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SPATIAL DISTRIBUTION OF LIGHTNING STRIKES TO GROUND DURING SMALL THUNDERSTORMS IN FLORIDA

E. Philip Krider
Institute of Atmospheric Physics
The University of Arizona
Tucson, Arizona 85721
U.S.A.

ABSTRACT

The spatial patterns of the strike points produced by cloud-to-ground lightning under three small thunderstorms have been analyzed to determine the area flash density as a function of radius from the storm center, the distribution of nearest-neighbor distances, and the distribution of the horizontal distances between successive flashes. The storm average flash densities range from about 0.8 to 1.6 Fl/km^2, and the average lightning fluxes range from 0.03 to 0.05 $Fl/km^2/min$. The mean nearest-neighbor distances are about 0.7 km and smaller than but still in good agreement with a theory that assumes an infinite and uniform flash density. The mean distance between successive flashes ranges from 3.2 to 4.2 km, and a sizable fraction of this variation could be due to channel geometry.

1. INTRODUCTION

Networks of gated, wideband magnetic direction-finders† [1,2] are now being used throughout the U.S., Canada, and many other countries to locate lightning strikes to ground. These systems are being used for research on basic lightning phenomenology [3-5], on the relationship between lightning and the meteorological environment [6-8], on the effects of lightning on power systems [9-11], and for a host of other applications [12]. This instrumentation is also being used at the NASA Kennedy Space Center (KSC) and the Cape Canaveral Air Force Station (CCAFS) to detect lightning and to provide thunderstorm warnings for a variety of ground operations, launches, and landings [13,14].

For thunderstorm warning applications, the spatial and temporal development of the pattern of ground strike points is important because these patterns can be used to forecast, at least to some extent, when and where the next strikes will occur. The detailed spatial variations of the strike points are controlled by the meteorological and electrical structure of the storm as it evolves in both space and time, by the random and highly tortuous nature of the stepped-leader as it develops from cloud-to-ground, and by any systematic and/or random errors that may be present in the lightning locating system.

In this paper, we will examine the spatial statistics of the ground strike points that were produced by small, isolated thunderstorms near Cape Canaveral, Florida. The locations of the storms and the accuracy of the detection system were such that random errors in the lightning locations were small compared to the overall dimensions of the storm cell.

2. DATA

The data that we have analyzed were obtained from a 3-station network of medium gain LLP direction-finders (DFs) that are operated at the KSC and the CCAFS. The locations of all DF stations are shown in Fig. 1 together with the locations of the lightning strikes that we have studied. The straight-line distances between direction-finders 1 and 2, 2 and 3, and 3 and 1 are 78.3, 64.6, and 65.4 km, respectively.

† Manufactured by Lightning Location and Protection, Inc. (LLP), Tucson, Arizona

The LLP direction-finders operate with a bandwidth that extends from about 1.5 to 500 kHz so the essential features of the lightning field waveforms are preserved. The signatures that are produced by return strokes are selected on the basis of their risetime and width together with certain other requirements on the polarity of the leader impulses that precede the return stroke and on the amplitude and polarity of any waveform peaks that follow the first peak [2]. When a return stroke is detected, the NS and EW components of the magnetic field waveform are sampled at the time of the first peak to provide an accurate direction to the ground strike point [1,15]. In this paper, all lightning locations are for the first return stroke in each flash to ground. If a subsequent stroke should strike in a different location than the first stroke, the subsequent location is ignored. The lightning locations are the standard outputs from the LLP system after corrections have been applied for systematic "site errors," and only the most frequent negative return strokes have been analyzed.

Table 1 shows a summary of the lightning data for each of the three storms that have been analyzed. Following Peckham et al. [3], we define a storm to be a spatially isolated grouping of flashes that occur in a relatively compact time sequence. The beginning time is the time of the first flash in the group and the ending time is the time of the last flash, provided that there was no other discharge in a 5-minute interval before or after that flash, respectively. The storm areas were estimated by drawing a smooth curve around all lightning locations in the storm group in a fashion similar to Peckham et al. [3]. The average flux of ground strikes for all storms in Table 1 is 0.019 strikes km^{-2} min^{-1}, which is almost the same as the average of 0.018 strikes km^{-2} min^{-1} found by Peckham et al. [3] for single-peak storms in the Tampa area, except that we have not applied any correction factor for the system detection efficiency.

