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THE DISTANCE BETWEEN SUCCESSIVE LIGHTNING FLASHES

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ABSTRACT

The distribution of the distance between successive cloud-to-ground (CG) flashes has been studied for storms in several regions of the United States. This information is useful for the understanding of several aspects of lightning phenomenology. It is particularly important for personal safety strategies, so that a person can estimate the likelihood that the next flash could be a personal threat. The study concentrates on this application. Use was made of the National Lightning Detection System (NLDN) database.

1. INTRODUCTION

Lightning is one of the most important weather hazards in the United States. Typically, more people are killed by lightning during a year than by hurricanes and tornadoes (Holle et al., 1995a; López and Holle, 1995). Because of the random nature of the lightning distribution, it is difficult to forecast and warn the public about the local threat of lightning. Subsequently, individuals must take responsibility to protect themselves from lightning. One method that has been emphasized in lightning safety publications (Holle et al., 1995a, 1995b) is to be aware of the presence of thunderstorms in the vicinity, and to estimate the distance to lightning activity by using the "flash-to-bang" method. The person is then urged to seek shelter when the lightning activity gets too close.

One important question remaining in lightning safety is "how close is too close?" To answer this question, it is necessary to know the frequency of the next lightning flash striking the ground at varying distances from the previous one. Thus, after estimating the distance to the last lightning strike, one can estimate the likelihood that the next flash from the same storm will strike at that same distance from the previous flash. If the frequency is high, the observer is in danger of being a victim of lightning.

Holle et al. (1995a, 1995b) recommended that a person should be in a safe structure before flashes are closer than 5 km (3 miles). That recommendation was based on a recent study of three Florida thunderstorms by Krider (1988). He found that the average distance between successive strike points was 3 to 4 km with a standard deviation of 2 to 2.5 km. The clusters of flashes in the three storms were from 10 to 15 km in diameter and had a flash density that decreased with distance from the center of the clusters to the edge.

Several other examinations of this distance have taken place. Feteris (1952), Hatakeyama (1958), and Carte and Kidder (1977) found that the diameters of isolated clusters are around 10 km. Hatakeyama (1958) in Japan observed that the average distance between successive flashes was 3.5 km, and the probability of the next flash occurring farther than 6 km was less than 8%. Jacobson and Krider (1976) found the static field under active Florida storms to reverse within 2 to 3 km of a ground strike. Mach et al. (1999) found that Oklahoma flashes typically clustered between 3 to 7 km, and Kitagawa et al (1999) found that most successive flashes in Japan were 2 to 6 km apart.

Krider (1988) is of the opinion that the random spatial variation of successive strike points around the center of a cluster is due to the random tilting of the lightning channel from the vertical, which has a standard deviation of about 18 degrees (Uman et al., 1980).

Although these results are extremely valuable for personal lightning safety, they are based on the study of only a few small, isolated thunderstorms. It is not clear how they apply to larger, more complicated storm systems such as multicellular storms, thunderstorm clusters, squall lines, supercells, and mesoscale convective systems. These storms can be prolific cloud-to-ground lightning flash producers. They can encompass several active updraft systems at different stages of development (convective cells) as well as extensive stratiform regions with their own mesoscale vertical circulations and *in situ* charge separation (Rutledge and MacGorman, 1990). Successive lightning flashes can come from different lightning-producing regions in a storm that might be separated by several kilometers. Even in the case of the small isolated storms analyzed by Krider (1988), some successive flashes occurred up to 12 km from the previous ones.

To a person, the entire storm presents a potential threat of death and injury from lightning. The important information to know from a lightning safety perspective is the likelihood that the next flash from anywhere in the storm might strike the ground at a distance from the previous flash equal to the distance of that flash to the person. For example, if the person can estimate (using the flash-to-bang method) that a flash occurred at 6 miles (9.6 km) away, what is the probability that the next flash from somewhere in that storm might strike at that same distance from the observed flash? The purpose of this study is to obtain statistics on the distribution of the distance between successive flashes for different types of storms in various parts of the country.

2. SOURCE OF LIGHTNING DATA

The data used in this study were collected by the National Lightning Detection System (NLDN) operated by Global Atmospherics, Inc. in Tucson, Arizona. Since 1995, the network has consisted of 59 time-of-arrival sensors and 47 sensors combining magnetic direction-finding and time-of-arrival technology (IMPACT). Holle and López (1993) describe these detection methods. Before 1995, the NLDN was composed of up to 130 magnetic direction finder sensors, but in 1994 some IMPACT technology sensors had been incorporated into the network. Cummins et al. (1998) describe the development of the network since 1989.

Previous to 1995, the estimated location accuracy of the network was not better than 2 to 4 km, according to the length of the 50% semi-major axis of the location error ellipse (Cummins et al., 1998). The error ellipse covers a region in which there is a 50% probability of finding the true stroke location.

After 1995, when the network was upgraded, and time-of-arrival and IMPACT sensors were exclusively used, the location accuracy was estimated to be 0.5 to 1.0 km. Similarly, the flash detection efficiency for the NLDN is estimated as 80 to 90% since 1995, and 65 to 80% before 1995. After the upgrade of 1995, the increased detection efficiency was accompanied by an increase in the number of weak positive flashes detected. These weak positives, with stroke peak currents less than 5 ka, were found to be cloud discharges that were now detected because of the increased sensitivity of the system (Cummins et al., 1998) The detection efficiencies quoted above apply only to stroke peak currents greater than 5 ka. Only cloud-to-ground flashes (CG) with stroke peak currents above 5 ka were used in this paper.

The network detects both negative and positive CG lightning flashes. Krider (1996) summarized the development of the methods to detect and locate CG flashes using both direction-finding and time-of-arrival techniques. Data from individual sensors are used to compute an optimum flash location using the least squares method of Hiscox et al. (1984). The procedure obtains the flash position and time of occurrence that minimizes the angle deviations and timing differences from different sensors detecting the flash. An average of 6 to 8 sensors detect flashes that have peak currents greater than 25 ka.

Almost all cases discussed in this paper come from 1995, with the exception of a severe weather situation in 1996. Data from Florida, northwest Colorado, northeast Colorado, and Oklahoma were used. These regions are considered to represent small-to-medium storms in moist coastal and dry continental environments, as well as large mesoscale severe storms from the Central Plains.

3. THE SUCCESSIVE-FLASH ALGORITHM

An algorithm was developed for identifying successive CG flashes. Each CG flash over a given region and time interval was examined to determine its successive or next flash. This was done by the following three steps:

- First, information for all flashes in the region is contained in a time-ordered data set.
- Then, the successive flash to the first flash in the dataset is the next one in the ordered list that is not separated from the first one by more than 15 km or 5 minutes.
- Once this successive flash is found, the next flash to it is determined in the same way, and so on.

A series of consecutive flashes constitutes a cluster of flashes. The search for successive flashes for a cluster is terminated when a flash is found in the ordered data set that occurred more than 5 minutes later than the last flash assigned to the cluster. Flashes that are too far away or too late are identified as candidates for other possible clusters of successive flashes. The algorithm is run again on a time-ordered list of the unused flashes. Eventually all flashes in the set become part of a cluster or are classified as isolated flashes if no flash is found close enough in time or distance to them.

The mean and standard deviation of the spatial separation, as well as the time separation between consecutive flashes were determined for each cluster. The total duration and root mean square (rms) radius from the mean position of all flashes in the cluster were also computed. Statistics were similarly determined for the frequency distribution of the space and time separation between pairs of consecutive flashes for the entire sample without regard to cluster relationship.

4. RESULTS FROM FLORIDA

A. LIGHTNING CLUSTERS

Figure 1 shows the locations of all flashes detected over South Florida on 20 July 1995 from 1200 to 1400 EST. This was a day of prevailing southwest to west flow but it was not synoptically disturbed. As is typical under those conditions, the sea breeze developed early on the west coast and propagated inland rapidly. By contrast, the sea breeze was late in developing along the east coast and the sea breeze front remained quasistationary in that region (López and Holle, 1987). Several clusters of flashes are clearly seen northeast and east of Tampa Bay. Figure 2 shows the area in more detail. The clusters are 10 to 15 km in diameter and are separated by 20 to 25 km from one another. Not all clusters were active simultaneously, but some did overlap in time. In some cases close clusters succeeded each other in time, apparently as a result of formation of new convective elements in the same thunderstorm system. This redevelopment of new cells was also recognized in Tampa Bay area storms by Peckham et al. (1984).

The position of cluster number 5 is indicated in Figure 2 by an arrow; an enlarged view of this cluster is shown in Figure 3. It is oriented southwest to northeast, and is less than 10 km wide by nearly 20 km long. The 53 subsequent flashes are grouped into three subclusters that form sequentially to the southwest of the initial flashes. These appear to be new upwind convective cells. Most of the flashes of the first (most northeasterly) group occurred before the flashes of the other groups began. The other two, however, overlapped more in time. Therefore, in some cases the next flash in time to a previous flash in one of the groups occurred within the neighboring group, while the next flash to that one would occur back at the first group. This alternation between groups happened several times.

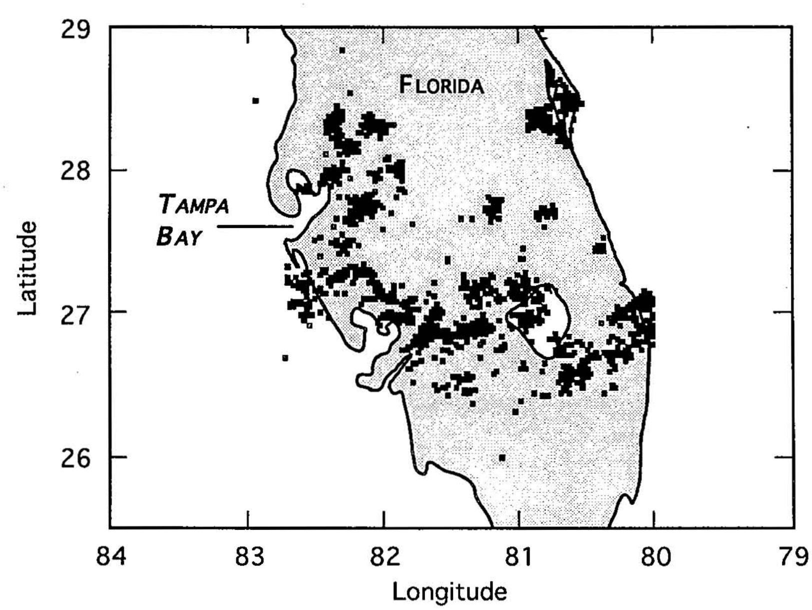

FIGURE 1. Map of south Florida showing locations of all flashes detected on 20 July 1995 from 1200 to 1400 EST.

