ANALYSIS OF THE LIGHTNING-PRECIPITATION RELATIONSHIP FOR CONVECTIVE STORMS OVER ALBUQUERQUE, NEW MEXICO

by

Carol L. Rison

Independent Study

Submitted in Partial Fulfillment of the

Requirement for the Degree of Master of Science

in Geology

New Mexico Institute of Mining And Technology

Socorro, New Mexico

June 17, 1991

Abstract

Lightning and precipitation data for twenty-three convective storms that occurred over Albuquerque, New Mexico, during the summers of 1986-1988 were processed and analyzed in an attempt to determine a possible statistical correlation between them. Lightning data were recorded by magnetic direction-finders and archived by the Bureau of Land Management. Storm rainfall depths were recorded by an irregular network of twelve gages covering an area of 150 km^2, operated by the United States Geological Survey.

Analysis included Thiessen and grid-point rain-depth interpolation to determine total storm volume and a rain-volume per cloud-to-ground lightning flash (VPF). Correlation was assessed by non-parametric, ranked values because a continuous storm record was not available. Storm cell lightning-rainfall lag was determined by peak intensity and also by center-of-mass, to indicate the validity of their time-association. An attempt was made to apply near-storm atmospheric-moisture conditions to predict VPF values.

Interpolated rain averaged half the Thiessen-derived amount; nevertheless a relatively high mean VPF was determined for Albuquerque storms compared to values measured by researchers in other localities of the United States. A threshold lightning count indicated associated increases in precipitation for Albuquerque's largest storms. This threshold was substantiated by the results of ranked correlation. The surveys of twenty rain cells revealed a mean lightning-rain lag time of ten and twelve minutes, respectively. Moisture conditions below cloud base did not correlate with VPF, but a larger data sample may reveal relationships for specific geographic locations.

Contents

List of Figures

List of Tables

Acknowledgment

Many people contributed to this effort. John P. Borland and Richard Thomas (formerly) with the United States Geological Survey Water Resources Division in Albuquerque, New Mexico, provided raingage and runoff data. Kevin Metzker of the USGS checked the accuracy of those records. Dr. David Raymond and Dr. Alan Blyth, atmospheric physicists at New Mexico Institute of Mining and Technology, assisted with rainfall interpolation and humidity calculations, respectively. Former New Mexico Tech physics students Thomas Mark Blackman and Robert Solomon helped with data conversion. Sandra Kieft, New Mexico Tech Langmuir Lab office manager, contributed wordprocessing advice, accounting skill, and patience. Last, but far from least, my husband, Bill Rison, donated much technical and emotional support. My sincere thanks to all of you.

1 Purpose

This study is a first attempt to determine precipitation and lightning relationships in summer convective storms over Albuquerque, New Mexico. Although thunderstorms have proved to be difficult entities to study scientifically, much work continues to be undertaken all over the world, concerning storm properties such as wind, rain and lightning intensities and the hazards they pose to life and property.

One question in particular has prompted inquiry from atmospheric scientists: are lightning and precipitation related in these storms? If so, to what extent? This project was conducted to examine the characteristics of Albuquerque thunderstorms to determine, if possible, whether a threshold cloud-to-ground lightning count might be used to indicate a time-associated precipitation volume. Such a value might make it possible to use real-time lightning data to supplement radar and satellite data in weather forecasting. For example, assessment of flash flood probability could be much improved in this manner.

2 Introduction

2.1 General Aspects of Convective Storms

Convective storms occur most frequently at low latitudes, where excess heat and moisture initiate vertical instability. They also contribute significant rainfall in temperate zones, when favorable climatic conditions prevail (Kessler, 1986 and Krehbiel, 1986).

Solar radiation reaching the ground surface is absorbed and re-radiated at infrared wavelength; then this energy gets absorbed by carbon dioxide and water vapor present in the atmosphere and is converted to heat. Heat-energy redistribution, or convection, is the result of air density (pressure) gradients, which force warm air to rise buoyantly. Convergent air nearer the ground surface cools slowly as it rises, due to absorption of latent heat of vaporization. The most intense thunderstorms occur when such an air parcel eventually expands and cools at a steep lapse rate, or, steep temperature change with altitude increase.

2.1.1 Precipitation

During air-mass cooling, condensation occurs on nuclei of airborne salt, nitrates or sulfates. Some lose moisture by evaporation and others grow by accretion. Growth rate is dependent upon particle size and composition, and size differential is enhanced by air turbulence and collisions.

Convective storm rainfall is intermittent due to the contrasting effects of this condensation: updrafts are caused by release of latent heat of vaporization; downdrafts occur when air density and mass increases in the presence of condensed particles. Hail results when updrafted liquid and ice become cooled, and liquid adheres to ice nuclei. It thus releases latent heat and becomes warmer than the surrounding air. The air parcel in which all of this occurs is called a "storm cell," which generally has a lifetime of ten to fifteen minutes, although it often belongs to a longer-lasting, organized system of multiple cells.

Three stages of thunderstorm precipitation development have been described by Beard and Ochs (1986):

1. cloud stage: cloud droplets and drizzle drops develop
2. rain stage: raindrops are formed by accretion of cloud droplets
3. hail stage: upper cumulus precipitation (soft hail) is formed by accretion of supercooled droplets

2.1.2 Electrification and storm charging mechanisms

"A thundercloud is an electrical generator converting mechanical energy to electrical energy by means of moving charged particles in the convective system of its cells. The generator is loaded by its connection to the Earth-ionosphere system, and some of the charge moment separated recombines in lightning," (Nisbet *et al.*, 1990). Electric fields generated by thunderstorms indicate the strength and direction with which charged storm particles attract or repel other particles. Figure 1 illustrates the typical arrangement of convective-storm charge.

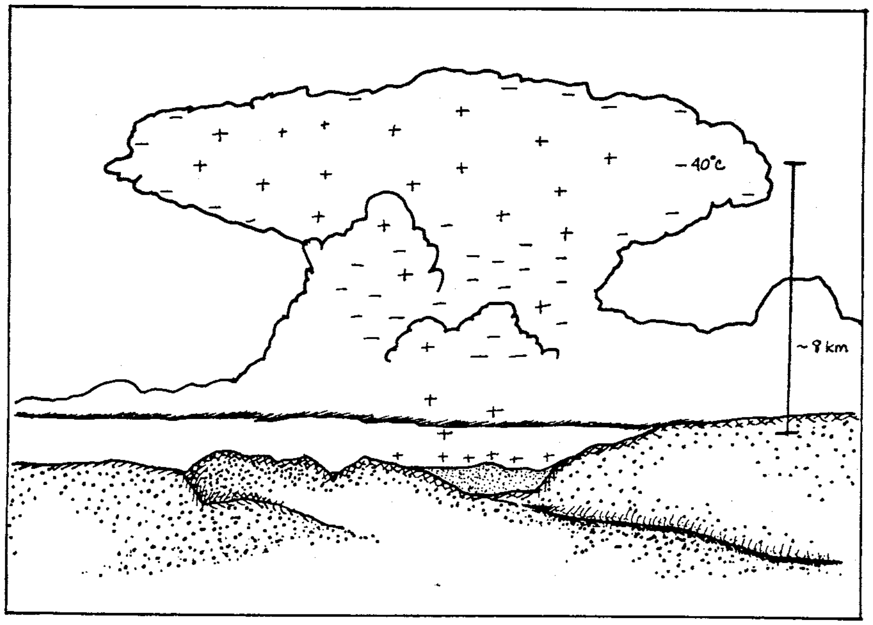

Figure 1: Thunderstorm charge distribution (from Krehbiel, 1986).

The actual mechanism of charge separation has been a controversial subject in atmospheric science for some time. Currently, two theories compete to explain the phenomenon: the convection method and the precipitation method.

Prominent researchers B. Vonnegut, C. B. Moore and co-workers (1958, 1962, 1964) maintain that convection is the driving force for initial charge separation, based on their measurements that electric fields built up before radar observations detected in-cloud precipitation, in storms over New Mexico and one in the Bahamas. Their explanation is that the normal presence of moderate fair-weather electric fields provides positive charge at the ground surface, which gets carried to cloud tops on small droplets, by convective updrafts of warm, moist air. Similarly, the predominantly negative charge existing in the fair-weather upper atmosphere is carried around the outside of developing thunderstorm cells by downdrafts.

Other scientists (Workman and Reynolds, 1949, Lhermitte and Krehbiel, 1979, Krehbiel, 1986, Beard and Ochs, 1986, Levin and Tzur, 1986, Dye *et al.*, 1989) have observed that forms of precipitation initiate enhanced electric fields in thunderstorms by means of their differential charges; this phenomenon has been extensively studied in the field and laboratory. According to Beard and Ochs, there are two ranges of charging mechanisms:

- microscale: charging of cloud and precipitation particles
- cloud scale: electrical field build-up and lightning

operating within the three stages of thunderstorm development previously described. Microscale mechanisms range from diffusion and ion charging during the cloud stage, to induction (collision) and ice-liquid-interface charging during the hail stage.

Krehbiel describes convective storm electrification in terms of three phases. Initially, at altitudes where the temperature is about -10° C, precipitation particles acquire charge according to their size; during collisions between particles, the larger particles acquire negative charge and smaller ones acquire positive charge. Convective updrafts carry the smaller, positively-charged particles to cloud tops, and larger, negatively-charge particles accumulate below, due to gravity settling. Major charge reservoirs develop as seen in Figure 1. A strong positive charge at the ground surface accumulates during this phase, responding to the buildup of negative charge in the cloud base.

As soon as the first lightning occurs, the storm enters the active stage, characterized by the most intense intracloud (IC) and cloud-to-ground (CG) lightning, and resulting electric field fluctuations. As detected from the ground, positive fields jump to negative, then positive fields slowly build again. Pronounced negative jumps are associated with downdrafts and some precipitation during this phase.

The final stage is typified by decreased lightning activity and ground fields which swing slowly from positive to negative and back. At this time a positive CG flash may sometimes occur, in contrast to the negative polarity usually recorded for this type of lightning.

Each CG lightning flash actually consists of several large current surges, or strokes. In the words of Krider *et al.* (1980):

> "A typical flash begins with a faint *stepped leader*, which proceeds rather slowly from cloud to ground in a series of short, intermittent steps. When the stepped leader contacts ground, a very energetic and bright *return stroke* propagates rapidly back up the ionized path established by the leader. After a pause of 30-50 ms, a *dart leader* often propagates down the previous channel and is followed by another bright return stroke propagating upward. A typical flash to ground contains three or four leader-return stroke combinations, which almost always transfer negative charge to ground."

Although the two theories dispute the method in which charge separation is initiated in thunderstorms, they agree that convection is the separation mechanism. Both methods are consistent with a possible relationship between lightning and rainfall, and observations suggest that this is probable (Williams *et al.*, 1989).

2.1.3 The lightning-precipitation relationship

Williams *et al.* (1989) summarized the common characteristics of thunderstorm electrification and precipitation that have been observed by Workman and Reynolds (1949), Lhermitte and Krehbiel (1979), MacGorman *et al.*, (1986), Lhermitte and Williams, (1984) Atchley *et al.*, (1983), Poehler (1978) and Krehbiel (1981), in diverse geographical regions of the United States:

- Summer storms in Florida, Oklahoma, Alabama and New Mexico are dominated by IC lightning in the early stage, which is clearly associated with updraft development and the growth of ice particles in the presence of supercooled water droplets and graupel. Charge separation is seen to result from precipitation-particle collisions in the manner described above. Ten or more IC flashes may occur before the first CG flash.

- The main negative reservoir location is determined by temperature (ranging from below 0 to -25° C), which generally places it at an altitude of 6 kilometers or more. Winter storm cells in Japan tend to have the main negative charge centers of CG lightning located at similar temperature levels (although not necessarily the same altitude) as thunderstorm cells studied in Florida and New Mexico (Krehbiel).

- IC lightning is initiated at the upper boundary of this reservoir and travels upward; CG lightning begins at the lower boundary and propagates, of course, to ground.

- Cloud-to-ground lightning activity typically lags the first IC peak by five to ten minutes, and it is often less consistent and frequent. The first CG flash is associated with hail and graupel descent through the main negative reservoir, where charge transfer may be enhanced. Gravitationally-induced passage of particles through the (minor) lower-cloud positive region may bring about the predominantly negative charge that is carried by CG lightning.

- Microburst outflows at the ground level are caused by melting of ice particles as they descend past the 0°C isotherm. They lag peak lightning activity by five to ten minutes, which is the travel time between the main negative charge reservoir and the ground surface. Williams *et al.* (1989) indicate that IC lightning is the more reliable microburst predictor, of the two types of discharges.

Beard and Ochs propose that the relatively high percentage of intracloud lightning results from the lower atmospheric pressure in upper-cloud regions, which in turn reduces the critical electric field threshold required for discharges to occur. Its association with rapid upward cloud growth seems to indicate that much of the convective cell life-cycle is devoted to upward and/or lateral expansion, and the portion dominated by gravitational processes neutralizes cloud fields relatively quickly.

2.2 Previous convective-storm lightning-rainfall studies

As discussed above, roughly predictable patterns in thunderstorm development are beginning to be revealed by persistent research. One of the additional, and more recent, objectives of this work is to ascertain whether storm characteristics vary due to climate differences. As technology for lightning location detection has advanced, several studies have been conducted to determine a possible lightning-precipitation relationship for certain areas of the United States. Previous and future applications of their results include rainfall enhancement by thunderstorm cloud-seeding, detection of lightning-induced forest fires, and design criteria for lightning and flood wave early-warning systems. Weather forecasters concerned with missile, rocket and shuttle launches also see this as a significant data source (Uman, 1986).

Methods for gathering data have been diverse and inconsistent, as discussed in the following examples. Certain investigators emphasized both intracloud and cloud-to-ground flashes, or just IC flashes, but most looked for a cloud-to-ground lightning-precipitation relationship in accordance with the detection technology available to them. The most sought-after correlation has been that of rain volume typically associated with each CG flash, hereinafter referred to as "VPF."

Louis J. Battan, an atmospheric scientist with the University of Arizona in Tucson, conducted the first published lightning-rainfall study (1965) with summer storm data collected in the Santa Catalina Mountains northeast of Tucson. Precipitation was recorded by twenty-nine gages spaced an average of 7 kilometers apart, and the rain depth was averaged over an area of 1000 km^2 with a 5000 foot elevation change. CG lightning was simply visually sighted from a lookout tower. Battan determined that average rainfall occurred in the volume-per-CG-flash of 3.0×10^4 m^3. However, one may reconstruct from his data a VPF for "light-rain" and "heavy-rain" storm days, respectively, of 8.47×10^4 m^3 and 6.55×10^4 m^3.

Oklahoma thunderstorms were studied by Kinzer (1974), as squall-line storm cells and an individual air-mass cell. His lightning detection equipment included a pair of circular-loop, perpendicular antennas to detect negative charge transferred to ground as sferic pulse-trains. Radar recorded greater precipitation intensity in areas of higher rates of CG lightning. An unquantified correlation was seen between these parameters in both location and time. For both storms, an average VPF was 1.6×10^4 m^3, probably due to the greater overall number of CG flashes in Oklahoma than in Arizona storms, Kinzer concluded.

A Florida study of the lightning-rainfall relationship was conducted by Piepgrass *et al.* (1982) with a 25 tipping-bucket raingage network and the same number of electric field mills, covering an area of 250 km^2 at the NASA Kennedy Space Center. Lightning-detection efficiency for field mills depends upon type of flash and storm location. The effective area for flash detection was considered to be 625 km^2; the raingage perimeter was therefore 40% of the flash perimeter. Two storms were studied in detail. A large and a small event each yielded approximately 2.0×10^4 m^3 VPF, based upon an estimated CG:IC flash ratio of 38% for this area (Livingston and Krider, 1978). Best-time correlation yielded a lag time of 9 and 4 minutes, respectively, between total flashes and total rain at 1-minute averaging intervals.

In contrast, a CG:IC flash ratio of 5.5% was determined for one storm near Huntsville

Alabama, studied by Goodman *et al.*, (1988), using Doppler radar and electric field-change sensors for measurement. The first IC lightning occurred 4 minutes after hail was observed by radar, during rapid vertical cloud growth. 5 minutes later, the first CG flash occurred coincident with a downdraft. Perhaps most significantly, the first cloud-to-ground flash was followed by:

- (3-4 minutes later): peak flash rate coinciding with maximum water content
- (another 2 minutes later): peak precipitation rate
- (another 3 minutes later): rain microburst at ground surface

The authors observed that factors affecting cloud electrification include: a) the concentration of small and large precipitation particles, b) the cloud liquid water content and c) the volume of the cloud in which particle collisions occur. They calculated a VPF of 2.0×10^4 m^3.

Further work in the Alabama, Tennessee and central Florida areas has recently been performed by Buechler *et al.* (1990), Goodman and Buechler (1990) and Buechler and Goodman (1991). Using magnetic direction finder equipment (see page 16) to assess lightning, and radar for rain volume, daily composites of six convective storm events indicated an order of magnitude VPF variability, ranging from 1.1×10^4 m^3 to 9.9×10^4 m^3, as shown in Table 1. These researchers attribute this range to several possible factors:

- Measurement methods have significantly differed from study to study. Particularly the validity of using ground-surface human observers may be questioned, because it is difficult to visually distinguish some cloud-to-ground lightning from intracloud lightning. They consider the use of raingage networks to be inferior to radar to determine accurate VPF values, because raincells are often not ideally situated over gages.

- The vertical distribution of precipitation in a convecting cloud has been recently observed to affect the volume of rainfall reaching the ground. A high center of mass, detected by radar to be located near the main-negative charge reservoir, inhibits maximum VPF values, according to these authors. Strong storm updraft enhances cloud electrification, as previously noted by other atmospheric scientists, yet may have the opposite effect on rainfall that reaches the ground.

- An important factor that has been mentioned but not directly considered by researchers is the effect of subcloud evaporation. Certainly this is a consideration in the drier southwestern United States climate, where *virga*, a visible rain curtain reaching part way to ground surface, often occurs.

