The Calculated Risk of Experiencing a Lightning Caused Unplanned Detonation

by
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This paper presents data and theorem to calculate the risk of experiencing undesirable lightning related events while blasting or while engaged in other lightning sensitive activities. The paper provides an overview of lightning hazards in blasting operations and a brief history of lightning related blasting accidents. Lightning continues to be the primary cause of premature initiations of explosives in mining; on average, over two such incidents are reported to the Mine Safety and Health Administration (MSHA) each year. The energy contained in lightning discharges and how this energy sets off explosives in mining is presented. Three categories of lightning warning methods: public media, lightning detectors, and atmospheric electrostatic field measurement are discussed. The remainder of the paper presents recently acquired data on the spatial characteristics of lightning development. This data is used to estimate the risk assumed by blasters under certain conditions. Risk estimations are made for electric and nonelectric blasting if persons are evacuated when cloud-to-ground (c-g) lightning approaches within a certain distance. For example, about 0.6% of all c-g lightning strikes have no other c-g lightning strikes within 25 miles in the previous 30 minutes. The paper shows that a typical blaster using nonelectric initiation in a high lightning density area with a 100% accurate lightning detector set to alarm at 25 miles would have a lightning caused unplanned detonation every 14,000 years.

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Introduction

Lightning has a long history of causing accidents in mining and construction blasting. Considering the amount of energy, it is no wonder lightning has devastating effects. The average lightning strike reaches a peak current flow of about 30 kiloamperes (kA) in less than 10 microseconds. About 1 strike in 100 has over 200 kA current flow (1)[2]. This energy is released in the soil and air of the contiguous United States 10 to 20 million times a year. Areas of Central Florida lead the Nation in lightning density with over 10 strikes per square kilometer per year (s/km^2/yr) (2) and over 130 thunderstorms per year (3). As seen in figure 1 (an adaptation from a discontinued GeoMet Data Services Inc.'s[3] (GDS) World Wide Web page), lightning density is heaviest in the coastal regions of the Southeast and the Midwest, Figure 2 (an adaptation from Changery), shows that thunderstorm frequencies do not decrease the way lightning density does in the west. The implications of this will be discussed in the following analysis.

As in this paper, many others have estimated lightning related risk based on observed lightning frequencies. For example, King estimated a metallic borehole casing extending 1 m (3 ft) from the surface in a flat location with a lightning density of 4 s/km^2/yr would be hit by lightning once every 364 years (4). Since this is a Poisson process, the probability that any area will be hit by lightning in a certain number of years is:

$$y = \frac{1}{A \times f}$$

where;
y = average years between lightning strikes
A = area of concern, and
f = annual lightning strike density

Then, a randomly placed, 20 m (22 yards, yds) diameter circle in a 4 s/km^2/yr area will be hit by lightning about once every 800 years. Another way to define y would be to say that if 800 such circles existed, there should be a hit to one of them every year.

Lightning's annual onslaught results in somewhere between 100 and 200 deaths in the U.S. A U.S. Bureau of Mines' report summarizing Mine Safety and Health Administration (MSHA) data showed that from 1978 to 1993, lightning caused 40 unplanned detonations of explosives in mines (5).

Electrically and nonelectrically initiated surface and underground blasts are at risk from lightning. Indeed, nonelectric blasts have been set off in surface (6) and underground mines (7) by lightning. In the only known underground mining case, lightning energy followed a conductive path, a cased borehole, from the surface into the blasting round. Electric detonators are initiated by lightning induced potential differences in the ground or by lightning's electromagnetic pulses. Previous studies estimated lightning current can penetrate 875 m (2,870 ft) deep in mountainous terrain (8) and electromagnetic pulses from lightning can set off electric detonators over 20 km (11 miles) away (9). Nonelectric detonators are initiated by direct strikes to the tubing, detonator or cord.

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[2] Numbers in parentheses refer to references listed at the end of this report.

[3] Mention of specific companies or products does not imply endorsement by NIOSH.

Taking action such as evacuating a shot under certain conditions greatly reduce personnel risk but do not effect the substantial economical risks of an unplanned detonation (10). Most often, these conditions are seeing lightning or hearing thunder. Safer programs incorporate weather information, lightning detection, and even atmospheric electrostatic field monitoring.

Much weather information is available to the public through the broadcast media, the internet, and subscription services. All blasters, at the very least, should have a day-to-day knowledge of weather forecasts. This can be supplemented by NEXRAD radar data from the internet (usually an hour old) or subscription services (real time). This provides the location and tracking of atmospheric conditions that tend to generate c-g lightning.