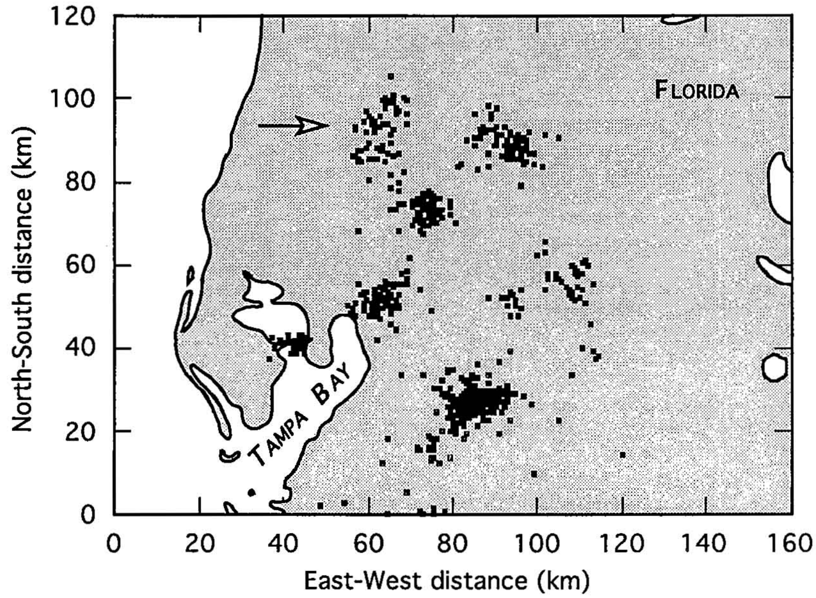

FIGURE 2. Enlarged map of the region northeast and east of Tampa Bay showing all flashes detected on 20 July 1995 from 1200 to 1400 EST.

The largest observed between-flash distances corresponded to these alternations between groups. The isolated flash at the north edge of the cluster occurred 12.7 km from its previous flash in the middle group 15 minutes after all activity in the first group ceased. From a safety point of view, this would have been a very dangerous situation to foresee for a person north of the storm. A flash struck ground about 5 km ahead of an area that had been quiescent for 15 minutes and 12.7 km from the previous flash in an active area that had developed farther away from the observer. It is not known if this flash originated from the cloud remnants of the first group or the northeast-expanding anvil of the second. The third (most southwesterly) group had a subsequent flash occurring far away from the other flashes to the southeast. The flash was the subsequent flash to a previous one 6.1 km away in the third group. Although this is well within the algorithm's next-flash criterion of 15 km, it appears isolated in position from the other flashes in the group. This flash could be from another updraft system further to the south.

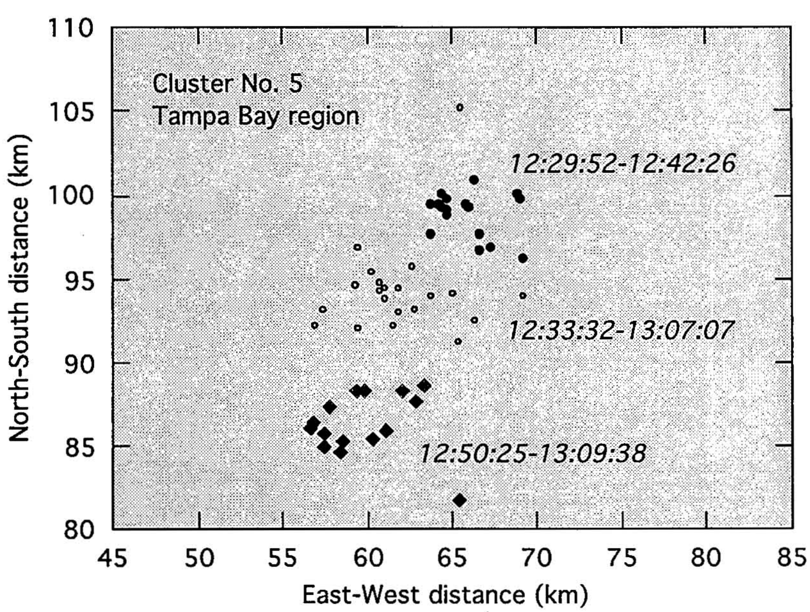

FIGURE 3. Enlarged view of cluster number 5 in the Tampa Bay region.

B. 15-KM DISTANCE CRITERION

The algorithm for identifying successive flashes was applied to the Tampa Bay region (Table 1). The algorithm identified 47 clusters of consecutive flashes. When consecutive flashes from all of the 47 clusters were considered, the average separations were 5.2 ± 3.5 km and 27 ± 38 seconds. The majority of these consisted of only a few flashes. Only 11 clusters had more than 10 consecutive flashes (Table 1). The root-mean-square (rms) radius around the centroid of flash positions varied among the 11 clusters from 4.1 to 8.5 km. The average distance between successive flashes ranged from 3.8 to 7.3 km with standard deviations between 1.5 and 5.6 km.

Figure 4 shows the histogram of the distribution of successive flash separations by half-kilometer intervals. The distribution is quasi-lognormal with most of the successive flashes striking close to one another. A few are as distant as 15 km, the largest distance allowed. The most frequent separations were from 1 to 3 km, and 50% of all successive flashes occurred at 4.6 km or less from the previous flash (Table 2 and Figure 5). A total of 75% of the flashes struck ground at 7.0 km or less from the previous flash, while 95% struck at 12.7 km or less. Not much significance is given to the spurious peak in the 4.5 to 5.0 km interval, since these values are well distributed throughout the major clusters and these flashes have no obvious peculiarities.

TABLE 1. Statistics for flash clusters northeast and east of Tampa Bay on 20 July 1995 from 1200 to 1400 EST using a maximum separation criterion of 15 km.

Cluster number	Number of flashes	Mean separation (km)	Standard deviation (km)	Mean interval (seconds)	Standard deviation (seconds)	Duration (minutes)	rms radius (km)
3	14	4.7	2.5	82	45	17.8	4.1
5	53	5.3	3.2	46	51	39.8	6.4
6	11	7.3	5.6	84	74	14.0	5.6
10	276	5.0	3.4	14	22	66.0	5.0
11	32	4.5	3.4	50	50	26.1	4.5
20	12	3.8	1.5	45	30	8.3	2.7
24	87	4.9	3.2	24	37	34.9	8.5
25	68	5.9	3.2	18	13	20.2	4.5
30	43	4.7	2.7	16	12	11.4	5.1
31	49	5.1	4.1	21	15	17.1	4.8
39	12	5.7	4.3	40	17	7.4	4.5

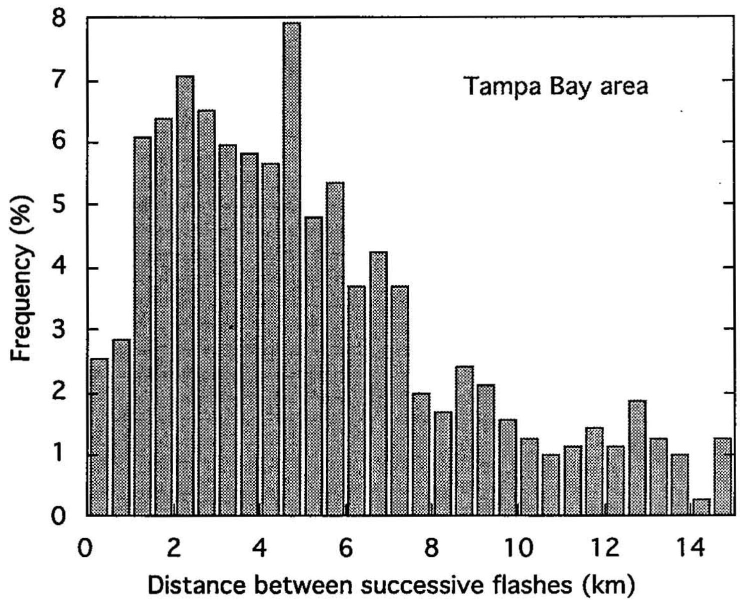

FIGURE 4. Histogram of the distribution of successive flash distances (km) in Tampa Bay flash clusters on 20 July 1995 from 1200 to 1400 EST using a maximum separation criterion of 15 km.

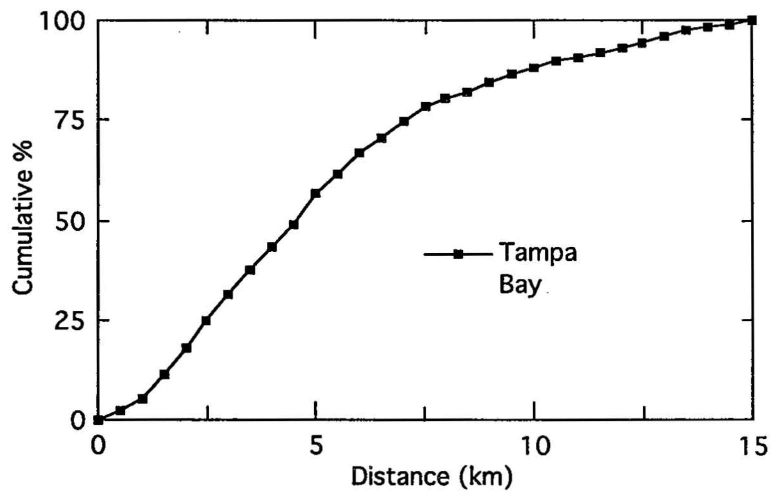

FIGURE 5. Cumulative percentage of successive flash distances (km) in Tampa Bay flash clusters on 20 July 1995 from 1200 to 1400 EST using a maximum separation criterion of 15 km.

