INVESTIGATION OF LIGHTNING FLASHES AS A FUNCTION OF TERRAIN ELEVATION

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Introduction

The Nevada Test Site (NTS) Lightning Detection System has been in operation for many years and was designed to provide high-detection capability on and within 170 km of the NTS. This network has been described elsewhere (Randerson, 1999, and Randerson and Sanders, 1999) and will not be repeated here. Krider et al. (1980) documented lightning-detection technology and Scott (1988) described the original NTS network of magnetic direction finders in detail. High resolution of cloud-to-ground (CG) flashes on and around the NTS was achieved by establishing short base lines for the magnetic direction finders (DFs). East-West baselines of 40 km and North-South baselines of nearly 75 km were established on the NTS. The mean distance between the DFs was 60 km. With the requirement for a high-resolution flash detection capability on the NTS, the DF gains were reduced to be compatible with the baseline length of the NTS detectors. Consequently, we estimate the detection efficiency to be approximately 90% and the positioning accuracy to be 0.5 km.

June through September is thunderstorm season for southern Nevada (Quiring, 1983, Randerson, 1997, and Skrbac, 1999). Consequently, CG lightning flash activity for these months was collected and assembled to form the 976-day, warm-season (June through September) database for 1993 through 2000. This database has been analyzed (Randerson and Sanders, 2002) to characterize lightning activity on the NTS.

Procedure

In this study, the lightning database was melded with high resolution USGS terrain data. DEM (Digital Elevation Model) data were used to identify terrain elevations. Elevations produced by this model are 3 arc-second quadrangle average elevations from the USGS Landsat radar mapping of the United States. These quadrangles are about 250 ft by 300 ft near the NTS (E-W & N-S dimensions). Flash locations, in latitude/longitude, were matched against the corresponding DEM terrain elevations at each flash location. Total area enclosed by each elevation bin was calculated by simple integration. Each whole quadrangle was treated as an area of constant elevation.

The area selected for this study was a quadrangle defined as longitudes from 115^0W to 117^0W, and latitudes from 36^0N to 37.75^0N (Fig. 1). Large variations in terrain elevation are enclosed within this area. High terrain elevations range from 9000 ft MSL to near 12000 ft MSL over the large mountain ranges, down to terrain located below sea level in Death Valley.

CG flashes were summed into elevation bins of 500-ft intervals. The total number of flashes in each 500-ft bin was plotted against the lower limit of the range. For example, in Figure 2, the flash data plotted for the 5000-ft bin (bin 50), on the horizontal axis, represent the total number of flashes in the 5000-ft to 5499-ft range. The "0" bin includes all terrain elevations below 500-ft MSL. The data were not adjusted for detection efficiency.

The CG lightning database contained 103,581 flashes within the 34,573-km^2 area for a flash density of 3.0 fl/km^2 for the eight warm seasons; or 0.37 fl/km^2/warm season. This flash density matches that reported by Orville and Silver (1997) for southern Nevada. However; based on the guidance provided by Cummins, et al. (1998), only CG flashes with peak currents ≥5 kA were considered in this study. Under this

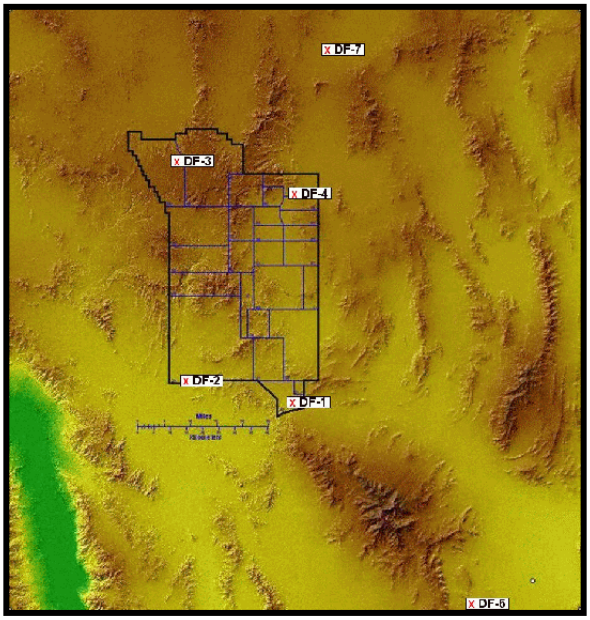

Figure 1. Terrain image of the area used in this analysis. The "DF" stations identify the locations of the NTS lightning detection system direction finders. Green shading is Death Valley.