Atmospheric electrostatic field monitoring (AEFM) at the ground level can detect an electrical charge in the atmosphere. This allows detection of charge building in clouds overhead and is the only way to warn of the first strike from a thundercloud. Electric field mills are the most common instrument used for this, but they are not portable and cannot detect any field change from ambient over 10 to 20 km (5.4 to 11 miles) away from a thunderstorm (11). The *effective* range of this method is only about 2 km (1 mile). Usually, only permanent facilities such as rocket launch pads, airports, amusement parks, military test beds, and others, which cannot risk an unannounced lightning strike, employ AEFM. These facilities often deploy a network of field mills to provide a reasonable warning time.

Because of the high false alarm rate of AEFM (12), lightning detection is required for reasonable protection without frequent false alarms. An AM radio can provide crude detection of lightning, and "lightning detectors" automate the process. Some of the best lightning detection is done by the National Lightning Detection Network (NLDN), a network of sensors and computers that record the location (within 2 km (1 mile)), time, and other parameters of nearly all c-g lightning strikes to the U.S.

When using lightning detection, precautionary action takes place when lightning comes within a specified range. The greater the range, the less likely a failure-to-alarm will occur. The shorter the range, the more likely a failure-to-alarm will occur. The remainder of this paper outlines how to determine the failure-to-alarm probability based on range and other variables.

Discussion of Variables and Data

Four main variables determine the probability of experiencing a lightning caused unplanned detonation. The first is the frequency of lone lightning strikes and is presented for the first time in this paper (to the best knowledge of the author). Lone lightning strikes are those without any other lightning strikes within a certain distance in the previous 30 minutes. These are the first strikes from developing thunderclouds or are "out-of-the-blue" and present the greatest threat to blasters. The strong relationship shown in figure 3[4] was derived by analyzing 4.4 million lightning strikes recorded by the NLDN in 1995. Only strikes inside the boundary shown in figure 4 were queried for their "lone" characteristics, but all strikes in the previous 30 minutes, even those outside the boundary, were examined for their proximity to the potential "loner".

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[4] Figures 3 and 5 are in English units because most lightning detectors in the U.S. have range settings in English units.

When the data was sorted by the regions shown in figure 4, two clear relationships came out in figure 5 east and west of the -102° longitude dividing line. Even though the west has less lightning per unit area than the east, western storms are more dangerous since they contain a higher percentage of loners. This is an effect of the differences noted in figures 1 and 2. The different thunderstorm genesis processes in the east and west (13) explain this. Topographical effects influence the sporadic thunderstorm development in the west (14). Elsewhere, thunderstorms are caused by collisions of hot and cold air masses which generate lightning under more localized processes than in the west.

The other variables affecting risk are the annual lightning strike density as shown in figure 1, the area of vulnerability, and the time exposed. The vulnerable area for a nonelectric blast is simply the size of the blast. The vulnerable area for an electric blast is not nearly as clear cut since it depends on terrain, geology, legwire orientation, and lightning channel orientation. This complicated situation will be clarified in the example.

If lightning activity were evenly spread over time, the effect of exposure time would be straightforward. However, hourly lightning activity has daily, seasonal, and local variations (15). Figure 6 is a graph of the percentage of lightning strikes per hour per day in Central Daylight Time within the boundary shown in figure 4 from 6/12/96 to 10/9/96. By adding the percent of daily lightning activity in figure 6 for each hour normally exposed and accounting for days off, the percentage of lightning strikes which occur during working time can be calculated. Even though 10.5 million lightning strikes were analyzed to arrive at the relationship shown in figure 6, it is only an approximation since it shows data from across 4 time zones and for only 5 months of the year. Localized data is available through GDS for any location in the U.S. and would improve the risk estimation.

These four main variables (lightning flash density, loner percent, vulnerable area, and exposure factor) provide a reasonably accurate long-term lightning risk assessment for any blasting operation in the contiguous U.S. Other variables affect risk and could improve the risk calculation for a specific operation at a specific time. For example, data used in the following examples assume handling explosives will not occur for 30 minutes after a lightning threat is declared. As seen in figure 7, the waiting time observed will affect the number of lone lightning strikes experienced. Figure 7 shows the number of lone lightning strikes based on different waiting times for three data sets, 25-mile (46 Km) loners on 8/20/95 and 8/22/95, and 50-mile (93 Km) loners on 9/1/95. The relationship represented in figure 7 suggests the standard 30 minute waiting time is practical. For example, if the waiting time was increased 50% to 45 minutes on 8/20/95, the number of lone lightning strikes would have only decreased by 15%.