TABLE 2. Distribution of successive flash separations in Tampa Bay area using maximum separation criterion of 15 km.

Percentiles	
25th	2.2 km
50th	4.6 km
75th	7.0 km
95th	12.7 km
Number of pairs	706
Average separation	5.2 ± 3.5 km

C. TIME

The Tampa Bay clusters lasted from 7.4 to 66.0 minutes (Table 1). The average time separation between flashes was from 14 to 84 seconds with standard deviations of 12 to 74 seconds.

Figure 6 shows the distribution of the time intervals between successive flashes. Again, it is a strongly biased distribution and most of the successive flashes occur close in time. Actually, 73% of the flashes struck within 0.5 minutes of the previous flash and 88% within 1 minute. The results for the Tampa Bay region in general are similar to those obtained by Krider (1988) in the Cape Canaveral area of Florida and others (Feteris, 1952; Hatakeyama, 1958; Carte and Kidder, 1977) in other regions of the world.

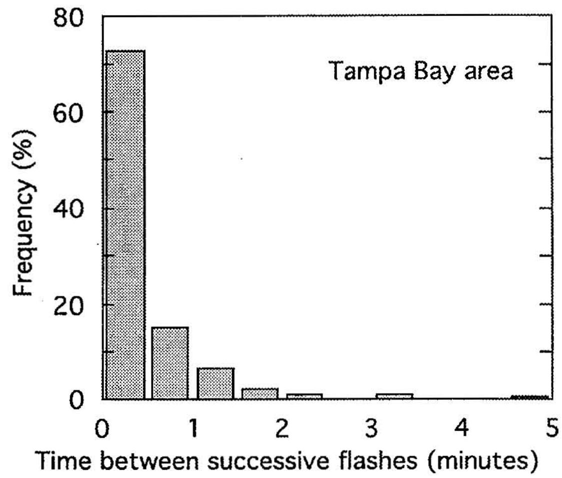

FIGURE 6. Histogram of the distribution of successive flash time intervals (minutes) in Florida flash clusters.

D. 20-KM DISTANCE CRITERION

If the distance criterion in the algorithm is relaxed to allow a successive flash to be up to 20 km away, some of the clusters identified before (using a maximum of 15 km) merge into larger clusters when the algorithm is applied. These now show more internal subclustering. Using 20 km, the average separation between consecutive flashes in the entire sample becomes 6.1 ± 4.6 km and 26 ± 38 seconds. The histogram of distances in Figure 7 again shows most frequent separations between 1.5 and 3 km, as when the limit was 15 km, but now larger distances are included from flashes in nearby subclusters that are producing flashes during the same time interval. Still, 50% of the successive flashes were less than 4.7 km away from the previous flash which is similar to the 4.6 km value using a maximum separation of 15 km.

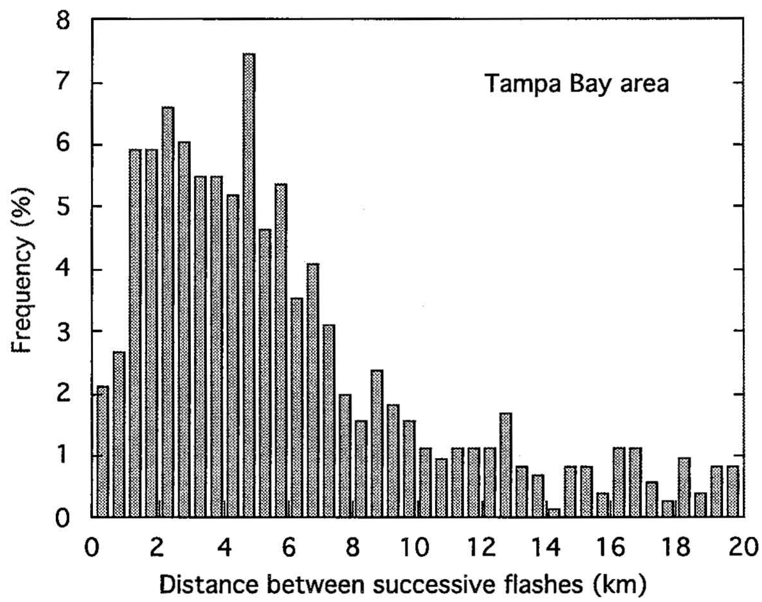

FIGURE 7. Histogram of the distribution of successive flash distances (km) in Florida flash clusters using a maximum separation criterion of 20 km.

E. SUMMARY

From this sample of 47 Florida flash clusters it can be inferred that although successive flashes most frequently strike about 1 to 3 km from the previous flash, a significant number (75%) strike at distances up to 7 km, while the rest can occur at 12 km or more. In some instances it appears that the most distant flashes came from nearby thunderstorms or from new convective elements of the same storm system. There is also the possibility that distant flashes might come from the anvils or stratiform remnants of earlier active regions. From the point of view of personal safety, being 7 km or less from a previous flash puts one under a relatively high danger situation, although there is still a non-trivial risk at distances of 12 km or larger. The implication is that a person should be aware not only of one flash-producing storm, but also of others in the vicinity (perhaps overhead or behind) and of new developing regions next to existing ones.

5. RESULTS FROM COLORADO

A. INTRODUCTION

Colorado is another region having frequent isolated thunderstorms during the summer. In this case, the mountain breeze is responsible for the formation of a recurring pattern of afternoon storms. A particularly susceptible area is the northeastern region of the state. There, as the east-facing mountain slopes heat up during the day, a strong upslope circulation is developed that brings air from the eastern plains against the Front Range and the Pike's Peak region from Fort Collins in the north to Colorado Springs in the south. The daily distribution of lightning flashes outlines clearly the mesoscale circulation that develops in the region (López and Holle, 1986). Because of the recurrent pattern of flashes, population density, and the popularity of outdoor recreation in the area, lightning safety is a major concern (López et al., 1993, 1995).

A day of medium activity was selected to study the distribution of successive flash separation. Figure 8 shows the location of all flashes detected over Colorado during 21 July 1995 from 1400 to 1600 MST. The linear nature of the flash clusters in the western part of the state is a result of the propagation of storms along the basic westerly flow producing long tracks of lightning from relatively small storm systems. The northeastern region, however, shows more localized, stationary clusters of flashes because of the strong circulations that develop between the eastern plains and the east-facing slopes of the mountains.

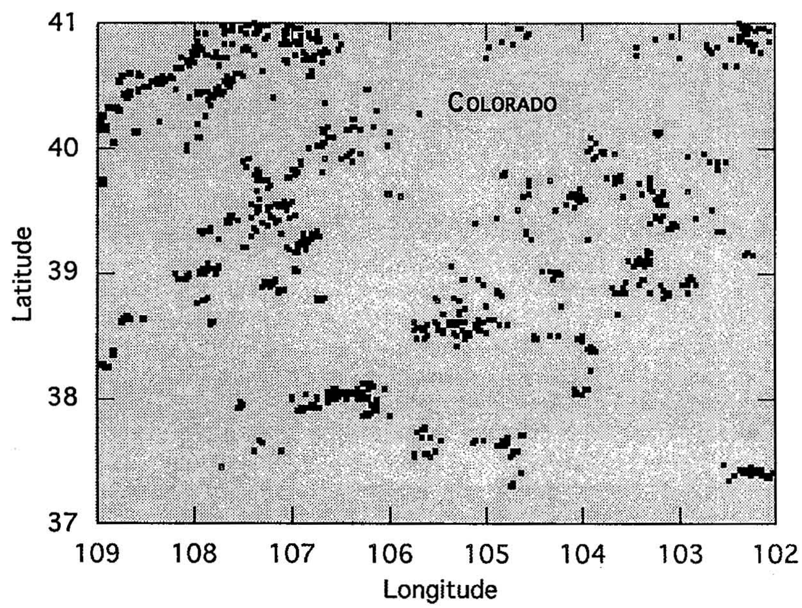

FIGURE 8. Map of Colorado showing locations of all flashes detected on 21 July 1995 from 1400 to 1600 MST.

B. NORTHWEST COLORADO

Figure 9 shows a more detailed view of the northwestern region from 1400 to 1600 MST. Most of the flash clusters are less than 10 km across but can be 30 to 40 km long. The algorithm for identifying successive flashes was applied to this area using a maximum distance and a maximum time interval between consecutive flashes of 15 km and 5 minutes. The algorithm identified 129 clusters of consecutive flashes, but as in Florida, the majority of the clusters consisted of only a few flashes.

Only 9 clusters had more than 10 consecutive flashes (Table 3). The rms radius around the centroid of flash positions varied among these 9 clusters from 4.1 to 12.1 km and lasted anywhere from 6.7 to 40.7 minutes. The average distance between successive flashes ranged from 3.2 to 7.6 km with standard deviations from 1.8 to 4.7 km. On the other hand, the average time separation between flashes was from 45 to 123 seconds with standard deviations of 29 to 78 seconds. When consecutive flashes from all 129 clusters were considered together, the average separation was 5.3 ± 4.2 km and 87 ± 72 seconds. A total of 375 flash pairs was included in this sample.