The storms that are plotted in Fig. 1 have been selected because the clusters get progressively closer to the DF network. As the storms get closer to the sensors, the effects of random errors in the magnetic direction measurements have less effect on the root-mean-square (rms) error in the lightning position computation. (Note: A complete discussion of the errors in DF position fixing has been given by Stansfield [16].) The last column in Table 1 shows the rms errors that could be present in the LLP positions near the center of the storm clusters. These values have been computed using the theory of Stansfield [16] and assume that the locations are derived from the intersections

TABLE 1. Storm Data

Date (m/d/y)		Start (GMT)	Stop (GMT)	Duration (min)	No. of Flashes Detected	Storm Area (km^2)	Storm Area Density ($F\ell/km^2$)	Storm Average Flux ($F\ell/km^2/min$)	RMS Position Error (km)
7/24/85	B	20:57:39	21:24:00	26.4	56	167	0.34	0.013	2.7
8/10/85	A	16:40:23	17:21:15	40.9	83	114	0.73	0.018	1.3
8/10/85	B	16:43:14	17:16:47	33.6	86	103	0.84	0.025	1.1
					Average		0.64	0.019	

of the two closest DF vectors. The standard deviations of the random direction errors have been assumed to be one degree [13, 17].

3. SPATIAL STATISTICS

The storms in Fig. 1 were small and almost stationary throughout the lightning interval. Note that in all cases the lightning clusters are only 10 to 15 km in diameter, and that this dimension is several times larger than the rms position errors. The radial distances from each strike point to the center of the lightning cluster (i.e., the average x- and the average y-coordinate of all flashes in the storm) are summarized in Fig. 2. The storm average flash densities are plotted in Fig. 3 as a function of radius from the storm center. Note in Fig. 3 that the flash densities are not uniform and that there tends to be a uniform, almost Gaussian, decrease from the center of the storm to the edge. The density function on 7/24/85 may also be broadened somewhat by the 2.7 km rms position error.

The distributions of the nearest neighbor distances between all strike points are given in Fig. 4. If the location of a given lightning strike is known, then the nearest-neighbor distribution can be used to estimate the probability that the storm will produce the nearest neighbor at a particular distance. Note that the average nearest-neighbor distance ranges from about 0.5 to 1.0 km.

Finally, Fig. 5 shows the distribution of the straight line distances between successive flashes, or the free-path distances between the strike points, in each storm. Note that the most probable distances are in the range from 1 to 4 km, that the average distances are 3 to 4 km, and that one strike occurred about 12 km from the previous flash.

4. DISCUSSION

The spatial statistics that are summarized in Figs. 3, 4, and 5 are subject to two types of errors: random errors in the lightning positions and the fact that some flashes will be missing because the detection efficiency of the LLP system is less than unity [3,17]. Our estimates of the random position errors have already been summarized in Table 1. The principal effect of the random error will be to broaden the area of the strike pattern and hence decrease our estimates of the flash densities. If the rms value of the position uncertainty is ρ, then the average increase in the radius of the storm, R, will be about $2\rho/\pi$, and the fractional increase in the area of the storm, A, will be about $4\rho/\pi R$. Using the areas and the values of ρ in Table 1, the area increase on 7/22/85 will be about 49% and on 8/10/85 A,B, the increase is 19 and 25%, as shown in Table 2.

If we assume that the detection efficiency of the medium gain LLP system at the KSC and CCAFS is the same as that of the medium gain LLP system studied by Peckam et al. [3] and that each lightning location is derived from the intersection of the two closest DF vectors, then we can use the data of Peckham et al. to estimate an efficiency correction factor for each storm. These values and the values of the average flash densities and fluxes after the area and efficiency corrections are applied are shown in Table 2. Note that the corrected fluxes are now about a factor of 2 larger than the estimates of Peckham et al. [3].