It should be noted that the Alabama lightning detection array covered recorded flashes within an area of 300 km^2, although a mobile lightning detection unit extended this range. The six Gulf Coast thunderstorms covered areas ranging from 26 km^2 for single air-mass types to 12,000 km^2 for multi-cell mesoscale storms. Table 1 lists results of previous studies.

Table 1: Estimates of total rain volume per flash for previous studies.

Study	Year	Location	Rain volume per flash (10^4 m^3)	
			cloud-to-ground	all flashes
Piepgrass et al.	1982	Florida	1.8-2.2	0.67-0.85
Battan	1965	Arizona	3	
Kinzer	1974	Oklahoma	1.6	
Grosh	1978	Illinois		1.4
Maier et al.	1978	Florida	1.1-9.2	
Goodman et al.	1986	Alabama	1.1	0.26
Goodman "	1986	Alabama	2.3	0.12
Goodman "	1986	Tennessee	5.5	
Goodman "	1986	Tennessee	1.7	
Goodman "	1986	Tennessee	9.9	
Goodman "	1986	Ala/Tenn	3.6	

2.3 Albuquerque lightning-precipitation study

2.3.1 Climate characteristics

Most of the studies seeking a possible lightning-precipitation relationship have focussed on thunderstorms fueled by Gulf of Mexico moisture. These systems often encompass many convection cells and grow to squall-line super-storms. In contrast, the summer "monsoon" season of the southwestern United States is characterized by two types of precipitation events, both of which have a Pacific Ocean moisture source. These include dissipating tropical cyclones having regional precipitation of relatively long duration, and intense localized thunderstorms of short duration.

Tucson, Arizona, lies in the direct path of the Pacific moisture flux. Topographic influences raise the moist air to a higher elevation in that area; during July and August, air transported over Tucson experiences enhanced convection. It may contain 20% more precipitable water than the air over western New Mexico, located on the other side of the Continental Divide. Tropical air fluxes sometimes continue to pulse northward during the month of September.

Albuquerque is located $4\frac{1}{2}$ degrees longitude, east, and 3 degrees latitude, north, of Tucson, therefore significant Gulf of California moisture pulses occur less frequently. Typical thunderstorms are less intense, with less precipitation and fewer cloud-to-ground lightning flashes. Evaporation is a significant environmental influence on VPF here. As much as half of the precipitable thunderstorm rainfall never reaches the surface (Easterling, 1988).

Easterling reported on a study of thunderstorm duration, which indicated that this area of the western United States exhibits the modest average duration of one hour. However, the northeast section of metropolitan Albuquerque lies at the western foothills of the 10,000-foot high Sandia Mountains, so an orographic effect occurs. Sudden lifting of moist southwesterly air enhances the probability of maximum rainfall occurring west of the Sandia crest, in the foothills, or the metropolitan area, or both.

2.4 Methods of data accumulation

2.4.1 LLP: the "Lightning, Location and Protection" network

Lightning data used in this study were acquired from the archives of the Boise Interagency Fire Center, operated by the United States Bureau of Land Management. A principal objective of the agency is to locate potential and actual forest fires throughout the western United States by means of cloud-to-ground lightning flash locations, in real time, since about ten thousand fires are started by lightning annually in the United States (Krider *et al.*, 1980). Systems for locating cloud-to-ground flashes have been available for many years, but recent advances in electronic remote communications have made data calculations and availability more economical as well as accurate (MacGorman and Rust, 1989). Lightning strikes over New Mexico were first recorded (by LLP) in June 1986; this study made use of data for the years 1986 through 1988.

The LLP network detects the sudden changes in magnetic field induced by large currents in the return strokes. (Typical peak current values range from 15-40 kA). Figure 2,

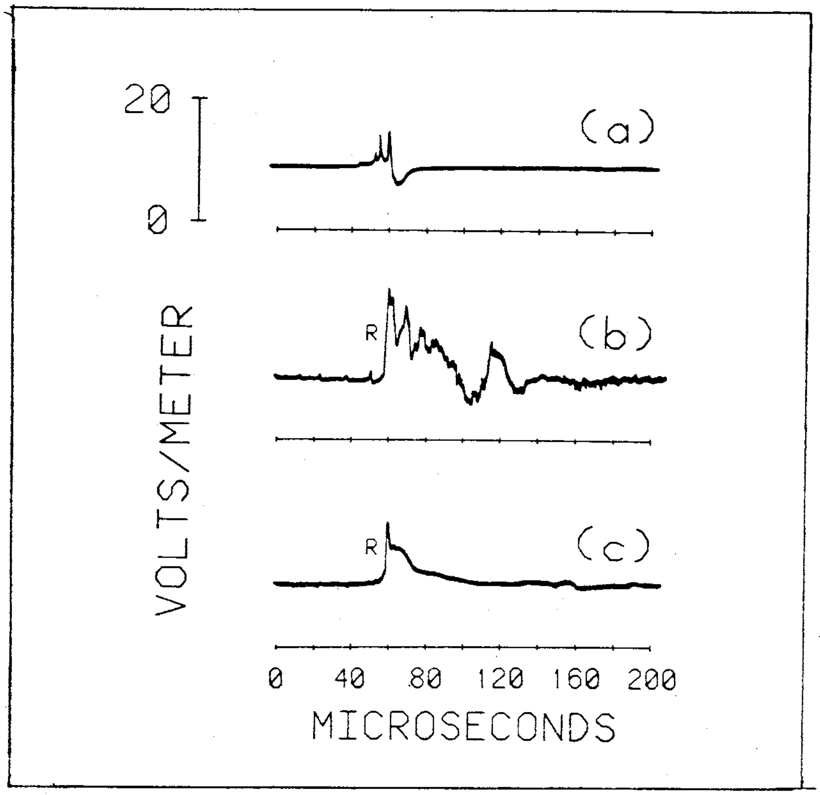

Figure 2: Cloud-to-ground lightning electromagnetic waveforms (from Krider, *et al.*, 1980).

from Krider, shows radiation field signatures produced by a typical CG lightning discharge. Figure 2a is an intracloud impulse. 2b is the waveform associated with the first return stroke, and 2c is for a subsequent return stroke, all of which were recorded at a distance of 60 kilometers by two orthogonal magnetic-loop antennas, or magnetic "direction finders." The ratio of the signal that a flash induces in one loop to the signal induced in the other is proportional to the tangent of the azimuth of the flash, with respect to the antenna orientation. The point of detection is located approximately 100 meters above the point on the ground where the return stroke has originated. Detailed descriptions of the apparatus may be found in Krider *et al.* (1980) and MacGorman and Rust (1989).

Actual latitude-longitude location of CG flashes is calculated after each flash is located by triangulation among the closest of twenty-six magnetic field sensors arranged throughout the western U.S. and Alaska. (See Appendix A for a list and map of LLP, or "Lightning Location and Protection," sensors). One direction-finding sensor, or "DF," is located at Kirtland Air Force Base, about thirteen kilometers south of the watershed selected for this study. The next closest two are respectively located in Socorro and Gallup, New Mexico. A minimum distance of ten kilometers is needed to maintain azimuthal accuracy within reasonable error bounds and to avoid systematic DF error (MacGorman and Rust, 1989). See Section 2.4.4 for a discussion of potential errors.

2.4.2 The NE Albuquerque raingage network

Thunderstorms are characterized by their precipitation variability, in terms of areal coverage, duration and total volume. Accurate estimate of such rainfall is, however, important in hydrology, climatology, agriculture and flood control, and many attempts have been made to quantify it properly. Currently available measurement techniques include satellite remote sensing, radar, and raingage networks. Although it is preferable to use different types of data collection during the same storm events, it is not often feasible to use more than one. The present study utilized data from a raingage network.

Northeast metropolitan Albuquerque exists in a watershed separate from other sections of the city. Storm runoff is contained in an area that reaches from the northern city limits south to Tijeras drainage, and from the crest of the Sandia Mountains west to the Rio Grande. Most of the watershed surface is an alluvial fan, of minor elevation (2% slope) and topographic variation. Precipitation falling over this drainage is monitored by an irregular network of six tipping bucket and seven float-in-pipe raingages. (See Figure 3 and Figure 4).

The perimeter of the network encloses an area of approximately 120 km^2. However, a gage in the foothills of the Sandia Mountains did not record rain for two of the three years of this analysis, and it was therefore decided to consider the area surrounding the remaining twelve gages only, encompassing 67 km^2. Due to the fact that thunderstorm cell diameters in this part of the United States average about 3 kilometers (Dye, *et al.*), a margin of this width was added to the ground surface area surrounding the network, in order to ensure that lightning detected near the network perimeter would be correctly represented by interpolated rainfall in that vicinity. This was necessary because rain-depth data was converted to rain-volume by multiplying it by the area. The size of ground surface used to calculate the volume then became 150 km^2, as seen in Figure 5.

The float-in-pipe gages provide continuous data, recorded in hundredth's of an inch, as totals for each 5-minute period. These gages are less accurate than the tipping-bucket type during the most intense storms because the shallow collectors tend to splash. The tipping bucket gages record every 1 minute, up to a maximum intensity of 0.01 inch per minute. Calibration determines the amount of dripped volume needed to tip the bucket. Data are stored and retrieved electronically.

The United States Geological Survey Water Resources Division in Albuquerque monitors the raingage network. They provided daily average precipitation and runoff data for the water years 1986-1988. Most useful for this study, they also contributed five-minute-

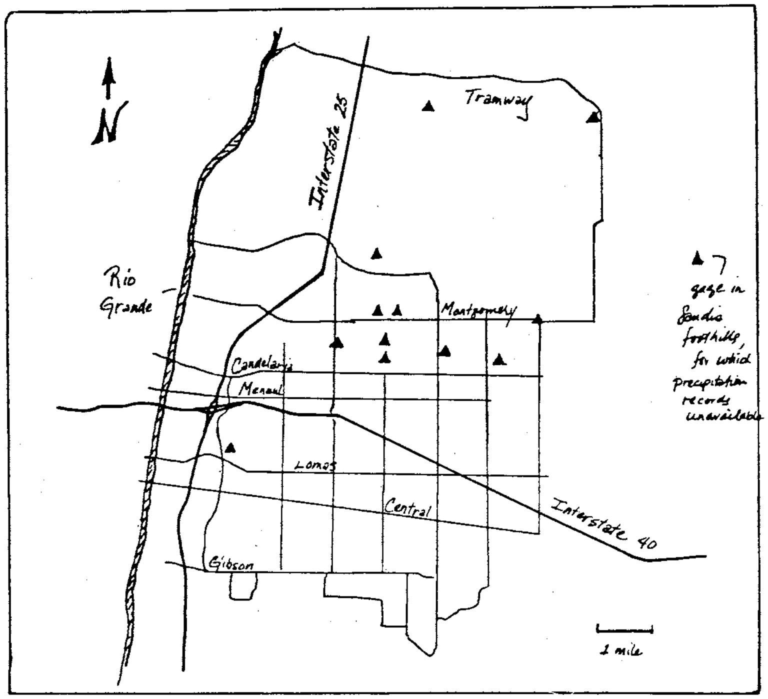

Figure 3: Northeast Albuquerque raingage network.

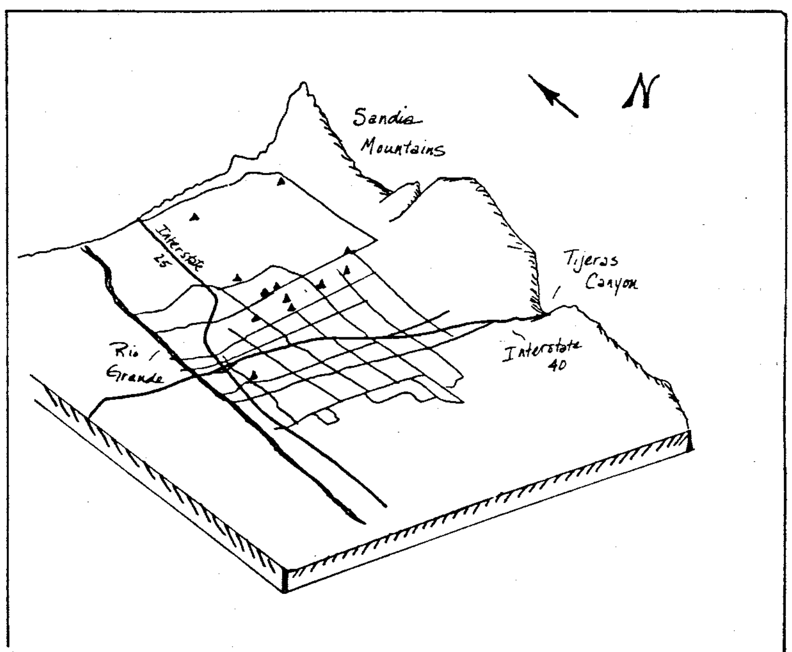

Figure 4: Oblique view of the raingage network, showing topography.

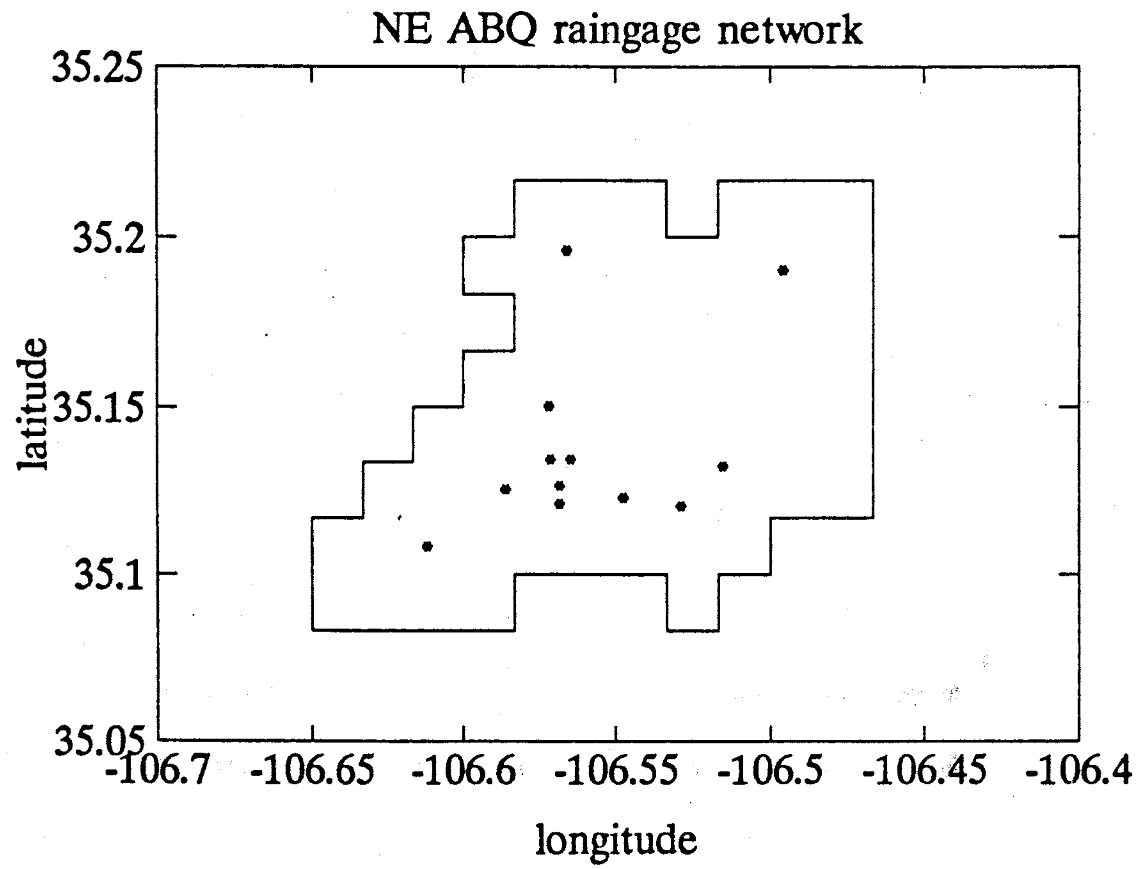

Figure 5: Latitude and longitude of the raingage network perimeter, including extended area for marginal storms (see text).

interval data for selected storm dates in July, August and September for those years. These data were supplied on magnetic tape in a condensed format. A computer program was written to convert these data to a readable format, and another computer program transferred rows of five-minute precipitation depths, in inches, to columns suitable for comparison with lightning. (See Appendix B for programs.)

2.4.3 Cloud base temperature and dewpoint

The possibility of loss of ground-surface rain volume due to evaporation was considered in this study, by correlating relative humidity and absolute humidity calculated below thunderstorm cloud base to VPF. Albuquerque upper air sounding data, specifically air temperature and dewpoint, were retrieved from National Weather Service data, received by satellite link and archived on magnetic tape at New Mexico Institute of Mining and Technology.

2.4.4 Error sources

At this point it is important to mention sources of possible error in the data used for Albuquerque lightning and precipitation analysis.

- There are two types of location errors that occur using the LLP magnetic direction-finder network (MacGorman and Rust, 1989):
    1. Site errors pertain to a single station, are systematic, and test results indicate they are generally less than 5°.

2. As mentioned, lightning location is calculated from the measurement of the return stroke signal at the peak in the waveform, based on the assumption that the lightning channel is effectively vertical at that time during a flash. Error in lightning channel orientation is random and hard to correct; however, it is less than 1° for lightning occurring farther than 10 kilometers from the nearest direction-finder. Since the closest raingage in the NE Albuquerque network is 13 kilometers from the direction-finder at the Kirtland Air Force Base, it is a small concern for the present study. Channel orientation is perhaps more of a problem in the Gulf Coast and Florida, or even Oklahoma, where massive mesoscale systems have much cloud-to-ground lightning which propagates laterally before the first return stroke peak occurs.

It has been determined (MacGorman and Rust, 1989) that overall LLP efficiency in detecting CG flashes ranges from 65-90%, but it is typically 70-80%.