constraint, numerical review of the database produced a total of 61,827 flashes, of which, 1784 (or 2.9%) were positive. Figure 2 illustrates the distribution of the 61,827 flashes as a function of 500-ft elevation bins. In this figure notice that flash counts closely match bin areas. A little arithmetic shows that 15% of the CG flashes were in the 4500-ft bin and 60% of the flashes were concentrated between 3500-ft and 6000-ft MSL.

Flash Density and Terrain Elevation

To reveal any variation in CG flash counts with terrain elevation, total flash counts for each 500-ft bin were tabulated and normalized with respect to bin areas. The result of this process is shown graphically in Figure 3. The largest flash densities occur between 7500 and 9500-ft MSL and the maximum flash density (total counts) for the eight warm seasons was between 8500 and 9000-ft MSL, namely, 4.63 fl/km^2 or 0.58 fl/km^2/warm season. The plot in Figure 3 portrays a steady increase in flash density from below sea level (bin 0) up to the 8500-ft level (bin 85). Above that level, the bin areas become very small so that the confidence in the data representing anything meaningful is uncertain. Schultz and Diendorfer (1999) reported a similar increase over the Austrian Alps, but only up to approximately the 6000-ft level MSL. Above 6500 ft, flash densities decreased rapidly. Reference to Figure 2 reveals that bin areas become quite small for the higher terrain elevations. In fact, the top five bins contain only 0.7% of the flashes and include 0.3% (1200 km^2) of the total area. The top bin (bin 110) area is only 3.1 km^2. Consequently, as the area becomes small, the addition of a single flash can have a large impact on the flash density. Review of the data indicates that the flash densities above the 9000-ft level are not statistically robust. Kaney et al. (2001) reported similar results in an analysis of flash density versus terrain elevation over Arizona, Utah, Colorado, and New Mexico.

A least squares fit to the flash densities for all 23 elevation bins yields,

$$F(z) = [4.78 + 0.00348z]10^{-1} ,$$

where F is the flash density for the eight warm seasons, z is terrain elevation in feet, and r^2 = 0.79. This equation represents a good fit to the data; however, there is considerable scatter for the upper five bins (those above the 8500-ft level).

Positive CG flash densities were also stratified into elevation bins. However, the data are insufficient above the 7500-ft level to yield any meaningful results. The top seven bins contained only 1% of the positive flashes and bins 95 through 110 contained only three positive flashes. Outside of these bins, the greatest positive flash densities appear to be concentrated between 6000 ft and 8000 ft MSL with the peak flash density (0.9 fl/km^2) between 6500-ft and 7500-ft levels for all eight warm seasons.

Flash Density, Terrain Elevation, and Local Time

When adequate moisture is present over the southwestern United States, CG lightning

activity is modulated primarily by topography and the solar heating cycle (i.e. Reap, 1986, Lopez and Holle, 1986, Watson, et al., 1994, Randerson, 1999, and Randerson and Sanders, 2000). To portray these processes, summertime CG lightning activity was examined relative to terrain elevation and local daylight time (centered on the hour, ± 30 min). The result of this summary is shown in Figure 4. The data plotted in this figure clearly illustrate a pronounced diurnal minimum between 0500 and 1100 PDT, a dramatic increase in CG activity between 1100 and 1300 PDT, and a gradual decline in activity after 1600 PDT. Furthermore, notice the shift in peak flash activity from 1300/1400 PDT over the highest terrain to between 1500 and 1700 PDT over the lowest elevations. Several other fascinating data areas appear in Figure 4. A late evening maximum appears at 2200 PDT for terrain above 7000 ft MSL and another small increase in activity occurs between 0200 and 0300 PDT at essentially all levels above 2000 ft MSL. Of course, the intense heating of the ground during the summer months drives the afternoon lightning maximum. However, the physical reason for the late evening maximum just before local midnight is unknown and requires further study. It may be related to the maintenance of strong convective instability remaining over the desert long after sunset (Randerson, 1997). As thunderstorms move away from the high terrain into this unstable air, new thunderstorms may develop along outflow boundaries. The weak maximum after local midnight may be an artifact in the database. This maximum is closely tied to three independent thunderstorm events that occurred in September 1997, 1999, and 2000. These may have been synoptically driven.