Another interesting variable observed in the data is the effect of how much lightning there is in a day. As one would expect, the percentage of lone lightning strikes is inversely proportional to the number of lightning strikes per unit area. This trade-off results in about the same number of loners per day regardless of how many total strikes there are in that day (for days with over 50,000 strikes). Figure 8 shows there are about 100 lightning strikes each day in the U.S. with no other lightning strikes within 100 miles (185 km) in the previous 30 minutes. These variables will be given more consideration in future work.

Example Calculations of Risk

To calculate a blaster's risk of experiencing a lightning caused unplanned detonation, the previous formula can be modified to:

$$y = \frac{1}{A \times f \times l \times t}$$

where:
l = loner frequency in percent, and
t = exposure time factor in percent.

Loner frequency can easily be read from figure 5 using the appropriate curve depending on one's location relative to figure 4. The determining factor is the distance c-g lightning is allowed to approach before an alarm is declared. If seeing lightning or hearing thunder is used as a warning, an exact and consistent range is impossible since terrain and weather conditions dictate the observance of these. In addition, cloud-to-cloud (c-c) lightning, which is not detected by the NLDN, both lights the sky and causes thunder. Since thunder is typically inaudible beyond 15 km (8 miles) (16), this range is selected to represent a typical noninstrumented approach in the following examples. If a c-g lightning detector is used, a protocol usually dictates the range. In the following examples, 46 km (25 miles) represents a lightning detector approach. The loner frequencies at 15 km (8 miles) and 46 km (25 miles) would then be 6% and 1.5% in the west, and 2.5% and 0.5% in the rest of the U.S. respectively.

The exposure time factor depends on the time period exposed and lightning's diurnal pattern. The blaster must determine his usual time period exposed. Refer to figure 6 for lightning's diurnal pattern or use localized data if available. The exposure factor is then the sum of each hour's daily lightning percent for the period exposed times the percentage of days exposed per year. For example, suppose a blaster's routine was to shoot two shots a day, the first from 7:00 a.m. to 11:00 a.m., and the second from 1:00 p.m. to 5:00 p.m. Assuming this blaster worked in the Central Time Zone, his exposure factor per day worked would be: 2% + 2% + 2% + 2% + 7% + 10% + 12% + 13% = 50% or 0.50. Assuming this blaster shoots 200 days out of 365, the annual exposure factor would be: 50% X 200/365 = 27 % or 0.27. In other words, 27% of all lightning in the U.S. occurs while this blaster is handling explosives.

The vulnerable area depends on the initiation system used. In the following example, nonelectric and standard electric detonators (250-milliampere no-fire level) are considered. With nonelectric initiation, the area is the plan view size of the shot plus at least 10 m (33 ft) in all directions since arcs several meters long extending from a lightning strike point have been photographed (17). It is assumed any lightning strike in this zone will initiate explosives. In the following example, a nonelectric shot 100 by 25 m (330 by 80 ft) is assumed. The vulnerable area would be approximately: 120 (m) X 45 (m) = 5,400 m^2 or 0.0054 km^2 (58,000 ft^2).

The probability of initiation of an electric detonator is not as easy to determine since it depends on the proximity of the lightning strike, the amplitude of that strike, the terrain, and circuit characteristics like resistance and orientation. Although several authors have addressed this issue (18, 19), none have come up with simple answers that can be used here. The best data may come from eyewitness accounts of unplanned detonations of electric shots. In almost every case, the eyewitness says they saw a lightning flash and the explosives went off moments later. In a few cases, the investigators thought they found the actual strike location. Although we cannot be certain, it is assumed in the following example that any lightning strike within 200 m (660ft) of an electric shot will set it off and any strikes further away will not. Given the same size shot as in the nonelectric example, the vulnerable area would be: 500 (m) X 425 (m) = 212,500 m^2 or .2125 km^2 (2.3 million ft^2).

The lightning strike frequency is read from figure 1 based on the blaster's location. Assuming locations in New Mexico, Central Florida, and Southern Illinois, the lightning strike frequencies would be 2, 10, and 4 strikes per km^2 per year.

Table 1 summarizes the different possibilities outlined above.