- Measurement of convective precipitation

Two properties of raingage networks must be considered to determine valid area-averaged rainfall: uniformity and density of gage spacing. (Woodley *et al.*, 1975). Given the significant variability of thunderstorm precipitation, these factors become even more important during those storms.

Many studies have been devoted to the assessment of optimum gaging (Gilman in Chow, 1964, Osborn *et al.*, 1969, Huff, 1970, Woodley, *et al.*, Lenton and Rodriguez-Iturbe, 1977, Simanton and Osborn, 1980, and Silverman, *et al.*, 1981). Most authors agree with Huff, that storm-sampling standard error is directly proportional to size of area receiving rain, and inversely proportional to storm duration and gage density.

All agree that regularly spaced gages assure greater reliability, but they differ in their assessment of how much nonuniformity may be allowed. A 31 km^2 gage area measures convective precipitation greater than 0.25 mm, within a factor of 2, for 90% of the days monitored, according to Woodley and his co-workers, who studied Florida storms. Silverman *et al.* examined the sampling variance of various gage networks and concluded that a range of 45-80 km^2 per gage is adequate provided that there are least two gages per rain cell. Lenton and Rodriguez-Iturbe referred to an earlier work by French scientists Delhomme and Delfiner in which it was found that "optimal kriging weights do not differ much from the weights determined by the Thiessen method of polygons." Simanton and Osborn tested a reciprocal-distance estimate method for missing point rainfall which is valid for distances of less than 10 km between gages in the southwest United States, whether regularly spaced or not.

The foregoing assumes that gages are spread over moderate to negligible change in surface elevation. The elimination of the foothill gage from the Albuquerque network improved the situation for the purposes of this study. However, the gages in this part of the city vary by about 60 vertical meters between each two nearest neighbors. Total vertical range between gages from one end of the network to the other is 317 meters. Unfortunately these raingages are also not very uniformly spaced. They record rain over areas ranging from 1 km^2 to 26 km^2, but the distances between them range from 1 km to 16 km, which places them within the realm of validity indicated by most studies.

3 Analysis Methods

3.1 Data processing

3.1.1 Lightning data

The BLM lightning data arrived in condensed form on magnetic tape. After reformatting, each lightning flash occurring during the period of 1986 through 1988 was listed on a separate line, in the format described below. A computer program was written to scan the data for all flashes occurring within the perimeter selected by availability of rainfall data within the metropolitan Albuquerque watershed, as discussed earlier.

These flashes were stored in a file, as shown in Figure 6. Each line of data refers to a separate flash, as defined by Krider (1980). Column 1 refers to Greenwich Mean Time, in hours and minutes, at which the flash was detected. Columns 2, 3 and 4 list decimal latitude and longitude, respectively, and flash polarity and intensity (amps). The number of lightning return strokes is indicated in column 5. Column 6 lists the Julian calendar day the flash occurred, and, to help avoid error, in column 7, is the Roman calendar day.

Note that, relative to Greenwich Mean Time, Mountain Daylight Time is six hours later in New Mexico in the summer. Since raingage data are recorded in MDT, lightning flash times had to be converted. Any flash recorded earlier than 6:00 am, Greenwich, actually occurred before midnight, the previous day, in Albuquerque. Thus flashes listed for a particular day in Albuquerque may appear to have occurred on two separate dates.

This inconvenience was circumvented during the next step in data preparation. In

1	2	3	4	5	6	7
02:58:00.00	35.174	-106.468	-27.1	7	d88199	7 17
20:21:00.00	35.144	-106.505	-16.4	1	d88199	7 17
00:48:00.00	35.146	-106.421	-5.2	2	d88200	7 18
00:52:00.00	35.165	-106.538	-6.3	2	d88200	7 18
01:21:00.00	35.164	-106.572	-11.3	1	d88200	7 18
20:46:00.00	35.198	-106.475	-51.5	5	d88200	7 18
22:38:00.00	35.149	-106.478	-17.6	1	d88200	7 18
22:39:00.00	35.118	-106.444	-13.8	2	d88200	7 18
23:08:00.00	35.133	-106.603	-17.3	3	d88200	7 18
23:18:00.00	35.205	-106.497	-38.2	2	d88200	7 18
23:25:00.00	35.102	-106.560	-30.3	2	d88200	7 18
23:26:00.00	35.110	-106.536	-15.0	1	d88200	7 18
23:26:00.00	35.128	-106.495	-15.1	4	d88200	7 18
23:27:00.00	35.175	-106.469	-22.1	1	d88200	7 18
23:28:00.00	35.186	-106.551	-15.8	1	d88200	7 18
23:29:00.00	35.116	-106.541	-14.4	1	d88200	7 18
23:30:00.00	35.139	-106.510	-17.9	6	d88200	7 18
23:31:00.00	35.167	-106.551	-15.3	1	d88200	7 18
23:36:00.00	35.087	-106.646	-32.6	2	d88200	7 18
23:36:00.00	35.115	-106.645	-32.6	3	d88200	7 18
23:37:00.00	35.128	-106.520	-24.2	8	d88200	7 18
23:38:00.00	35.132	-106.513	-40.9	3	d88200	7 18
23:40:00.00	35.111	-106.613	-24.4	2	d88200	7 18
23:43:00.00	35.108	-106.631	-9.7	5	d88200	7 18
21:53:00.00	35.176	-106.528	-9.2	1	d88201	7 19
22:42:00.00	35.187	-106.494	-27.8	2	d88206	7 24
00:12:00.00	35.174	-106.491	-109.7	1	d88207	7 25
18:40:00.00	35.098	-106.622	-9.7	9	d88209	7 27
21:29:00.00	35.117	-106.471	-21.4	1	d88209	7 27
21:58:00.00	35.122	-106.499	-20.9	9	d88209	7 27
22:31:00.00	35.141	-106.599	-21.8	1	d88209	7 27
00:01:00.00	35.102	-106.621	-19.3	1	d88210	7 28
00:28:00.00	35.106	-106.649	-18.1	3	d88210	7 28
00:36:00.00	35.104	-106.508	-25.7	1	d88210	7 28

Figure 6: Sample of lightning flash data. See text for interpretation.

order to study individual storm days in a detail to match that of the Albuquerque precipitation records, a computer program was written to count all flashes occurring within a five-minute time interval and to list the sum. (See Appendix B for programs.)

3.1.2 Rain depth-to-volume conversion

Several techniques for estimation of rainfall areal coverage have become standardized during the last few decades, including the isohyetal and Thiessen polygon methods, and simple averaging. Now, however, with the development of computer technology, grid-point approaches are proliferating. Total Albuquerque thunderstorm rainfall was interpolated by a computerized grid-point approach, and depth for each event was multiplied by the gage-network area to determine volume.

3.2 Procedure

3.2.1 Interpolation

Since the primary objective of this project was to evaluate volume of precipitation associated with cloud-to-ground lightning flashes, it was necessary to determine area-averaged rain depth over the gage network. This interpolation was carried out by two separate methods due to concern with the potential effect of nonuniform gage spacing. The Thiessen and grid-point methods (Linsley, *et al.*, 1986) were used.

The Thiessen approach provided a weighting factor for each gage, based on areas created by drawing perpendicular bisectors to connecting lines between gages plotted on a map. The weights were percentages of the entire network surface area.

The grid-point method was performed by computer generation of a 32 x 44 mesh, with node dimensions equal to fifteen seconds of latitude and longitude, respectively. Each unknown grid rainfall depth (in inches) was calculated by a computer program adapted from Barnes (1964) by Dr. David Raymond, Professor of Physics at New Mexico Institute of Mining and Technology. The program determines the distance from each node to each raingage. It was modified for the present study to compute precipitation using a reciprocal-distance weighting technique developed by Dean and Snyder (1977), based on the known total for those gages for a particular storm, as follows:

$$C_i = \frac{\sum_{j=1}^{n} \left(\frac{P_j}{D_{i,j}^b} \right)}{\sum_{j=1}^{n} \left(\frac{1}{D_{i,j}^b} \right)} \tag{1}$$

where $D_{i,j}$ is the distance from an ungaged grid point (i) to each known discrete raingage location (j), b is the power to which the distance is raised, P_j is the known rain depth for the gage at j, C_i is the interpolated rainfall at the ith node, and n is the number of raingages. The method gives the greatest weight to the nearest gage and reduces weight proportionally as distance increases. The denominator normalizes actual precipitation.

The exponent b is the critical component of equation 1 because it determines the magnitude of the effect of each gage measurement on a node, based on the distance between them. When b equals 0, the reciprocal-distance formula is the same as the method for unweighted area-averaging of rainfall. When b equals ∞ the measurement at the closest gage is the only amount which influences the interpolation at a node, similar to the Thiessen method. Dean and Snyder found that an exponent of 2 gave best results for the estimation of thunderstorm precipitation, using widely-spaced gages in the Piedmont region of the southeast United States.

In 1980, Simanton and Osborn published results of tests they conducted, based on the reciprocal-distance work of Dean and Snyder, for optimum estimation of thunderstorm rainfall in the southwest. They attempted to determine if a different value of b would give best results. Their method was to use equation 1 to interpolate precipitation at gage k without the measured value at k:

$$C_k = \frac{\sum_{j=1_{j\neq k}}^{n} \left(\frac{P_j}{D_{j,k}^b}\right)}{\sum_{j=1_{j\neq k}}^{n} \left(\frac{1}{D_{j,k}^b}\right)} \tag{2}$$

with symbols the same as previously described.

For every gage k, Simanton and Osborn correlated measured *vs.* interpolated (calculated) rainfall depth, using values of b between 0 and 4. While 1.5 gave the highest r value, they determined that values between 1 and 3 showed no statistically significant difference. For the current study a b value of 2 was used to interpolate rainfall at each node.

Figures 7 and 8 are two representations of interpolated rainfall for a particular storm day. Figure 7 shows rain-depth contours of $\frac{1}{2}$ inch. Figure 8 illustrates (above) lightning flash locations and (below) interpolated rain over the grid. No obvious spatial correlation was evident between lightning and precipitation in the storms plotted in this manner.

Interpolated precipitation was related to cloud-to-ground lightning activity for selected storm days occurring during the summer months of July, August and September of the years 1986-1988. Not all rainfall events were actually recorded by the Geological Survey during those years. Twenty-three convective storm events were selected out of a total of

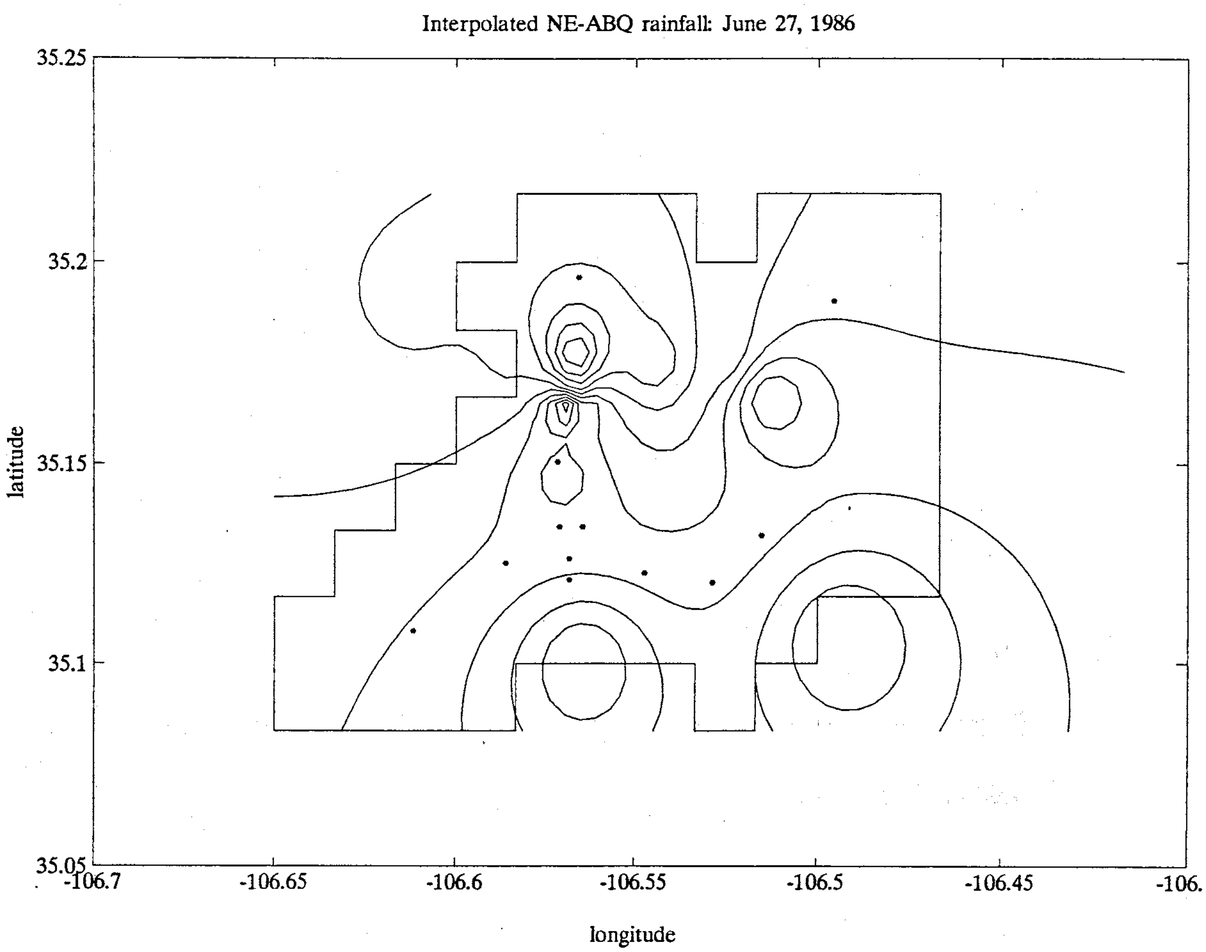

Figure 7: $\frac{1}{2}$-inch rain depth contours, interpolated over the grid area for the storm indicated.

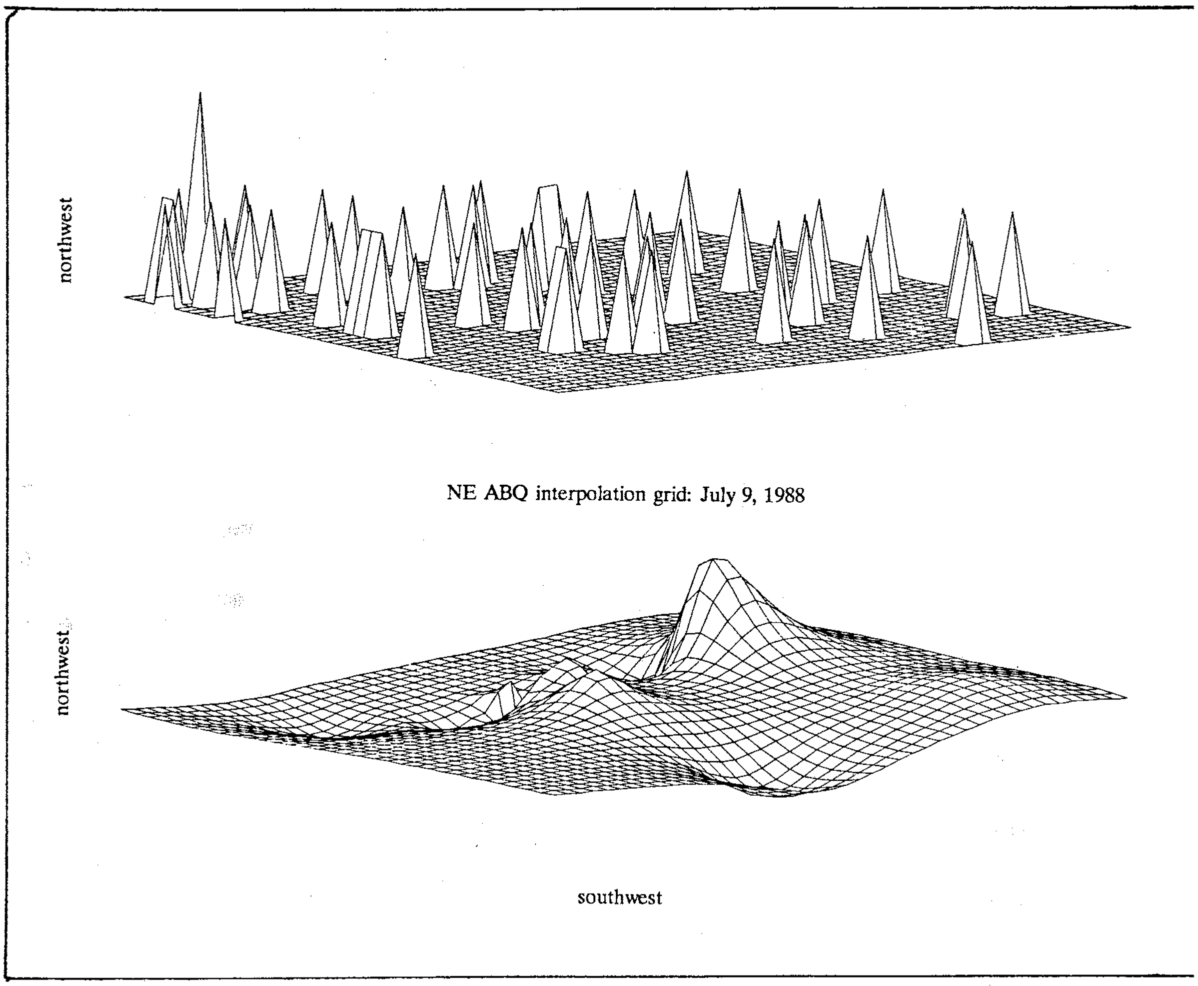

Figure 8: Mesh plots of the NE Albuquerque interpolation grid, showing (above) lightning and (below) rainfall over the grid. Lightning spike lengths indicate the number of flashes at respective nodes. Precipitation was interpolated over the area.

thirty-five for which data were available, because they each had five or more lightning flashes, and were therefore more likely to reveal possible correlative properties.

