for all eight events combined.

The two floods listed in Table 1 with the most damage, 20 and 24 July, have the highest peak flash rates. Several days in Fig. 3 have peaks in lightning from 2 to 4 h before the flood report. 1 day has two major peaks, and 3 days have relatively few flashes. On the 3 days with fewest flashes, some runoff was outside the hydrologic region (Fig. 2). Storm Data (Table 1) on 10 July mentions Ryan Field southwest of Tucson and on 15 July mentions Avra Valley northwest of Tucson, but the narrative on both days includes eastern Pima County, which is partly within the 40-km square (Fig. 1). Storm Data is not specific concerning location on 16 July.

b. Composites of flood events

The number of CG flashes is composited in Fig. 4 with respect to the eight flash floods in the 40-km-square area. There is no single time period with distinctly higher flash frequencies, since flashes are spread across the period between 10 h before and the time of the floods. There are almost no flashes after the flood reports.

The number of flood events with lightning is composited in Fig. 5 rather than the number of flashes. There is a steady increase in the presence of lightning during 5-min increments from 9 h before the floods, up to the time of the floods. No more than one of the eight flood events had flashes at most times earlier than 8 h before the flood, or more than 1 h after the flash flood. There were two time periods around 2 h before the floods when there was lightning during six of the eight flood events (Fig. 5). For this analysis, any flash in a 5-min increment associated with a flash flood qualifies as a flood event in that time period.

There was a low ratio, 1.3%, of positive to total flashes associated with the eight floods. The ratio of positive flashes was 1% or less at all hours until they reached 2%–3% during the last few hours before the floods. No storm showed a significantly higher ratio of positive flashes. The national ratio of positive to total flashes for the entire year is 4% (Orville 1994), but positive flashes in the desert regions of Arizona in summer are quite
rare (Maddox et al. 1997). High positive flash ratios have been used as indicators of the end of storms and various types of severe weather (Holle and López 1993), but this increase does not appear to be true for flash floods during the monsoon season in Arizona.

![Figure 3](image1.png)

**Fig. 3.** Time series of lightning in 5-min increments from 12 h before to 2 h after eight flash floods in 40-km-square area around Tucson. Vertical dashed line is time of *Storm Data* flood report.

![Figure 4](image2.png)

**Fig. 4.** Composite time series of the number of CG flashes in 5-min increments from 12 h before to 12 h after eight flash floods in 40-km-square area around Tucson. Vertical line is time of *Storm Data* reports.

![Figure 5](image3.png)

**Fig. 5.** Composite time series of all flood events in 5-min increments from 12 h before to 12 h after eight flash floods in 40-km-square area around Tucson. Vertical line is time of *Storm Data* reports.
c. Duration

The preceding time series shows that number of lightning flashes and time periods with flashes do not indicate timing or magnitude of a subsequent flash flood, although some lightning, and therefore a thunderstorm, was present for all flash floods. Another factor to consider is duration of lightning. There were 43 consecutive days of data from the Tucson lightning detection network from 30 June to 11 August, except 1 day was missing. In the Tucson region, 8 days had floods and 34 days did not. One lightning flash in a 5-min increment occurred frequently, so the threshold of a higher flash rate was defined as two flashes in 5 min for two or more consecutive 5-min increments. Using this definition, lightning usually lasted much longer on days when floods were reported than on days without a flood (Table 2). Most important were prolonged uninterrupted periods with lightning lasting more than 20 time increments, a duration of more than 100 min, with at least two flashes in the 40-km-square area. These long-duration periods usually occurred from a few hours before the flood report, up to the time of the report. There were five of these lightning periods of 100 min or more on the 8 days with floods; three such periods occurred on days without a flood report. Recall from Fig. 3 that two prolonged periods occurred on 20 July, while three flood days had no periods with lightning as long as 100 min. A cumulative summary of Table 2 indicates that flood days more often had lightning periods lasting two or more 5-min increments than nonflood days, and the difference is greatest for the longest lightning durations.

d. False alarms

Lightning periods lasting more than 100 min were eight times as likely to occur on a day with a flood as on a day with no flood (Table 2). The differences are much less until durations of 100 min are reached. This result should be expected since long-duration thunderstorms over the hydrologic region, as indicated by lightning data, are more likely to produce flooding conditions on that day in Tucson.