The main effect of the system errors on the nearest-neighbor distances will be through the area density distribution. In a situation where there is an infinite area density, n, that is constant with radius, we can use the theory outlined by Chandrasekhar [18] to show that the probability of finding the nearest neighbor between r and r + dr, w(r)dr, is given by

$$w(r) = 2\pi rn \exp[-\pi r^2 n] \quad (1)$$

With this distribution, the average nearest-neighbor distance, $\bar{D}$, is

$$\bar{D} = \frac{1}{2\sqrt{n}} \quad (2)$$

which has a reciprocal $\sqrt{n}$ dependence. In Table 3, we show the

TABLE 2. Storm Average Flash Densities and the Fluxes of Strikes to Ground

Storm		Area (km^2)	$\bar{R}$ (km)	ρ (km)	$\frac{\Delta A}{A}$	Distance to 2nd Closest DF (km)	Efficiency Correction Factor	Corrected Area Density (Fl/km^2)	Corrected Average Flux ($Fl/km^2/min$)
7/24/85	B	167	7.3	2.7	0.47	90 - 100	1.6	0.80	0.030
8/10/85	A	114	6.0	1.3	0.28	65 - 75	1.5	1.4	0.034
8/10/85	B	103	5.7	1.1	0.25	70 - 85	1.5	1.6	0.049
							Average	1.3	0.038

TABLE 3. Nearest-Neighbor Distances

Storm		Average Flash Density (Fl/km^2)	Measured $\bar{D}$ (km)	Corrected $\bar{D}$ (km)	$\bar{D}$ from Uniform Theory (km)
7/24/85	B	0.80	1.0	0.65	0.56
8/10/85	A	1.4	0.54	0.72	0.42
8/10/85	B	1.6	0.63	0.72	0.40

measured values of $\bar{D}$, the same quantities after a reciprocal $\sqrt{n}$ correction (using the data in Table 2), and an estimate of $\bar{D}$ derived from Eq. (2) using the average densities in Table 2. Note that the average nearest-neighbor distances are all about 0.7 km and that the values computed using the theory for a constant area density are smaller than but still within a factor of 2 of the actual measurements.

The distributions of the distances between successive strike points that are given in Fig. 5 should be substantially independent of the detection efficiency but will be broadened somewhat by the rms position errors. The average values range from 3.2 to 4.2 km. It is well-known that the geometry of a lightning channel is branched and tortuous, and it is also known that the standard deviation of the tilt angles from the vertical is about 18 degrees, at least near the ground [19]. Now, if the charge structure of the storm and the discharge is such that a cloud-to-ground flash effectively deposits positive charge at an altitude of 7 to 9 km [20], and if the angle that the entire discharge makes from the vertical is about 18 degrees, on average, then there should be at least a 2.3 to 2.9 km random spatial variation between strike points, even if the source of successive discharges is highly localized.

Previous literature on the spatial pattern of lightning strike points is apparently limited to brief reports by Feteris [21], Hatakeyama [22], and Carte and Kidder [23]. All of these authors have found that the diameters of isolated lightning clusters are on the order of 10 km. Feteris [21] suggests that the "lightning centres" in the cloud are highly localized. Hatakeyama [22] and Carte and Kidder [23] claim that the flash density is uniform within a storm cluster. In the future, it would be interesting to combine measurements such as ours with simultaneous radar observations of the thundercloud, measurements of the charge distributions within the cloud, and photographs of the lightning channel geometry.