Total storm rainfall was divided by cloud-to-ground lightning flash count to determine rain volume per flash, or VPF. In addition, total rainfall was divided by the number of lightning return strokes to assess a possible effect on precipitation, as manifested in the variability of the results. Finally, total rain was divided by total storm lightning current (amps). (While it is preferable in this last assessment to compare rain volume to total storm *charge*, this would require knowledge of the duration of each flash. However, duration data are not available from LLP). Minimum, or threshold, values of CG flash and return stroke counts are counts which might predict an associated rain volume; these were looked for, as indicated by linearity in the VPF and other plots.

3.2.2 Correlation

In standard applied hydrology, continuous and discrete hydrologic phenomena are characterized by their probability of occurrence. Unfortunately for this study, 5-minute precipitation and runoff data were recorded on unsystematic occasions, and a continuous record could not be inferred. In order to circumvent the problem of not knowing the frequency distribution of counts of lightning flashes or VPF, Spearman's Rank-Order Correlation (Press *et al.*, 1986) was used to determine the correlation coefficient. This provided another method to determine if CG lightning-count threshold values exist.

Spearman's rank-order correlation coefficient, r_s, is equal to

$$\frac{\sum_{i=1}^{n}\left(R_i-\overline{R}\right)\left(S_i-\overline{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(R_i-\overline{R}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i-\overline{S}\right)^2}} \tag{3}$$

for R_i equivalent to the rank of each flash count and S_i equivalent to the rank of each VPF among the n ranks.

The t statistic for significance of a nonzero value of r_s was determined in standard fashion, by

$$t = r_s\sqrt{\frac{N-2}{1-{r_s}^2}} \tag{4}$$

which is distributed like the Student's distribution, with $N-2$ degrees of freedom. t and r were calculated for three groups of thunderstorms: 1) twenty-three storms of various intensity and duration, and having at least 5 flashes, 2) seven storms having at least 20 flashes, and 3) five storms having at least 30 flashes.

3.2.3 Lag

Based on the hypothesis that a CG lightning-rainfall interaction is valid, the lag, or time-correlation between the two was examined. This assessment was made with 5-minute-interval sums of flash count and rain depth, by two methods, in order to substantiate the results: 1) Lag time was determined between peak intensities (maximum-per-5-minutes) of each variable, for uninterrupted storm cell activity separated by 15 minutes or more of no activity. 2) Lag time was determined as 50% of the cumulative center-of-mass of the same storm cells.

3.2.4 Evaporation

Storm-day tephigrams (diagrams of atmospheric thermodynamics) were generated from National Weather Service sounding data by New Mexico Tech's atmospheric physics Candis data format programs (Raymond, 1988). Air temperature and dewpoint were determined from the tephigrams of 6 pm soundings below cloud base (at 750 mb). Then relative humidity (f) at this elevation was calculated by the relation

$$f = \frac{e_s(T_d)}{e_s(T)}(100) \tag{5}$$

as a percent, where $e_s(T_d)$ refers to dewpoint vapor pressure, and $e_s(T)$ is for air temperature saturation vapor pressure. A standard table was used to determine values for these vapor pressures. Relative humidity below cloud base was plotted against rain-volume per flash.

An indication of the volume of convective storm rainfall likely to reach the ground is absolute humidity, or vapor density, at cloud base. This value was determined as

$$\rho_v = \frac{e}{R_v T} \tag{6}$$

for e as vapor pressure (equal to $e_s(T_d)$), and R_v as the gas constant for water vapor (in J kg^{-1} K^{-1}) and T in degrees Kelvin. Units for vapor density are kg m^{-3}.

4 Results

4.1 Interpolation

Tables 2 and 3 list the results of the grid-point interpolation and cloud-to-ground flash counts determined for twenty-three storm days, each of which had a minimum of five lightning flashes and gage-recorded rainfall. Also shown are precipitation volume per cloud-to-ground flash (VPF), number of lightning return strokes, precipitation volume per return stroke, total storm-day CG-flash electrical current and precipitation per amp. All figures pertain to grid-point results. The Thiessen-interpolated VPF was about twice that of gridded VPF.

Figures 9, 10, 11, and 12 are plots of these data. Figure 9 shows the relationship between flash counts and total interpolated rainfall for all twenty-three storms. The horizontal line in Figures 10 and 11 represents a limiting precipitation volume per flash, and per return stroke, respectively.

4.2 Correlation

Table 4 shows results of r_s and t values for three magnitude groupings (and their associated ranks) of storms, as indicated.

4.3 Lag

The range of storm cell lightning-rainfall lag times is listed for both methods in Table 5. Center-of-mass lightning occurred an average of ten minutes before center-of-mass of the

Table 2: Measured rain-depths, interpolated rain volumes, total flash counts, relative humidity and absolute humidity, for 23 storm days during July, August and September of 1986-1988.

Date	Rain depth	Interpolated Rain	Total flashes	Relative humidity	Absolute humidity
	inches	10^4 m^3	CG	%	g/m^3
1986					
June 27	5.59	180	6		
June 28	0.03	1	10		
July 4	2.19	74	11		
July 6	2.80	100	13		
Aug 25	3.94	120	7		
1987					
July 24	7.34	240	10	20.0	0.042
Aug 4	0.76	21	5	33.6	0.078
Aug 21	3.57	120	7	33.0	0.068
Aug 22	5.39	200	5		
Aug 25	4.35	150	7	82.1	0.1
Aug 26	5.28	180	29	66.2	0.064
Aug 27	2.69	94	32	50.9	0.064
1988					
June 10	3.74	150	42	28.9	0.064
June 11	3.04	120	12		
July 5	1.88	68	6	19.0	0.045
July 8	5.08	190	44		
July 9	1.38	540	58		
July 28	4.57	170	24	67.7	0.1
Aug 9	3.45	120	38	32.7	0.064
Sept 1	1.18	39	17	55.1	0.078
Sept 11	2.15	79	9		
Sept 13	7.27	270	18		
Sept 22	4.67	170	5		

Table 3: Rain volume per flash, per return stroke and per amp of lightning current, for the same dates.

	Volume per Flash	Return Strokes	Volume per Return Stroke	Flash Intensity	Volume per Flash Intensity
	10^4 m^3		10^4 m^3	amps	m^3
	29.9	13	13.80	353	5087
	0.1	36	0.02	802	11
	6.8	38	1.96	755	986
	7.8	42	2.42	642	1584
	17.8	11	11.34	500	2493
	24.2	36	6.71	801	3015
	4.2	11	1.90	169	1237
	17.4	12	10.15	506	2409
	39.8	5	39.84	572	3484
	21.8	17	8.99	401	3811
	6.2	78	2.32	1964	922
	2.9	60	1.56	1998	469
	3.6	125	1.19	866	1725
	10.4	45	2.77	238	5231
	11.3	14	4.83	176	3848
	4.3	124	1.52	887	2123
	9.3	159	3.39	1114	4844
	6.9	62	2.69	709	2349
	3.1	105	1.12	854	1374
	2.3	40	0.97	466	835
	8.8	23	3.44	188	4211
	14.9	59	4.55	516	5206
	34.5	6	28.72	253	6811
mean	12.5		6.79		2602
std	10.9		9.55		1607

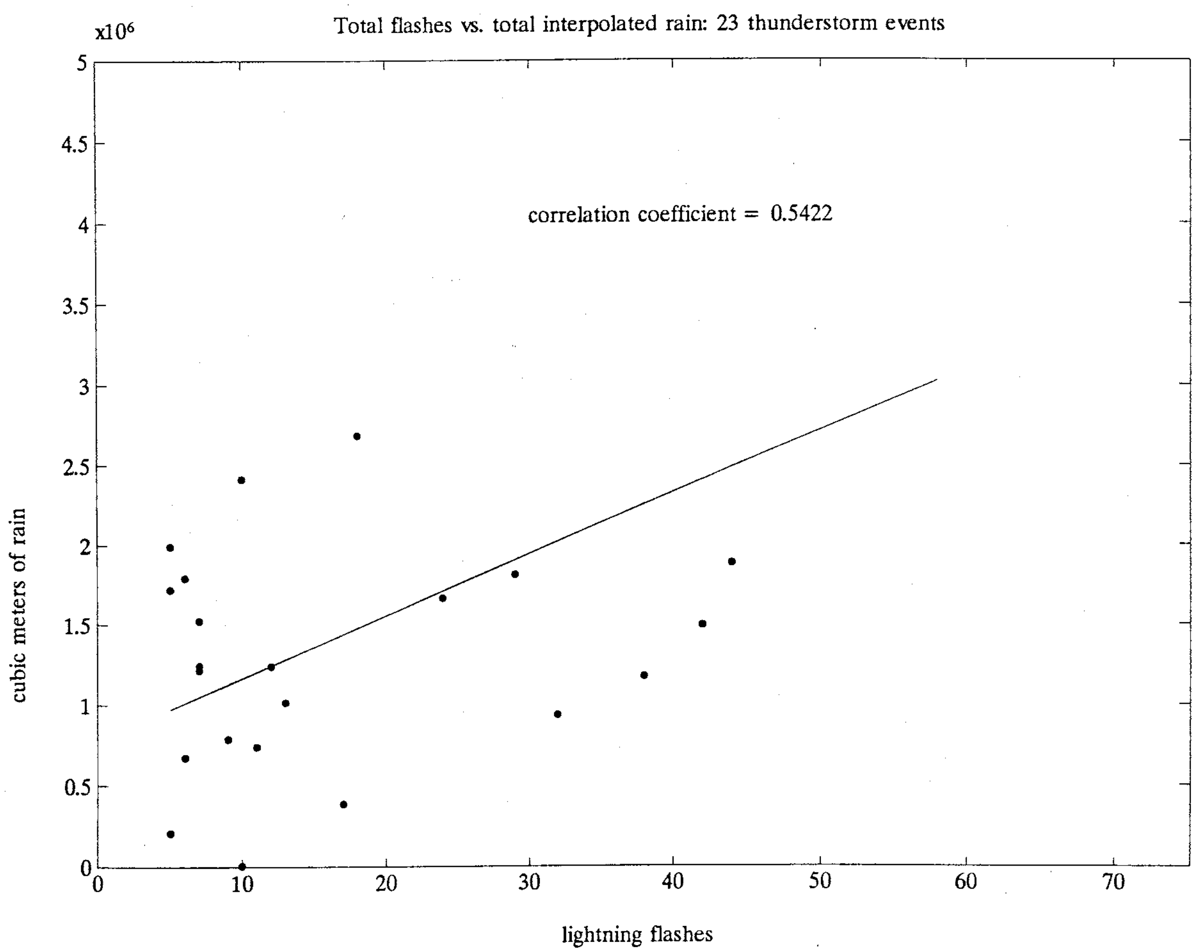

Figure 9: Number of flashes *vs.* interpolated rain for 23 thunderstorms.

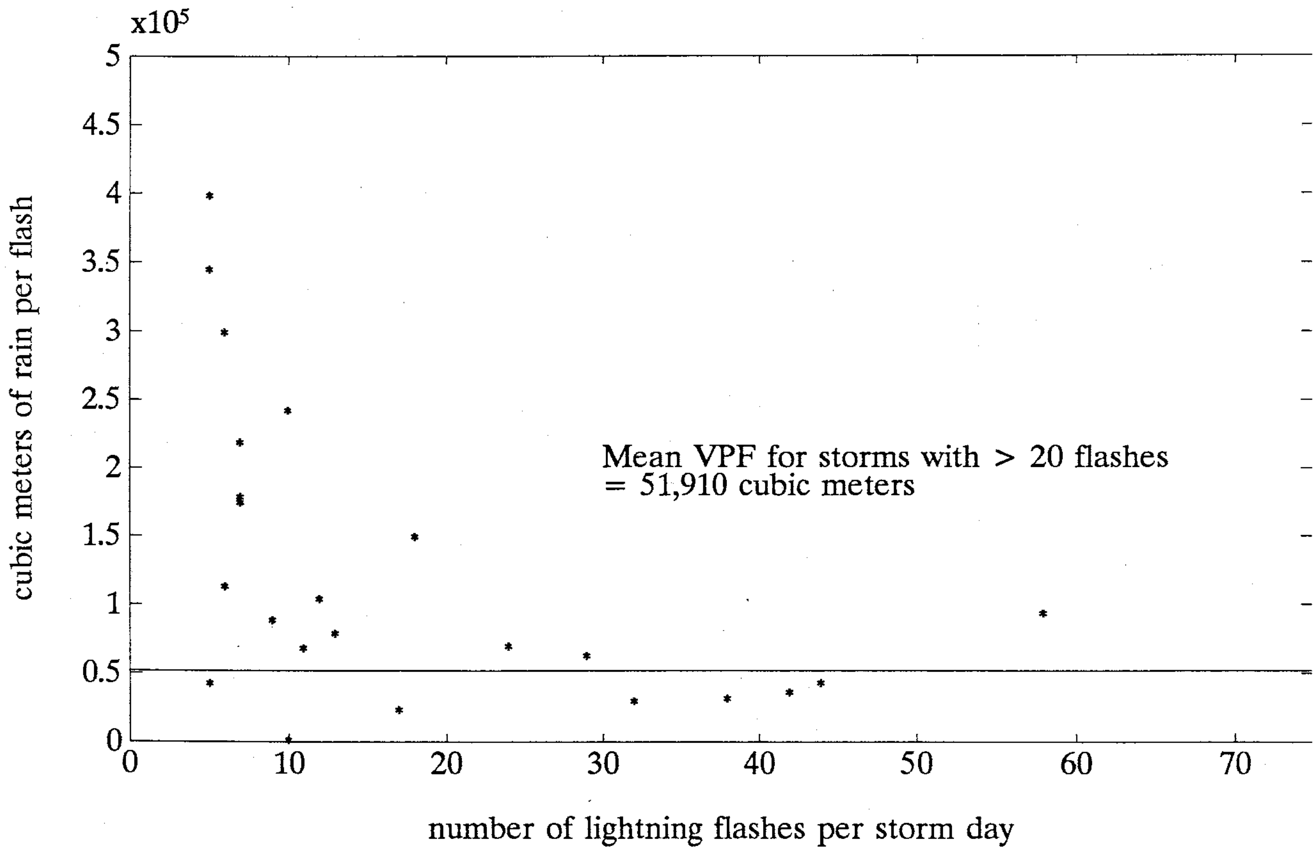

Figure 10: Number of flashes *vs.* precipitation volume per flash for 23 storms.