A contingency table analysis was made (Table 3) by considering the 42 whole days with lightning with respect to floods in 12-h periods on either side of the flood. The probability of detection is 4 of 7 days, or 0.57; the false alarm ratio is 4 of 8, or 0.50; and the probability of false detection is 3 of 34, or 0.09. The critical success index is 0.36 (Donaldson et al. 1975), and the true skill statistic is 0.41 (Flueck 1987; Doswell and Flueck 1989). The two long-duration lightning periods on 20 July were treated as one period for that day. While the lightning data were able to identify many of the flash flood events and avoid most false detections, the sample size was very small and there were no other cases for an independent test. Also, the results are from only one summer and one region, so the dataset needs to be expanded to take into account more of these factors to determine wider applicability.

4. Streamflow

a. Introduction

The preceding section described relationships between lightning periods in the 40-km-square area and entire flash flood events. This section will show specific time relationships between lightning and streamflow gauges in the area on 2 days. Figure 2 shows locations of the largest rivers and streams that flow out of the mountains into Tucson. Waterways are marked as intermittent since they are often dry. The Santa Cruz River, flowing south to north, is the largest. Other Tucson-area waterways are Sabino Creek, and the Tanque Verde, Pantano, and CanaÄada del Oro Washes, Sabino Creek and Pantano Wash flow into the Rillito River, then into the Santa Cruz at the western point of the hydrologic region (Fig. 2). The rapid mountain runoff into a large city makes short-term monitoring and warnings very important in this hydrologic region.

b. 24 July

There was a major flooding event on 24 July (Table 1) in the Tucson area; McCollum et al. (1995) studied storms on the same day in the Phoenix region. Rainfall in the watershed headwaters of the mountains and foothills to the north and east averaged 3.6 cm (1.42 in.), according to the Pima County Flood Control District. Figure 6 locates the 553 flashes lowering both negative and positive charge to ground during the flood event.

Table 2. Number and number per day of consecutive 5-min increments with at least two flashes from 30 June to 11 August 1990 in 40-km-square area. There were two long-duration events on 20 July.

<table>
<thead>
<tr>
<th>Consecutive 5-min increments</th>
<th>Flash flood (8 days)</th>
<th>No flash flood (34 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>No. per day</td>
</tr>
<tr>
<td>2–5</td>
<td>14</td>
<td>1.75</td>
</tr>
<tr>
<td>6–10</td>
<td>3</td>
<td>0.38</td>
</tr>
<tr>
<td>11–20</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>&gt;20</td>
<td>5</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Table 3. Contingency table of days with at least 100 consecutive minutes with two or more flashes per 5-min increment versus flash flood events from 30 June to 11 August 1990 in 40-km-square area.

<table>
<thead>
<tr>
<th>Flash flood observed on day</th>
<th>Yes</th>
<th>No</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥100 consecutive min with 2 flashes per 5 min</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Sum</td>
<td>8</td>
<td>34</td>
<td>42</td>
</tr>
</tbody>
</table>
Fig. 6. Locations of 533 cloud-to-ground lightning flashes from 0400 to 1100 MST (1100–1800 UTC) and daily rain gauge totals (in.) in the 40-km-square area on 24 July 1990. Streams, rivers, stream gauges, and hydrologic region as in Fig. 2.

Also shown are district rain gauge reports of 1.6–8.9 cm (0.63–3.50 in.) on the eastern side of the 40-km-square area. Other rain gauge totals for the day were between 2.8 and 5.6 cm (1.10–2.02 in.) over Tucson, and 0.4–5.1 cm (0.16–2.00 in.) in the northern Santa Catalina Mountains 15 km to the north of Fig. 6. Storm Data (Table 1) has a maximum rainfall of 7.7 cm (3.03 in.) but no specific location is given. During the lightning period in the 40-km square (Fig. 8), NWS observers at the Tucson airport (located at 1.10 in. rainfall amount in the southwest portion of Fig. 6) saw occasional CG and in-cloud flashes; a heavy thunderstorm was reported from 0750 to 0830 MST.