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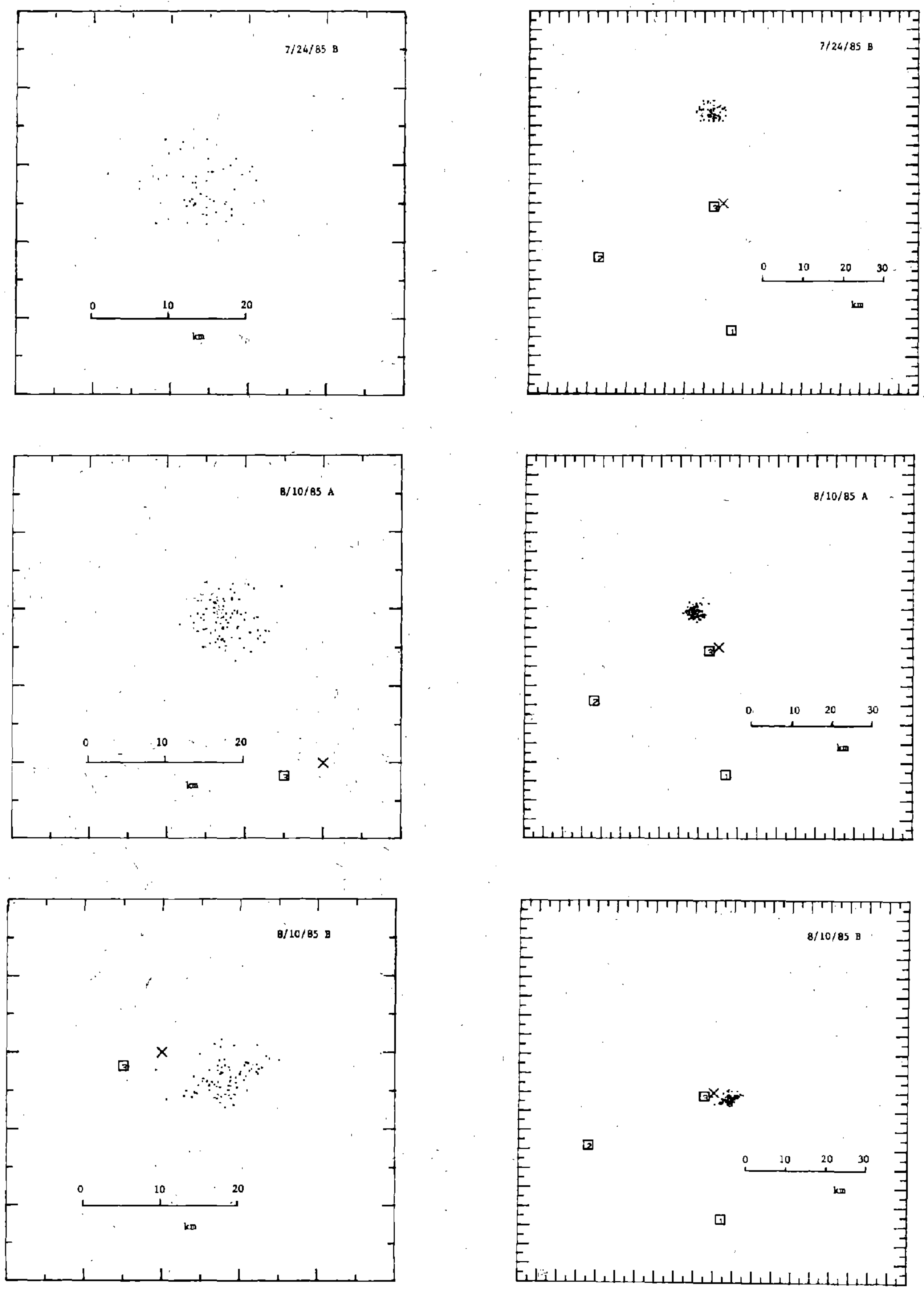

Fig. 1. The locations of the DF sites and the strike points produced by the three storms listed in Table 1.