The large flash densities plotted in bin 110 are the result of a few flashes in a very small area. The peak value plotted in this bin is due to 3 CG flashes, for this hour, in a 3-km^2 area, in eight summers.

Terrain Elevation, Peak Currents, and Flash Counts

Peak current data were matched against terrain elevation and flash counts for both negative and positive flashes. Figure 5 summarizes the results for the negative flashes. In general, this figure shows that the more intense negative flashes are located between the 2000-ft and 7000-ft levels MSL. Moreover, the flash intensity appears to decrease with increasing terrain elevation, especially above the 7000-ft level. Desert thunderstorms over southern Nevada tend to have high cloud bases, usually in the 10000-ft to 12000-ft range MSL. This condition yields long flash channels over the lower desert and short channels over terrain above the 7000-ft level. Consequently, the long flash channels, at lower elevations, should contain more charge and therefore more peak current; and visa versa for the higher terrain.

The average negative flash intensity was 9 to 10 kA. The maximum negative flash intensity detected was -222 kA. The average negative flash intensity (kA) for each 500-ft bin was calculated and plotted as a function of terrain elevation. Only flash intensities ≥5 kA were considered. The plot was approximately linear with an $r^2 = 0.79$. Average flash intensity, Φ, can be approximated by;

$$\Phi(z) = [740 + 0.043z]10^{-2} ,$$

where z is in feet and Φ is in kA.

Positive discharges were also analyzed. However, according to Cummins et al. (1998), positive flashes with peak currents <10 kA may be cloud discharges. Consequently, only flashes ≥10 kA were considered, reducing that database to only 1448 positive flashes. Based on the available data, Figure 6 shows that there were very few positive flashes above the 8000-ft level (bin 80) or below the 2500-ft level (bin 25). The more intense positive discharges appear to be concentrated between the 2500-ft and 6500-ft levels with many of the stronger flashes being in bin 40, or between 4000 and 4500 ft MSL. The most powerful positive flash detected was 163 kA and the average was approximately 14 kA.

Locations of all the positive flashes in this database were plotted on a USGS terrain map. The distribution of these flashes appeared to be random. There was no obvious preference for

the higher terrain or for the large mountain ranges. Positive flashes were scattered over all terrain, from Death Valley to terrain above the 8000-ft level MSL. There were some mountainous areas where the highest terrain was essentially devoid of positive flashes (Sheep Range). Figure 7 shows that when positive flashes ≥10 kA where plotted on a terrain map this result was even more dramatic. This phenomenon may relate to the observation that positive flashes tend to occur during thunderstorm dissipation; or, in this analysis, as the thunderstorms move away from the mountains and dissipate. Fuquay (1982), Orville, et al. (1983) Rutledge and MacGorman (1988), Holle' et al. (1994), and Rakov and Uman (2003) have all suggested that positive flashes tend to occur in the stratiform region or decaying stage of the thunderstorm cycle. This process may be especially true for southwestern desert thunderstorms.

Summary

1. The largest flash densities occur between the 7500- and 9500-ft levels. CG flash activity increases rapidly after 1100 PDT, reaching a peak over the highest terrain between 1300 and 1400 PDT and between 1500 and 1700 PDT over terrain below 6000 ft MSL.

2. There was a solid correlation between terrain elevation and flash density up to the 8500-ft level MSL. Above this level, terrain area becomes too small to yield statistically meaningful results. Moreover, there was no terrain above the 12,000-ft level. Consequently, it is not known if flash densities increase above the 8500-ft level.