Comparisons of lightning flash counts and streamflow on 24 July are in Figs. 7 and 8. Lightning occurred between 0400 and 0800 MST (Fig. 7), but streamflow at the Dodge Boulevard gauge on the Rillito River (location in Fig. 2) was zero until lightning flashes start to decrease in frequency. Streamflow increases rapidly to its peak value within 2 h, reaches a second peak 5 h later, then decreases over the next few hours. Such a rise in a time series is indicative of a flash flood (Dunne and Leopold 1978; Hirschboeck 1987). Streamflow at two additional sites in Fig. 8 begins with dry or nearly dry conditions, followed by a rapid rise in flow. The streamflow at Chiva Tank and Tanque Verde Ranch starts at the same time as at Dodge Boulevard. The first of the two highest lightning frequencies is 2 h before the rapid increase in streamflow at the three gauges. Flooding was reported to have occurred all morning in Storm Data (Table 1).

Satellite imagery was used to assess qualitatively the type of convection associated with the flash flood. Figure 9 indicates at 0600 and 0900 MST the rapid development of a large mesoscale convective system over southern Arizona during the lightning period. Mc...
Collum et al. (1995) showed that the convective system formed quickly from a merger of previous convective systems to the north of Tucson and moved south-southeastward across the city during the morning. Upper-air data on 24 July indicated moist southerly flow at the surface and 850 mb with a trough to the northwest, while there was weak flow from the north to west at higher levels. These patterns were very similar to the monsoon burst composites in Fig. 18 of Watson et al. (1994).

c. 19–20 July

There was also a major flooding event on 19–20 July in and near Tucson. While the case is treated by Storm Data in Table 1 as one episode on 20 July, there were two separate lightning and rain periods. Lightning frequencies and rainfall amounts in the first period were about twice as large as in the second. Rainfall in the mountains and foothills north and east of Tucson averaged 2.8 cm (1.09 in.) on 19 July and 1.3 cm (0.50 in.) on 20 July, according to the Pima County Flood Control District. On 19 July, Fig. 10 (top panel) plots...
993 negative and positive flashes, and district rain gauge totals from 1.8 to 3.9 cm (0.71–1.54 in.) on the eastern side of the 40-km-square area. Other rain gauge totals on 19 July were 0.1 cm (0.05 in.) at the Tucson airport (southwest portion of map) and up to 1.4 cm (0.57 in.) in the Santa Catalina Mountains 15 km north of Fig. 10. Several hours later on 20 July, Fig. 10 (bottom) plots 505 flashes and rain gauge reports of 0.5–2.0 cm (0.20–0.78 in.) to the east, while 2.6 cm (1.04 in.) fell at the airport and up to 1.4 cm (0.56 in.) was recorded in the northern Santa Catalinas.

During the first lightning period (Fig. 11), when 0.05 in. of rainfall fell at the airport, NWS observers saw occasional CG flashes, then occasional in-cloud and cloud-to-cloud lightning were also seen near the end of flashes in the 40-km square. During the second lightning period when 1.04 in. of rainfall fell at the airport, observers saw frequent in-cloud and CG flashes through the entire period; a heavy thunderstorm was reported at 0350 MST.

The first of two separate lightning periods on 19–20 July (Fig. 11) has more flashes and peaks about 7 h before the second period. The two upstream gauges to the east, Chiva Tank and Tanque Verde, show rises in runoff following both lightning periods and flow returning to zero between the lightning periods. To the west and farthest downstream, the Dodge Boulevard gauge recorded no streamflow in association with the first lightning period. The water apparently was absorbed into the soil before reaching that location, but there was a fast rise in association with the second lightning period. Streamflow lagged after the peak lightning frequencies by 1–3 h (Fig. 11), similar to downstream lags shown by Osborn and Renard (1969) in southwest U.S. floods.