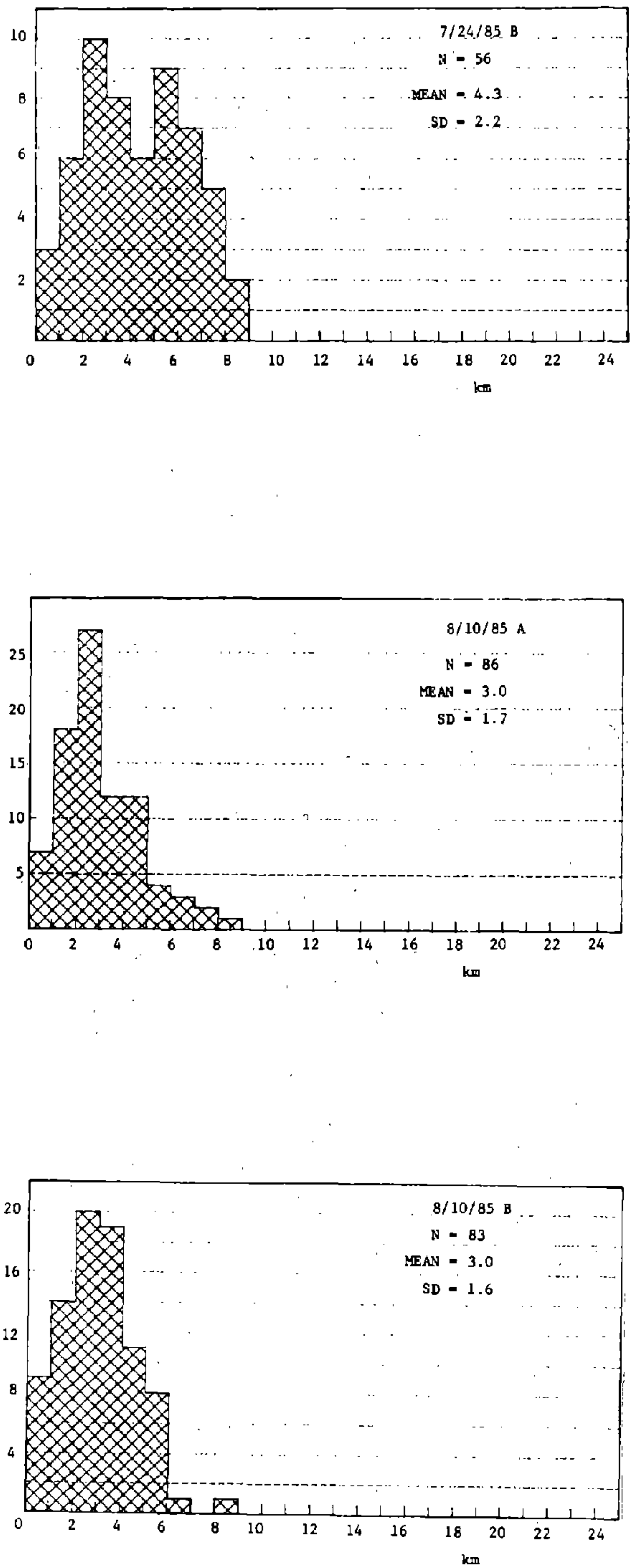

Fig. 2. Histograms that show the frequency of radial distances from the center of the storm in kilometers.