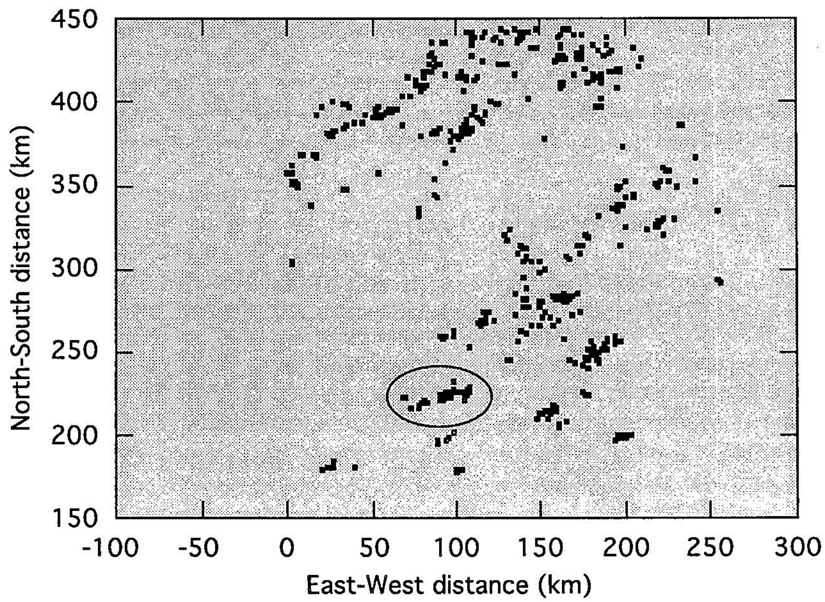

FIGURE 9. Enlarged map of northwest Colorado showing all flashes detected on 21 July 1995 from 1400 to 1600 MST.

TABLE 3. Statistics for flash clusters in northwest Colorado on 25 July 1995 from 1400 to 1600 MST.

Cluster number	Number of flashes	Mean separation (km)	Standard deviation (km)	Mean interval (seconds)	Standard deviation (seconds)	Duration (minutes)	rms radius (km)
8	39	4.5	3.5	45	33	28.3	11.1
19	13	7.6	4.2	102	78	20.4	7.4
21	13	4.7	4.7	123	73	24.6	5.2
24	18	7.5	4.2	82	76	23.3	12.1
66	14	3.2	1.8	69	29	14.9	4.1
79	34	4.9	3.9	74	74	40.7	10.5
85	24	6.4	4.3	90	75	34.7	11.5
104	28	4.7	2.5	52	33	23.3	7.6
114	12	5.8	4.6	36	31	6.7	6.9

The histogram for the distribution of successive flash separations is shown in Figure 10. The distribution for northwest Colorado is also quasi-lognormal so most of the successive flashes strike close to one another but a few are as distant as 15 km. The most frequent separations were from 0.5 to 3 km and 50% of all successive flashes occurred at 3.8 km or less from the previous one (Figure 11 and Table 4). A total of 75% of the flashes struck at 8.2 km or less from the previous one, and 95% struck at 13.6 km or less. The distribution tends to be somewhat more biased towards closer successive flashes than in the Florida case, although the means and standard deviations are quite similar (5.3 ± 4.2 km for Colorado and 5.2 ± 3.5 km for Florida).

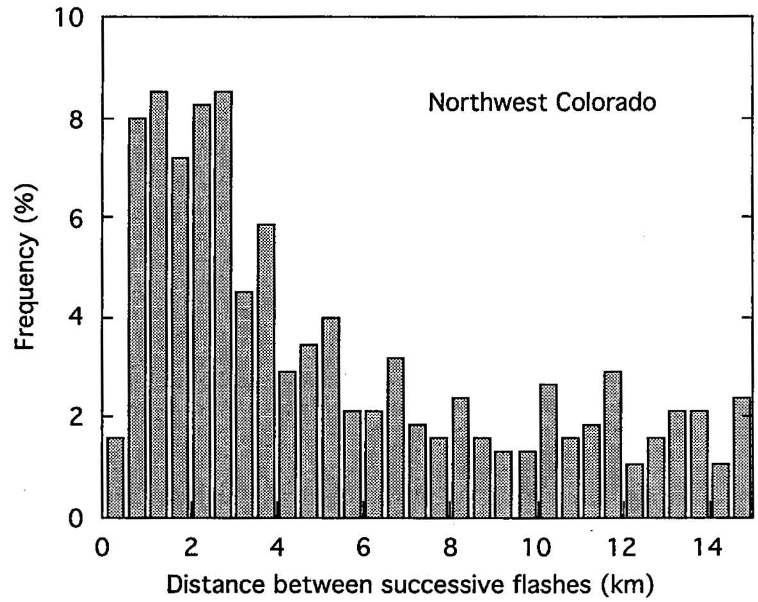

FIGURE 10. Histogram of the distribution of successive flash distances (km) in northwest Colorado flash cluster on 21 July 1995 from 1400 to 1600 MST using a maximum separation criterion of 15 km.

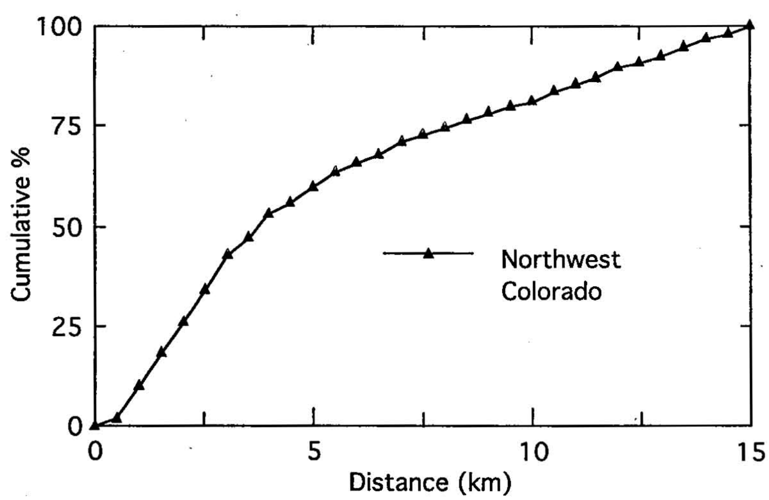

FIGURE 11. Cumulative percentage of successive flash distances (km) in northwest Colorado flash clusters on 21 July 1995 from 1400 to 1600 MST using a maximum separation criterion of 15 km.

TABLE 4. Distribution of successive flash separations in Northwest Colorado using maximum separation criterion of 15 km.

Percentiles		
25th	2.1 km	
50th	3.8 km	
75th	8.2 km	
95th	13.6 km	
Number of pairs		375
Average separation		5.3 ± 4.2 km

Figure 12 shows the distribution of time intervals between successive flashes. In the case of northwest Colorado, the distribution is not as strongly biased as in Florida. The most frequent time delay between successive flashes was between 0.5 and 1.0 minutes, while in Florida 73% of the flashes struck within 0.5 minutes of the previous flash. Only 49% of the flashes were within 1 minute (88% in the Tampa area) and the average time delay was 1.5 minutes instead of 0.5 minutes. Thus, the temporal separation between successive flashes was greater in northwest Colorado than was the case for Florida.

Figure 13 illustrates the progression of lightning flashes in cluster number 8. This cluster is shown enclosed by an oval in Figure 9. In Figure 13 the first and last flashes are identified as well as the time for the three portions of the cluster. The overall progression of flashes is from west to east in a narrow path about five km wide and 40 km long. The flashes, however, succeed each other in space in a random zigzag with a mean separation of 4.5 ± 3.5 km (Table 3).

The cluster shows a structure of 3 smaller subclusters separated by 5 to 10 km from each other. The maximum separation between successive flashes was 13.5 km as the lightning activity shifted from the first to the second subcluster. The second and third subclusters, however, overlapped in time and it was common for subsequent flashes to alternate between the two subclusters. The groups of flashes probably correspond to separate updraft systems or cells that form on the leading edge of the storm as it moves east. The individual subclusters lasted 9 to 14 minutes while the total succession of flashes lasted 28.3 minutes. The last flash of the second subcluster occurred 8.6 km to the north of the previous flash, isolated by more than 5 km from any other flash (marked by an arrow in Figure 13). This was a negative single-stroke flash. The next flash occurred in the third cluster, and from that point on, all other flashes occurred in that group.

From the point of view of personal safety, this sample of northwestern Colorado clusters suggests that, although successive flashes most frequently strike less than about 4 km from the previous flash, a substantial number (75%) strike at distances up to 8 km, while the rest can occur at 14 km or more. In some instances it appears that the most distant flashes came from new convective elements of the same storm system. There is also the possibility that distant flashes may have come from the anvil or stratiform regions associated with the main updraft. Being at 8 km or less from a flash puts a person under a relatively high danger situation, but there is still a risk at a distance of 14 km or greater.

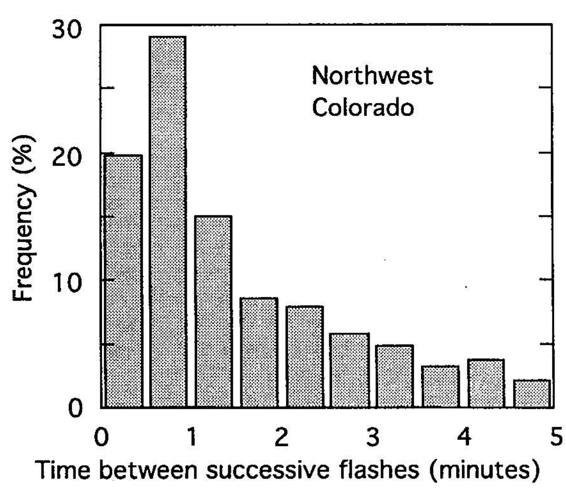

FIGURE 12. Histogram of the distribution of successive flash time intervals (minutes) in northwest Colorado flash clusters.

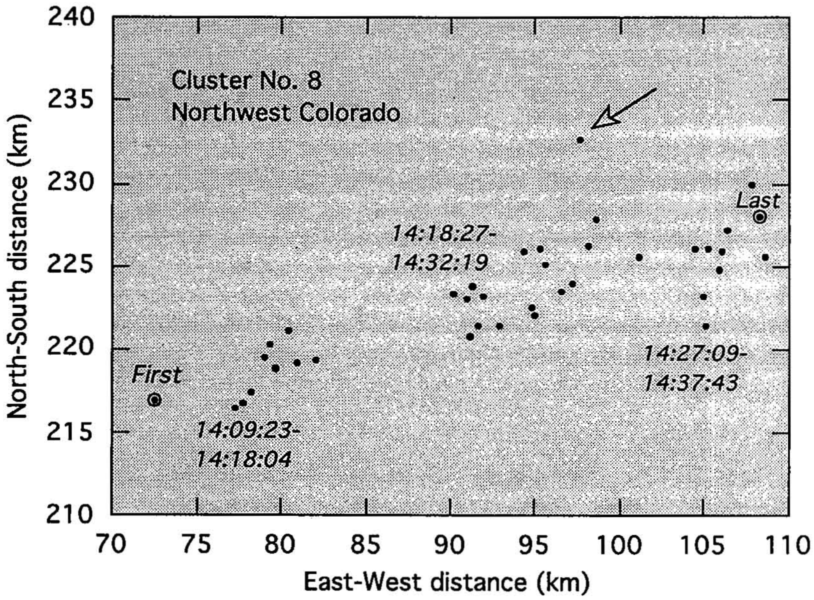

FIGURE 13. Enlarged view of cluster number 8 in northwest Colorado.