3. The largest positive flash densities appear to be concentrated between 6000 ft and 8000 ft MSL with the peak flash density (0.9 fl/km^2) between 6500-ft and 7500-ft levels.

4. The more intense negative flashes were located between the 2000-ft and 7000-ft levels MSL; and negative flash intensity appears to decrease with increasing terrain elevation, especially above the 7000-ft level.

5. The more intense positive discharges appear to be concentrated between the 2500-ft and 6500-ft levels with many of the stronger flashes occurring between 4000 and 4500 ft MSL.

6. Positive CG flashes appear to be random and not a function of terrain elevation. This result is especially true for positive flashes ≥10 kA.

7. Positive CG flashes appear to be associated with the dissipation stage of thunderstorms.

Acknowledgement

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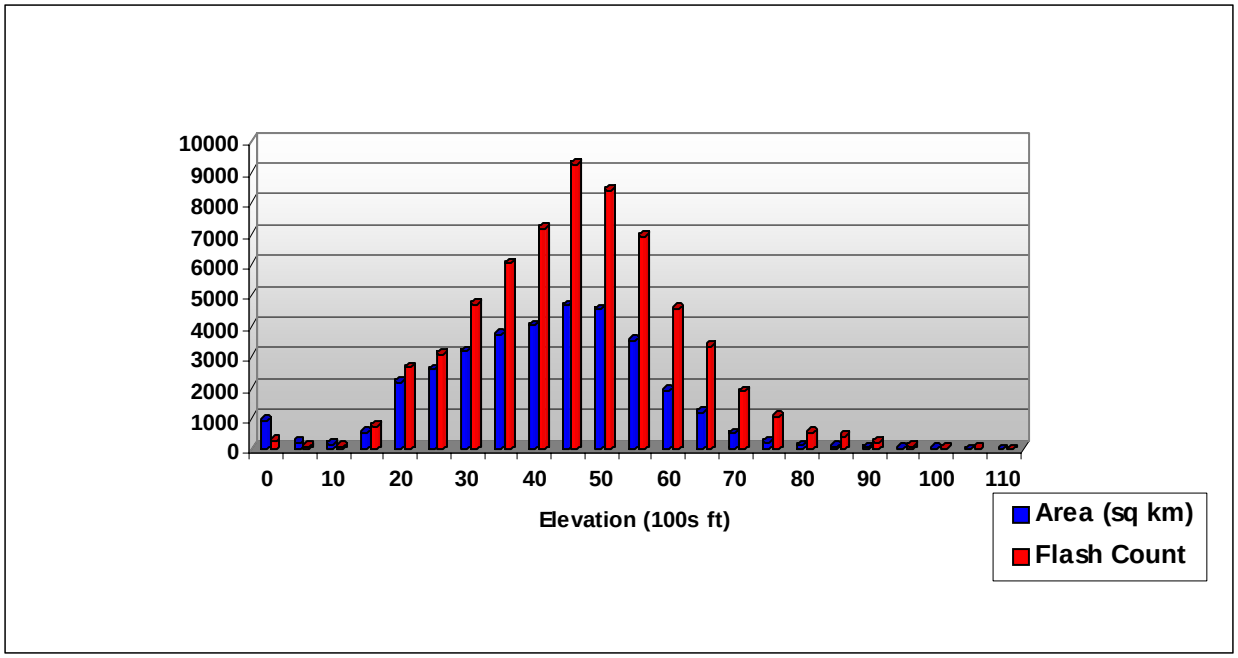

Figure 2. Total number of cloud-to-ground flashes ≥ 5 kA and terrain area (km^2) as a function of elevation bins.