Table 1 shows the probability of experiencing a lightning caused unplanned detonation is not insignificant. To put this risk in perspective, a comparison can be drawn using data from fatal vehicle accidents. In 1995, the fatality rate per 100 million miles traveled was 1.7, and the fatality rate per 100,000 population was 16 (20). This equals one fatality per for every 59 million vehicle miles traveled. If a person drove 12,000 miles (19,050Km) a year, it would take about 5,000 years to travel 59 million miles (53.7 million Km) at which point they would have been expected to be involved in a fatal accident. Reducing the fatality rate per population shows that one in every 6,250 persons died in a vehicle accident in 1995. These are the same levels of risk as some of the examples in Table 1.

As different blasting situations lead to different levels of risk, so do different transportation means. As one might expect, motorcyclists were 16 times more likely than passenger car occupants to be involved in a fatal accident per mile traveled. Since we make a choice whether or not to travel by motorcycle, we should be able to make blasting choices based on fact. The motorcycle/car analogy can be applied to each of the blasting variables. The following have a 16 fold increase in lightning risk, blasting in central Florida compared to on the west coast, and allowing lightning to come within 8 miles (13 km) compared to 63 miles (100 km).

Based on accident history, the estimated probability of an electric blast being initiated by lightning is about right. The Institute of Makers of Explosives reports that there were about 1.8 million blasts in 1993 (21). Assuming about ½ of all detonators sold in the U.S. in 1993 were electric (22), we can estimate there were about 900,000 electrically initiated blasts in 1993. If they averaged 4 hours in loading time, it would require 3.6 million blaster-hours. Since the typical blaster in the example is exposed 1,600 hours per year, it would require 2,250 typical blasters to do all the electric shots per year. There are about the right number of incidents since there are about 2.5 lightning caused unplanned detonations per year reported to MSHA. Table 1 shows 1 in 350 electric blasting operations should have an unplanned detonation caused by lightning each year if all were located in an area with lightning density of 2 s/km^2/yr and used a detection range corresponding to a loner percent of 2.5 (8 mile eastern warning). Assuming this is an average condition, there would be 875 typical electric blasters (2.5 incidents/year x 350 years/incident/blaster). Although this is different from the 2,250 electric blasters calculated above, consider that the calculated value includes nonmining blasts and the actual incident rate in mining is probably higher then the reported rate.

Error in the examples could come from at least two possible sources. One could be the distance at which lightning will set off electric detonators as discussed earlier. If the vulnerable distance were reduced from 200 to 100 m (660 to 330 ft), the years between premature blasts would increase by a factor of 3. To use the motorcycle/car analogy again, if the vulnerable distance was 120 m (390 ft), the risk would be 16 times greater than for the same sized nonelectric shot in the example. The second source for error is in the assumption that when lightning is seen or thunder is heard, precautions are taken, and c-g lightning was no more than 8 miles away. In reality, blasters probably interpret c-c lightning and thunder as threats and halt operations. This type of lightning often precedes c-g lightning in developing thunderclouds, but is not detected by the NLDN. Also, most blasters probably rely on more than the reactionary approach outlined here which would lead to safer operations.

Conclusions

Lightning is a serious threat to all blasting operations. The risk of experiencing an unplanned detonation caused by lightning while blasting is determined by four main factors:

- annual lightning flash density;
- percentage of lone lighting strikes;
- vulnerable area of the blast; and,
- percentage of lightning exposed to.

The annual flash density is uncontrollable but the other three factors are controllable. The percentage of lone lightning strikes experienced, and hence the risk, is two to three times higher in the western U.S. than elsewhere. Blaster's can dramatically reduce their risk of having an unplanned detonation from lightning by using an accurate lightning detection system, by using nonelectric initiation, and blasting in the morning. Depending on exact circumstances, the probability of a blaster experiencing an unplanned detonation from lightning ranges from once every 10 to once every 100,000 years.

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Table 1. Probability of experiencing an unplanned detonation from lightning.

Western Region

Lightning Strike Frequency, (strikes per km^2 per year)	Loner Frequency, %	Vulnerable Area, (km^2)	Exposure Factor, %	Average Years Between Lightning Caused Unplanned Detonations
2	6	0.0054	27	5,700
2	1.5	0.0054	27	23,000
2	6	0.2125	27	150
2	1.5	0.2125	27	580
4	6	0.0054	27	2,900
4	1.5	0.0054	27	11,000
4	6	0.2125	27	73
4	1.5	0.2125	27	290
East, Gulf, and Central Regions				
2	2.5	0.0054	27	14,000
2	0.5	0.0054	27	69,000
2	2.5	0.2125	27	350
2	0.5	0.2125	27	1,700
4	2.5	0.0054	27	6,900
4	0.5	0.0054	27	34,000
4	2.5	0.2125	27	170
4	0.5	0.2125	27	870
10	2.5	0.0054	27	2,700
10	0.5	0.0054	27	14,000
10	2.5	0.2125	27	70
10	0.5	0.2125	27	350