C. NORTHEAST COLORADO

Figure 14 shows flashes in northeast Colorado on 21 July 1995 from 1400 to 1600 MST, the period of greatest activity. Most flash clusters are from 10 to 20 km in diameter and not as elongated as in the northwest. The algorithm identified 84 clusters of consecutive flashes; the majority of them had less than 10 flashes.

The six clusters with more than 10 are presented in Table 5. The rms radius around the centroid varied from 4.3 to 7.5 km and lasted from 15.1 to 32.3 minutes. The average distance between successive flashes ranged from 5.0 to 7.4 km and the average time separation between flashes was from 81 to 150 seconds. The average separation for all of the 84 clusters was 5.5 ± 3.9 km and 110 ± 79 seconds. A total of 171 flash pairs was used.

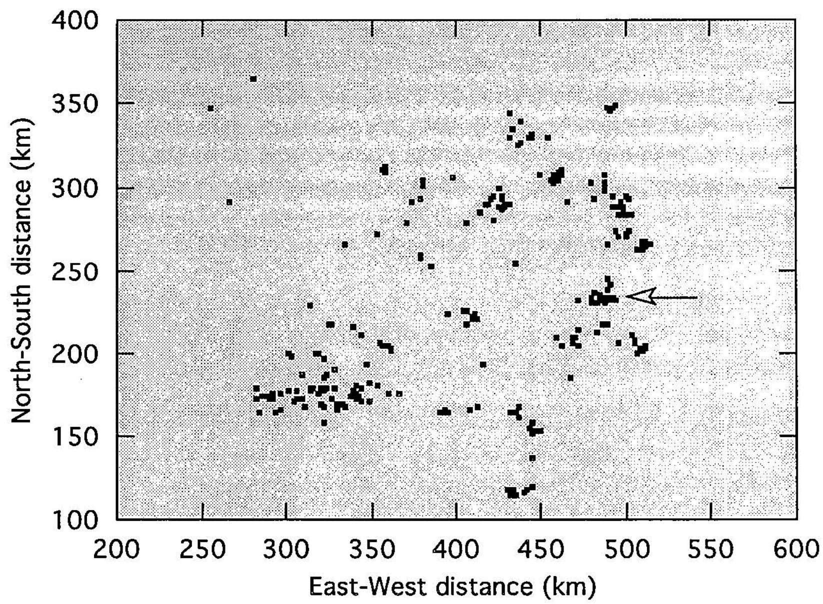

FIGURE 14. Map of northeast Colorado showing locations of all flashes detected on 21 July 1995 from 1400 to 1600 MST.

TABLE 5. Statistics for flash clusters in northeast Colorado on 25 July 1995 from 1400 to 1600 MST.

Cluster number	Number of flashes	Mean separation (km)	Standard deviation (km)	Mean interval (seconds)	Standard deviation (seconds)	Duration (minutes)	rms radius (km)
7	25	5.8	3.8	81	73	32.3	5.6
17	10	6.0	2.9	111	94	16.6	5.9
19	10	5.8	3.1	150	67	22.4	4.3
41	11	5.0	5.0	115	54	19.1	7.5
44	10	7.4	4.4	101	54	15.1	6.2
80	14	5.4	3.7	82	80	17.8	7.3

The histogram for the distribution of flash separations for northeast Colorado is shown in Figures 15 and 16, and Table 6. The distribution is similar to that of northwest Colorado. The mean and standard deviation are 5.5 and 3.9 km, respectively. The distribution of time intervals between successive flashes, however, is somewhat different (Figure 17). The mean is 110 seconds instead of 87 seconds for the northwest, and there is a smaller percentage of flashes closer in time than 1 minute (35% versus 49%). It appears that successive flashes in northwest Colorado tended to occur closer in time to the previous flash than in the northeast region.

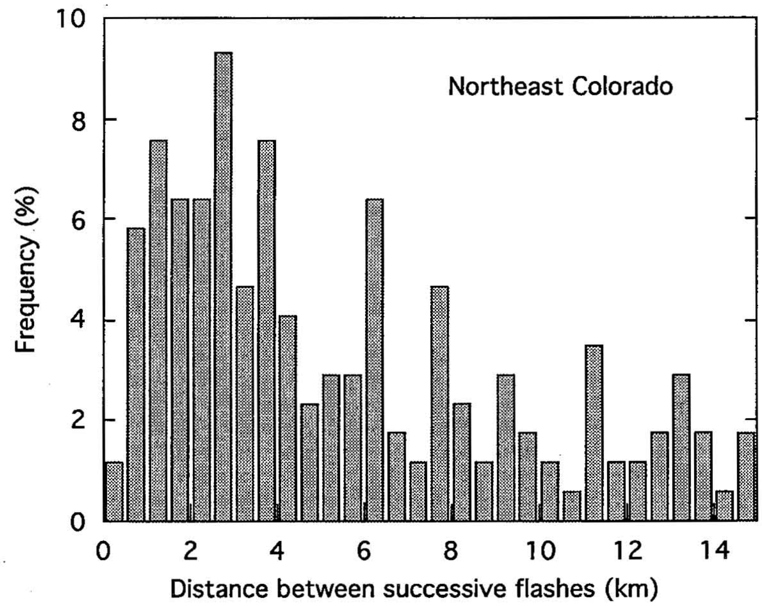

FIGURE 15. Histogram of the distribution of successive flash distances (km) in northeast Colorado flash clusters using a maximum separation criterion of 15 km.

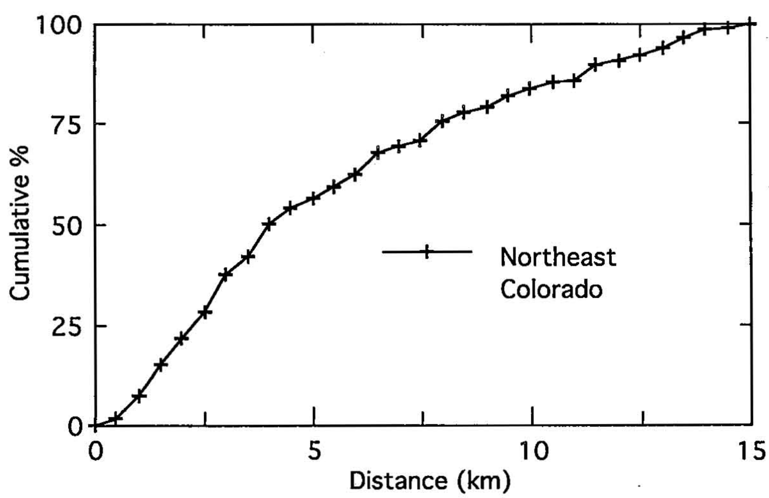

FIGURE 16. Cumulative percentage of successive flash distances (km) in northeast Colorado flash clusters on 21 July 1995 from 1400 to 1600 MST using a maximum separation criterion of 15 km.

TABLE 6. Distribution of successive flash separations in Northeast Colorado using maximum separation criterion of 15 km.

Percentiles		
25th	2.1 km	
50th	4.1 km	
75th	8.0 km	
95th	13.3 km	
Number of pairs		171
Average separation		5.5 ± 3.9 km

Cluster number 7 is identified in Figure 14 by an arrow. This was a fairly isolated cluster consisting of 25 successive flashes. The mean sequential flash separation was 5.8 km with an rms radius of 5.6 km.

A closeup view of the cluster is shown in Figure 18 with lines connecting successive flashes. The first and last flash are labeled. The cluster consists of a denser inner area where flashes were very close together. However, these often alternated in time with flashes in the periphery and resulted in larger between-flash distances. The largest distance between successive flashes was 14.8 km and there were 5 more pairs with distances greater than 9 km. Although the farthest flashes to the north and east in most cases occurred later, there were some early alternations with flashes in the core. It is possible that this was a multicellular storm with updraft systems in different stages of development overlapping in time producing lightning. The distant flashes, however, may have also come from anvils.

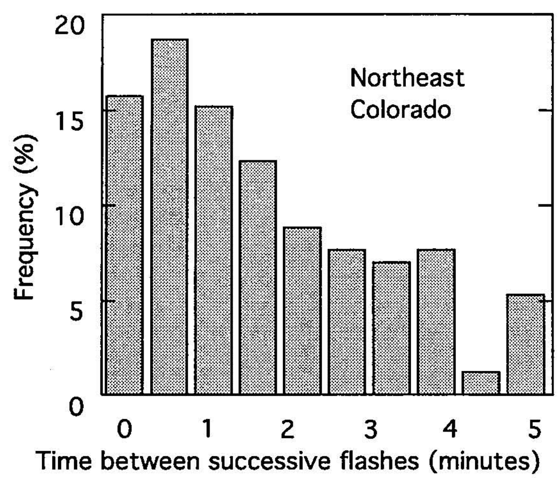

FIGURE 17. Histogram of the distribution of successive flash time intervals (minutes) in northeast Colorado flash clusters.