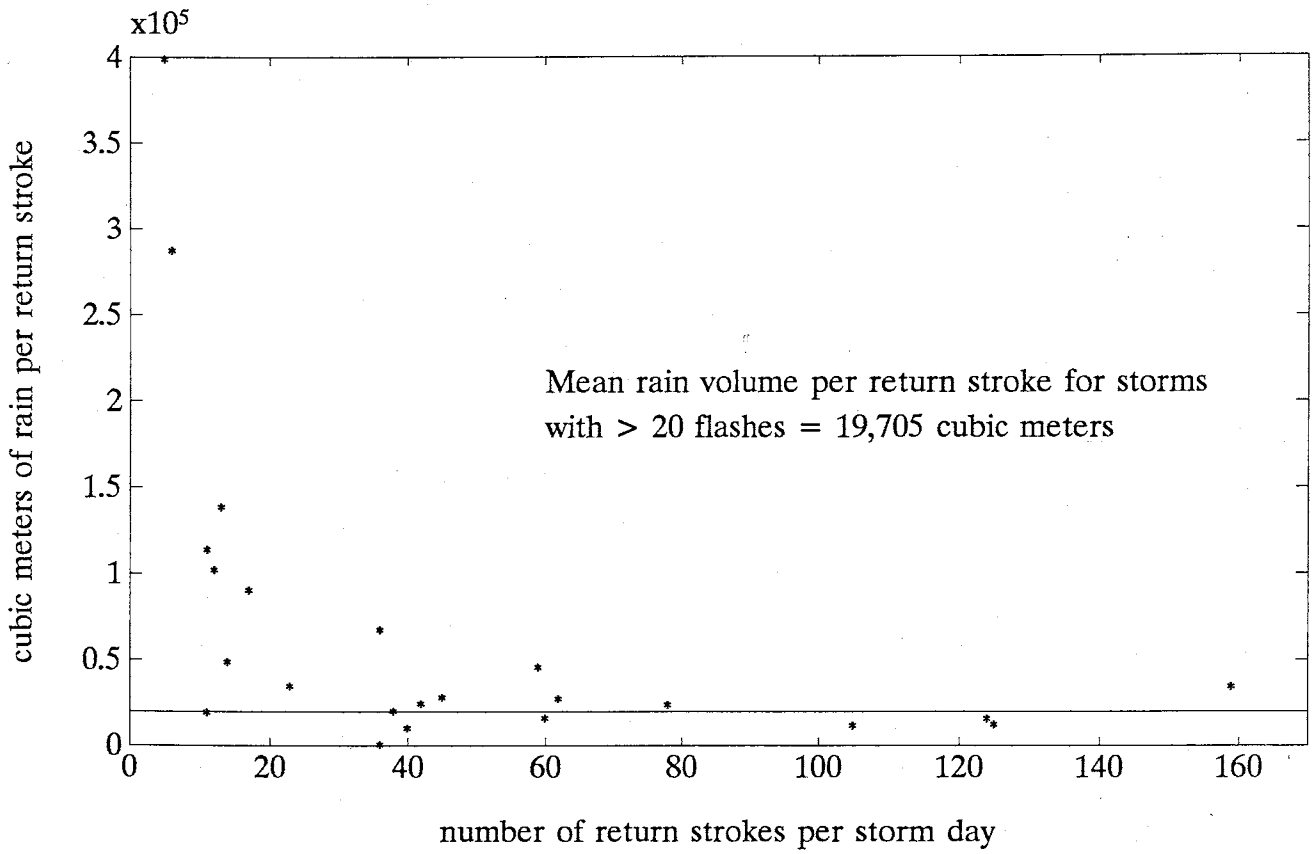

Figure 11: Return strokes *vs.* precipitation volume per return stroke

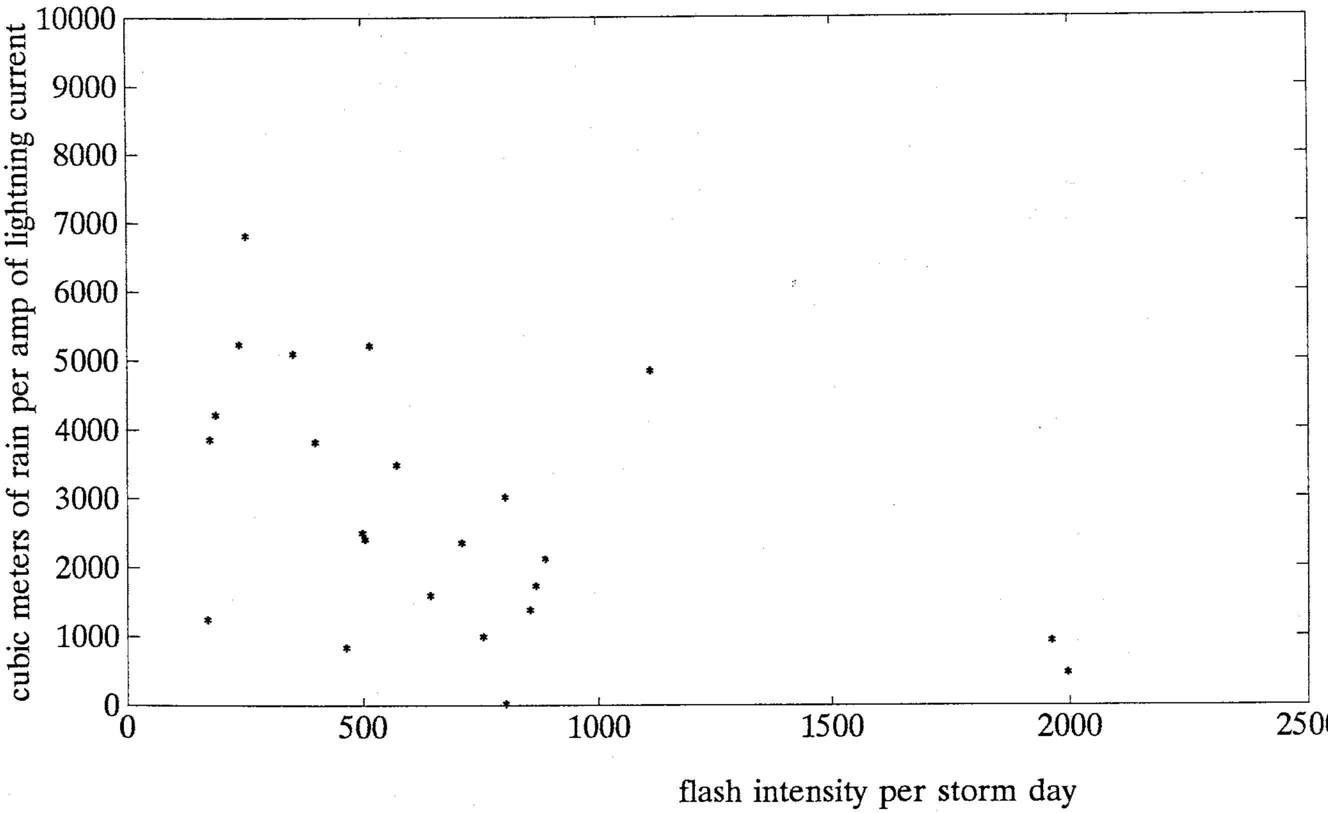

Figure 12: Flash intensity *vs.* precipitation volume per amp, for 23 storms.

Table 4: Rank, r_s and t, for a) 23 storms having 5 or more flashes, b) 7 storms having 20 or more flashes, and c) 5 storms having 30 or more flashes

	r_s	t
(a)	-0.58	-3.26
(b)	0.10	0.24
(c)	1.00	∞

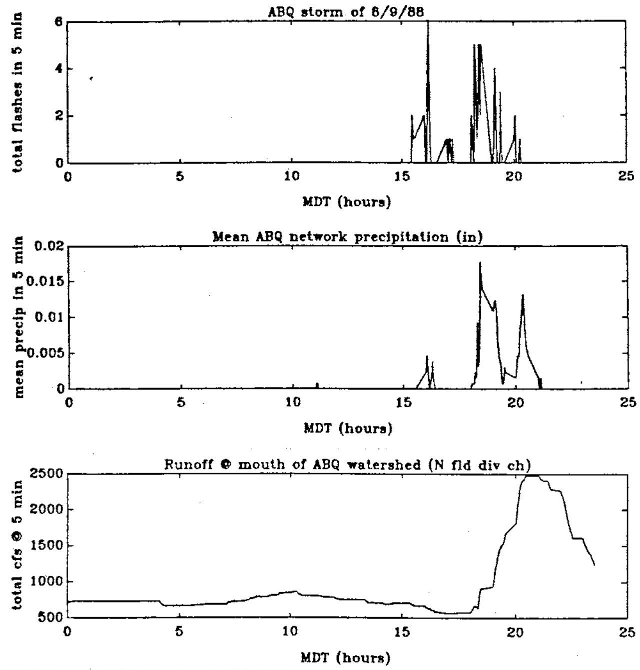

Figure 13: Lightning, precipitation and NE Albuquerque flood-channel runoff for the twenty-four hours of August 9, 1988.

rain, for half of the storm cells studied. When lag was determined from peak intensity of each parameter, strongest lightning activity occurred first 65% of the time, by a mean of twelve minutes.

Figure 13 shows the chronological relationship between lightning, precipitation and Albuquerque flood-channel runoff on August 9, 1988. The metropolitan flood-control channels are smooth and lined with cement, and therefore runoff response rapidly followed rain during most of the thunderstorms studied. Basin lag is an important property of watersheds. In the early stages of this study some work was done with runoff data from various unpaved, unlandscaped basins in rural New Mexico, to see if lightning may be used to predict flash floods in such areas. See section 7 for further discussion of this topic.

Table 5: Lag between lightning and precipitation for twenty storm cells occurring on the dates listed, determined by a) peak intensity and b) center of mass, in minutes. A negative value means lightning preceded rain.

Date	Cell Number	Peak Intensity	Center of Mass
August 27, 1987	1	-25	-10
	2	20	20
	3	20	20
June 10, 1988	1	10	10
	2	-5	-5
	3	20	15
	4	-5	0
	5	0	0
July 8, 1988	1	-10	-10
	2	-20	-20
July 9, 1988	1	-5	-5
	2	5	5
	3	0	5
	4	-17	-17
	5	-10	-10
August 9, 1988	1	-20	-15
	2	-13	-13
	3	-20	5
	4	-5	0
	5	-10	-15
	abs(mean)	12	10
	abs(std)	8	7
	Number Negative	13	10

Figure 14 shows the cumulative plot of both lightning flashes and precipitation (depth in inches) for the storm of July 9, 1988. The time that lightning began is defined as "zero" time, and the rainfall time is relative to that. The horizontal line at 50% indicates the center of mass of each parameter for this storm event, and the time difference between them at the intersection with this line is defined as the lag. For this storm cell, rainfall onset preceded lightning by about 13 minutes.

4.4 Evaporation

Table 2 includes calculations of relative humidity and absolute humidity. Figures 15, 16 and 17 show these values graphically. Figure 15 represents VPF *vs.* relative humidity below cloud base for eleven storms (the only ones for which data were available). Figure 16 is a close-up view of seven of these storms, all of which happened to have low VPF values. Figure 17 shows VPF vs. vapor pressure, or absolute humidity, for eleven storms. (It should be noted that for each of these plots, the cloud-base relative humidity of 67.7% and absolute humidity of 1.0×10^{-4} kg m^{-3} was determined from a 6-am sounding, because the storm occurred between 11 pm and midnight of the previous day.)

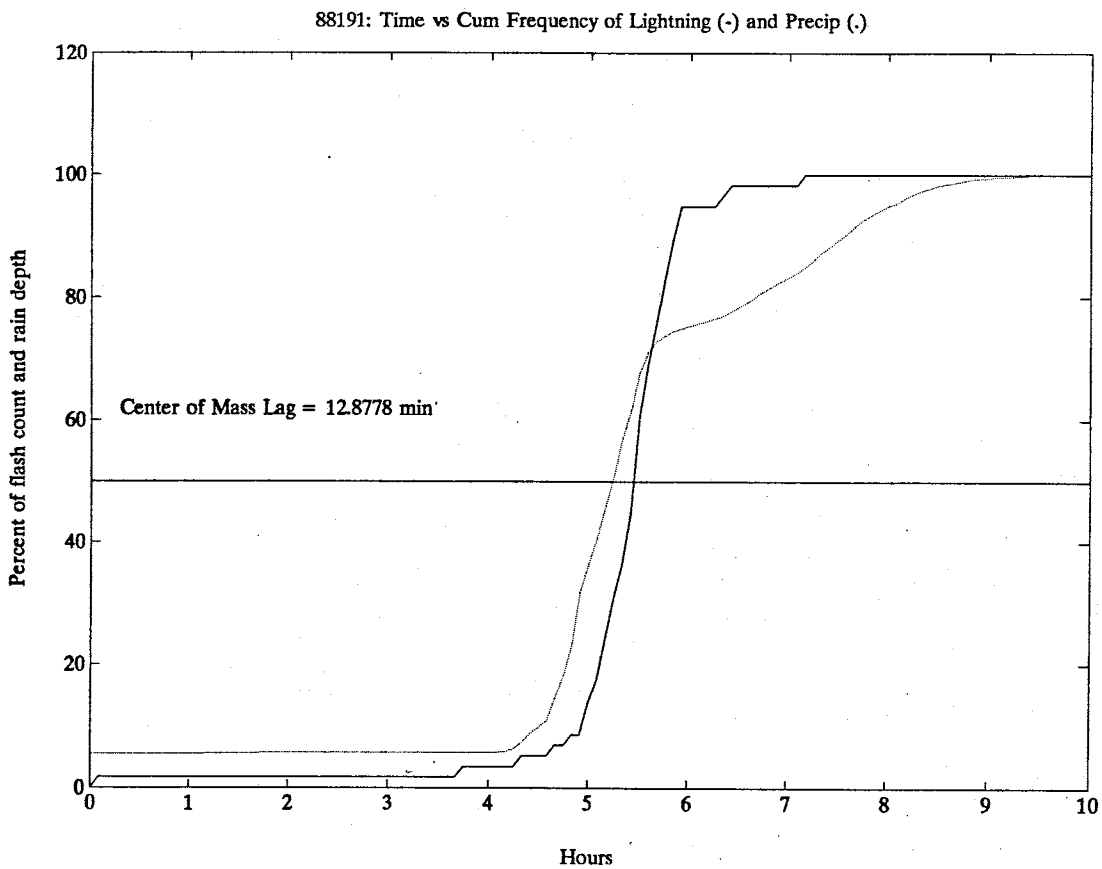

Figure 14: Time elapsed since beginning of lightning, *vs.* cumulative frequency of flashes and rain depth, on July 9, 1988. Precipitation began before lightning.

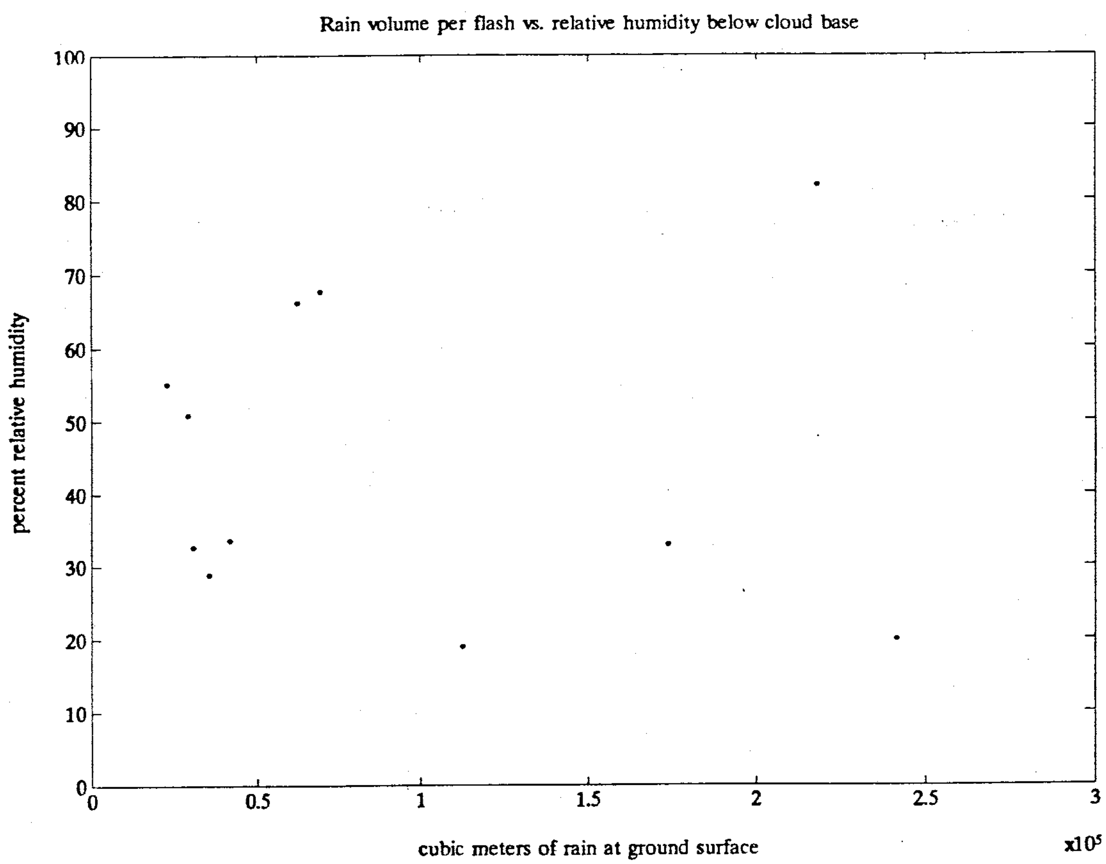

Figure 15: Thunderstorm rain VPF *vs.* relative humidity below cloud base for 11 storms.

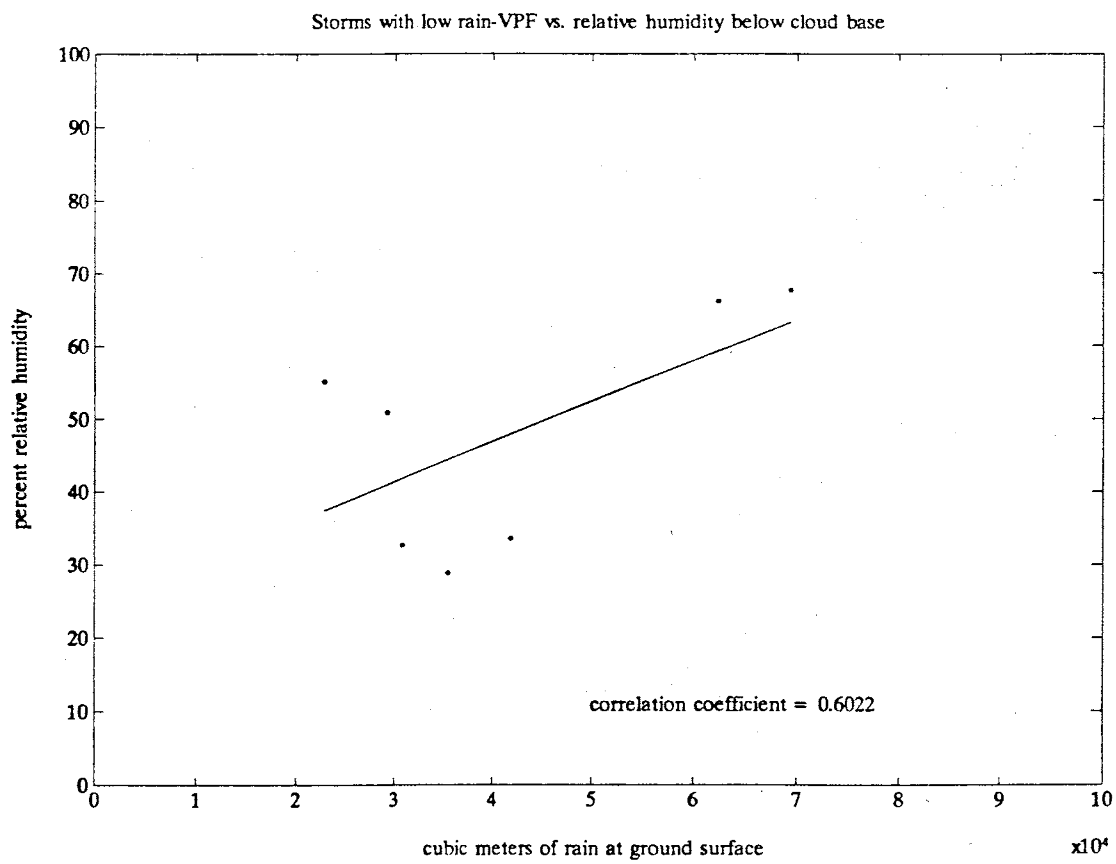

Figure 16: Thunderstorm rain VPF *vs.* relative humidity below cloud base for 7 low-VPF storms.