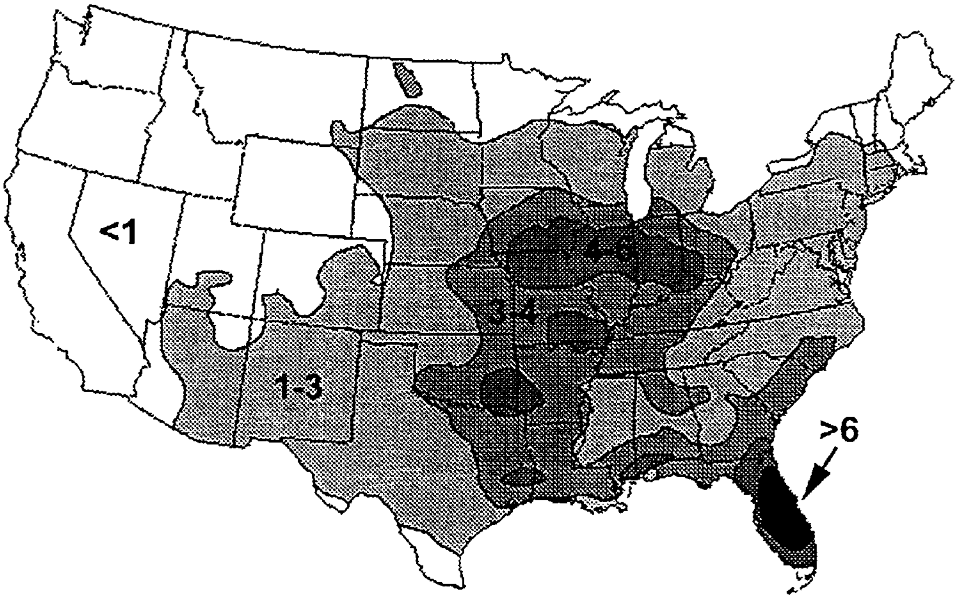

Figure 1. NLDN measured lightning flash density (strikes per square kilometer per year) from 1989 to 1993 (© GeoMet Data Services, Inc.).

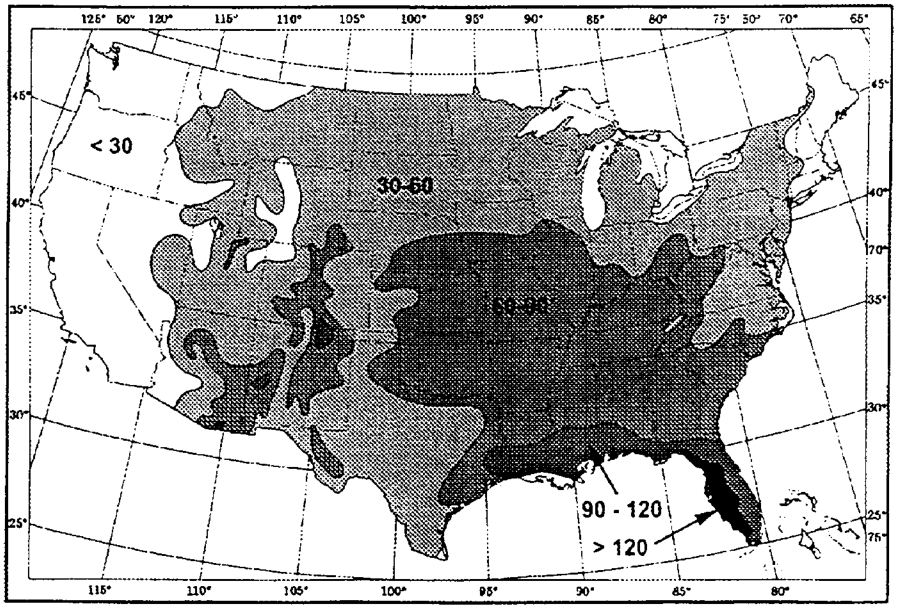

Figure 2. Average number of thunderstorms per year based on thunder reports from weather observers (from M.J. Changery, 1981).