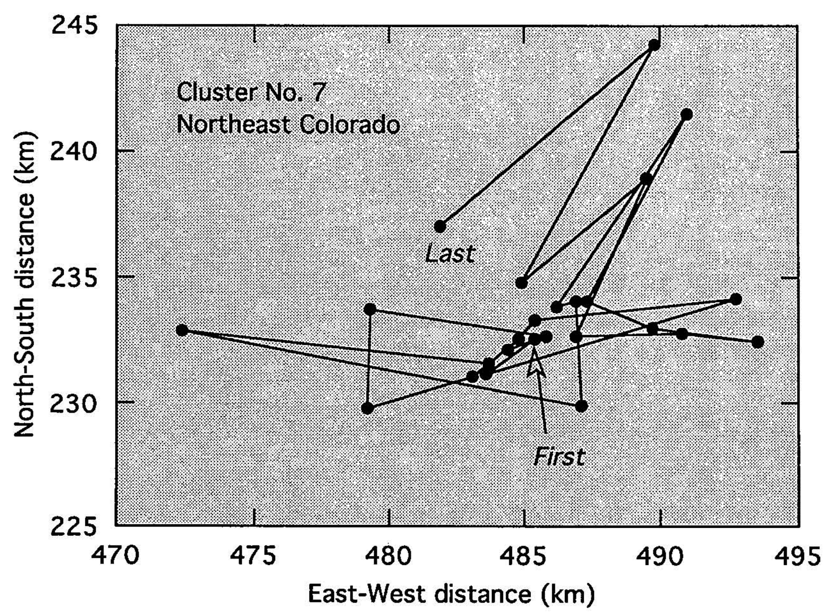

FIGURE 18. Enlarged view of cluster number 7 in northeast Colorado.

6. RESULTS FROM OKLAHOMA

The state of Oklahoma is subject to a large number of mesoscale storm systems, particularly during the spring and fall, that often produce large numbers of cloud-to-ground flashes. On 6 June 1996 there was an outbreak of severe storms producing 33,138 flashes in 24 hours over the state. The map of 4802 flashes detected in the region from 2300 to 2400 UTC is shown in Figure 19. The flashes show an internal structure of 5 to 7 large clusters that correspond to different reflectivity maxima seen with the National Severe Storms Laboratory's Cimarron radar located at the center of the grid. López and Aubagnac (1997) have made a detailed study of the lightning activity of one supercell of a similar system and its relation to changes in the microphysics of the storm as inferred from polarimetric radar observations.

The algorithm for identifying successive flashes was applied to this time period and region and it produced 848 clusters, most of them with less than 10 flashes (Table 7). Only 56 had more than 10 consecutive flashes. Eleven of the clusters had more than 50 flashes, three had more than 100, and one consisted of 1086. The rms radii around the centroid of flash positions are the largest of all the cases already considered, reaching a maximum of 21.6 km. The total durations of the clusters were not particularly long, with a maximum of 60.0 minutes. The average distance between successive flashes, however, were the largest so far, ranging from 4.6 to 10.7 km. The standard deviations are relatively small, as they go from 2.3 to 4.9 km. The average time separation between flashes was small in general (2 to 55 seconds). When the consecutive flashes from all of the 202 clusters were considered together, the average separation was 8.6 ± 4.0 km and 10 ± 22 seconds. These space separations were 1.6 to 1.7 times larger than those for the clusters in Florida or Colorado (Tables 2, 4, 6).

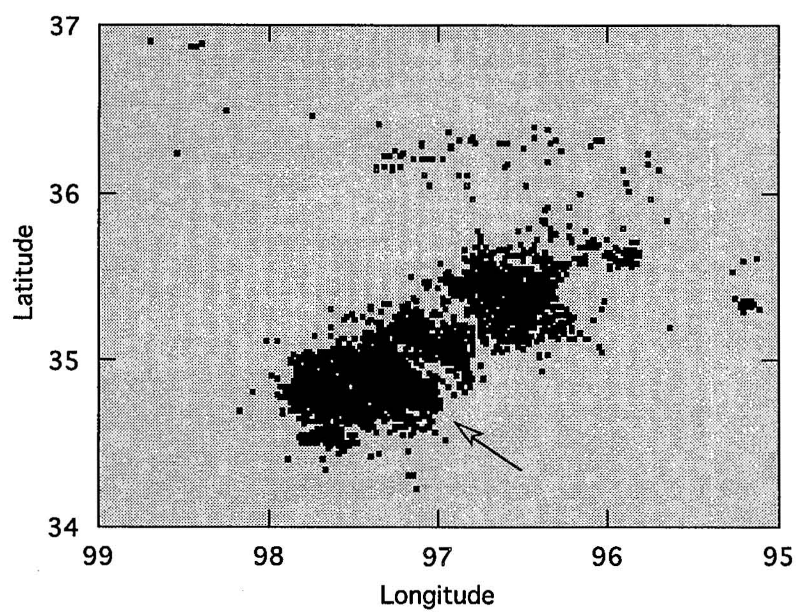

FIGURE 19. Map of central Oklahoma showing locations of all flashes detected on 6 June 1996 from 2300 to 2400 UTC.

TABLE 7. *Statistics for flash clusters in central Oklahoma on 6 June 1996 from 2300 to 2400 UTC.*

Cluster number	Number of flashes	Mean separation (km)	Standard deviation (km)	Mean interval (seconds)	Standard deviation (seconds)	Duration (minutes)	rms radius (km)
1	1086	8.4	4.0	3	4	60.0	19.4
5	19	7.2	3.9	6	4	1.9	10.2
8	31	7.7	3.9	9	9	4.5	7.2
11	614	8.2	4.0	6	6	59.7	17.9
19	38	7.5	4.1	8	19	5.2	21.6
52	39	8.3	4.0	7	23	4.4	9.9
66	58	8.7	4.3	7	7	6.6	10.3
78	22	8.0	3.5	4	4	1.4	8.5
99	10	6.7	4.3	5	4	0.8	6.8
107	10	7.5	4.0	14	23	2.1	7.6
114	24	7.4	3.9	21	43	7.9	11.5
125	10	10.2	3.3	32	74	4.7	17.2
138	17	10.1	3.5	4	5	1.2	11.5
148	10	9.5	3.3	2	1	0.3	6.3
152	13	5.5	4.1	6	4	1.1	5.5
168	10	10.7	2.3	10	10	1.5	8.9
171	14	7.6	4.1	10	8	2.1	9.8
184	28	8.1	3.7	3	2	1.3	7.5
190	12	7.4	4.3	16	14	3.0	11.1
197	76	8.7	3.8	7	9	8.5	10.3
209	24	5.9	4.2	23	26	8.9	16.5
216	43	5.9	3.6	7	5	4.9	6.1
218	14	8.2	4.9	6	3	1.2	6.9
272	68	8.5	4.0	8	18	8.4	20.2
299	11	8.1	3.8	14	8	2.4	7.8
303	22	7.3	3.6	4	2	1.3	6.2
321	54	8.8	3.7	3	3	2.9	8.9
326	14	5.9	4.2	36	37	7.8	6.2
350	193	8.4	4.1	11	10	33.6	11.4
354	12	8.3	4.3	55	69	10.0	8.7
356	17	7.8	3.9	2	1	0.6	7.2
378	12	9.1	3.5	2	2	0.4	8.6
382	49	8.5	4.0	4	4	2.9	7.8
430	67	7.7	4.1	3	4	3.5	9.0
478	10	5.5	3.4	3	2	0.5	4.6
486	53	7.7	3.8	4	4	3.2	10.8
504	27	6.4	3.4	3	2	1.3	5.2
522	42	6.9	3.7	33	28	22.7	6.4
533	14	9.6	2.8	7	15	1.5	13.2
544	56	7.6	4.0	20	23	18.0	11.7
546	12	9.9	3.7	7	5	1.3	8.6
552	58	9.6	3.6	8	10	7.2	11.7
554	25	7.9	2.7	5	5	2.0	9.4
560	28	5.4	3.7	3	2	1.2	5.0
570	16	8.4	3.6	52	77	12.9	10.6
621	14	10.6	4.2	20	42	4.3	16.0
641	10	9.6	4.2	5	3	0.7	13.8
701	26	8.2	3.3	9	10	3.7	9.1
707	21	4.6	2.8	29	14	9.6	3.6

724	15	10.1	3.0	3	2	0.8	8.4
733	16	8.6	4.2	15	25	3.6	16.5
737	11	8.5	4.4	17	17	2.8	13.3
754	17	7.1	4.0	24	17	6.3	8.3
783	15	10.4	3.5	9	7	2.2	11.5
790	41	9.1	4.1	6	6	3.7	10.7
823	12	9.9	3.5	6	5	1.1	7.9

Figures 20 and 21 show the distribution of successive flash separations for this Oklahoma storm. The histogram and cumulative distribution are very different from those for the previous regions. Rather than having a maximum at 2 to 3 km, the maximum occurs around 12 km. Instead of a relative rapid decay in frequency with range, there are uniformly high frequencies all the way to the maximum separation allowed in the algorithm (15 km). The 50th percentile of successive flashes occurs at 9.1 km, the largest of all cases. The 75th percentile is 12.1 km while the 95th percentile is 14.4 (Table 8).

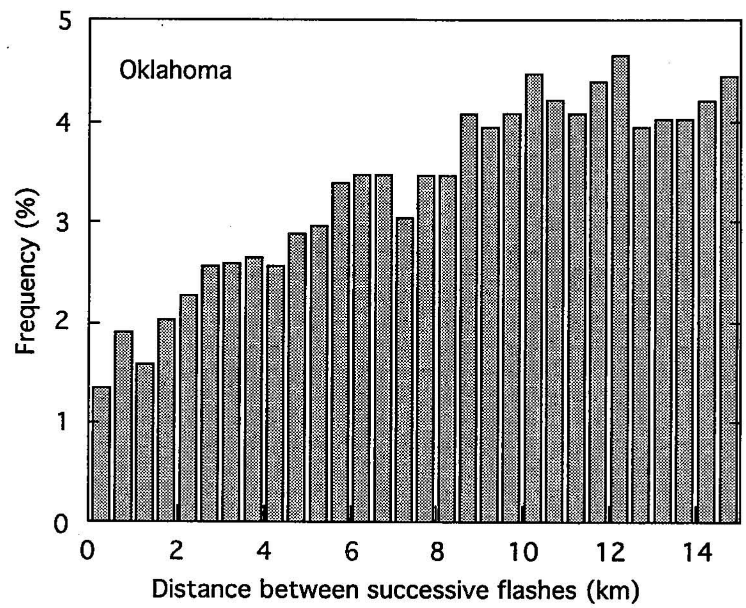

FIGURE 20. Histogram of the distribution of successive flash distances (km) in central Oklahoma flash clusters using a maximum separation criterion of 15 km.