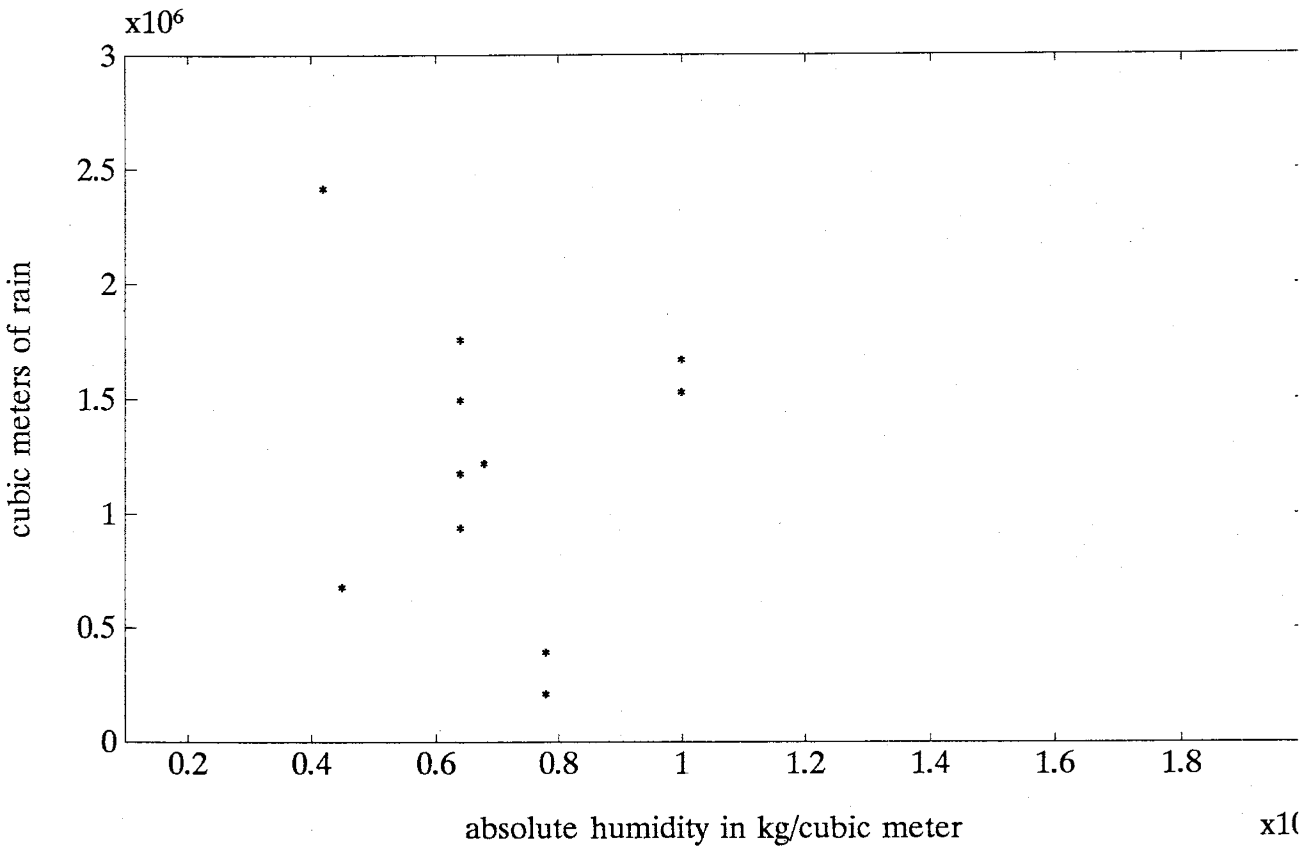

Figure 17: Thunderstorm rain volume *vs.* absolute humidity below cloud base for 11 storms.

5 Discussion

Thunderstorm lightning counts and flash rates vary from one event to another in any area, but, peak values determined for certain airmass storms provide a rough comparison of these rates across the United States. In the Gulf Coast, observed CG flash counts per storm range from 6 to 1500, and peak flash rates vary from 1 per minute to 20 per minute. Localized midwest storms have anywhere from 8 to several hundred CG flashes, at rates of 1.2 to 18 per minute. Maximum CG flashes in one Arizona storm numbered 175, and they occurred at the low rate of 0.6/minute. Of the twenty-three Albuquerque storms studied, a maximum of 58 CG flashes per storm occurred at about 1.2 per minute. As indicated in Table 1, thunderstorm VPF's are also highly diverse, due to the large number of interdependent climatological factors involved. The situation is exacerbated by the use of inconsistent methods to study the phenomenon.

An exhaustive study conducted by Rosenfeld and Gagin (1989) determined, by multiple regression, several storm characteristics affecting rainfall volume. They studied thousands of thunderstorms over semi-arid climates in central South Africa and Israel. The South African storms seem to parallel those in Albuquerque in that they mostly occur on summer afternoons, due to air-mass convection of a tropical tropopause.

Rosenfeld and Gagin found that the most important factor influencing total convective storm rain volume is height of cloud cell above freezing level. Next in significance is the number of rain cells in a cluster, which influences areal spread, intensity and duration, followed by absolute humidity at cloud base and air stability. They did not research lightning characteristics, and therefore did not address the question of whether or not precipitation might be predictably associated with it. However, the results of their study affirm the significance of cloud growth-rate and ultimate altitude-determined temperature, with respect to total thunderstorm rain yield. These two properties have already been seen to affect lightning activity, as indicated by the work of Lhermitte and Krehbiel (1979), Krehbiel (1986), Dye *et al.* (1989), and Buechler *et al.* (1990).

5.1 Interpolation

Precipitation-volume-per-CG flash obtained by the grid-point method (mean of 1.25×10^5 n are about half of the Thiessen values for the Albuquerque area (mean of 2.30×10^5 m^3). While the validity of using such irregularly spaced raingage point data would benefit from further study, the Simanton-Osborn interpolation procedure may be applicable for the current raingage network. Simanton and Osborn qualified their recommendations with a warning about estimations from gages located at rainfall minima and maxima.

Another source was consulted to provide a check. The storm of July 9, 1988 far exceeded 100-year recurrence predictions for the City of Albuquerque, so an independent consulting firm (Wright Water Engineers, Inc., 1989) conducted an assessment of the flood control system with respect to the depths of rainfall recorded by a combination of National Weather Service, Geological Survey and privately-owned gages on that day. An isohyet map constructed for this event indicates a total rain volume of approximately 3.05×10^6 m^3 for the area included in the perimeter used in this study. (Much more rain fell just to the south of this area.) This volume is 57% of that which was interpolated by the grid-point method for July 9th. Since the grid-point interpolation values fall between results determined by the Thiessen method and Wright Water Engineers, Inc. the grid-point method was acceptable.

A potential disadvantage associated with use of the LLP network to count CG lightning is that a critical decision must be made concerning the perimeter to use, within which to count lightning flashes. For example, a perimeter was originally chosen for this study which included the entire runoff watershed area, from the Sandia Crest west to the Rio Grande, and encompassing about 260 km^2. The number of flashes counted for that area exceeded those counted nearer to the rain gages by 47%. Recall, furthermore, that only about 75% of all CG flashes are recorded by LLP; this affects VPF results as an *over*estimation.

In any case, Figures 9 and 10 illustrate the great variability of precipitation from thunderstorms over Albuquerque, which, although true for other locations in which these events have been studied, is particularly characteristic of this drier climate. 1.25×10^5 m^3 is the mean VPF for twenty-three storms having at least five lightning flashes, apiece. The variance was almost as large at 1.09×10^5 m^3. 5.1×10^4 m^3 is the mean VPF for all storm days having more than 20 CG flashes. This count may be considered a threshold value, potentially to be used by Metropolitan Flood Control to monitor storm development.

The mean rain-volume-per-flash for large storms in Figure 10 is higher than that obtained by some researchers. This indicates that, while typical Albuquerque summer convective storms produce less total gage-recordable precipitation than is recorded elsewhere in the United States, there are also far fewer cloud-to-ground lightning flashes per storm event. The predicted high volume of rain flux associated with each Albuquerque flash makes it important to pay attention to flash rates during storms; access to real-time data is of minimal cost.

It is not known what total return stroke counts or current intensities are carried by CG flashes elsewhere, to assess whether Albuquerque storms are comparable in this respect. However, Figure 11 indicates that a predictable relationship exists for lightning return stroke counts during large storms. It may be simpler to observe total flashes than to keep track of return strokes for early warning or other purposes.

5.2 Correlation

Interpretations of the linear correlation statistic r are meaningful only if the joint probability distribution of rain volume and number of flashes forms a two-dimensional Gaussian distribution around their means, but the unknown Albuquerque distributions of these two variables made it difficult to assess r for that area. Non-parametric correlation was performed between the known regular-interval distributions of the *rank* of each lightning and precipitation magnitude.

The linear correlation coefficient was significant for only the very largest storms. Five out of twenty-three events showed a perfect relationship between associated increases of precipitation with increases in lightning count. Each of those storms had over thirty flashes. Storms with twenty or more flashes had some relationship. The threshold above which one variable may reliably be inferred from the other is probably between the two counts.

5.3 Lag

Figures 13 and 14 illustrate what is shown in Table 5: large convective storm cells over Albuquerque (determined as described above, to include storms having twenty flashes or more) reveal a consistent time association of about ten minutes between the occurrence of center of mass or peak intensity lightning and precipitation reaching the ground. In the northeast metropolitan area, runoff can be seen to respond rapidly as well, due to the large percentage of paved areas and smooth, unobstructed flood control channels. It remains impossible to predict whether lightning or rain will happen first at the ground surface; storm dynamics are so variable that each preceded the other about half of the time.

5.4 Evaporation

A definitive relationship between VPF and relative humidity below cloud base (in Figure 15) was not determined. This may be a result of the small sample number of available temperature and dewpoint soundings. However, the cluster of humidity values for low-VPF storms shows a possible correlation (in Figure 16). Further work may clarify this matter.

Rosenfeld and Gagin (1989) observed that vapor pressure, or absolute humidity, at cloud base correlated better with other variables than directly with total thunderstorm rain volume. However, they observed that rain volume could be doubled by increasing vapor pressure by 50% in South Africa. Four out of eleven Albuquerque storms show such a relationship, in Figure 17. It stands to reason that, other factors remaining constant, the actual atmospheric moisture content significantly affects the amount that will reach the ground. The trick is to simultaneously document enough of the storm characteristics to predict the outcome of their interrelationships.

5.5 Lightning-rainfall protection applications

Elaborate techniques for early warning of lightning are usually designed for protection specifically from high current intensity. However, another concern might be alleviated by the application of lightning data to predict rainfall. Although lightning is a leading cause of deaths in the United States each year (about one hundred, annually, according to Orville (1986)), flash floods have claimed victims in every thunderstorm season.

Lead time is critical in thunderstorm forecasting, since electric fields build quickly. Therefore field-strength criteria may not provide adequate warning. On the other hand, magnetic direction-finders such as the LLP network, with their long-range detection capabilities, provide clear evidence of storm direction and speed. Even 25-35% of missed CG flashes should not affect early-warning accuracy, with the attractive and rapidly updated graphics available today.

A recent evaluation of the use of lightning data by forecasters at the National Severe Storms Forecast Center, concluded that lightning activity added knowledge about convective storms that could not be obtained from either satellite or radar data (Goodman, 1991). Specifically, 78% of 153 large storm events and 64% of 301 weaker storms were more correctly forecast. With improvements in consistency, accuracy and availability of atmospheric-condition soundings, the combination of such data with lightning direction-finder observations may provide high statistical reliability for long lead-time thunderstorm forecasting.

6 Conclusions

This study of twenty-three thunderstorms has demonstrated the high variability of events producing both lightning and rainfall, in the Albuquerque area. Near-storm-cell atmospheric conditions, such as vapor pressure, fluctuate more in the western New Mexico thunderstorm environment than they do in areas of the United States receiving regular pulses of tropical moisture. However, the convection and cold-rain processes parallel those of storms in some other geographical areas, notably those in semi-arid climates such as that of central South Africa. It is important to monitor more factors affecting storm development in these climates, in order to predict accurately the wide range of storm outcomes.

It can be seen that even one variable, lightning, may be used to predict time-associated precipitation for large events (mean VPF for large storms was 5.1×10^4 m^3). The limiting value lightning counts (twenty to thirty flashes) determined by ranked correlation supports the validity of the VPF-determined threshold of twenty flashes. Any VPF error due to raingage nonuniformity was systematic for this study.

7 Recommendations for Future Work

It would be worthwhile to characterize semi-arid environment thunderstorms more closely. To do so might not require a huge financial investment, although an investment of time is necessary. Much of the data which would be helpful to such a study are already being recorded and archived, although by many different agencies.

An excellent raingage record is stored in Tucson, Arizona, for the nearby Walnut Gulch watershed. This is a long-standing record archived by the United States Department of Agriculture, for a gage density of ninety equally-spaced gages over a 60 mi^2 area. A difficulty exists because the USDA employees don't regularly have time to screen their data, and to thereby make them available to others. The National Center for Atmospheric Research, NCAR, in Boulder, Colorado, archives atmospheric sounding and near-ground-surface data for two recording stations in New Mexico, and information is probably available for other states as well. Lightning data, as discussed, are inexpensively available from one or more DF networks.

Problems encountered in the present work include the fact that LLP lightning has only been archived since 1986, which seriously limited the number of storms available for study. Parameters as variable as arid-climate thunderstorm properties could be much better quantified by large data sets. An example of another difficulty is that, early in this study, an attempt was made to relate runoff to lightning by means of rainfall occurring in several rural watersheds of New Mexico. This approach was abandoned because too few gages exist in the areas examined; also most streams and rivers in this climate are diverted for irrigation, or have upstream reservoirs with high evaporation rates. Streamgage records in this climate are not sufficient to indicate actual storm rain volumes.

However, an investigator confident of his record for many predictive thunderstorm variables ought to consider applying his results to a watershed-model study of runoff response. "RIOFISH" is such a model, currently used by researchers at New Mexico State University. They hope to be able to input lightning data as an inexpensive convective-storm rainfall predictor for ungaged areas, in order to see possible runoff-sediment load responses affecting fish nutrition in Caballo Reservoir in south-central New Mexico.

A demonstrated CG lightning-precipitation relationship should improve basin water balance calculations which are used to predict correct subsurface recharge. The amount of water available for uses such as irrigation, rangeland management, and human consumption needs to be known accurately. Some of the investigators referenced in this report hope to use lightning and other thunderstorm properties to design better satellite-imaging technology for weather forecasting. Clearly, potential applications for an established lightning-precipitation relationship are not limited.

8 References

Atchley, A. A., et al., TRIP 1979: Case study of August 7 thunderstorm over Langmuir Laboratory, in *Proceedings in Atmospheric Electricity*, edited by L. H. Ruhnke and J. Latham, A. Deepak, Hampton, Va., 1983.

Barnes, S. L., A technique for maximizing details in numerical weather map analysis, *J. Appl. Meteor., 3*, 396–409, 1964.

Battan, L. J., Some factors governing precipitation and lightning from convective clouds, *J. Atmos. Sci., 22*, 79–84, 1965.

Beard, K. V. K. and H. T. Ochs, Charging mechanisms in clouds and thunderstorms, *The Earth's Electrical Environment*, National Academy Press, Washington, DC, 114–130, 1986.

Buechler, D. E. and Goodman, S. J., Radar characteristics of cloud-to-ground lightning producing storms in Florida, *Preprints*, 25rd Intern. Conf. on Radar Meteor., Paris, France, Am. Meteor. Soc., Boston, MA, 1991.

Buechler, D. E., P. D. Wright and S. J. Goodman, Lightning/rainfall relationships during COHMEX, *Preprints*, AMS Conf. on Atmospheric Electricity, Kananaskis Provincial Park, Alta., Canada, 1990.

Dean, J. D. and W. M. Snyder, Temporally and areally distributed rainfall, *Journal of the Irrigation and Drainage Division, ASCE, 103*, Proc. Paper, 221-229, 1977.

Dye, J. E., W. P. Winn, J. J. Jones, and D. W. Breed, The Electrification of New Mexico thunderstorms, 1, Relationship between precipitation development and the onset of electrification, *J. Geophys. Res., 94*, 8643–8656, 1989.

Easterling, D. R., Regionalization of thunderstorm rainfall in the contiguous United States, *Intern. J. Climatology, 9*, 567–579, 1989.

Gilman, C. S., Rainfall, *Handbook of Applied Hydrology*, edited by V. T. Chow, Chapter 9, 1-68, McGraw-Hill Book Company, New York, NY, 1964.

Goodman, S. J., Sensor fusion techniques for predicting thunderstorm evolution using lightning and radar networks, *Preprints*, 25rd Intern. Conf. on Radar Meteor., Paris, France, Am. Meteor. Soc., Boston, MA, 1991.

Goodman, S. J. and D. E. Buechler, Lightning-rainfall relationships, *Preprints*, AMS Conf. on Operational Precipitation Estimation and Prediction, Anaheim, CA, 1990.

Goodman, S. J., D. E. Buechler, P. D. Wright and W. D. Rust, Lightning and precipitation history of a microburst-producing storm, *Geophys. Res. Lett., 15*, 1185–1188, 1988.

Grosh, R. C., Lightning and precipitation — The life history of isolated thunderstorms, *Preprints*, AMS Conf. on Cloud Physics and Atmospheric Electricity, Issaquah, WA, 617–624, 1978.

Hales, J. E., Jr., Southwestern United States summer monsoon source—Gulf of Mexico or Pacific Ocean?, *J. Appl. Meteor., 13*, 331–342, 1974.

Huff, F. A., Sampling errors in measurement of mean precipitation, *J. Appl. Meteor., 9*, 35–44, 1970.

Kessler, E., Thunderstorm origins, morphology, and dynamics, *The Earth's Electrical Environment*, National Academy Press, Washington, DC, 81–89, 1986.

Kinzer, G. D., Cloud-to-ground lightning versus radar reflectivity in Oklahoma thunderstorms, *J. Atmos. Sci., 31*, 787–799, 1974.

Krehbiel, P. R., An analysis of the electric field change produced by lightning, Ph.D. Thesis, Univ. of Manchester, England, 1981.

Krehbiel, P. R., The electrical structure of thunderstorms, *The Earth's Electrical Environment*, National Academy Press, Washington, DC, 90–113, 1986.

Krider, E. P., R. C. Noggle, A. E. Pifer and D. L. Vance, Lightning direction finding systems for forest fire detection, *Bull. Am. Meteorol. Soc., 61*, 980–986, 1980.