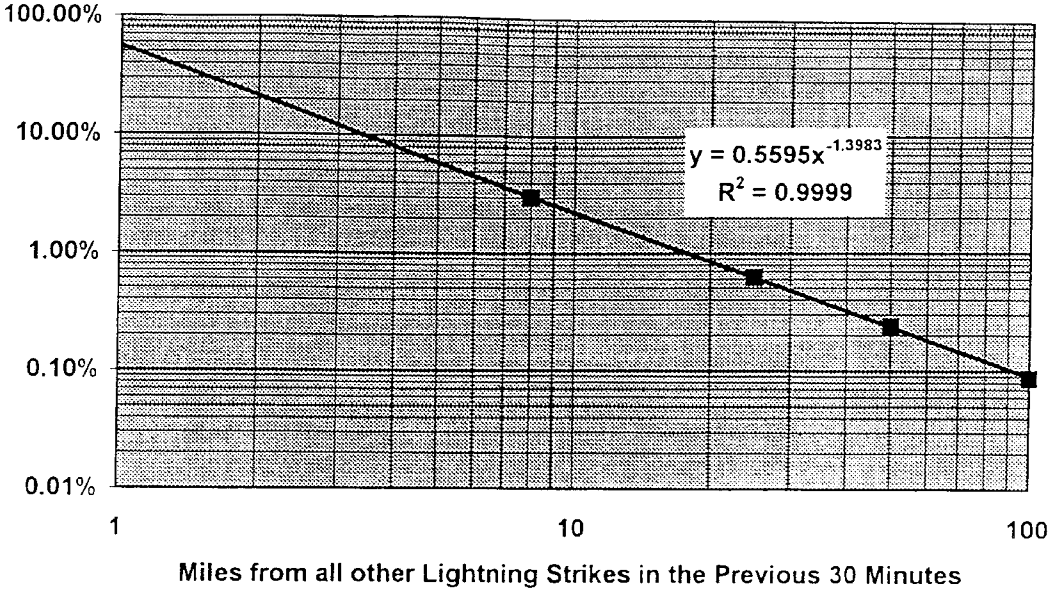

Figure 3. Frequency of lone lightning strikes

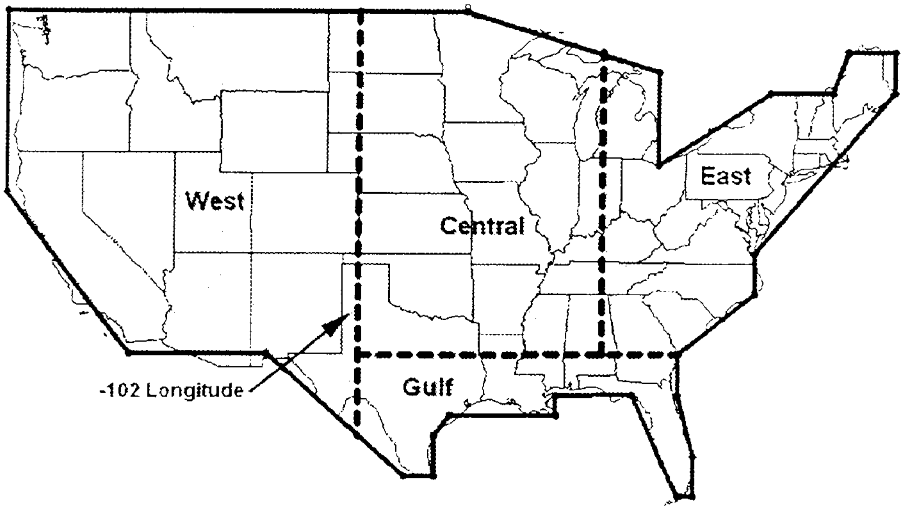

Figure 4. Boundary and regions for the lightning data analyzed.