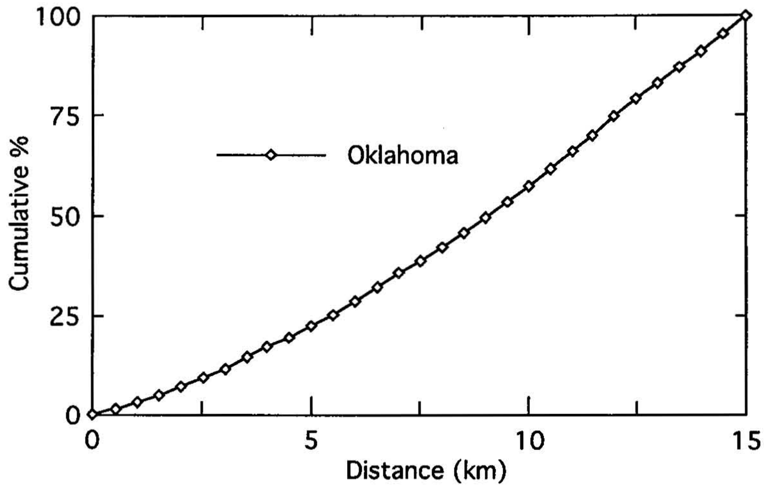

FIGURE 21. Cumulative percentage of successive flash distances (km) in central Oklahoma flash clusters on 6 June 1996 from 2300 to 2400 UTC using a maximum separation criterion of 15 km.

TABLE 8. Distribution of successive flash separations in Oklahoma using maximum separation criterion of 15 km.

Percentiles		
25th	5.5 km	
50th	9.1 km	
75th	12.1 km	
95th	14.4 km	
Number of pairs		4725
Average separation		8.6 ± 4.0 km

The distribution of time intervals between successive flashes for Oklahoma, however, is not that different from the other cases (Figure 22). It is also a strongly biased distribution, since most successive flashes occur close in time. A total of 94% of the flashes struck within 0.5 minutes of the previous one, and 97% were within one minute.

The individual sequential flashes of cluster number 1 (indicated by an arrow in Figure 19) are displayed in Figure 23. Most of the 1086 flashes are concentrated in 4 to 5 areas that are 15-20 km in dimension. The two center subclusters show considerable elongation in a NW-SE direction and contain a slender area of higher density of flashes not more than 5 km across. The northeast and southwest areas are part of clearly defined separate clusters (Figure 19). Some of their flashes are included with the larger cluster because the three are so close together and active that successive flashes alternate between the three centers of flash production, as explained above for the previous regions.

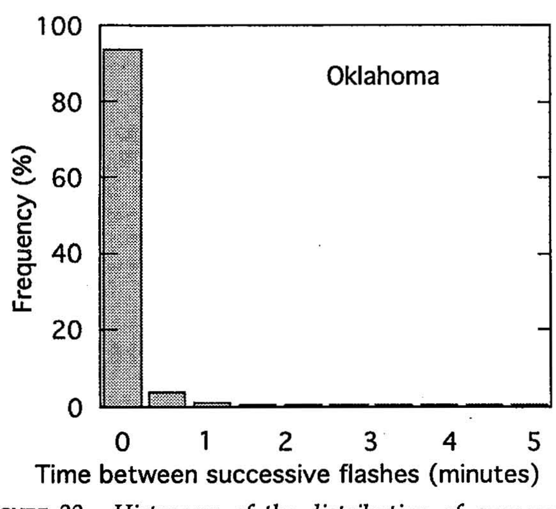

FIGURE 22. Histogram of the distribution of successive flash time intervals (minutes) in central Oklahoma flash clusters.

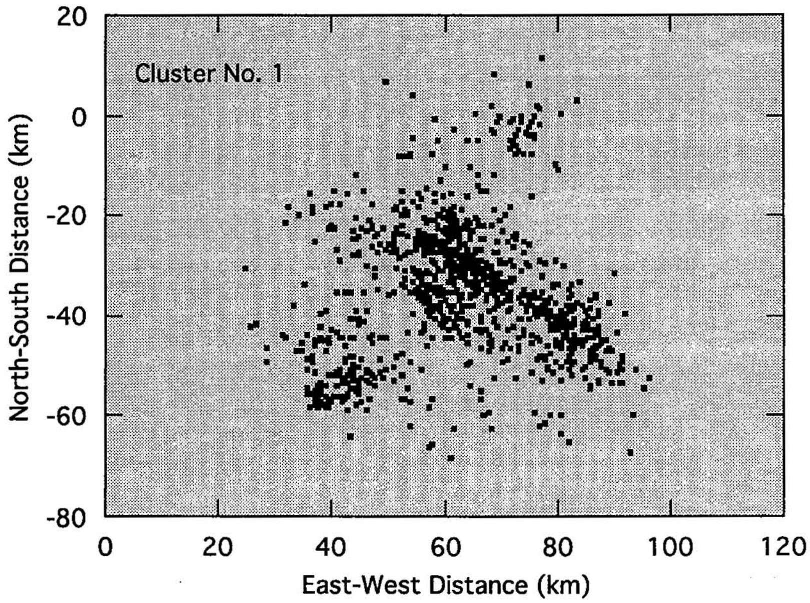

FIGURE 23. Enlarged view of cluster number 1 in central Oklahoma.

Figures 24a to 24f show the development of cluster number 1 in time steps of 10 minutes. Considering only the center area, there is considerable displacement of the flash activity towards the southeast. This displacement coincides with the translation of a line of very intense (50-60 dBZ) reflectivity centers in the same direction. It is interesting to note that the highest concentration of flashes lie in a thin band about 5 km wide. This band extends for about 40 km during the hour under consideration but is broken off into two parts by an interval of slow production of flashes. Southwest of the thin band there is a more diffuse band that reaches its maximum density of flashes between 2320 and 2330 (Figure 24c). Surrounding the denser regions there is always present a scattering of flashes that can extend 10-15 km away.

Thus, it appears that subsequent flashes, even in this large cluster, tend to occur more frequently in core regions of about 5 km in dimension surrounded by less dense areas 10-15 km across. The long linear nature of the cluster is due to the fast motion and long lasting flash production of the storm. The proximity of various centers of flash production and the rapid succession of flashes account for the large width of the cluster. Again, from the point of view of an untrained observer looking at the storm from a distance, the flashes make a valid succession of flashes, as they did for the algorithm with the 15 km maximum separation constraint. Because of the multicellular nature of this storm and its large dimensions, the observer would have noticed that a large number of the successive flashes were occurring at much larger distances from each other than in the previous cases of smaller and simpler storms.

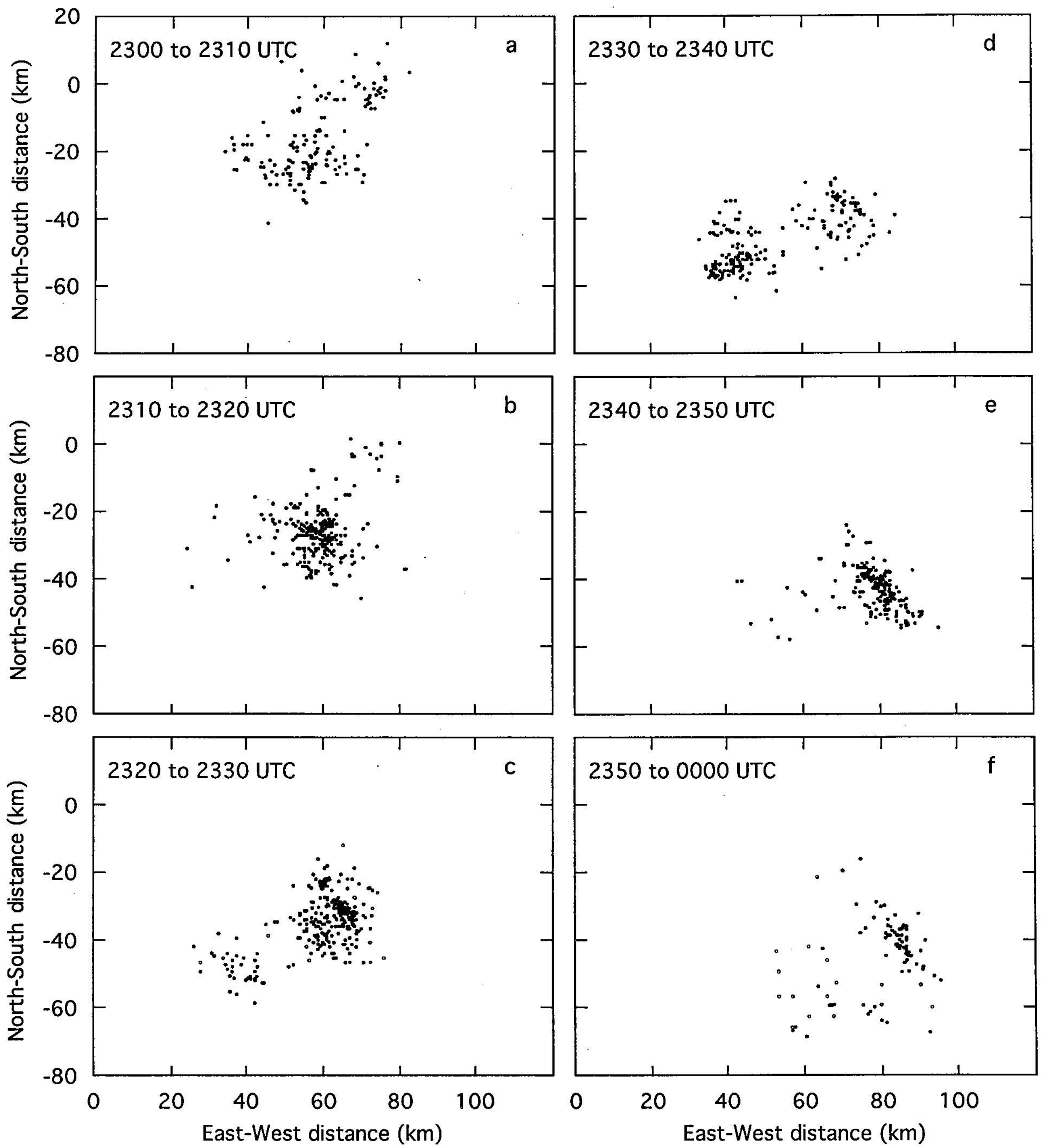

FIGURE 24. Enlarged view of the development of cluster number 1 in central Oklahoma every 10 minutes.