Lenton, R. L. and I. Rodríguez-Iturbe, Rainfall network systems analysis: The optimal estimation of total areal storm depth, *Water Resour. Res., 13*, 825–835, 1977.

Levin, Z. and I. Tzur, Models of the development of the electrical structure of clouds, *The Earth's Electrical Environment*, National Academy Press, Washington, DC, 131–145, 1986.

Lhermitte, R. M. and P. R. Krehbiel, Doppler radar and radio observations of thunderstorms, IEEE Trans. Geosci. Electron., *GE-17(4)*, 162–171, 1979.

Lhermitte, R. M. and E. R. Williams, Cloud electrification, *Rev. Geophys., 21*, 984–992, 1985.

Linsley, R. K., Jr., M. A. Kohler and J. L. H. Paulhus, *Hydrology for Engineers, 3rd Edition*, McGraw-Hill Book Company, New York, NY, 1982.

Livingstone, J. M. and E. P. Krider, Electric fields produced by Florida thunderstorms, *J. Geophys. Res., 83*, 385–401, 1978.

MacGorman, D. R., V. Maxur and W. D. Rust, Lightning rates relative to mesocyclone evolution in a tornadic storm on 22 May 1981, *Preprints*, 23rd Conf. on Radar Meteor., Snowmass, CO, Am. Meteor. Soc., Boston, MA, J300–J303, 1986.

MacGorman, D. R. and W. D. Rust, An evaluation of the LLP and LPATS lightning ground strike mapping systems, *Preprints*, 5th Intern. Conf. on Interactive Information and Processing Systems, American Meteorological Society, Anaheim, CA, 1989.

Maier, M. W., A. G. Boulanger and J. Sarlat, Cloud-to-ground lightning frequency over South Florida, *Preprints*, AMS Conf. on Cloud Physics and Atmospheric Electricity, Issaquah, WA, 605–610, 1978.

Moore, C. B., B. Vonnegut, and A. T. Botka, Results of an experiment to determine initial precedence of organized electrification and precipitation in thunderstorms, in *Recent Advances in Atmospheric Electricity*, Proceedings of 2nd Conf., edited by L. G. Smith, Symposium Publications Division, Pergamon Press, NY, 1958.

Moore, C. B., B. Vonnegut, J. A. Machado and H. J. Survilas, Radar observations of rain gushes following overhead lightning strokes, *J. Geophys. Res., 67*, 207–220, 1962.

Moore, C. B., B. Vonnegut, E. A. Vrablik and D. A. McCaig, Gushes of rain and hail after lightning, *J. Atmos. Sci., 21*, 646–665, 1964.

Nisbet, J. S., J. R. Kasha and G. S. Forbes, A case study of the Thunderstorm Research International Project storm of July 11, 1978 2. Interrelations among the observable parameters controlling electrification, *J. Geophys. Res., 95*, 5435–5445, 1990.

Orville, R. E., Lightning phenomenology, *The Earth's Electrical Environment*, National Academy Press, Washington DC, 23–29, 1986.

Osborn, H. B., L. J. Lane and J. F. Hundley, Optimum gaging of thunderstorm rainfall in southeastern Arizona, *EOS, Trans. Am. Geophys. Union*, 1969.

Piepgrass, M. V., E. P. Krider and C. B. Moore, Lightning and surface rainfall during Florida thunderstorms, *J. Geophys. Res., 87*, 11193–11201, 1982.

Poehler, H. A., LDAR observations of a developing thunderstorm, and weather radar data including the first report of the design and capabilities of a new, time-of-arrival ground-strike location system (GSLS), *Contract. Rep. CR-15426*, NASA, Kennedy Space Center, Fla., Sept. 1978.

Press, W. H., B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, *Numerical Recipes*, Cambridge Univ. Press, Cambridge, 1986.

Raymond, D. J., A C language-based modular system for analyzing and displaying gridded numerical data, *J. Atmos. Oceanic Technol., 5*, 501–511, 1988.

Rosenfeld, D. and A. Gagin, Factors governing the total rainfall yield from continental convective clouds, *J. Appl. Meteor., 28*, 1015–1030, 1989.

Silverman, B. A. and L. K. Rogers, On the sampling variance of raingage networks, *J. Appl. Meteor., 20*, 1468–1478, 1981.

Simanton, J. R. and H. B. Osborn, Reciprocal-distance estimate of point rainfall, *Journal of Hydraulics Division Technical Notes, ASCE, 106*, 1242-1246, 1980.

Uman, M. A., Application of advances in lightning research to lightning protection, *The Earth's Electrical Environment*, National Academy Press, Washington, DC, 61–69, 1986.

Williams, E. R., M. E. Weber and R. E. Orville, The relationship between lightning type and convective state of thunderclouds, *J. Geophys. Res., 94*, 13213–13220, 1989.

Woodley, W. L., A. R. Olsen, A. Herndon and V. Wiggert, Comparison of gage and radar methods of convective rain measurement, *J. Appl. Meteor., 14*, 909–927, 1975.

Workman, E. J. and S. E. Reynolds, Electrical activity as related to thunderstorm cell growth, *Bull. Am. Meteor. Soc., 30*, 142–144, 1949.

Wright Water Engineers, Inc., *Assessment of the July 9, 1988 Storm and the City of Albuquerque Flood Control System*, Report to Risk Management, Legal and Public Works Dept., City of Albuquerque, NM, 1989.

A LLP direction-finder locations

DF LOCATIONS

from BIFC, in Boise, Idaho, (208-389-2488), 25 June 1987;
latitude, longitude and abbreviations added 10 Jan 1989

Sta #		Location	Latitude	Longitude
1	VLE	Vale, Oregon	43.9666	-117.2499
2	BYI	Burley, Idaho	42.5104	-113.7931
3	TUS	Tucson, Arizona	32.1200	-110.9299
4	BKF	Bakersfield, California	35.4347	-119.0532
5	APV	Apple Valley, California	34.5919	-117.1679
6	SJQ	San Joaquin (near Fresno, California)	37.0894	-119.7221
7	GJT	Grand Junction, Colorado	39.1253	-108.5283
8	MTV	Monte Vista, Colorado	37.5826	-106.1968
9	IDF	Idaho Falls, Idaho	43.5182	-112.0655
10	BTM	Butte, Montana	45.9286	-112.5111
11	LWT	Lewiston, Montana	47.0511	-109.4531
12	MLC	Miles City, Montana	46.3965	-105.8615
13	MSO	Missoula, Montana	46.9241	-114.0939
14	EKL	Elko, Nevada	40.8619	-115.7333
15	ELY	Ely, Nevada	39.2931	-114.8440
16	ONM	Socorro, New Mexico	34.0682	-106.9139
17	LKV	Lakeview, Oregon	42.1560	-120.4089
18	RDM	Redmond, Oregon	44.2599	-121.1433
19	CDC	Cedar City, Utah	37.6964	-113.0822
20	CNY	Cheney, Washington (near Spokane)	47.4166	-117.5285
21	RKS	Rock Springs, Wyoming	41.6286	-109.2305
22	IGM	Kingman, Arizona	35.2540	-113.9410
23	VIN	Vina (near Chico, California)	39.9290	-122.0280
24	ROW	Roswell, New Mexico	33.3076	-104.5274
25	GBL	Greybull, Wyoming	44.5011	-108.0581
26	EUG	Eugene, Oregon	44.1256	-123.2143
27	KRT	Albuquerque, New Mexico (Kirtland AFB)	34.9475	-106.5590
28	WSP	Warm Springs, Nevada (near Tonopoh)	38.3128	-116.2776
29	OLM	Olympia, Washington	46.9731	-122.8965
30	OMK	Omak, Washington	48.4579	-119.5164
31	PDL	Pendleton, Oregon	45.6925	-118.8381
32	GUP	Gallup, New Mexico	35.5126	-108.7768
33	LUK	Luke AFB, Phoenix Arizona	33.5457	-112.3808
34	DGY	Dugway, Utah	40.1067	-112.8070
35	LKS	Lakeside, Utah	41.0528	-112.9339

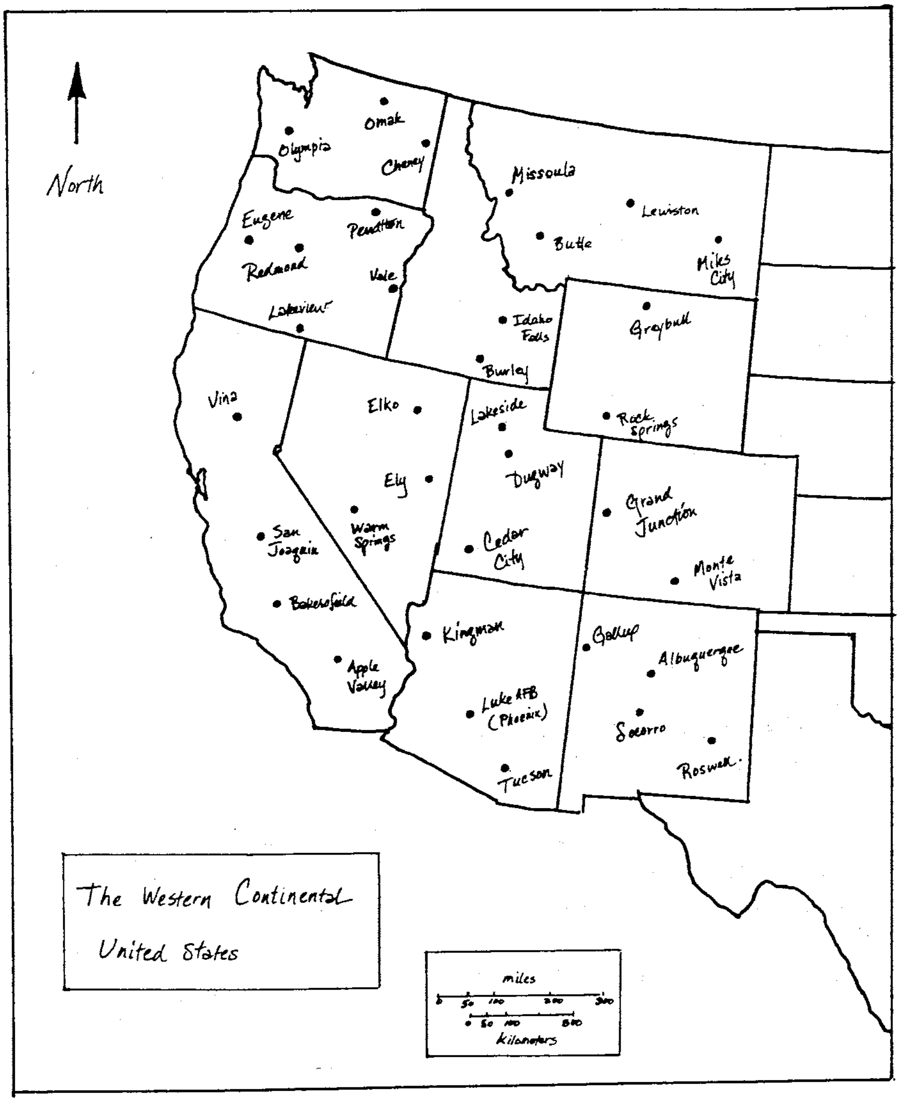

Figure 18: Map of LLP DF Locations.