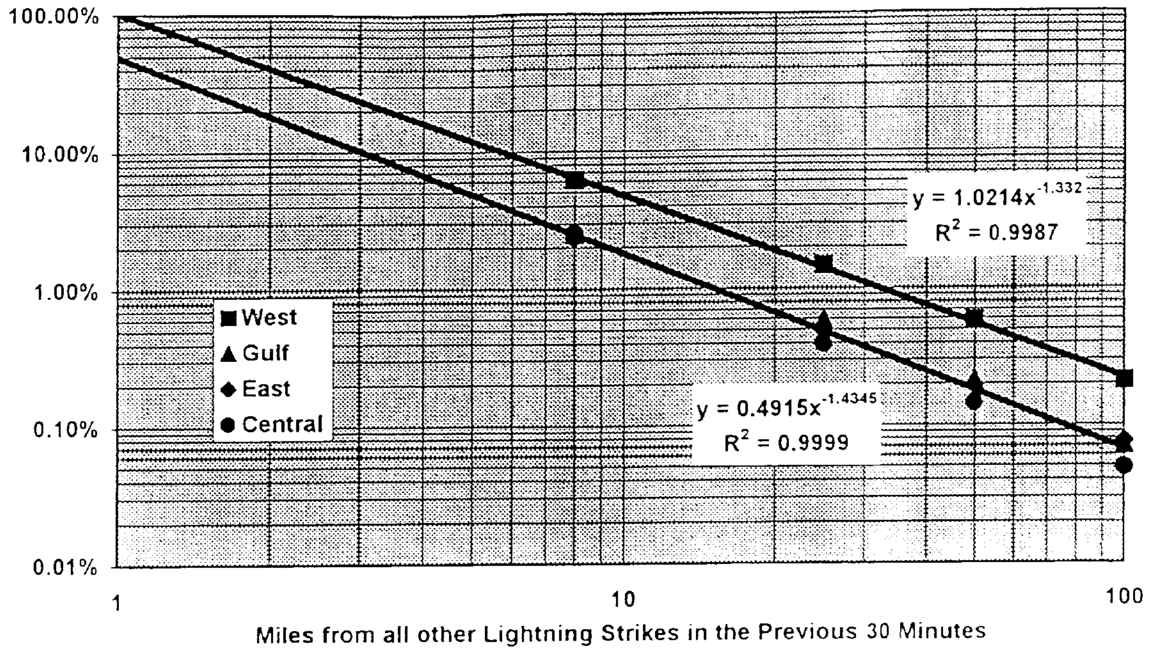

Figure 5 Difference in the frequency of lone lightning strikes from east and west of -102° longitude

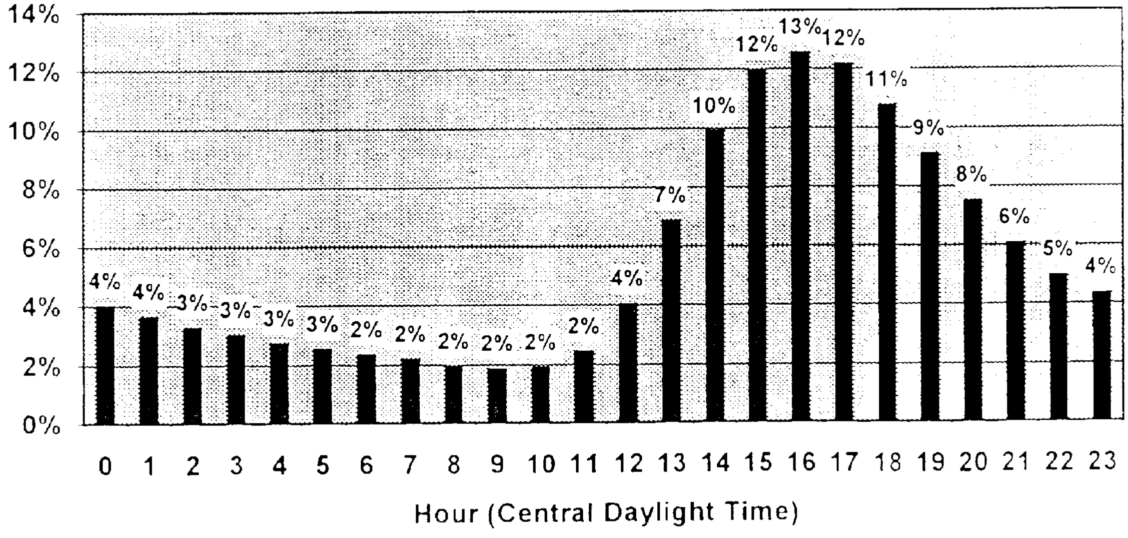

Figure 6 Lightning's diural pattern from 6/12/96 to 10/9/96.