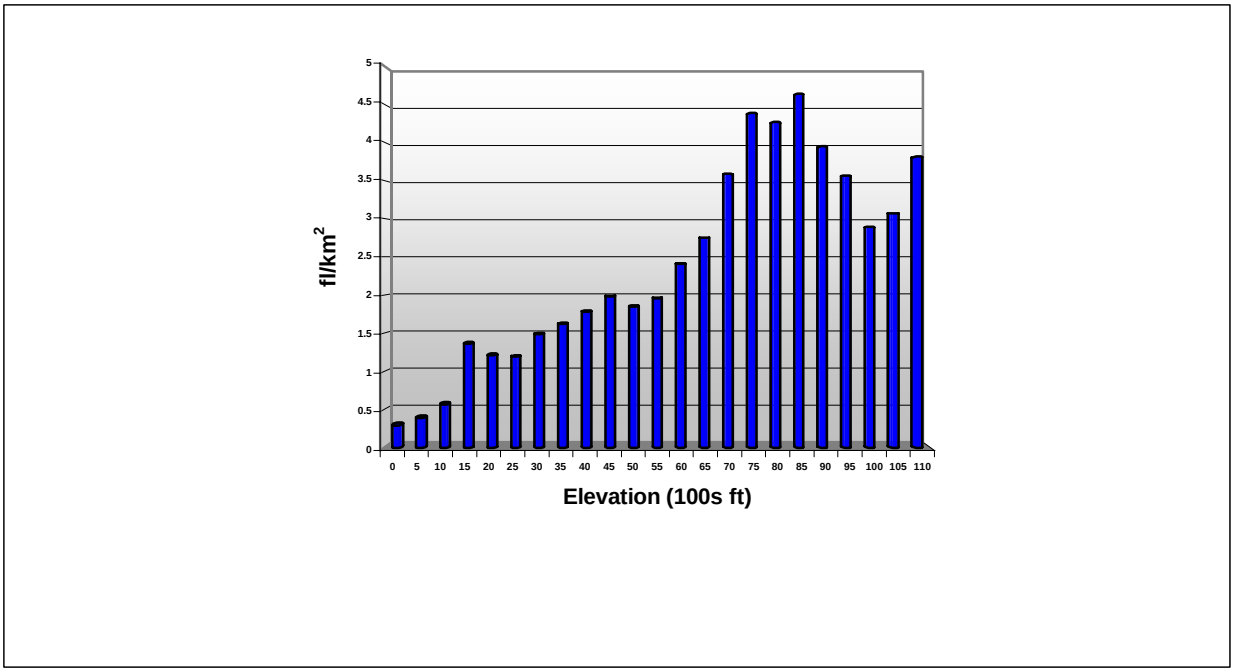

Figure 3. Flash density for all CG flashes with peak currents ≥ 5 kA as a function of terrain elevation for eight warm seasons