2 Computer programs

```
/* Program ABQFLASH.c reads lines of lightning flash data and counts the number
/* which occurred within the Albuquerque lat-long perimeter on specific dates.

#include <stdio.h>
#define MAXLINE  100


FILE    *in, *out;
int     doy1,doy2,hour;
char    line[MAXLINE];

main    (argc,argv)
int     argc;
char    *argv[];
{       int     i=0, flash=1;

        if(argc !=3)
        { fprintf(stderr,"Usage: %s totalabq output_file\n", argv[0]);
            exit(1);
        }
        if((in = fopen(argv[1],"r")) == NULL)
        { fprintf(stderr,"Cannot open file %s\n",argv[1]);
            exit(1);
        }
        if((out = fopen(argv[2],"w")) == NULL)
        { fprintf(stderr,"Cannot open file %s\n",argv[2]);
            exit(1);
        }
        doy1 = doy2 = 0;

        while  (!feof(in))
        {   fgets(line,MAXLINE,in);
            if (line[0] != '/')
            {
              hour = atoi(line);
              doy1 = atoi(line+48);
              if (doy1 != 0 && hour < 6 ) --doy1;
              if (doy1 == doy2 )
                    ++flash;
              else {
                if (doy2!=0) fprintf (out,"%d %02d\n",doy2,flash);
                flash =1;
              }
              doy2 = doy1;

            }

        }



        fclose(in);  fclose(out);
}

getline (s,lim,dfile)

char    s[];
int     lim;
FILE    *dfile;
```

```
{       int c, i;

        i=0;
        while (--lim>0 && (c=fgetc(dfile)) !=EOF && c != '\n')
            s[i++] = c;
        if (c == EOF) return (EOF);
        if (c == '\n')
            s[i++] = c;
        s[i] = '\0';
        return (i);
}
```

```
 * occurring within 5-minute intervals.  Saved to file.
 */

#include  <stdio.h>
#define    MAXLINE  100
#define    MAXMIN   1440
#define    MAXHOUR  24

double     atof();

FILE      *in,  *out;
int       getline();
char      line[100];
int       hour, min, flash[288];
int       hourp,minp;
long      day;

main    (argc, argv)
int      argc;
char    *argv[];
{       int i=0,day=0,dayprev=0,interval,index,tmin;
        float junk;
        if (argc != 3)
        { printf (stderr,"Usage: %s llp_file output_file\n", argv[0]);
          exit (1);
        }
        if ((in = fopen(argv[1],"r")) == NULL)
        { printf ("Cannot open file %s\n",argv[1]);
          exit (1);
        }
        if ((out = fopen(argv[2],"w")) == NULL)
        { printf ("Cannot open file %s\n",argv[2]);
          exit (1);
        }

        for(i=0;i<288;i++) flash[i]=0;   /* There are 288 5-minute intervals
                                            in a 24-hour day. */

        while (getline(line, MAXLINE, in) != EOF) {
            if (line[0] == '/') continue;
            sscanf(line,"%d:%d:%*f %*f %*f %*f %*d %*ls%d %*d %*d",
                    &hour,&min,&day);
            hour=hour-6;          /*   GMT to MDT  */
            if(hour<0)             /*  for MDT less than 6:00 am  */
            { hour=hour+24;
              day=day - 1;
            }
            if ((day != dayprev)&&(dayprev != 0)) {
              for ( interval=0;interval<288;interval++) {
                tmin=interval*5;
                hourp=tmin/60;
                minp=tmin-(hourp*60);
                fprintf (out,"d%ld  %2d:%2d MDT  %4d\n",
                dayprev,hourp,minp,flash[interval]);
                flash[interval]=0;
              }
            }
            index=(int)((hour*60+min)/5);
```

```
                dayprev= day;
        }

         fclose(in); fclose(out);
}

getline(s, lim, dfile)    /* get line into s; return length */

char    s[];
int     lim;
FILE     *dfile;
{
        int c, i;

        i=0;
        while (--lim>0 && (c=fgetc(dfile)) != EOF && c != '\n')
           s[i++] = c;
        if (c == EOF) return (EOF);
        if (c == '\n')
           s[i++] = c;
        s[i] = '\0';
        return (i);
}
```

```
/*  into 132-character lines for readability. */


#include <stdio.h>

main()
{   int c,i,j;

    while((c=getchar())!=EOF)
    {   for (i=0;i<7;i++) getchar();
        {   for(i=0;i<10;i++)
            {   for(j=0;j<132;j++)
                {   c=getchar();
                    putchar(c&0x7f);
                }
                putchar('\n');
            }
        }
    }
}
```

```
/*  Program GSDUMP.c reads ALBQ Geological Survey files for daily total precip and
/*  runoff, then stores in dayofyear array, in order to append to gauges array for
/*  years.  Saves to transition file.
 */

#include <stdio.h>
#include "day.h"
#define  MAXSTRLEN  135
#define  MAXLEN  100
#define  BEGOFLABEL 27   /* where the text of location begins */
#define  ENDOFLABEL 98   /* where the text ends (worst case) */
#define  NUMWORTHLESS 7 /* worthless lines between lat,lng and first day */

double atof();

FILE    *in, *out;
int     getline();
int     doy(),dayofyear,pickyr;
char    line[100] ;
int     hour,min,leap,day,month,year;
int     datayr,ii,jj,j,digit=0;
char    buffer[MAXSTRLEN];
char    loclabel[MAXSTRLEN];
char    gage[17];
char    blank[2];
char    tempfield[12];  /* only really need 10 */
char    s;
float   data[366],a=0.0,NaN;
long    lat,lng;

main  (argc,argv)
int     argc;
char    *argv[];
{   int     i=0,day=0;

    NaN = a/a;

    if (argc != 3)
      {  fprintf(stderr,"Usage:  %s gs-file pickyr\n", argv[0]);
            exit (1);
      }
    if ((in=fopen(argv[1],"r")) == NULL)
      {  fprintf(stderr,"Cannot open file %s\n",argv[1]);
            exit(1);
      }

      pickyr = atoi(argv[2]);
      year = 0;

    while (!feof(in) && pickyr != year)
    {
      fgets(buffer,MAXSTRLEN,in);
      while (buffer[0]!='1')
       fgets(buffer,MAXSTRLEN,in);

      sscanf(buffer,"%*d %d",&year);
    }
```

```
  sscanf(buffer,"%s",gage);          /* get the number location */

  strncpy(loclabel, buffer+BEGOFLABEL, ENDOFLABEL-BEGOFLABEL);

  /* the previous line should pull out everything between BEGOFLABEL
   and ENDOFLABEL */

  fgets(buffer,MAXSTRLEN,in);
  sscanf(buffer,"%*s %d %*s %d",&lat,&lng);

  for (i=0; i<NUMWORTHLESS; i++)
   fgets(buffer,MAXSTRLEN,in);

  day = 0;
  while (fgets(buffer,MAXSTRLEN,in) && strncmp("TOTAL",buffer+5,5))
  {
            i = 0;
            while (buffer[i]==' ') i++;
    if (buffer[i]=='\n') continue;
    day++;
    for (month=0;month<9;month++)
            { dayofyear=doy(month,day);
              if (dayofyear != -1)
              {strncpy(tempfield,buffer+(month*9)+36,9);  /* start at JAN colum
               digit = 0;
                              for (j=0; j<9 && !digit; j++)
                 digit = (tempfield[j]>='0' && tempfield[j]<='9');
               if (digit)
                  data[dayofyear-1]=atof(tempfield);
               else
                                     data[dayofyear-1]=NaN;

              }
            }
   }

       fgets(buffer,MAXSTRLEN,in);

  pickyr = (atoi(argv[2])+1);
  year = 0;

while (!feof(in) && pickyr != year)
{
  fgets(buffer,MAXSTRLEN,in);
  while (buffer[0]!='1')
   fgets(buffer,MAXSTRLEN,in);

  sscanf(buffer,"%*d %d",&year);
}

  fgets(buffer,MAXSTRLEN,in);   /* read a blank line */
  fgets(buffer,MAXSTRLEN,in);   /* read the line with the location */
  sscanf(buffer,"%s",gage);          /* get the number location */

  strncpy(loclabel, buffer+BEGOFLABEL, ENDOFLABEL-BEGOFLABEL);

  /* the previous line should pull out everything between BEGOFLABEL
   and ENDOFLABEL */
```

```
    sscanf(buffer,"%*s %d %*s %d",&lat,&lng);

    for (i=0; i<NUMWORTHLESS; i++)
     fgets(buffer,MAXSTRLEN,in);

    day = 0;
    while (fgets(buffer,MAXSTRLEN,in) && strncmp("TOTAL",buffer+5,5))
    {
              i = 0;
              while (buffer[i]==' ') i++;
      if (buffer[i]=='\n') continue;
      day++;
              for (month=9;month<12;month++)
              {  dayofyear=doy(month,day);
                 if (dayofyear != -1)
                 {strncpy(tempfield,buffer+((month-9)*9)+9,9);  /* start at OCT c
                 digit = 0;
                                for (j=0; j<9 && !digit; j++)
                   digit = (tempfield[j]>='0' && tempfield[j]<='9');
                 if (digit)
                    data[dayofyear-1]=atof(tempfield);
                 else
                                       data[dayofyear-1]=NaN;
                }
           }
     }
         fgets(buffer,MAXSTRLEN,in);


  for(i=0;i<365+leap;i++){
    printf("%9.2f %d\n",data[i],i+1);
  }



  fclose(in); fclose(out);
}

getline(s,lim,dfile)

char    s[];
int     lim;
FILE    *dfile;
{
    int c,i;

    i=0;
    while (--lim>0 && (c=fgetc(dfile)) != EOF && c != '\n')
        s[i++]=c;
    if (c == EOF) return (EOF);
    if (c == '\n')
        s[i++]=c;
    s[i]='\0';
    return(i);
}

doy(month, day)
```

```
  int i,temp=0;

  if (months[month].length<day && !(month == 1 && day == 29 && year%4 ==
        0))
     return(-1);
  for (i=0; i<month; i++)
    temp += months[i].length;

  temp += day + ((year%4 == 0) && (month>1));
  return(temp);
}
```

```
/* a specified calendar date (see usage line).

#include <stdio.h>
#include <math.h>

#define MAX 288
char tempfield[12];

main(argc, argv)
int argc;
char *argv[];
{

  float data[MAX];
  char line[200],*date;
  int found=0,digit,i,j,k;

  if (argc != 2){
    fprintf(stderr,"usage:  %s mm/dd/yy\n",argv[0]);
    exit(1);
  }

  date = argv[1];

  while (!feof(stdin) && !found){

    fgets(line, 200, stdin);
    found = (strncmp(line+5,date,strlen(date))==0);
  }

  for (i=0; i<24; i++){
    for (j=0; j<12; j++){
      strncpy (tempfield,line+26+j*9,9);
      digit = 0;
         for(k=0;k<9 && !digit; k++)
         digit=(tempfield[k]>='0' && tempfield[k]<='9');
         if (digit)
            data[i*12+j] = atof(line+26+j*9);
         else
            data[i*12+j]= 0.00;
    }
    fgets(line, 200, stdin);
  }

  for (i=0; i<MAX; i++)
    fprintf(stdout,"%03d %07.2f\n",i+1,data[i]);
}
```

```
% network and determines a total (totalr) for the 24-hour storm day.
% The date is given as the Julian calendar form of year and day number:
% For example, "88191" refers to the 191st day of 1988.

load academy88191.mat
r(:,1)=academy88191(:,2);
total(1,1)=sum(r(:,1));

load bear88191.mat
r(:,2)=bear88191(:,2);
total(2,1)=sum(r(:,2));

load borland88191.mat
r(:,3)=borland88191(:,2);
total(3,1)=sum(r(:,3));

load camino88191.mat
r(:,4)=camino88191(:,2);
total(4,1)=sum(r(:,4));

load campus88191.mat
r(:,5)=campus88191(:,2);
total(5,1)=sum(r(:,5));

load cueva88191.mat
r(:,6)=cueva88191(:,2);
total(6,1)=sum(r(:,6));

load deloso88191.mat
r(:,7)=deloso88191(:,2);
total(7,1)=sum(r(:,7));

load hahn88191.mat
r(:,8)=hahn88191(:,2);
total(8,1)=sum(r(:,8));

load hale88191.mat
r(:,9)=hale88191(:,2);
total(9,1)=sum(r(:,9));

load leonard88191.mat
r(:,10)=leonard88191(:,2);
total(10,1)=sum(r(:,10));

load nfhahn88191.mat
r(:,11)=nfhahn88191(:,2);
total(11,1)=sum(r(:,11));

load fire88191.mat
r(:,12)=fire88191(:,2);
total(12,1)=sum(r(:,12));

load sfhahn88191.mat
r(:,13)=sfhahn88191(:,2);
total(13,1)=sum(r(:,13));

totalr = sum(total(:,1))
totalg=total;
```

```
day 88191

load rgloc.dat
ri88191=[rgloc totalg];
save ri88191.dat ri88191 -ascii

ti88191=totalr;
save ti88191.dat ti88191 -ascii
```

```
% from interpolated depths

load in88191.dat
i=in88191;
day=88191
isoplot

itdrain=sum(i.*bound2)*0.0254*175741.85;
intvol=sum(itdrain)
% Converts interpolated raindepths in inches to metric
% volume at the Albuquerque lat and long areal dimensions.
save intvol88191.dat intvol -ascii
```

```
% with options for plotting the latitude and longitude raingage network,
% with or without precipitation depth contours.

load isoplot      %refers to ISOPLOT.mat, a binary Matlab file containing the
                  % lat-long boundary specifications and interpolation grid
hold off
axis(isoaxis)
%plot(plong2,plat2)
%title('NE ABQ raingage network')
%xlabel('longitude')
%ylabel('latitude')

%plot(plong2,plat2)
%contour(i,10,x,y)

%hold on
%plot(rgloc2(:,2),rgloc2(:,1),'*')
```

```
/* Adapted from Dr. David Raymond's "nwsgrid" function.
 * Program NWSG.c interpolates station data to a two-dimensional
 * grid.  The interpolation is done by weighting the rain depth
 * recorded at each gage based on its distance from an ungaged grid point.
 * The weighting function is (total precip / r*r)/(no gages / r*r),
 * where r is the distance between the data and grid point.
 */

#include <stdio.h>
#include <math.h>

#define BAD 1.0e30
#define BADLIM 0.999e30

#define NX 44
#define NY 32
#define MAXST 13

float *getbuff();

#define I(ix,iy) ix*ny + iy

main()
{    float svals[MAXST],xloc[MAXST],yloc[MAXST];
     int nstns;
     float x0,dx,y0,dy;
     int nx,ny;
     float radius;
     float *gvals;
     int i,ix,iy;

/*   For now, just assume we know the following variables.  In future, can
 *   read them from a file, or specify on command line
 */
     nx = NX;
     ny = NY;
     nstns = MAXST;

/*  All of the following dimensions are in degress of latitude (for y)
 *  or degress of longitude (for x)
 */
     x0 = -106.6500;
     y0 = 35.08333;
     dx = 15.0/3600.0;
     dy = 15.0/3600.0;
     radius = 0.125;

/*  Allocate space for gridded data  */

     gvals = getbuff(nx*ny);

/*  Read data for each rain gage from standard input  */

     for (i=0;i<nstns;i++) { scanf("%f %f %f",&yloc[i],&xloc[i],&svals[i]);
     }

/*  Now grid the data                */

     grid(svals,xloc,yloc,nstns,x0,dx,nx,y0,dy,ny,radius,gvals);
```

```
/*  print results to standard output */

    for (iy=0;iy<ny;iy++)
    {   for (ix=0;ix<nx;ix++)
        {   if (gvals[I(ix,iy)]<100.0) printf("%f ",gvals[I(ix,iy)]);
            else printf("%f ",0.0);
        }
        printf("\n");
    }
}

/* this routine does the gridding */

#define I(ix,iy) ix*ny + iy
#define NSTATMIN 3

grid(svals,xloc,yloc,nstns,x0,dx,nx,y0,dy,ny,radius,gvals)
float *svals;       /* station values */
float *xloc,*yloc;  /* station locations */
int nstns;          /* number of stations */
float x0,dx,y0,dy;  /* index parameters */
int nx,ny;          /* sizes of index fields */
float *gvals;       /* gridded values */
float radius;       /* weighting factors */
{
  int ix,iy,istns;              /* looping variables */
  int x1,x2,y1,y2;              /* limit values on grid */
  static float *denom = NULL;   /* work space pointer */
  static short *nstats = NULL;  /* more work space */
  float xgrid,ygrid;            /* difference values of x and y */
  float weight;                 /* weighting factor */
  float rsq;              /* squared radii */
/* allocate work space only once */
  if (denom == NULL) {
    denom = getbuff(nx*ny);
    if ((nstats = (short*)malloc(nx*ny*sizeof(short))) == NULL) {
      fprintf(stderr,"nwsgrid: can't get enough memory\n");
      exit(1);
    }
  }

/* zero work space */
  for (ix = 0; ix < nx*ny; ix++) {
    gvals[ix] = denom[ix] = 0.;
    nstats[ix] = 0;
  }
/* loop on stations */
  for (istns = 0; istns < nstns; istns++) {
/* skip stations with bad locations or data */
    if (fabs(xloc[istns]) > BADLIM) continue;
    if (fabs(yloc[istns]) > BADLIM) continue;
    if (fabs(svals[istns]) > BADLIM) continue;

/* loop on grid portion near station */
    for (ix = 0; ix < nx; ix++) {
      for (iy = 0; iy < ny; iy++) {

/* compute weight */
        xgrid = x0 + dx*ix - xloc[istns];
```

```
/*
if (ix == 0 && iy == 4) fprintf(stderr,"rsq = %f \n",rsq);
*/

/* increment grid fields */
          gvals[I(ix,iy)] += svals[istns]/rsq;
          denom[I(ix,iy)] += 1.0/rsq;
        }
/*
if (ix == 0 && iy == 4) fprintf(stderr,"  xgrid = %f; ygrid = %f; rsq = %f; istns =
*/
      }
    }
/* normalize gridded field */
  for (ix = 0; ix < nx; ix++) {
    for (iy = 0; iy < ny; iy++)
      gvals[I(ix,iy)] /= denom[I(ix,iy)];
    }
}



/* getbuff -- This routine uses malloc to allocate float buffer
 * space.  The argument nelem defines the number of floating
 * point elements.  It returns a float pointer to the space.  If malloc
 * fails, getbuff dies with an error message.
 */
#include <stdio.h>

float *getbuff(nelem)
long nelem;
{
  float *point;
  if ((point = (float*)malloc(sizeof(float)*nelem)) == NULL) {
    fprintf(stderr,"getbuff: can't get enough memory\n");
    exit(1);
  }
  return(point);
}
```

```
%correlation between ranks of magnitude of two variables, in this case
%lightning flash count and rain volume per flash. The number 60 is the
%sum of:  the number of tied ranks for each storm, cubed, minus the number
%of tied ranks for that storm, in other notation, as the sum of
%((f_k)^3 - f_k). (See Press et al., in references.)

load f.dat          %(flash count for each storm)
load vpf.dat        %(VPF for each storm)

rank(:,1)=f(:,2);
rank(:,2)=vpf(:,2);
for i = 1:23,
 diff(i)=(rank(i,1)-rank(i,2));
 sq(i)=diff(i).^2;
 end
N=23;
D=sum(sq)
D_exp=(1/6)*(N^3-N)-(60/12)
var_D_exp=(((N-1)*N^2*(N+1)^2)/36)*(1-(60/(N^3-N)))
r_s=(1-(6/(N^3-N))*(D+0.5*60))/(1-(60/(N^3-N)))          %(r value)
t=r_s*sqrt((N-2)/(1-r_s^2))                              %(significance of r)
```

```
* the National Weather Service.  This file plots
* temperature and dewpoint tephigrams.
*/

cdftsel date 10 10 <su88.cdf|cdftsel month 6 6> su162.cdf
cdftsel station 1 1 <su162.cdf> su162.abq
cdfcat hour 0 30 60 <su162.abq>su162.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su162.cat
pglj

cdftsel date 11 11 <su88.cdf|cdftsel month 6 6> su163.cdf
cdftsel station 1 1 <su163.cdf> su163.abq
cdfcat hour 0 30 60 <su163.abq>su163.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su163.cat
pglj

cdftsel date 5 5 <su88.cdf|cdftsel month 7 7> su187.cdf
cdftsel station 1 1 <su187.cdf> su187.abq
cdfcat hour 0 30 60 <su187.abq>su187.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su187.cat
pglj

cdftsel date 8 8 <su88.cdf|cdftsel month 7 7> su190.cdf
cdftsel station 1 1 <su190.cdf> su190.abq
cdfcat hour 0 30 60 <su190.abq>su190.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su190.cat
pglj

cdftsel date 9 9 <su88.cdf|cdftsel month 7 7> su191.cdf
cdftsel station 1 1 <su191.cdf> su191.abq
cdfcat hour 0 30 60 <su191.abq>su191.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su191.cat
pglj

cdftsel date 28 28 <su88.cdf|cdftsel month 7 7> su210.cdf
cdftsel station 1 1 <su210.cdf> su210.abq
cdfcat hour 0 30 60 <su210.abq>su210.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su210.cat
pglj

cdftsel date 9 9 <su88.cdf|cdftsel month 8 8> su222.cdf
cdftsel station 1 1 <su222.cdf> su222.abq
cdfcat hour 0 30 60 <su222.abq>su222.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su222.cat
pglj

cdftsel date 1 1 <su88.cdf|cdftsel month 9 9> su245.cdf
cdftsel station 1 1 <su245.cdf> su245.abq
cdfcat hour 0 30 60 <su245.abq>su245.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su245.cat
pglj

cdftsel date 11 11 <su88.cdf|cdftsel month 9 9> su255.cdf
cdftsel station 1 1 <su255.cdf> su255.abq
cdfcat hour 0 30 60 <su255.abq>su255.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su255.cat
pglj
```

```
cdfcat hour 0 30 60 <su257.abq>su257.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su257.cat
pglj

cdftsel date 22 22 <su88.cdf|cdftsel month 9 9> su266.cdf
cdftsel station 1 1 <su266.cdf> su266.abq
cdfcat hour 0 30 60 <su266.abq>su266.cat
cdfplot 6,22,x/-10,40,y/9,11,t/hour,temp,p/hour,dewpt,3,p < su266.cat
pglj

cdftsel date 10 10 <su88.cdf|cdftsel month 6 6> so162.cdf
cdftsel station 72365 72365 <su162.cdf> so162.abq
cdfuaplot pres temp dewpt upres u v < so162.abq
pglj

cdftsel date 11 11 <su88.cdf|cdftsel month 6 6> so163.cdf
cdftsel station 72365 72365 <su163.cdf> so163.abq
cdfuaplot pres temp dewpt upres u v < so163.abq
pglj

cdftsel date 5 5 <su88.cdf|cdftsel month 7 7> so187.cdf
cdftsel station 72365 72365 <su187.cdf> so187.abq
cdfuaplot pres temp dewpt upres u v < so187.abq
pglj

cdftsel date 8 8 <su88.cdf|cdftsel month 7 7> so190.cdf
cdftsel station 72365 72365 <su190.cdf> so190.abq
cdfuaplot pres temp dewpt upres u v < so190.abq
pglj

cdftsel date 9 9 <su88.cdf|cdftsel month 7 7> so191.cdf
cdftsel station 72365 72365 <su191.cdf> so191.abq
cdfuaplot pres temp dewpt upres u v < so191.abq
pglj

cdftsel date 28 28 <su88.cdf|cdftsel month 7 7> so210.cdf
cdftsel station 72365 72365 <su210.cdf> so210.abq
cdfuaplot pres temp dewpt upres u v < so210.abq
pglj

cdftsel date 9 9 <su88.cdf|cdftsel month 8 8> so222.cdf
cdftsel station 72365 72365 <su222.cdf> so222.abq
cdfuaplot pres temp dewpt upres u v < so222.abq
pglj
```

```
cdftsel station 72365 72365 <su245.cdf> so245.abq
cdfuaplot pres temp dewpt upres u v < so245.abq
pglj

cdftsel date 11 11 <su88.cdf|cdftsel month 9 9> so255.cdf
cdftsel station 72365 72365 <su255.cdf> so255.abq
cdfuaplot pres temp dewpt upres u v < so255.abq
pglj

cdftsel date 13 13 <su88.cdf|cdftsel month 9 9> so257.cdf
cdftsel station 72365 72365 <su257.cdf> so257.abq
cdfuaplot pres temp dewpt upres u v < so257.abq
pglj

cdftsel date 22 22 <su88.cdf|cdftsel month 9 9> so266.cdf
cdftsel station 72365 72365 <su266.cdf> so266.abq
cdfuaplot pres temp dewpt upres u v < so266.abq
pglj
```