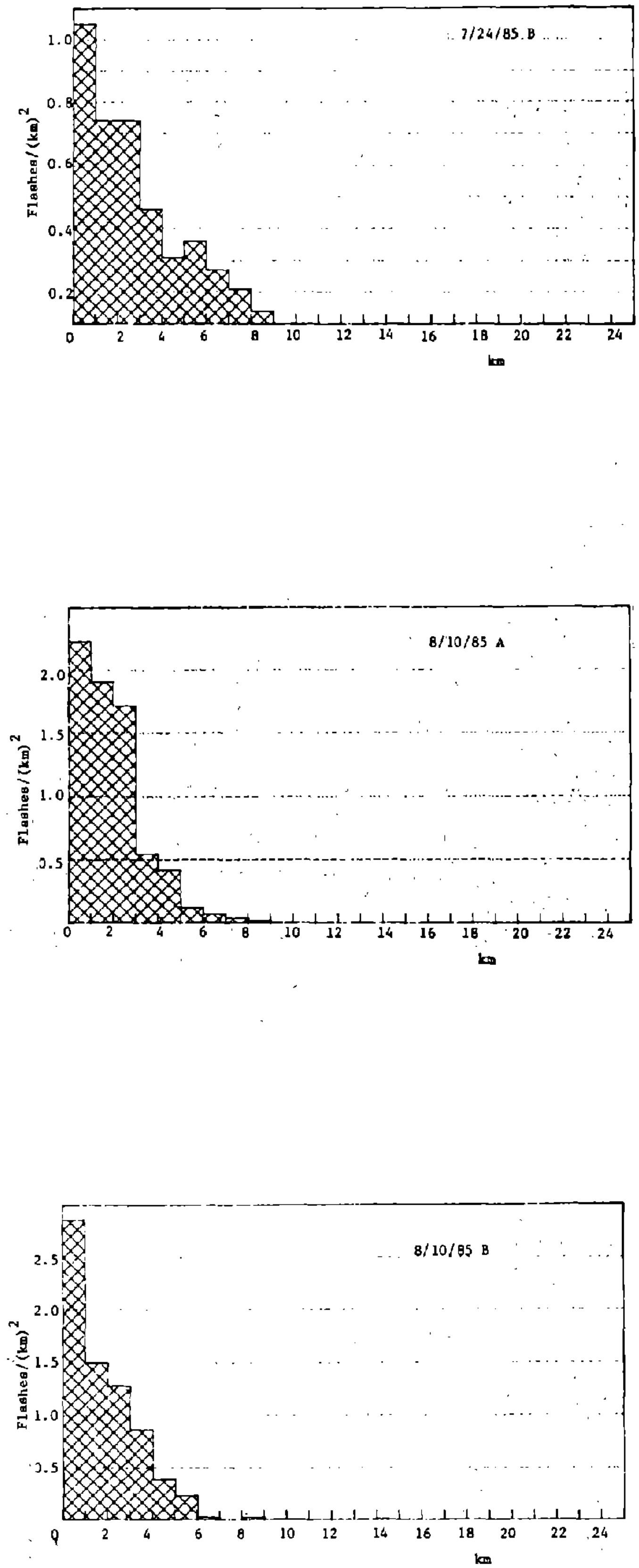

Fig. 3. The area flash density vs. radius from the center of the storm.