7. SUMMARY AND CONCLUSIONS

The frequency distribution of the distance between successive cloud-to-ground lightning flashes has been studied for varying types of storm systems in several regions of the U.S. This information is very important for personal safety strategies and other applications. A person can estimate, using the flash-to-bang method, how far away a flash has occurred. The question is then, is that person too close to where the lightning is occurring? Statistics on the separation of successive flashes can help make an assessment of the risk involved.

The present study made use of the National Lightning Detection Network (NLDN) database. The network was upgraded in 1995 to use both time-of-arrival and direction finding technology resulting in a location accuracy estimated at 0.5-1.0 km. Similarly, the flash detection efficiency for the NLDN is estimated as 80-90% since 1995. Data from Florida, northwest Colorado, northeast Colorado, and Oklahoma have been used. These regions have small-to-medium storms in moist coastal and dry continental environments, as well as large (mesoscale) severe storms from the Central Plains. The regions were explored to derive statistics for the distance between successive flashes, and to study clusters of successive flashes. An algorithm was developed for identifying the successive flash after each CG flash over a given region and time interval. The successive flash of an initial flash is the next one in a time-ordered list that is not separated from the initial one by more than a distance of 15 km or a time interval of 5 minutes.

Results summarized in Figure 25 and Table 9 indicate that clusters of successive flashes in all regions tend to have an internal structure of subclusters with dimensions of about 10 km. These subclusters probably correspond to lightning-producing convective-cloud cells. In some cases, an area of about 5 km across can be seen with a higher density of flashes.

In clusters of small and medium dimensions from Florida and Colorado, the most common successive flash separation is 3 or 4 km. Fifty percent of all successive flashes are less than 4 to 5 km from the previous flash and probably come from the same subcluster. Twenty five percent, however, are separated by 5 to 8 km and some may come from adjoining subclusters. Five percent of the successive flashes can still be separated by 13 km or more, probably representing flashes occurring in anvil regions. In the case of a large mesoscale storm from Oklahoma, half of the successive flashes are separated by 9 km, and 25% of successive pairs are separated by over 12 km.

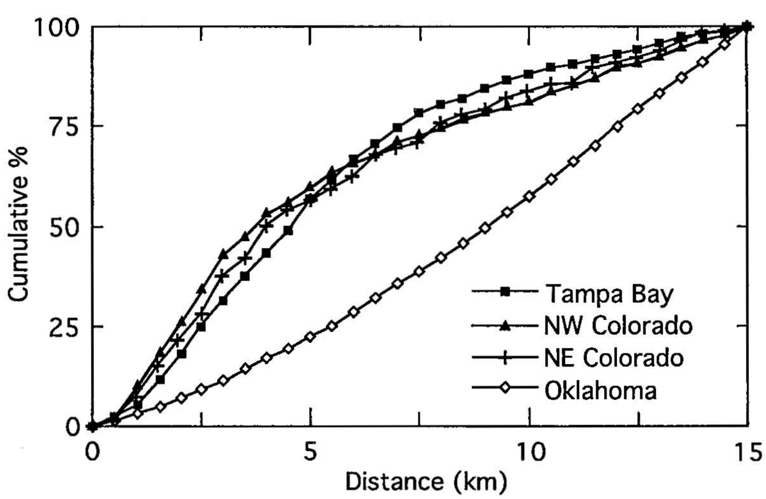

FIGURE 25. Cumulative percentage of successive flash distances (km) for flash clusters in all regions using a maximum separation criterion of 15 km.

TABLE 9. Summary of the distribution of successive flash separations in the regions considered.

Region	Average separation (km)	Number of pairs	Percentiles (km) 25th	50th	75th	95th
Tampa area	5.2 ± 3.5	706	2.2	4.6	7.0	12.7
NW Colorado	5.3 ± 4.2	375	2.1	3.8	8.2	13.6
NE Colorado	5. 5± 3.9	171	2.1	4.1	8.0	13.3
Oklahoma	8.6 ± 4.0	4725	5.5	9.1	12.1	14.4

From the point of view of personal safety, being 8 km or less from a flash puts one in a relatively high danger situation. However, there is still a non-trivial risk at distances of 13 km or larger. The situation is even worse for very large storms. The implication is that a person should be aware not only of one flash-producing storm, but also of others in the vicinity (perhaps overhead or behind) and of new developing regions next to existing ones. It appears that safety rules need to be modified to increase the distance from a previous flash which can be considered to be relatively safe, to at least 10 to 13 km (6 to 8 miles). In the past, 3 to 5 km (2 to 3 miles) was used in lightning safety education.

The information presented in this paper is not intended to provide estimates of the probability that the next flash will strike at the position of a person. But it does provide an estimate of the probability that the next flash will strike at the same distance the person was from the previous flash *somewhere* around that previous flash. It is very difficult to obtain the probability that a person will be hit after detecting a previous flash. This study has indeed shown that, except for very small isolated storms, the distribution of flashes in a medium-sized storm can be very complicated. Storms can have many simultaneous electrically active centers or cells at varying stages of development with different lightning rates. Lightning can come from anvils or nearby storms. In addition, lightning clusters can be arranged in many configurations: thin lines, amorphous clustering, broad bands, large stratiform/anvil regions, etc. In addition, storms can be moving fast or slow, regularly or erratically. The probability that a person is hit after detecting one flash from somewhere in a storm depends, in addition to the next-flash characteristics studied in this paper, on where the observer is in relation to that storm and to other storms in the vicinity.

For example, consider a person to the right or left of the path of an isolated fast-moving small storm in northwestern Colorado. A person is probably safer 3 to 5 km from a previous flash from that storm, than a person at those same distances ahead of a storm where new cells or anvils are being formed. However, the knowledge that in about 50 to 70% of the cases, the next flash can strike at those distances somewhere around that first flash, could be the basis for an informed strategy to be followed in conjunction with motion of the storm, past history, visual aspect, and relative position of the person.

In some cases it is difficult to obtain other information in a timely way, or the person does not have the know-how to obtain it. Then the results of this paper, although being on the conservative side, provide general criteria for a safety decision. All of this points to another important issue. In the case of events or situations where there are many people or high economic stakes involved, there should be a knowledgeable person tasked with gathering all available information and making decisions to minimize false alarms without compromising safety. At that point, the use of cloud-to-ground or other lightning detection equipment might be advisable.

One could convert the successive flash separation distributions presented in this paper to probability of strike distributions. The conversion could be done by dividing the frequency of successive flash distances in particular distance intervals by the area of the corresponding distance interval rings. In reality however, the flash density of a storm is a complicated function of storm morphology, movement, and history as discussed above. Dividing by area in this case would produce an average probability that would overestimate the probability for some areas while underestimating it for others. We prefer to present the successive flash distance information in its original form so that no inaccurate estimates of probability of being struck will be used. There is enough information in this paper to demonstrate the complexity of flash distributions in even medium-sized storms. We propose that using a criterion of at least 10 to 13 km (6 to 8) miles is a conservative rule to use if no other information is available. We are aware of the large false alarm margin involved, and recommend that for sensitive or high vulnerability situations, more information is used, preferably by a designated knowledgeable individual.

The emphasis of this study has been on obtaining statistics on successive flash separations that can be used in personal safety strategies. The results of this work, however, are also relevant for the understanding of storm morphology in connection with a storm's electrical activity. Many other features, such as cluster flash density and the distribution of nearest neighbor separations, are also important in this respect. Those other features were not explored in this paper because it was felt that the information on successive flashes is the most relevant for personal safety considerations. Similarly, relating successive flash clusters to radar parameters is important for understanding storm electrification and lightning production. Again, this study did not explore that issue because it was not considered to be as important for personal safety as the next flash.

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NATIONAL SEVERE STORMS LABORATORY

The NSSL Technical Memoranda, beginning at No. 28, continue the sequence established by the U.S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151, a microfiche version for $4.00 or a hard copy, cost depending upon the number of pages. NTIS numbers are given below in parenthesis.

No. 1 National Severe Storms Project Objectives and Basic Design. Staff, NSSP. March 1961. 16 p. (PB-168207)

No. 2 The Development of Aircraft Investigations of Squall Lines from 1956-1960. Brent B. Goddard. 34 p. (PB-168208)

No. 3 Instability Lines and Their Environments as Shown by Aircraft Soundings and Quasi-Horizontal Traverses. Dansey T. Williams. February 1962. 15 p. (PD-168209)

No. 4 On the Mechanics of the Tornado. J. R. Fulks. February 1962. 33 p. (PD-168210)

No. 5 A Summary of Field Operations and Data Collection by the National Severe Storms Project in Spring 1961. Jean T. Lee. March 1962. 47 p. (PB 165095)

No. 6 Index to the NSSP Surface Network. Tetsuya Fujita. April 1962. 32 p. (PB-168212)

No. 7 The Vertical Structure of Three Dry Lines as Revealed by Aircraft Traverses. E. L. McGuire. April 1962. 10 p. (PB-168213)

No. 8 Radar Observations of a Tornado Thunderstorm in Vertical Section. Ralph J. Donaldson, Jr. April 1962. 21 p. (PB-174859)

No. 9 Dynamics of Severe Convective Storms. Chester W. Newton. July 1962. 44 p. (PB-163319)

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