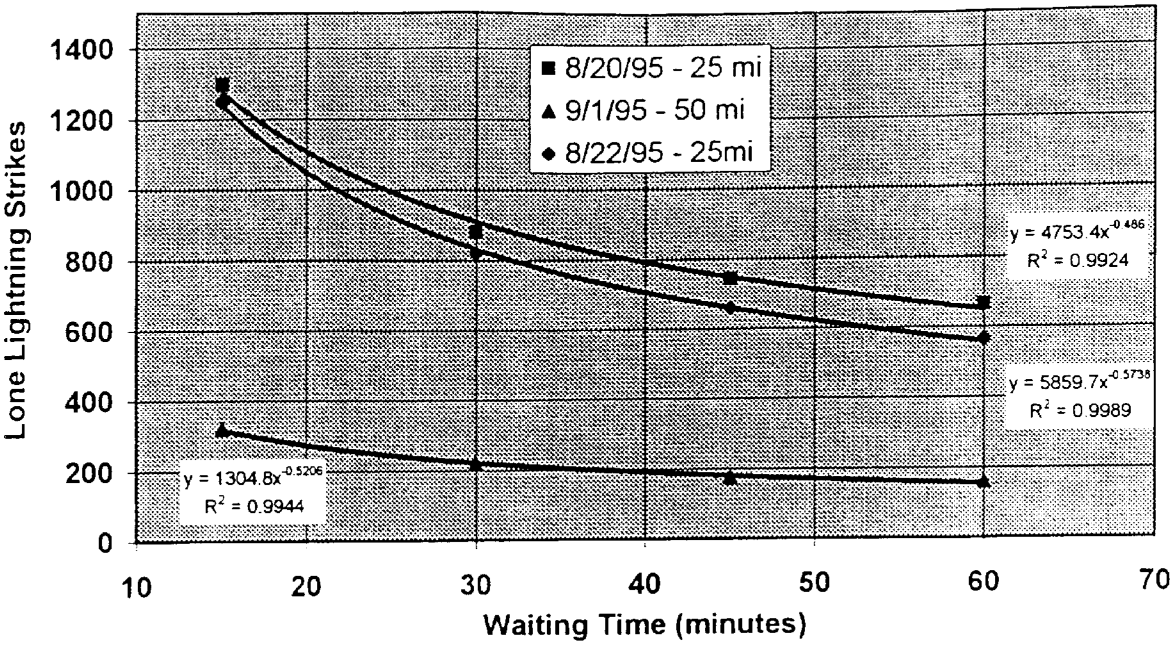

Figure 7. Number of lone lightning strikes as a function of waiting time after a lightning threat has been declared.

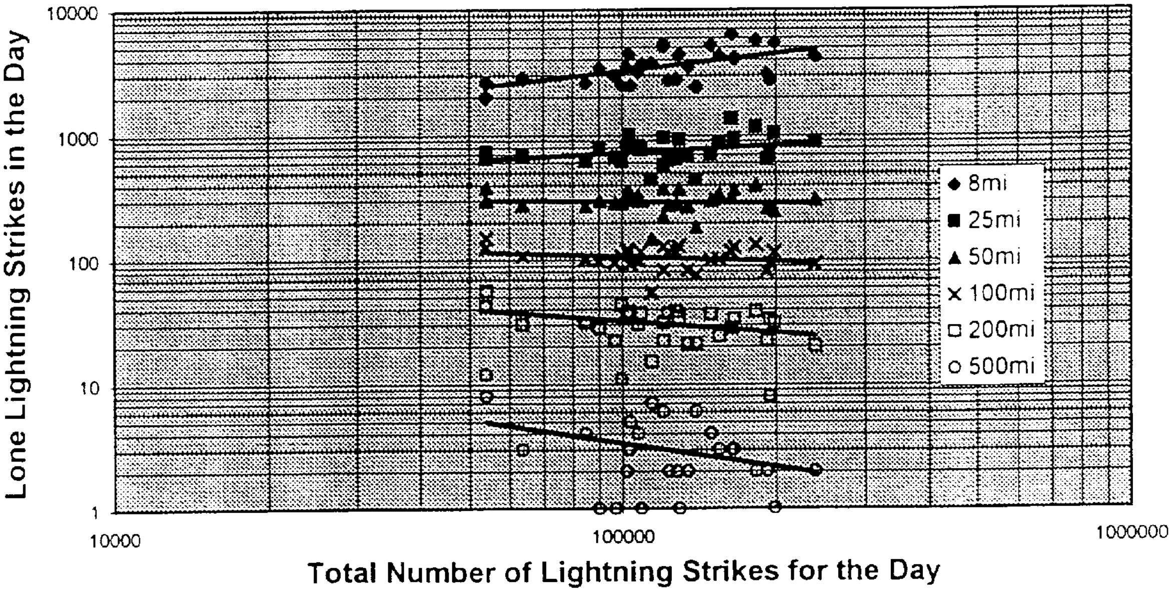

Figure 8. Number of lone lightning strikes in a day as a function of the total number of lightning strikes in that day.