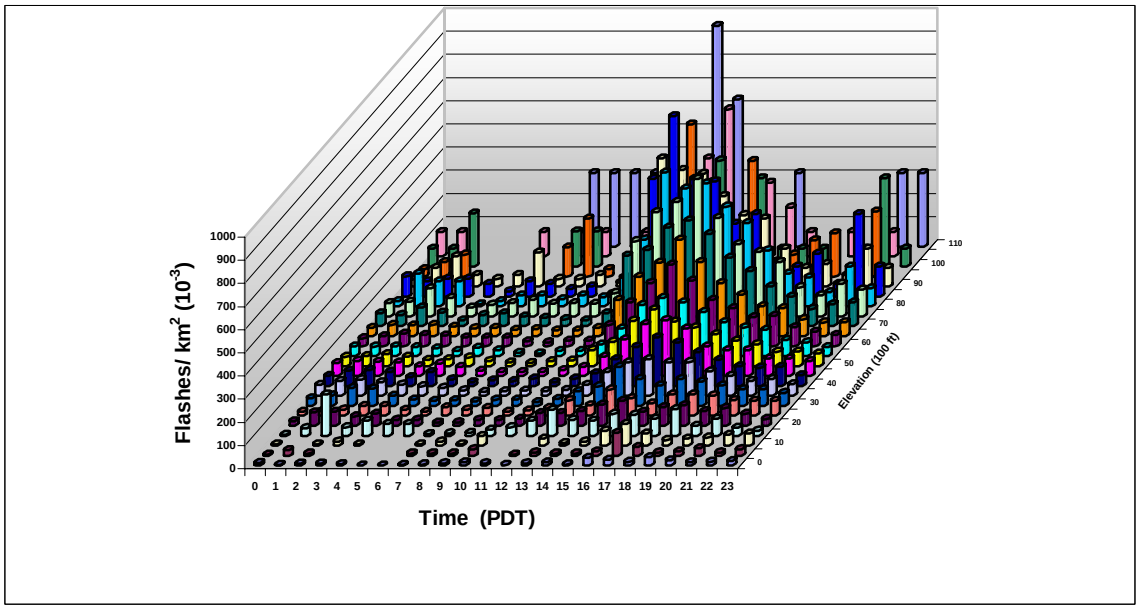

Figure 4. Warm-season flash densities as a function of terrain elevation and local time (PDT) over southern Nevada (1993-2000).

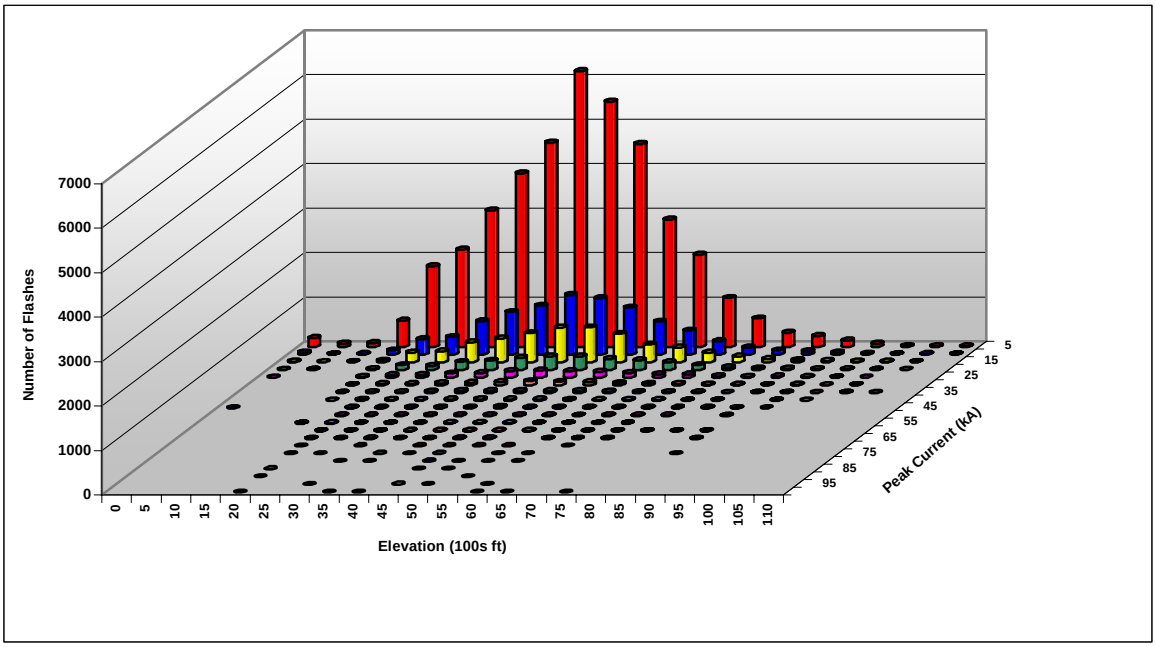

Figure 5. Number of negative cloud-to-ground flashes versus peak current and terrain elevation.