Figure 12 shows satellite imagery at the times of the two lightning periods in Fig. 11. During the first lightning period a convective system is growing very rapidly over Tucson (Fig. 12, top), while a large convective system is located near the Arizona–Mexico border and southward. By the time of the second lightning period, the convective system over Tucson has merged with others to the north into a mesoscale convective system (Fig. 12, bottom) that is separate from another in Mexico. Upper-air conditions on 19–20 July (not shown) indicated southerly flow at the surface and 850 mb with a trough over southern Arizona, but the low levels were not as moist as during the 24 July case. At higher levels, flow prevailed from the north to west. These patterns were somewhat similar to burst composites in Watson et al. (1994).

d. Discussion

In addition to CG flashes, it is likely that a large number of lightning flashes did not reach the ground, as reported by NWS observers at the airport in both cases. The National Lightning Detection Network does not report cloud flashes, but such lightning data may be useful in anticipating flash floods if available for 5-min intervals in real time.

Since there were only a few total-storm rain gauge measurements available during the two cases, flash–rain volume statistics could not be determined. However, the cases were associated with mesoscale convective systems, for which a value of 1.3 flashes per 10⁶ m³ of rainfall for system lifetime on the southern plains was derived (Holle et al. 1994). A similar value has been found in storms in some other regions, but this value is an order of magnitude larger than that found in storms in other regions (Holle et al. 1994). In order for lightning to be used in a flash flood situation, the relationship between flashes and rainfall, or streamflow, would need to be established for the type of storm, region, and season of interest where floods are being monitored.

5. Summary and conclusions

Cloud-to-ground lightning flashes detected by a high-resolution network were associated with eight flash
floods reported by Storm Data (NOAA 1990) in the Tucson area. Analyses were made in a 40-km-square hydrologic region that included mountainous terrain north and east of Tucson.

Floods were much more likely on days with prolonged lightning periods than on days without prolonged lightning activity. These long-duration lightning periods were defined by two or more CG flashes per 5-min increment lasting more than 100 min in the 40-km square. The number of flashes had minimal information about the timing and strength of a subsequent flood, except that most floods were preceded by the relatively common occurrence of two or more flashes at a few times between 2 and 4 h before the flash flood. Virtually all lightning ended at or before the flood reports. There were few positive CG flashes.

Rapid increases in streamflow were closely related to the occurrence of lightning for two cases during the preceding few hours in the small watershed flowing across the north and east sides of Tucson. The quick rises in streamflow were indicative of flash floods. Nearly all rapid increases in runoff at three sites in the hydrologic region on 19–20 and 24 July started about 2 h after the peak lightning rate; such timing is potentially useful in building a better flood alert/warning system for Tucson using lightning in the analysis area. The two lightning periods on 19–20 July were separately identifiable in the runoff at two of the three stream gauge sites.

The study shows that attention should be paid to duration of lightning over a geographical region of interest. Then the time trend of lightning should be monitored over a specific watershed for the next several hours until a peak in lightning frequency is reached. The use of lightning data alone has the greatest value over rough and/or isolated terrain where there are no other minute-by-minute data on convective activity that may lead to sufficiently heavy rainfall for producing a flash flood.

The national lightning detection network has recently reached accuracies and detection efficiencies (Cummins et al. 1996) similar to the 1990 Arizona research network. Therefore a larger sample can be considered in other regions and meteorological situations with varying locations, seasons, storm types, and precipitable water in both the boundary layer and middle levels. Since some of the most extensive uses of this approach may be over rugged terrain of the western United States, situations should be emphasized that include low humidities in typically arid to semiarid areas. More data than were used in this exploratory study are needed on the duration, intensity, and timing of lightning related to flash floods, and more cases with streamflow gauges are needed to develop correlations between peak flow and lightning frequency and duration.

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