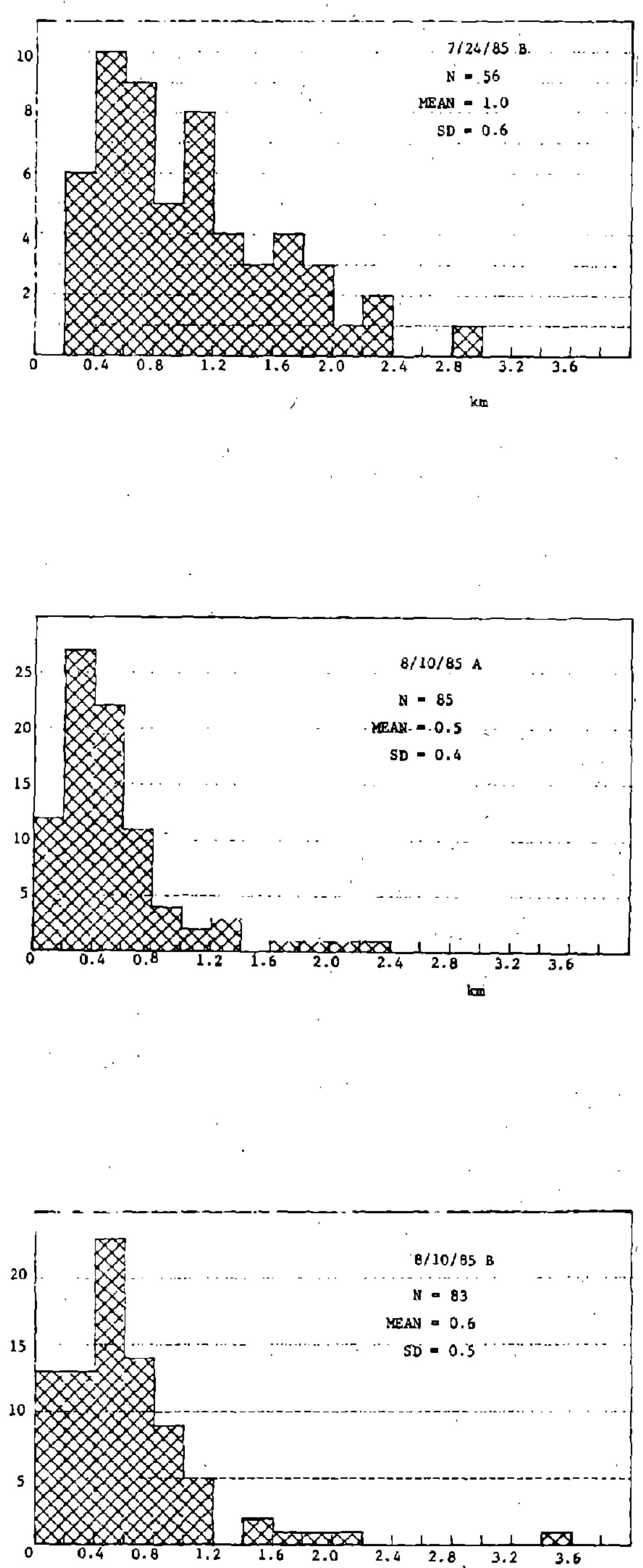

Fig. 4. Histograms that show the frequency of nearest-neighbor distances in kilometers.

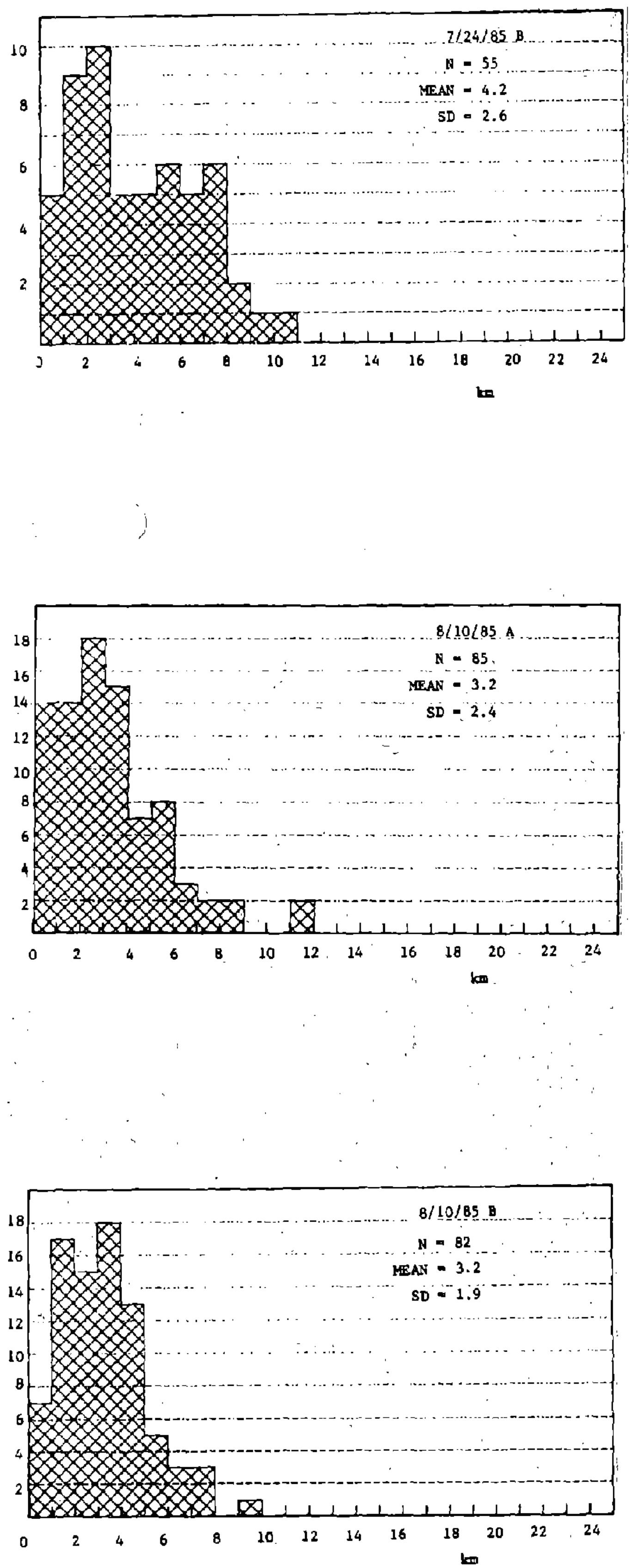

Fig. 5. Histograms that show the frequency of the straight-line distances between successive strike points in kilometers.