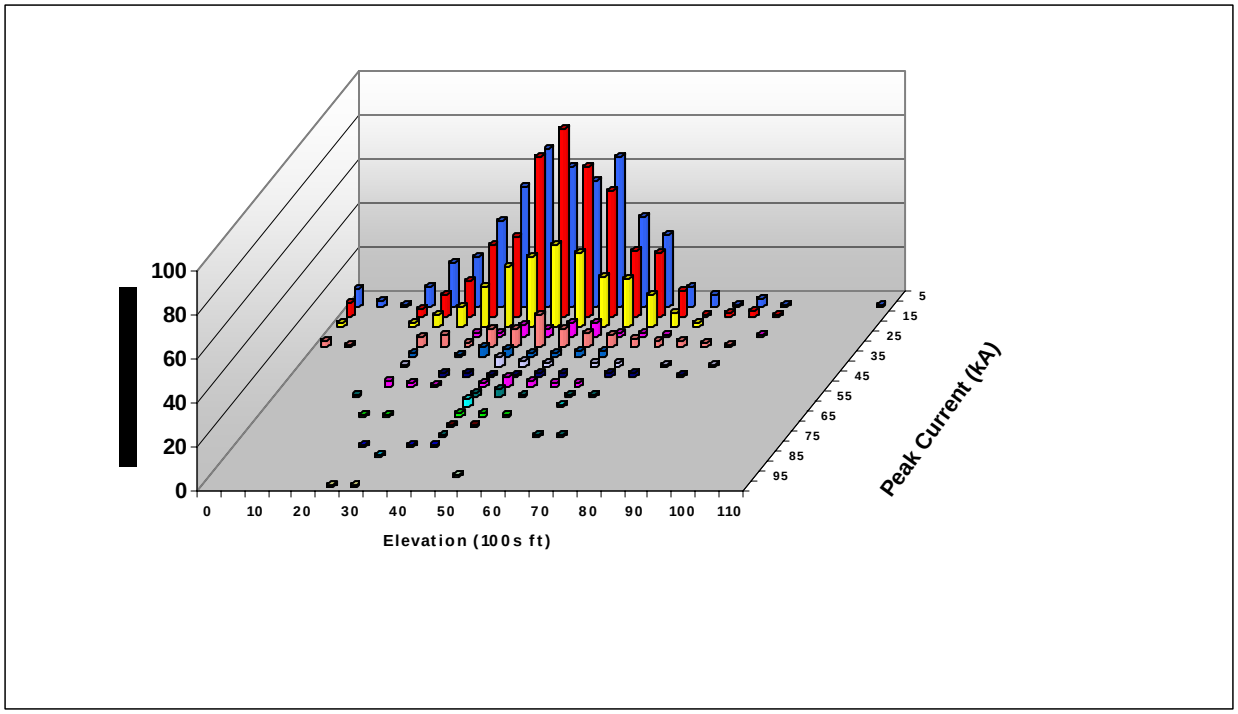

Figure 6. Number of positive cloud-to-ground flashes versus peak current and terrain elevation.

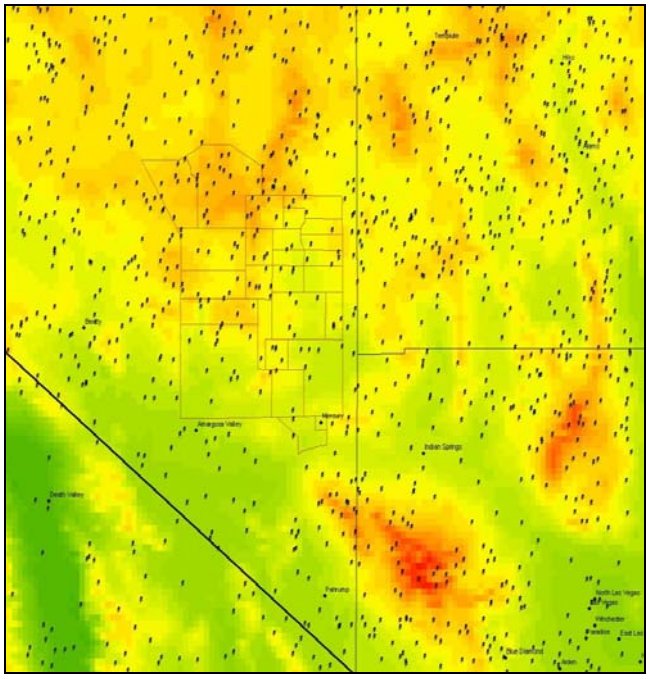

Figure 7. Locations of all positive cloud-to-ground flashes ≥10 kA for the 1993-2000 warm seasons.